ME 4131

Thermal Environmental Engineering Laboratory

Spring 2007

Instructors:
T.H. Kuehn
J.W. Ramsey

TAs:
Josh Rocklage
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ME 4131 Thermal Environmental Engineering Laboratory
Syllabus

Instructor:	Dr. J.W. Ramsey; ME 1100A 625-8390 jwramsey@me.umn.edu	Dr. T.H. Kuehn; ME 3101 C 625-4520 kuehn001@umn.edu
TA:	Josh Rocklage; ME 261 625-8523 rock0105@umn.edu	Nick Stanley; ME 362 625-1510 stan0332@umn.edu

Required text:

ME 4131 Thermal Environmental Engineering Lab Manual.

Reference texts:

- Kuehn, Ramsey, and Threlkeld. Thermal Environmental Engineering, 3rd ed., 1998
- McQuiston and Parker. Heating Ventilating and Air Conditioning, 6th ed., 2005
- Duffie and Beckman. Solar Engineering of Thermal Processes, 1991
- ASHRAE Handbook series

Grading distribution:

2 formal reports	30 % (10 % for draft, 5 % for revised final version)
5 informal reports	45 % (9 % each)
5 data sheets, 1 test	15 % (2.5 % each)
lab participation	5 %
pre-lab quizzes	5 %
Total	100 %

Due dates:

- Informal reports and data sheets are due one week after the completion of the lab, at the beginning of the next lab meeting.

- For formal reports, the first draft is due two weeks after the completion of the lab. The report will be returned with comments. The final draft of the formal report is due one week after the first draft is returned. No late final versions of the formal reports will be accepted.

- The following table shows the due dates and penalties for all reports:

Lab Day	Due Date	15% Penalty if received by:	No Credit:
Wednesday	following Wednesday	Monday after due date - 4 pm	after 4 pm Monday
Friday	following Friday	Wednesday after due date - 4 pm	after 4 pm Wednesday

The lab participation grade is determined by lecture attendance, participation in lab, and evaluations of each student by their group members. The peer evaluation will be done at the end of the semester.

Each student is responsible for his/her own work, i.e. any cases of plagiarism or copying of other reports will be treated as per the Student Conduct Code.

Working Together and Plagiarism

(from the AEM 4602 course website, used with permission from Tom Shield)

plagiarize

vt. [<L. *plagiarus*, kidnapper] to take (ideas, writings, etc.) from (another) and offer them as one's own. (source: *Webster's New World Dictionary of the American Language*, D. B. Guralnic, ed., William Collins Publishers (New York) 1979.)

Plagiarism is grounds for receiving an F in this class. You are assigned to do your laboratory experiment with a team. However, the contents of your report must be your original work. The following points may help clarify the situation:

- All of the text of your report must be your original writing with the exception of any direct quotes from sources that you clearly reference.
- All calculations must be performed by you. You may discuss data reduction with your lab partners and you may start from a common spreadsheet of raw data when the data is collected as a group. However, all analysis and comparisons to theory must be done by you individually.
- All figures presented in your report must have been prepared by you. Any exceptions to this must be clearly labeled as the work of others. Note that you are not allowed (by copyright laws) to copy the artwork (drawings, figures, photos, or plots) of others without permission. You may use a figure prepared by one of your lab partners, such as a drawing of the experimental apparatus, if you clearly cite the author.

ME 4131 - THERMAL ENVIRONMENTAL ENGINEERING LABORATORY SCHEDULE
Spring 2007

Week	Date	Lecture Date	Lecture Topic	Lab	Report	Report Due	
						# of Weeks	Date
1	Jan. 15 - Jan. 19	Jan. 16 JR TK	Introduction to class and experimentation used in course	**Read Appendix A: Data Acquisition prior to lab. A test on this material will be given at the beginning of next week's lab.** Lab tour, introduction to data acquisition system	N/A	N/A	N/A
2	Jan. 22 - Jan. 26	Jan. 23 JR	Fan performance and duct air flow measurements	Air Handling System Characterization	Informal	1	Jan. 31, Feb. 2
3	Jan. 29 - Feb. 2	Jan. 30 JR	Mixing of outdoor and return air, mixed air dampers, stratification	Mixing of Outdoor and Recirculated Air	Datasheet	1	Feb. 7, 9
4	Feb. 5 - Feb. 9	Feb. 6 JR	Psychrometrics, psychrometric chart, mass/energy balance	Psychrometrics: Heating and Humidifying	Formal	2	Feb. 21, 23
5	Feb. 12 - Feb. 16	Feb. 13 TK	Heat exchanger performance	Heat Exchanger Analysis	Informal	1	Feb. 21, 23
6	Feb. 19 - Feb. 23	Feb. 20 TK	Refrigeration: thermodynamic cycle analysis	Walk-in Cooler Part 1: Steady State Analysis	Datasheet	1	Feb. 28, Mar. 2
7	Feb. 26 - Mar. 2	Feb. 27 TK	Refrigeration: instrumentation and measurement	Walk-in Cooler Part 2: Transient Analysis	Informal	1	Mar. 7, 9
8	Mar. 5 - Mar. 9	Mar. 6 TK	Water chiller construction and instrumentation	Performance of a Small Refrigeration System	Datasheet	1	Mar. 21, 23
9	Mar. 12 - Mar. 16	Mar. 13	SPRING BREAK NO LECTURE -- NO LAB	N/A	N/A	N/A	N/A
10	Mar. 19 - Mar. 23	Mar. 20 JR	Solar energy, solar radiation instrumentation and measurement	Solar Radiation Measurements Part 1: Instrumentation	Datasheet	1	Mar. 28, 30
11	Mar. 26 - Mar. 30	Mar. 27 JR	Continue solar radiation material	Solar Radiation Measurements Part 2: ASHRAE Clear Day Predictions **Read Appendix D: Solar Radiation prior to lab.**	Informal	1	Apr. 4, 6
12	Apr. 2 - Apr. 6	Apr. 3 JR	Performance of flat plate solar collectors	Steady State Analysis of Flat Plate Solar Collectors	Formal	2	Apr. 18, 20
13	Apr. 9 - Apr. 13	Apr. 10 TK	Room airflow, local ventilation, flow visualization techniques	Airflow Visualization	Datasheet	1	Apr. 18, 20
14	Apr. 16 - Apr. 20	Apr. 17 TK	Particulate filtration, particle sampling and measurement	Filter Particle Removal Efficiency	Informal	1	Apr. 25, 27
15	Apr. 23 - Apr. 27	N/A	NO LECTURE Make-up labs if needed	N/A	N/A	N/A	N/A
16	Apr. 30 - May 4	N/A	NO LECTURE Make-up labs if needed	N/A	N/A	N/A	N/A
17	May 7 - May 11	N/A	FINALS WEEK	N/A	N/A	N/A	N/A

U of MN Department of Mechanical Engineering
Teaching Laboratory Safety Plan

Student Responsibility

You are responsible for knowing the operation procedures and the hazards of the materials you work with. Ask your professor; read the lab manual.

Know where your safety equipment is in the lab. Know where and what your resources are.

1. General Safety Information

General safety information will be available at www.dehs.umn.edu and for the Department of Mechanical Engineering at http://www.me.umn.edu/safety/.

If you have any question about safety, please feel free to send email to Mechanical Engineering Safety Committee, T. H. Kuehn, Chair, at me-safety@me.umn.edu.

2. General Emergency Procedure

Each laboratory larger than 1000ft^2 must have two unobstructed routes for emergency egress.

If you encounter an emergency such as a chemical or blood spill, please contact the Department of Environmental Health and Safety at **612-626-6002**. Evacuate the immediate area and alert others to the danger. Do not reenter contaminated room.

For exposure to bloodborne or other infectious pathogens, follow the procedures under "Needle Sticks."

For fire, personal injury and all other emergencies call 911. Use a hard wired University phone and remain on the phone if possible until emergency responders arrive. If using a cell phone, ask for the University of Minnesota dispatcher.

3. Chemical Procedures

All containers for chemical storage should be labeled appropriately. Liquid chemicals must be equipped with secondary containment. Gas cylinders are secured and stored appropriately.
Do not dispose of chemicals into sink or otherwise into the sewer system.
For hazardous waste disposal, please contact Melvin Chapin at ME180 mchapin@umn.edu.

4. Radioactive Materials Procedures

Students are not to handle radioactive sources in the laboratories expect under the guidance and supervision of instructor or TA.

All lab instructors using radioactive materials at the University of Minnesota must

- Complete required training modules; and
- Comply with the radiation policies and procedures of the university (contained in the Radiation Protection manual).

Training tapes can be viewed in Minneapolis in the Learning Resources Center (LRC) at the Biomedical Library in Diehl Hall. Or you can contact Mark Stolzenburg (ME 272, mstolz@me.umn.edu) for the radioactive training.

5. Laser Radiation Procedures

Student are not to move or adjust laser in the laboratories expect under the guidance and supervision of instructor or TA. Unexpected laser beams must be shrouded to prevent accidental beam reflection.

All instructors or TAs using Class 3b or Class 4 laser at the University of Minnesota must:

- Complete required training modules; and
- Comply with the radiation policies and procedures of the university (contained in the Radiation Protection manual).

For Class 3A and below laser, goggles are required for all students attending the lab.

6. Noise Extremes

Any laboratory operation that produces significant noise (100 decibels or greater) needs a hearing conservation program to protect students from excessive exposure, that is, exposure to significant noise for a 2-hour average duration.

7. Machine operation safety procedures

For machine tools used for teaching, the students and instructors must follow safety procedures for the specific class. A good safety plan is presented in ME3221.

For the machines in the ME student shop, contact Melvin Chapin in ME180 for safety and operation training before machine tools are used.

8. Laboratory-Specific Standard Operating Procedures

Each lab should prepare and post specific operating procedures for the equipment used in the lab. Emergency shut off procedures should be posted near the equipment and available near the door for emergency responders. Students should be given these written procedures prior to operating any equipment in a laboratory.

9. Personal Protective Equipment

Eye protection goggles are required for all students whose eyes may be exposed to physical hazards.

Lab coats or other similar clothing protectors are encouraged for all laboratory students.

Gloves made of appropriate material may be required to protect the hands and arms from thermal burns, cuts, or chemical exposure that may result in absorption through the skin or reaction on the surface of the skin.

Loose clothing, long hair, jewelry and other potentially hazardous items should be secured or removed prior to operating machinery.

Bare feet are not permitted in any laboratory. Sandals and open-toed shoes are strongly discouraged in all laboratories and are not permitted in any situation where lab coats and gloves are required.

center for writing

student writing support

Student Writing Support provides free writing instruction for all University of Minnesota students—graduate and undergraduate—at all stages of the writing process. In collaborative consultations, we help students develop productive writing habits and revision strategies.

student writing consultants

Our consultants are teachers of writing: graduate and undergraduate teaching assistants and professional staff. Some consultants specialize in working with non-native speakers, and others have experience with writing in specific disciplines.

consulting sessions

In one-to-one sessions, our writing consultants will help students—

- Get started on assignments
- Break through writer's block
- See their work from a reader's perspective
- Learn strategies for revising, editing, and proofreading
- Access writing resources

Look at our policies document (a pdf) to learn more about what to expect and how to get the most from your visit to the

Center.

computer lab

Through a generous grant from the CLA Student Information Technology Fees Committee, we have a sixteen-station eMac computer lab with ethernet connections and two laser printers for use on writing assignments, Internet research, & Internet-based library research.

- To reserve a computer in our lab, log on to the Lab Reservation System.
- For printing in the lab, we accept your UCard (you can load more money onto your UCard in the Language Center Multimedia Lab, 135 Jones Hall). Like other computer labs, we charge ten cents for each printed page.

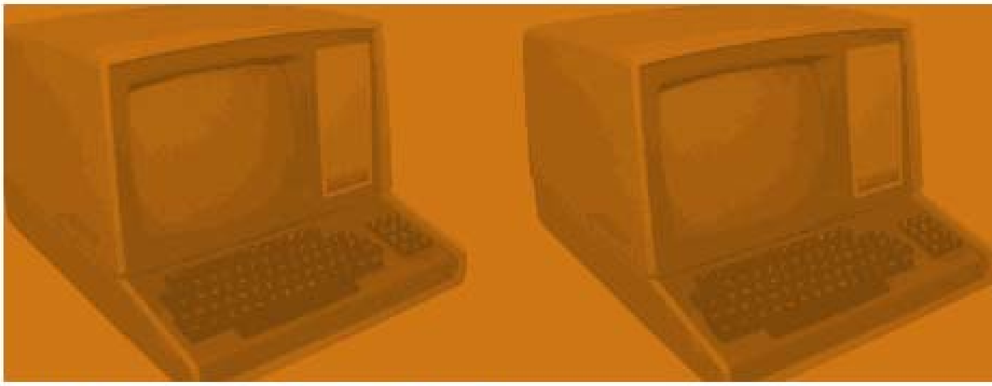
15 Nicholson Hall
216 Pillsbury Drive SE
Minneapolis, MN 55455

writing@umn.edu
appointments: 612.625.1893
information: 612.626.7579

THE OWL AT PURDUE

FREE WRITING HELP AND TEACHING RESOURCES. OPEN 24/7.

OWL



10 YEARS OF OWL 1995-2005

THE OWL AT PURDUE WELCOMES YOU

The original OWL at Purdue site can be found via this link. We're working hard to revise, update, and place all of our existing and brand-new material into this new version of the site.

Ongoing Updates at the Purdue OWL

Posted by Dana Lynn Driscoll on August 28th 2006 at 9:10AM.

We have been working hard to transfer our content and to polish the new Purdue OWL. We now have added a google search feature (viewable from the main page) and are working to refine our navigation system.

Updated and new content is appearing weekly on the Purdue OWL. Our **Using Appropriate Language**, **Paragraphing**, and **Pattern and Variation in Poetry** handouts have been moved to the new site with significant additions and revisions.

We have also recently transferred a number of handouts, including **Commas**, **Adding Emphasis**, **ASA Style**, and **Sentence Punctuation Patterns**.

NAVIGATION

- The Writing Process
- Professional, Technical, and Scientific Writing
- Job Search Writing
- General Academic Writing
- Research and Citation
- Grammar and Mechanics
- English as a Second Language (ESL)
- Literary Analysis and Criticism
- Writing in the Social Sciences
- Creative Writing
- Teaching Writing
- About the OWL at Purdue

http://owl.english.purdue.edu/owl

TABLE OF CONTENTS

INSTRUCTIONS

INTRODUCTION

In this course, various parameters associated with heating, ventilation, refrigeration, and solar energy equipment are measured. These parameters include temperature, flow rate, humidity content, electric power, and solar flux. The performance of the equipment is determined using these measured parameters. The performance could be in the form of a coefficient of performance, for example, for a refrigeration system. Some of the data is taken from manual readings of flow meters, pressure gauges, etc. However, an automatic data acquisition system is required for recording much of the data. This practice is common in industry.

This course also encourages the development of report writing skills and careful experimental technique. These skills are required in many engineering situations.

RESOURCES

The lab manual, syllabus, and laboratory equipment are the main resources. Read the relevant material in the manual before doing an experiment. Being well prepared in advance permits time to think about the results while the experiment is running and greatly facilitates the data analysis.

Lectures are given on some of the course topics. The lecture material covers the concepts that are employed in the laboratory during the following week.

The teaching assistant(s) and the course instructors are available by e-mail and at scheduled times for consultation.

COURSE REQUIREMENTS

Experiments: 12 experiments are performed in this laboratory. Data is analyzed according to the suggestions given for each lab in the manual.

Lab Notebook: Keep a bound lab notebook (sewn or spiral bound) with page numbers. For each experiment, record **in pen** the procedure that was followed, the data, and any observations.

Datasheets: For some of the experiments, the information requested is completed on a typed datasheet that is due one week after the lab period.

Informal Reports: Some of the experiments are written up as an informal report. The reports follow the format described in the **Informal Report** section and includes all the items on the **Informal Report Evaluation** sheet. Informal reports are typed and are due one week after the lab period.

Formal Reports: Two experiments are written up as formal reports. The reports follow the format described in the **Formal Report** section and include all the items on the **Formal Report Evaluation** sheet. The first draft of the formal report is due two weeks after the laboratory session. The final draft of the formal report is due one week after the first draft is reviewed and returned.

The data sheets, informal reports, and formal reports must cover all the **Report Requirements** listed at the end of each lab in the manual.

GRADING AND LAB ORGANIZATION: The grading and lab organization will be explained in the first lecture. These suggestions may be helpful:

1) Do the data analysis for each experiment carefully and completely. Do not rely on other lab members' work. If you understand the data analysis items, you have mastered much of the course material.
2) <u>Please do not eat or drink in the laboratory</u>. This prevents accidental spills on the equipment.

THE FORMAL REPORT

Formal reports are written for two of the laboratory experiments specified in the syllabus. Perform the experiments and complete the report requirements for that experiment given in the laboratory manual. The report must be typed. It must be neat and coherent.

Organize the report well and write with correct grammar in a clear, concise, easily understood style. Communicate clearly and efficiently to an audience that is **assumed to be unfamiliar** with this particular lab course. Assume the reader is a fellow engineering student who can follow a fairly sophisticated technical discussion, but is unfamiliar with the systems and equipment being studied. Inform the reader about the specifics of the experiment and the principles behind it. The lab manual may be referenced when appropriate. **Under no circumstances should any material be used without its origin being specified.**

To the extent possible, the formal report should simulate (in style, tone, and structure) the **Sample Formal Report** shown in the following pages. An outline of the report's structure, which is fairly standard, is given below. Lower case items are not headings. **Headings are in capital letters**. Lettered items are not headings either, but are simply descriptive labels for subsections of the report. The Introduction, Background/Theory, Methods, Results, and Discussion sections make up the **main body** of the report.

OUTLINE OF FORMAL REPORT

Title page

a. title
b. author's name
c. course
d. date of experiment

ABSTRACT

A summary of:

a. objectives
b. experimental methods
c. numerical results and other results
d. conclusion

TABLE OF CONTENTS

a. headings (including appendices)
b. page numbers

INTRODUCTION

a. purpose/overview
b. why important to field
c. objective(s) for this particular experiment

BACKGROUND/THEORY

a. basic principles studied
b. important governing equations
c. apparatus: understanding + description
d. schematic of apparatus

METHODS

a. procedure followed in obtaining results

RESULTS

a. description of results
b. important governing equations
c. tables and graphs presenting results
d. uncertainties
e. relevant comparisons with theory

DISCUSSION

a. brief review of results (if necessary)
b. discussion (trends in results, comparison with theory, answers to discussion questions in the Report Requirements)

CONCLUSION

a. summary of numerical results and other results
b. link with report’s objectives
c. summary of discussion and conclusions

APPENDICES

a. references
b. equipment list
c. sample calculations
d. uncertainty analysis
e. data acquisition program with a list of channel assignments
f. original data

ME 4131 - Formal Report Evaluation

Important!!!!

*Follow the directions given in the lab manual for the formal report.
*The formal report is typed except for the raw data and sample calculations.
*You are graded on the criteria listed below. Credit is given according to the percentages listed.

Section:	Topics	%	
(1) Title Page	Essential information. Title, author, course, date.	01	_____
(2) Abstract	Concise, informative for technical audience (i.e. other ME students). Gives objectives, methods, summary of numerical results, discussion, and conclusions.	10	_____
(3) Table of Contents	Presents an outline and the starting page of each section.	01	_____
(4) Introduction / Purpose	Gives introduction, purpose/overview, why important to field, objective(s).	05	_____
(5) Theory	Gives basic principles studied and governing equations.	06	_____
(6) Apparatus	Understanding and description.	03	_____
(7) Methods	Gives procedures used.	05	_____
(8) Results	Description of results, presents results in tables and graphs when appropriate, comparison with theory, governing equations, uncertainties.	12	_____
(9) Discussion	Review of results (if necessary), discusses trends, makes assumptions and/or comparisons, presents different aspects, draws conclusions supported by data.	12	_____
(10) Conclusion	Summary of results, links with report's objectives, summary of discussion and conclusions.	05	_____
(11) Appendices	Appropriately organized, sequenced, titled, and referred to in the body. References, equipment list, sample calculations, uncertainty analysis, DA program with channel assignments, original data.	12	_____
(12) Visuals	Appropriate and necessary to the report. Properly positioned, referenced, and labeled. Includes apparatus schematic, other pertinent diagrams and photos, tables, graphs, and plots.	07	_____
(13) Structure	Clearly organized in a logical structure as dictated by the report outline in the manual and shown in headings.	03	_____
(14) Paragraphs	Unified and coherent: fully developed yet fairly short. Built on an effective summary sentence at the beginning of each paragraph.	03	_____
(15) Coverage	Enough supporting evidence in the body that the audience can follow the report and accept the discussion and conclusions.	05	_____
(16) Audience Awareness	Information in abstract, body, and appendices appropriate to the audience (i.e. engineering peers).	03	_____
(17) Layout	Effective use of headings, white space, typefaces.	03	_____
(18) Mechanics / Style	Punctuation, spelling, and usage all correct. No typos. Readable sentences, appropriate use of terminology.	04	_____
		Total	_____ (/100)

SAMPLE FORMAL REPORT

Title Page:

Give the title of the report, the author's name, and the date the experiment was performed. The title should be specific and describe the work that was done. An example of the type of title expected is shown in Figure 1.

Calibration of Copper-Constantan and Iron-Constantan Thermocouples *Using Ice Point, Steam Point, and Tin Point References*

Figure 1: Sample Report Title

Do not title the report "Experiment 6 – Solar Collector", or something to that effect, as it does not tell the audience what was done. Do not give too general a title such as "Solar Collector", as this is more appropriate for a large work such as a book or treatise. A precise title helps orient the potential reader.

ABSTRACT:

The purpose of an abstract is to be read separate from the report, and often even in place of the report. It is a brief summary aimed at readers (your engineering peers) of the same familiarity with the technical subject as for the rest of the report. Write a one page abstract that concisely gives an overview of the objective, apparatus, methods, results, and discussion including conclusions of the experiment. Write an **informative abstract** as described in this section.

An example of an abstract is given in Figure 2. Notice that the first sentence does not begin with "The objective of this experiment is…" Instead, a definitive statement is made that implicitly indicates the objective. Again, be sure to include **numerical** results, as these are the heart of the findings. The information density required in an abstract is very great; take care in writing it.

Also notice that the sample abstract uses first person 'I' and 'we'. Unlike most abstracts that you may already have or will soon encounter, the abstract you are expected to write in this course is not intended for a larger, anonymous audience. Your readers are your course mates or fellow students who will take this course in the near future. It is, therefore, appropriate to use first person and to describe your actions during the experiment.

To familiarize ourselves with temperature measurement using thermocouples and computerized data acquisition, we performed the calibrations of a copper-constantan (Type T) thermocouple and an iron-constantan (Type I) thermocouple. The calibrations utilized the melting point of ice, the boiling point of water, and the melting point of tin as standard temperatures. We fit the date of electromotive force (emf) versus temperature to quadratic equations. We then plotted these equations for temperature ranging from 0^o to 235^oC.

The measured emf's at the tin point corresponded to temperatures of XXX.XX $\pm$ .13^{o}C (Type T) and XXX.XX $\pm$ .13^{o}C (Type J). The accepted temperature of the tin point is XXX.XX^{o}C. Therefore, the measured values deviated by .38% and .06% respectively. Similarly, the measured emf's at the steam point corresponded to temperatures XX.XX $\pm$ .13^{o}C (Type T) and XX.XX $\pm$ .11^{o}C (Type J). We calculated the actual temperature of the steam bath to be XX.XX^{o}C at 14.277 psi. Therefore, the measured temperatures deviated by 1.3% and 1.4% respectively.

Using the thermocouples, we measured the temperature of my fingertips to be XX.XX^{o}C (Type T and XX.XX^o (Type J). We used these data to demonstrate the Law of Intermediate Temperatures. The data fit the theory with less than 2% error.

Figure 2: Sample Informative Abstract

TABLE OF CONTENTS:

The Table of Contents is used by readers who want to quickly locate a particular portion of the report. It gives an outline of the sections in the report and the beginning page number of each section. The pages are numbered starting with the main body.

The main body of the report is comprised of five major sections: Introduction, Background/Theory, Methods, Results, and Discussion. Each of them is discussed separately below.

INTRODUCTION:

In this first section of the report's main body, the topic is introduced and defined. This section consists of two subsections: purpose and objective.

Purpose/Overview: This subsection provides a global overview of the subject matter. It contains a bird's eye view of how this topic is connected to other relative topics and stresses the topic's significance relative to these other topics. To write this section, review why the method in the experiment is so important to the field. **It is written in present tense**.

Temperature measurement is very often a critical aspect of engineering. However, temperature is one of the most difficult of all physical properties to measure. Fortunately, temperature can "be correlated with various objectively discernible changes in physical bodies" (Baker 1). These changes include volumetric expansion or contraction, change in resistance, or the production of an electromotive force. Temperature transducers such as thermometers, thermistors, and thermocouples convert these physical changes, respectively, to a measure of the temperature of a material whose physical properties may not show discernible change with change in temperature. However, these transducers must be calibrated to "known" temperatures, and the relationship between the input temperature and the output physical change must be found before they will be of service. The "known" temperatures are actually "fixed and reproducible equilibrium temperatures (fixed points) to which numerical values are "assigned" (Baker 6).

Figure 3: Sample Introduction Section

Objective(s): Here, describe in your own words what you are expected to do in the experiment. The objective section follows the instructions given in the lab manual very closely. But after conducting the experiment you may find that there is more information than you were initially asked for, in which case, expand upon the initial objective. **This section is written in past tense since it refers to the specific experiment you conducted.**

The purpose of this experiment was to calibrate a type T and type J thermocouple with reference to fixed temperature baths. Fixed temperature baths are used by the National Institute of Standards and Technology (NIST) to calibrate temperature sensors. The fixed temperatures that we used in our experiment were the freezing point of water, the steam point of water, and the melting point of tin. We also performed several exercises to gain an understanding of the basic operating principles of thermocouples.

Figure 4: Sample Objective Section

BACKGROUND/THEORY:

This section has two subsections: one is concerned with the theoretical background, the other with the operating principles of the device used. Enough theoretical background should be presented concerning the apparatus, experimental methods, and data reduction so that the reader is able to understand the rest of the report.

Basic principles studied: You are basically describing the knowledge acquired through this experiment. Do not give long derivations in the theory section. A few governing equations are usually sufficient to orient the reader. If a long derivation is necessary, put it in an appendix. Important equations are numbered. Be sure to give definitions of terms and units. A few sketches may be appropriate here. **Present tense is appropriate, since you are detailing generally accepted information**. An example of a theory section is given in Figure 5.

> ***Thermocouples***
> *The commonly used thermocouple is made up of two wires of dissimilar metals connected at two points called junctions. If these two junctions are connected in series, as shown in Figure 1, an electrical circuit is formed. When the two junctions are held at different temperatures, an electromotive force (emf) develops between the leads. Thermocouples do not actually measure the temperature but rather produce an emf that is a function of the difference in temperature between its junctions. As Liu discusses in the lab manual, "If one junction is held at a fixed temperature, usually 0°C, the thermocouple emf depends [only] on the temperature of the other junction" (3-1). In this case, a thermocouple can be used as a thermometer.*
> ***Law of Intermediate Temperatures***
> *One interesting aspect of thermocouples is the Law of Intermediate Temperatures. It states,*
>
> > *"If two dissimilar homogeneous metals produce a thermal emf E1, when the junctions are at temperatures T1 and T2, and a thermal emf of E2 when the junctions are at T2 and T3, the emf generated when the junctions are at T1 and T3, will be E1 + E2" (ASTM 14).*
>
> *This law allows us to use the thermocouple to measure the temperature of an object as long as the temperature of the reference junction is known. This is done by simply recording the emf of the thermocouple when one junction is at the known reference and the other is at the temperature to be measured. When this emf is added to the emf (from the thermocouple table) corresponding to the temperature of the known reference point, the sum of emf's will represent the emf of the temperature desired. The thermocouple table can then be used to find this temperature.*

Figure 5: Sample Background/Theory Section

Apparatus: The apparatus section has two parts to it. On the one hand, you are giving a generic theoretical description of the apparatus and how it is critical to the experiment. On the other hand, the apparatus can be part of the methods, where you specifically describe which parts of it were used in a particular portion of the experiment. For this second purpose, accurately identify the equipment used and tested (list all equipment details such as: make, model, and capabilities in an appendix); provide a schematic of the experimental set-up and a description of each piece of essential apparatus in the report body. Include accuracy, resolution, et cetera, when relevant.

When describing a piece of the apparatus or its basic principles, use present tense, **since what you are saying is always true. When you refer to the apparatus as it was specifically employed in the experiment, use past tense since you are talking about a one-time occurrence.** Note in the first sentence of the sample in Figure 6 that past tense is used to refer to the specific experiment. Sentences 2, 3, and 4, which describe the equipment in general, are written in present tense. Sentences 5 and 6 are, again, specifically referring to the experiment and are written in the past tense.

> *<u>Equipment Used for Tin Bath</u>*
> *Data acquisition for the Tin point measurement was done using a Nobilis data acquisition computer with a Pentium II processor connected to an HP3421A data acquisition system/control unit via an IEEE Interface Bus. The bus is responsible for input and output communication between the two. The HP3421A data acquisition system is capable of taking data from up to 30 independent inputs. The unit has an internal 5 ½-digit multimeter that can measure DC voltage, AC voltage, and resistance without the use of an external multimeter. It was assumed that this internal multimeter was accurate to 0.02% + 5 counts, the same accuracy as given for the HP3468A multimeter used for the other parts of this experiment (Liu 3-2 to 3-6). The data acquisition system was connected to the Type T and Type J thermocouples inserted into the top of the tin bath apparatus. A schematic of the experimental setup for the tin bath is shown in Figure 2.*
> ***Tin Bath Apparatus***
> *A schematic of the tin bath apparatus is shown in Figure 6. It consists of a heating coil connected to a variac voltage supply. The heating coil is wrapped around a slug of tin. The tin point is determined by observing when the emf data hardly deviates for a short time. This indicates the absence of temperature change during the phase change. The thermocouples to be calibrated were inserted in the top of the apparatus.*

Figure 6: Sample Apparatus Section

EXPERIMENTAL METHODS:

Here you identify the procedure that you followed in obtaining the results. You do not have to justify it, since it was given to you. The discussion of procedures should contain an expansion on the introductory remarks concerning the experimental approach. It should include a description of how measurements were made, noting special precautions for obtaining accuracy or controlling conditions. **Do not simply paraphrase the lab manual**, and do not include unimportant detail.

This section specifically refers to the experiment you conducted and, therefore, is written in the past tense. However, when referring to a graph or figure in the report, use the present tense. An example of an Experimental Methods section (partial) is given in Figure 7.

Notice that this procedure section does not contain a detailed step by step instruction list (as in the lab manual or a cookbook).

<u>Procedure</u>

The thermocouple experiment we performed consisted of three steps. First, the emf of the two thermocouples was measured at the tin point (1.5 hrs). Second, the emf was measured at the steam point (45 min.). Third, the Law of Intermediate Temperatures was demonstrated by making several measurements of emf's at different temperatures (10 min.).

<u>The Bath Procedure</u>

In the tin bath experiment, first the data acquisition system was turned on. We determined whether the bath was close to room temperature. We wanted the bath to start heating from room temperature to allow for a wide range of data points during heating of the tin.

Next, the data acquisition program was initialized. After the program has "booted up", we turned on the printer and the variac. A variac setting of 30 volts A.C. was used to heat the tin bath.

After the tin had reached its melting point (approximately thirty minutes after the variac was turned on), the computer requested that the variac be shut off. The system then cooled for another 30 minutes and the program was halted. The ADA then sent the tabulated data to the printer. A table and a graph of the data, (emf and time) for each thermocouple in the bath, was output to the printer (Appendix E).

<u>Steam Bath Procedure</u>

We started the steam bath experiment by setting up the apparatus and boiling the water. We added water to the steam bath until it was above the level of the heater. The steam bath had a mark for the top of the heater on its exterior. Then, we connected one of the thermocouples to the multimeter. Next, we placed the reference junctions in the ice bath. After we had set up the steam bath, we turned on the heater to bring the water to a boil. Reaching the boiling point was indicated by steam escaping through the vents on the bath. It was reached in about ten minutes.

The final step in the steam bath procedure was to measure the emf's produced by the thermocouples. We made ten measurements for each thermocouple (Appendix E). Each measurement was made after the multimeter was turned on and allowed to stabilize on a single reading.

<u>Fingertip Procedure</u>

We made three measurements of emf to check that the two thermocouples obeyed the Law of Intermediate Temperatures discussed previously (Appendix C). We made the first measurement with the reference junction in room air and the measuring junction between my fingers. We made another measurement with the reference junction in the ice bath and measurement between my fingers. We made the final measurement with the reference in the ice bath and the measurement at room temperature.

Figure 7: Sample Methods Section

RESULTS:

This section contains the results called for by the experimental objectives described in the introduction. Generally, you have two options to start this section: either jump right into presenting the results or create a transition between the procedure section and this section by describing how the results were obtained. If you did an excellent job describing how the tasks of the experiment were performed, it is unnecessary to relate the results to the particular part of the experiment that they came from (e.g. "Figure 1 shows the results of the calibration study."). You can simply use parallel subheadings in the Experimental Methods section and the Results section (see Figure 8). If the reader has any questions s/he can refer back to the Methods section to find out how you obtained the results.

Experimental Methods	***Results***
Tin Bath Measurements	*Tin Bath*
Steam Bath Measurements	*Steam Bath*
Etc.	*Etc.*

Figure 8: Parallel Structure of Experimental Methods and Results Sections

However, often a description of how results were obtained becomes necessary because the description of the experimental procedure was so extensive that it is not clear how a particular figure or table came about. It is unclear in which part of the experiment the data you are presenting originated. In this case, you should mention under what step in the experiment you gathered certain data.

If you did a very good job in the Experimental Methods section, all of the Results section can be in the present tense; after all, everything that you found is valid in general, not just for this specific experiment. If you do not separate methods and results very well, you will have to use a mixture of present and past tense because you will discuss the methods (past) and the results (present).

The actual results should be described in a logical sequential order. If uncertainty analysis is called for in the experiment, then the results of the uncertainty analysis are also presented in the Results section. Results and uncertainties are presented in graphs or tables dispersed among paragraphs of explanatory test and as close to the relevant text as possible. Again, make sure that you give the reader a general idea of how you obtained the results from the uncertainty analysis and what the trend of the data is. For a visual representation of the uncertainty, put error bars on the graph (see Figure 9). If the error analysis is simple, it may be discussed in an appendix with sample calculations.

Make sure that the axes of all graphs are labeled and that there are units on each axis. The sample graph in Figure 9 also includes a legend explaining the data that is represented. Scale the graph appropriately and include error bars whenever possible.

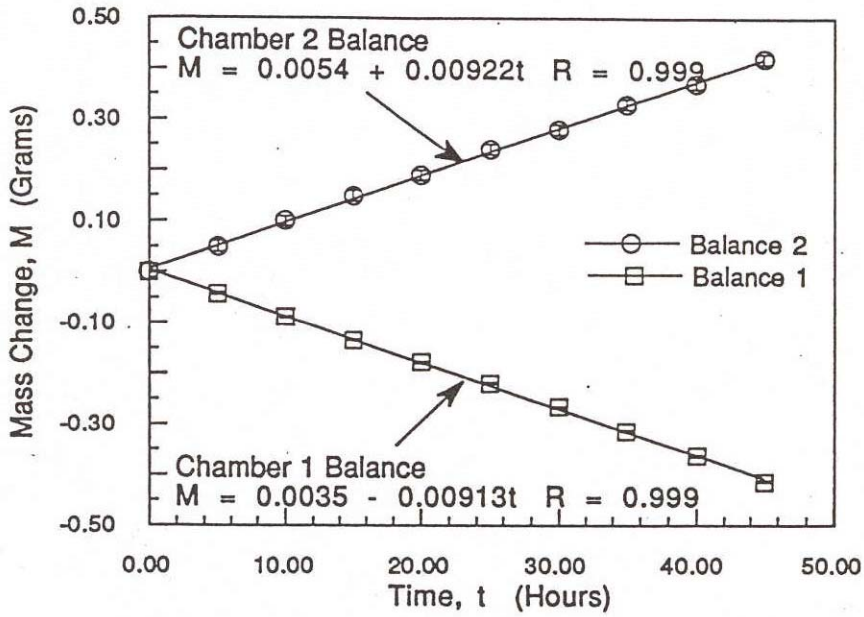


Figure 2 Plot showing the weight change of the balances on each side of a material sample as a function of time. The error associated with each of the balances is also shown.

Figure 9: Sample Figure Showing Plot with Results and Uncertainties

Relevant comparisons with theory are also included in this section. Include enough narration to adequately describe what is being presented, but keep the results section short and concise. A reader should be able to understand the general approach and the results after reading only the Introduction and Results section. These sections should not be overburdened with detail. Place intermediate results and sample calculations in appendices.

An excerpt from a Results section is given in Figure 10.

The Law of Intermediate Temperatures was confirmed by first recording the emf of the thermocouple while one junction was in the ice bath and the second was subject to room temperature. Then we recorded the emf while the first junction was subject to room temperature and the other was between my fingertips. Finally, we recorded the emf again while the first *junction was placed back into the ice bath and the other remained between my fingertips. The results are presented in Table 3.*

Table 3. Results from Law of Intermediate Temperature

Reference Junction	*Measure Junction*	*emf (mV)* *Type J*	*Type K*
Ice Bath	*Room Temperature*	*X.XXX*	*.XXX*
Room Temperature	*Fingertips*	*.XXX*	*.XXX*
Ice Bath	*Fingertips*	*X.XXX*	*X.XXX*

When applying the Law of Intermediate Temperatures to these data, one can see that the sum of the first two emf's in each column should equal the third emf in that column. The data from the Type J thermocouple demonstrates the law with an error of 1.9%. The data from the Type K thermocouple demonstrates the law with an error of only 1.2%. Considering the human variables (pressure exerted on junction, nervousness, etc.) the results are more accurate than expected.

Figure 10: Sample Results Section (partial)

DISCUSSION:

Again, you have two options here. You can write a separate Discussion section. This section should start with a review of the results that links the Discussion section with the preceding Results section. Or you can write a combined Results and Discussion section. Depending on the topic, you may have so many points to discuss that you will choose to combine results and discussion for greater continuity. The structure of the section will then look like this:

RESULTS AND DISCUSSION:

Results of Experiment 1
Discussion of Experiment 1
Results of Experiment 2
Discussion of Experiment 2
Results of Experiment 3
Discussion of Experiment 3
Etc.

Figure 11: Sample of a Combined Results and Discussion Section

If the results from individual experiments are substantial and require separate discussion, this combined Results and Discussion section will be a back-and-forth between a result followed by the discussion for that result and the next result followed by the discussion for it, etc. If the subsections are long enough, that is more than a few lines, subdivide the Results and Discussion section by using subheadings as suggested in Figure 11.

In either kind of Discussion section, conclusions are drawn with respect to the objectives of the experiment. Each conclusion is supported by specific reference to data and results. **Conclusions are not opinions. Conclusions are judgments that are supported by data.**

The Discussion section establishes the validity and accuracy of the results used to draw conclusions. Results of the error analysis are usually presented in the Results section; however, if the error analysis is complicated or subtle, it should be discussed in this section. Include the relevant equations and be sure to define the quantities that are used to determine the final uncertainty and explain how they were evaluated.

All of the Discussion section is in the present tense unless you are referring to specific instances of what you did in the experiment (past tense). An example of a Discussion section is given in Figure 12.

> ***DISCUSSION***
> *The calibration of a copper-constantan (Type T) thermocouple and an iron-constantan (Type J) thermocouple were successfully completed. The data obtained displays a relative error of less than .4% at the tin point and a relative error less than 1.4% at the steam point. The fit of the three data points was based on the prior knowledge that the output of a thermocouple is usually a quadratic function of temperature. It is this knowledge that makes this fit credible. However, better practice would be to use a platinum resistance thermometer with the thermocouple to obtain more data points at various temperatures. More data points would also allow the data to be fit to a polynomial up to the fifth degree, given at least six data points of extreme accuracy. The results indicate that the thermocouple emf is a quadratic function of temperature. The calibration equations were plotted for temperatures ranging from 0 to 235^{o}C. It is difficult to tell that the plots are not straight lines. The Law of Intermediate Temperatures was also demonstrated with the results fitting the theory with less than 2% relative error. This is quite good considering all of the human variables such as pressure exerted on the thermocouple or nervousness. An uncertainty analysis indicated that the fluctuations in the reading of emf for the tin point and steam point were the limiting factors in the precision of the calibration.*

Figure 12: Sample Discussion Section

CONCLUSION:

At the end of the report, summarize all the information you have just given to your reader in a short conclusion, link it with the report's objectives, and sum up the discussion of the results and conclusions.

APPENDICES:

The appendices contain supporting material that would be distracting if it were included in the body of the report:

- References
- Equipment list
- Sample calculations with formulas, substituted numerical values, and correct units
- Uncertainty analysis
- Data acquisition program with a list of channel assignments
- Original data (signed by you)

THE INFORMAL REPORT

The informal report, or short report, is more condensed than the formal report, but it is just as important. The writing style and audience for the short report are the same as for the formal report. The main difference is the sections that are omitted. An outline is given below.

Lower case items are not headings. **Headings are in capital letters**. Lettered items are not headings either, but are simply descriptive labels for the content of the report. The Introduction, Apparatus/Results, and Discussion sections make up the **main body** of the report.

OUTLINE FOR THE INFORMAL REPORT

Title page

a. title
b. author's name
c. course
d. date of experiment

INTRODUCTION

a. purpose/ overview
b. why important to field
c. objective(s) for this particular experiment

DESCRIPTION OF APPARATUS/RESULTS

a. apparatus: understanding + description
b. schematic of apparatus
c. procedure followed for obtaining results
d. important governing equations
e. description of results
f. tables and graphs presenting results
g. uncertainties
h. relevant comparisons with theory

DISCUSSION

a. brief review of results, if necessary
b. discussion (trends in results, comparison with theory, answers to discussion questions in Report Requirements section)
c. conclusions supported by data

APPENDICES

a. sample calculations
b. uncertainty analysis
c. data acquisition program with a list of channel assignments
d. original data

ME 4131 - Informal Report Evaluation

Important!!!!

*Follow the directions given in the lab manual for the informal report.
*The informal report is typed except for the raw data and sample calculations.
*You are graded on the criteria listed below. Credit is given according to the percentages listed.

Section:	**Topics**	**%**	
(1) Title Page	Essential information. Title, author, course, date.	02	_____
(2) Introduction / Purpose	Gives introduction, purpose/overview, why important to field, objective(s).	08	_____
(3) Apparatus	Understanding and description.	08	_____
(4) Results	Description of results, presents results in tables and graphs when appropriate, comparison with theory, governing equations, uncertainties.	16	_____
(5) Discussion	Review of results (if necessary), discusses trends, makes assumptions and/or comparisons, presents different aspects, draws conclusions supported by data.	16	_____
(6) Appendices	Appropriately organized, sequenced, titled, and referred to in the body. Sample calculations, uncertainty analysis, DA program with channel assignments, original data.	16	_____
(7) Visuals	Appropriate and necessary to the report. Properly positioned, referenced, and labeled. Includes apparatus schematic, other pertinent diagrams and photos, tables, graphs, and plots.	08	_____
(8) Structure	Clearly organized in a logical structure as dictated by the report outline in the manual and shown in headings.	04	_____
(9) Paragraphs	Unified and coherent: fully developed yet fairly short. Built on an effective summary sentence at the beginning of each paragraph.	04	_____
(10) Coverage	Enough supporting evidence in the body that the audience can follow the report and accept the discussion and conclusions.	05	_____
(11) Audience Awareness	Information in abstract, body, and appendices appropriate to the audience (i.e. engineering peers).	04	_____
(12) Layout	Effective use of headings, white space, typefaces.	04	_____
(13) Mechanics / Style	Punctuation, spelling, and usage all correct. No typos. Readable sentences, appropriate use of terminology.	05	_____
		Total	_____(/100)

NOTES ON REPORT WRITING

WRITING CONVENTIONS

Use 1 ¼ inch margins on the left side of the paper and 1 inch margins on the other three sides.

Double space the report, except long direct quotes, which may be single spaced.

Place illustrations (including graphs, tables, diagrams, and digital photos) close to the text they illustrate, on the same or following page whenever possible**. Material that is not original must be referenced.**

Avoid imprecise phrases. For instance, instead of “The error was very large…”, write “The error was 10%…”. Use quantitative descriptions whenever possible.

Do not use footnotes. Reference either by a number in square brackets, which is keyed to the reference list, or place the authors’ names and publication date in brackets in the text.

Don’t assume anything stated in the abstract is retained in the reader’s mind when writing the other sections. Ideally, write the abstract last, using the report as a reference.

Introduce and define each abbreviation. For example, “The flow rate was steady at 400 standard cubic feet per hour (SCFH).” After the first defining usage, use the abbreviation.

Define each variable, particularly in equations, or make a nomenclature list.

Introduce, define and discuss important terms in the Background/Theory section. This is how your understanding of the material is demonstrated.

All figures, tables, and graphs have numbers and titles together such as:
Table 1: Values of Temperature vs. Time for Three Flow Rates

Table titles appear above the table.

Figure and graph titles appear below the figure or graph.

Tables and figures are numbered separately: Table 1, Table 2, etc; Figure 1, Figure 2, etc.

GRAPHS

The formal and informal reports no doubt contain some visual aids such as graphs, tables, figures, etc. All visual aids in the report and in the appendices must be labeled and referred to in the text. Graphs are plotted according to the following guidelines.
Create graphs using the appropriate coordinate axes. These are:

Cartesian with linear divisions for equations of the type: $y = mx + b$,

log-log for equations of the type $y = ax^n$, and

semi-log for equations of the type $y = ae^x$.

Choose scales so that one division equals 1, 2, 4, 5, or 10 units or some power of ten times these values.

The independent variable is plotted on the abscissa (x-axis) and the dependent variable is plotted on the ordinate (y-axis).

Choose scales so that the resultant line makes an angle of 20^{O} to 60^{O} from the x-axis.

Label the names of the variables along the axes so they read from the bottom and from the left side. **Include units on each axis.**

Points determined experimentally are represented by a small circle, or if more than one curve is plotted on the same sheet, by small triangles, squares, or some other distinct symbol. Be sure that each curve is distinguishable, particularly if printing in color.

Curves plotted from equations have no indication of the calculated points.

The data obtained from the experiments in this course usually are related by some physical relationship. Therefore, the line representing this relationship is either a straight line or a smooth curve. Be sure to take note of and explain any data points that obviously do not fit the trend.

Do not extrapolate the lines beyond the data collected unless this can be justified in the report.

Present the title, labels on axes, and labels of plot lines in clear, concise language using standard engineering nomenclature. Do not use the variable in place of what it represents. For instance for a plot of velocity vs. time, do not use V vs. t. Variables represent different quantities in different situations. Remember the paper is being written for your engineering peers who are unfamiliar with this particular lab.

If the experiment involves the determination of an equation, show this on the graph.

REFERENCES

Markel, Michael H. 1988. Technical Writing Situations and Strategies. New York: St. Martin's Press.

Prepared with the help of Andreas Schramm.

Financial support for the revision of the formal and short report guidelines provided by a grant from the Center for Interdisciplinary Studies of Writing at the University of Minnesota.

Revised by Christi Saari 8/02

AIR HANDLING SYSTEM CHARACTERIZATION

I) Objective

The objective of this experiment is to determine the fan performance curves at two fan speeds and the duct system characteristic curve for the air handling system in the lab.

II) Background

References:

1) ASHRAE Handbook of Fundamentals, 1997, Ch. 14
2) ASHRAE HVAC Systems and Equipment Handbook, 1996, Ch. 18
3) Thermal Environmental Engineering, 3rd. ed., Kuehn, Ramsey and Threlkeld, Prentice Hall, 1998

Fan performance curves help in the design of an HVAC system by supplying the design engineer with information about how a fan will behave under different conditions. Using these curves, the correct fan can be selected which will provide the needed airflow when used with a given duct system.

The fan performance curves (see Figure 1 on the next page) illustrate the performance of the fan under different operating conditions. The fan characteristic curve, or fan pressure curve gives the pressure rise across the fan vs. the air flow rate through the fan at a given fan speed. Usually the pressure is the total pressure across the fan. Sometimes the static pressure rise is also given. Changing the rotational speed (rpm) of the fan changes the fan pressure curve. The fan power curve is a plot of the fan power requirement vs. flow rate for state points having the same fan speed. The fan power curve changes if the fan is run at different speeds. The mechanical power output by the fan is calculated by:

$$H_o = K_p \dot{V} \Delta P_t$$

where: H_o = mechanical power imparted to the air by the fan *(be sure to keep track of the proper units and convert to hp or watts)*

$\dot{V}$ = volumetric flow rate of air through the fan

ΔP_t = total pressure produced by the fan, $P_{t,\text{fan outlet}} - P_{t,\text{fan inlet}}$

K_p is a compressibility factor. If $\Delta P_t < 12$ in H_2O, then K_p is set equal to 1.

The fan efficiency is the ratio of the power imparted to the air to the mechanical power supplied to the fan.

$$\eta_t = H_o / \dot{W}$$

where: $\dot{W}$ = mechanical shaft power supplied to the fan

The system characteristic curve, or system curve gives the pressure drop through a duct system as a function of air flow rate. Note the curve passes through the origin (i.e. zero flow rate and zero pressure drop). The relationship between pressure drop and flow rate is quadratic so if only one point is known on the curve, the entire curve can be generated. The system or flow resistance changes if the duct system is changed (e.g., dampers are opened or closed). This changes the entire system characteristic curve.

In Figure 1, the balance point is the intersection of the fan pressure curve and the system characteristic curve. This is the operating point of the fan given the duct configuration in which it is operating.

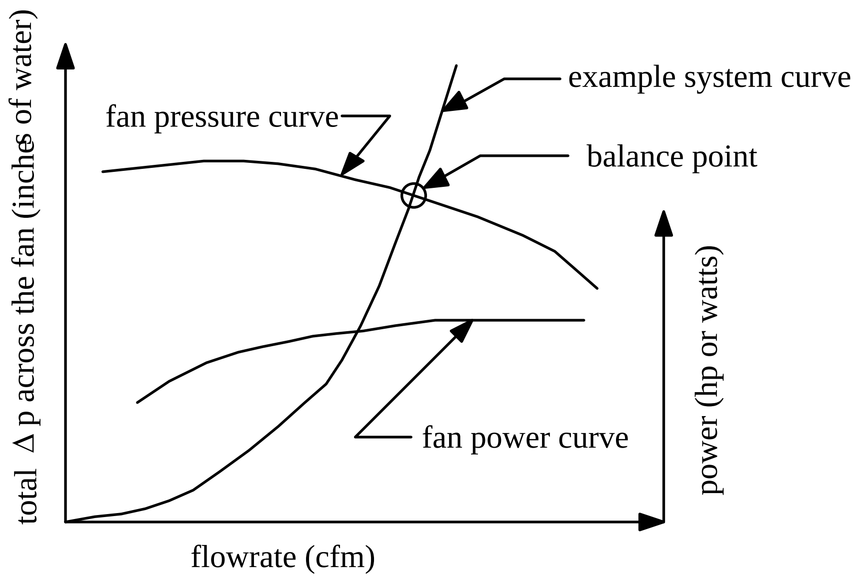


Figure 1: Sketch of fan pressure and system characteristic curves and fan power curve showing the balance point between the fan and the duct system.

Recall from fluid mechanics that the total pressure in a fluid stream is equal to the static pressure of the stream plus the velocity pressure:

$$P_t = P_s + P_v$$

P_S is measured easily with pressure taps and a manometer or a differential pressure gauge, but measuring P_V is difficult in field installations (like our air handling unit) because of physical constraints. Fortunately, P_V can be calculated if the flow rate and the area that the fluid is flowing through are known.

Airflows are measured several different ways. In the HVAC industry, the most common airflow measuring devices are pitot tubes, obstruction meters such as an orifice or a nozzle, and hot-wire anemometers (these methods can apply to other fluids besides air).

Pitot tubes: Pitot tubes measure the velocity pressure of a moving stream of air, which is converted to a velocity. A flow rate can be calculated if the average velocity in the duct is known.

Obstruction meters: Obstruction meters such as Venturi meters and flow nozzles create a pressure drop, which is measured and correlated to the mass flow rate passing through the meter.

Hot Film Anemometers: These anemometers measure electrical properties of a wire or sphere in a moving air stream. Generally, the wire is in one leg of a wheat stone bridge. The voltage needed to keep the wire at a constant temperature is measured, which is then correlated to the velocity of air going past the wire.

Rotating Vane Anemometers: These anemometers are also used to measure ambient wind speed at weather stations and consist of cups attached to a center shaft that rotates. The air speed is correlated to the rotation speed of the center shaft.

A pitot tube is used in this lab to measure airflow rates. Since the velocity of air in the duct may vary over the cross-section of the duct, it is necessary to measure the velocity in several different locations. This is called a traverse. Figure 2 shows the traversing scheme recommended by ASHRAE Standard 111 applied to the duct in the lab.

The average velocity, V_{avg}, is then calculated relatively easily:

$$V_{avg} = \frac{1}{30}\sum_{i=1}^{30} V_i$$

This more accurate procedure uses the log-Tchebycheff rule for rectangular or round ducts (See ISO *Standard* 3966 or ASHRAE *Standard* 111). This method locates the traverse points to account for wall boundary layer effects. At least 25 velocity measurement points are recommended (see p. 14.17 of Reference 1.)

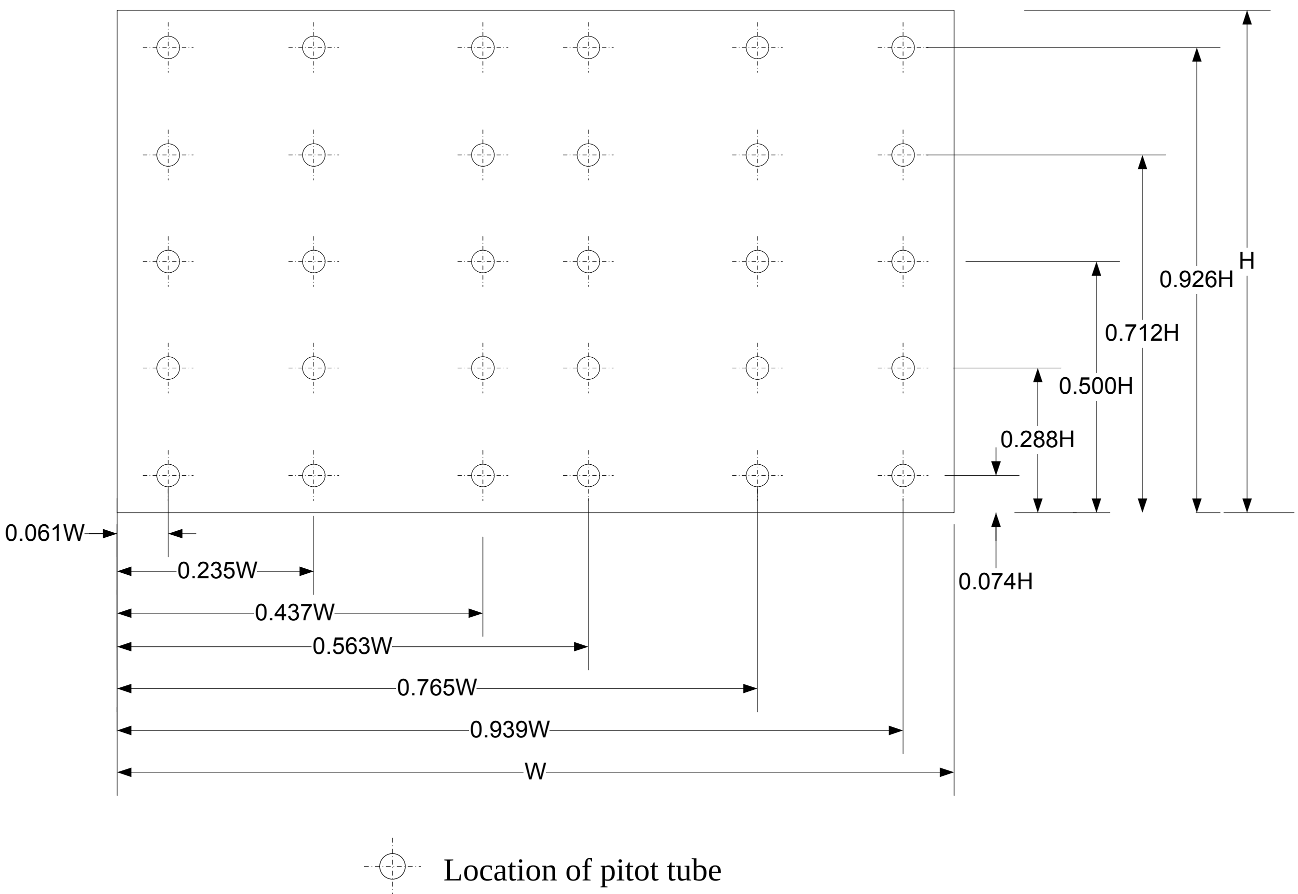


Figure 2: Cross-section of rectangular duct showing measurement locations

III) Procedure

1) Level and zero both manometers. At three different fan speeds (35 Hz, 45 Hz, 60 Hz) perform a pitot tube traverse at the upper end of the vertical duct of the air handling unit, and also measure the centerline velocity pressure. Do not change the position of the dampers in the duct system for these measurements.

2) The fan pressure curve for any given fan speed can be constructed as follows: at each flow rate, measure the static pressure at the inlet and outlet of the fan. Change the volumetric flow rate by opening (or closing) dampers on the ductwork. Opening or closing dampers changes the system characteristic curve and moves the balance point along the fan pressure curve. Record the electrical power supplied to the fan as read from the wattmeter.

Gather data to construct the fan pressure curves for the air handling unit fan at two different fan speeds. Make sure to record the fan speed for each test. Appendix C contains a calibration curve to obtain the fan speed from the frequency setting (i.e. rpm vs. frequency).

IV) Report Requirements

A) Calculate the centerline velocity, average velocity, and volumetric airflow rate, for each of the three fan speeds tested. Then plot average velocity as a function of centerline velocity (V_{avg} vs. V_{CL}). This is the velocity calibration curve for the downstream portion of the duct.

B) Plot the velocity profiles for each fan speed (35 Hz, 45 Hz, 60 Hz) on one graph. Determine if there are any similarities in them as far as some areas of the duct having higher or lower air velocities than other areas.

C) From data gathered in the second part of the experiment, plot the fan performance curves (total pressure rise vs. flow rate and mechanical power vs. flow rate) for both fan speeds (40 Hz and 60 Hz). Plot the electrical power vs. flow rate for each fan speed. Also plot the system curve for each system configuration (all dampers open to all dampers closed), using the balance points for each fan speed and the origin of the pressure vs. volumetric flow rate graph. Plot all curves on the same graph, using a secondary vertical axis for the mechanical and electrical power curves. Plot the curves in a manner similar to Figure 1.

D) For the points on the two fan pressure curves having the same system curve, do the calculations necessary to validate (or invalidate) Fan Law 1c (p. 18.4 of Reference 2):

$$\frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^5 \times \left(\frac{N_1}{N_2}\right)^3 \times \left(\frac{\rho_1}{\rho_2}\right) \qquad \text{[Fan Law 1c]}$$

where: H = mechanical power imparted to the air
N = fan speed (in rpm)
D = fan size (diameter of the impeller)
ρ = density of gas in which the fan is operating (usually air)

Compare these values to the electrical power supplied to the fan as read from the wattmeter. Explain any discrepancies.

E) Suppose the fan is operating at the higher of the two speeds tested and the duct system is operating with one damper closed. Now suppose that you want to reduce the volumetric airflow rate by a certain percentage. Compare the fan energy requirement using the following control strategies:

1) reducing the fan speed
2) closing more dampers (increasing system resistance and system pressure drop)

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY

Schematic of Air Handling System Apparatus--Locations of Interest

Number	Location		
1	Outdoor Air		
2	Return Air		
3	Mixed Air	upstream of filters	
4		downstream of filters	upstream of cooling coil
5	upstream of fan		downstream of cooling coil
6	downstream of fan	upstream of heating coil	
7		downsteam of heating coil	upstream of humidifier
8			downstream of humidifier
9	pitot tube measurement location		

For Labs:

- Air Handling System Characterization
- Mixing of Outdoor and Recirculated Air
- Heat Exchanger Analysis
- Psychrometrics: Heating and Humidification or Cooling and Dehumidification
- Filter Particle Size Removal Efficiency

Name ______________________________ Date ____________________

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY
Air Handling System Characterization Data Acquisition Sheet

Barometric Pressure __________ in. Hg

Air temp at pitot tube measurement location __________ °F

Part 1: Pitot traverse

wall

window

1	6	11	16	21	26
2	7	12	17	22	27
3	8	13	18	23	28
4	9	14	19	24	29
5	10	15	20	25	30

Velocity Pressures (in H_2O)

Location	35 Hz	45 Hz	60 Hz
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			
center			

Air Handling System Characterization Data Acquisition Sheet p. 2

Part 2: Fan Performance

Fan Speed = 40 Hz

Damper Position	Centerline Velocity Pressure (in. H_2O)	Static Pressure Rise [ΔP_s] across Fan (in. H_2O)	Electrical Fan Power (W)
All Open			
1 Closed			
2 Closed			
3 Closed			
All Closed			

Fan Speed = 60 Hz

Damper Position	Centerline Velocity Pressure (in. H_2O)	Static Pressure Rise [ΔP_s] across Fan (in. H_2O)	Electrical Fan Power (W)
All Open			
1 Closed			
2 Closed			
3 Closed			
All Closed			

Ductwork Dimensions:

Fan inlet area:	29 in x 22 3/4 in
Fan outlet area	25 1/4 in x 15 in
Pitot tube measurement area:	20 in x 12 in

MIXING OF OUTDOOR AIR AND RECIRCULATED AIR

I) Objective

Examine a mixed air process to determine the extent of stratification in the mixed air duct and also compare the measured average temperature to a mass average temperature known as the bulk temperature. Using a psychrometric chart we will see how close the actual mixed state is to theoretical 50/50 mixing.

II) Background

Outdoor air is required continuously to ventilate occupied spaces in commercial and institutional buildings. This ventilation air is used to control the concentration of airborne pollutants indoors by diluting them with cleaner outdoor air. The minimum amount of outdoor ventilation air that is required in a space is determined by ASHRAE Standard 62, "Ventilation for Acceptable Indoor Air Quality". This voluntary standard developed within ASHRAE has been incorporated by reference into many state building codes, including the Minnesota Energy Code, where it is an enforceable document. The outdoor air is introduced into a building through an outdoor air intake. The intake should be located away from contaminant sources such as roadways, loading docks and building exhaust stacks. The intake usually has a coarse screen to prevent birds and large debris from entering.

The disadvantage of bringing outdoor air into a building is that the air is usually not at the psychrometric conditions (i.e. temperature and humidity) desired in the building. In cold weather, this air requires heating and humidification. In hot weather, this air must be cooled and dehumidified. Thus there is an energy penalty associated with bringing in this outdoor ventilation air. Most of the time, the majority of the air distributed within a building is recirculated. The air returning from the building to the heating or cooling plant is at the desired indoor conditions so less energy is required to bring it to the supply air conditions than to treat outdoor air. This is not always true, however. There are certain times of the year when the outdoor air is just cool enough to provide the necessary cooling in the building without operating the cooling system. Under these conditions, the supply air can be all outdoor air. When the outdoor air conditions are near the yearly extreme values, only the minimum amount of outdoor air required is brought in to minimize the heating and cooling load on the mechanical equipment.

Most air handling systems are designed with mixed air dampers near the outdoor air intake. These dampers are controlled automatically in actual buildings to vary the amount of outdoor air brought in and the amount of air that is recirculated. The automatic control system monitors the outdoor temperature and humidity, or outdoor air enthalpy, and time of day to determine the amount of outdoor air that should be admitted. The remaining amount of air is recirculated. The damper positions are controlled by actuators that receive signals from the controller. Automatic dampers can be set to bring in any amount of return and outdoor air by adjusting the percent that the damper blades are open. However the relationship between percent open and flow is not linear. Figure 1 is an example of a damper characterization. Therefore if code required a minimum of 25% outdoor air at all times, the outdoor air dampers would need to have a minimum set-point of approximately 60%.

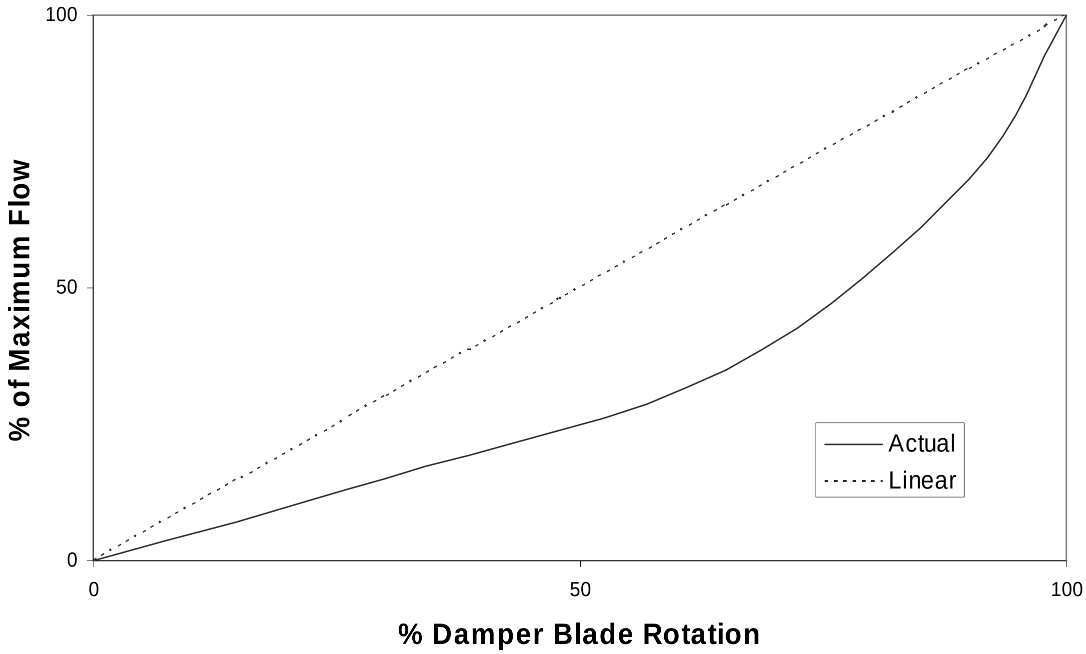


Figure 1: An example of a damper characteristic compared to a linear relationship.

The mixed air passes through a particulate air filter downstream of the mixed air dampers. Then the air can pass over a heating or cooling coil if the coils are located before the supply fan. One of the difficulties that arise in cold climates is the density difference that occurs between the outdoor air and the recirculated air. The cold, denser air tends to settle on the bottom of the mixed air duct. When its temperature is very low, this cold air can cause the lower portion of the coils to freeze. In an attempt to reduce this possibility, parallel blade dampers often direct the outdoor air and the recirculated air toward each other to reduce the possibility of stratification. If this low temperature air has a low flow rate, then it will have a minimum affect on the bulk air temperature.

The bulk air temperature is a mass average of the temperatures distributed throughout the duct cross-section. This bulk temperature may not agree with the temperature measured by the average temperature sensors because these averaging sensors do not account for air flow. These averaging sensors assume uniform flow throughout each cross section of the duct; however we know this not to be true from the Air Handling System Characterization lab.

III) Procedure

1) Run the fan with the frequency set at 60 Hz. Adjust the motorized damper positions to approximately 50% outdoor air and 50% return air.

2) Assemble instrumentation to measure the average temperature, velocity and relative humidity of the outdoor intake air, the room recirculated air and the mixed air. (See Appendix H for the channel assignment of the average temperature sensor.)

3) Measure the following parameters under conditions of approximately 50% outdoor air and 50% return air by setting the motorized damper positions manually:
   a) average velocity of outdoor and return air streams
   b) average temperature of outdoor and return air streams
   c) vertical temperature distribution of the mixed air
   d) vertical velocity distribution of the mixed air
   e) static pressure of the mixed air
   f) average velocity in the vertical section of duct downstream of the fan
   g) average temperature upstream of the filters

IV) Report Requirements

A) Describe the test facility used during these tests. Provide a sketch of the duct layout showing the intake ducts, dampers, fan, and measurement locations.

B) List the instrumentation used in the measurements. Explain how the readings were taken.

C) Comment on the agreement between the air mass flow rates as measured in the return air and outdoor air intake ducts and as measured in the downstream portion of the duct (pitot tube measurement location).

D) Provide plots of the vertical temperature profiles in the mixed air duct for all the tests conducted on one graph. Comment on this profile. Is there stratification in the duct? Provide plots of the velocity profiles in the mixed air duct for all of the tests conducted on one graph. Find the Bulk Temperature of the flow at the mixed air position. How does this calculated bulk temperature compare with the measured mixed air temperatures in the duct?

E) Suggest a better method of mixing the air streams in a real building where the mixed air duct dimensions are 10 ft x 10 ft.

F) Assume perfect mixing (50% return air and 50% outdoor air) for the 60 Hz fan speed setting. Show the return air, outdoor air, actual mixed air, and theoretical mixed air state points on a psychrometric chart. Compare this theoretical mixed air state assuming perfect mixing with the actual mixed air state. How much mixing of outdoor and return air occurred in the actual process?

Name ____________________

Date ____________________

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY
Air Mixing Data Acquisition Sheet

Barometric Pressure: ________ in. Hg

RA 50% open
OA 50% open

60 Hz.	**Window**		**Middle**		**Roomside**	
Position	T (°F)	P_v (in. H_2O)	T (°F)	P_v (in. H_2O)	T (°F)	P_v (in. H_2O)
10						
9						
8						
7						
6						
5						
4						
3						
2						
1						

Position	T (°F)	RH (%)
RA, 1		
OA, 2		
Mix, 3		

T_9 ________ °F

P_{T9} ________ in. H_2O

P_{v9} ________ in. H_2O

P_{S9} ________ in. H_2O

	$P_{V,OA}$ (in. H_2O)
average	

	$P_{V,RA}$ (in. H_2O)
average	

	$P_{V,OA}$ (in. H_2O)
average	

HEAT EXCHANGER ANALYSIS

I) Objective

To obtain the overall heat transfer coefficient (U-value) for the hot water heat exchanger under various fluid conditions.

II) Background

Reference text:

Thermal Environmental Engineering, 3rd edition, Chapter 11. Kuehn, T. H., Ramsey, J. W. and Threlkeld, J. L.

Heat exchangers are used extensively in HVAC applications to transfer energy from one fluid to another. A simple example of such a device is a cross flow hot water heat exchanger in an air duct. The device is simply a copper tubing network for hot water flow with aluminum fins attached that increase the heat transfer effectiveness of the device. The heat exchanger is mounted in the flow path and is designed to limit the air side and water side pressure drops.

Heat exchanger analysis is quite complicated and involves flow parameters and geometry quite heavily. Some simpler methods of analysis are the Log-Mean Temperature Difference (LMTD) method and the Number of Transfer Units (NTU) method. These methods will be described in class.

The liquid line contains a water and ethylene glycol mix (Dowtherm SR-1). A table of DowTherm SR-1 fluid properties is located in Appendix F.

III) Data Acquisition Procedure

Write a simple data acquisition program to measure the air and water inlet and outlet temperatures and the water volumetric flow rate. Set the fan speed to 40 Hz and the water pump speed to low. Monitor the system using the computer program until steady state is reached. Determine the airflow rate using the pitot tube. Measure the air and water side pressure drops across the heat exchanger. Repeat this procedure after increasing the fan speed to 60 Hz. Repeat the previous two trials after increasing the water flow rate to the high setting.

IV) Data Reduction Procedure for the NTU method

a) Determine which fluid has the smaller fluid capacity rate, $c_{\min} = \left(\dot{m}c_p\right)_{\min}$

Note: $\left(\dot{m}c_p\right)_{\min} \Delta t_{\max} = \left(\dot{m}c_p\right)_{\max} \Delta t_{\min}$

b) Compute the fluid capacity ratio, c_r

$$c_r = \frac{c_{\min}}{c_{\max}}$$

c) If the $c_{\min}$ fluid is the air (unmixed) use:

$$\varepsilon = \frac{\left(t_{c,o} - t_{c,i}\right)}{\left(t_{h,i} - t_{c,i}\right)}$$

and

$$\varepsilon = \frac{1}{c_r}\left\{1 - \exp\left(-c_r\left[1 - \exp\left(-NTU\right)\right]\right)\right\}$$

If the $c_{\min}$ fluid is the water (mixed) use:

$$\varepsilon = \frac{\left(t_{h,i} - t_{h,o}\right)}{\left(t_{h,i} - t_{c,i}\right)}$$

and

$$\varepsilon = 1 - \exp\left[-\frac{1}{c_r}\left(1 - \exp\left[-NTU\left(c_r\right)\right]\right)\right]$$

d) Solve for NTU from the appropriate equations from part c.

e) Determine the heat exchanger total external surface area, A_o

f) If the $c_{\min}$ fluid is the air:

$$U_o = NTUc_{air} / A_o$$

If the $c_{\min}$ fluid is the liquid:

$$U_o = NTUc_{liquid} / A_o$$

V) Report Requirements

A) Calculate the amount of heat transferred to the air and the amount of heat transferred from the water for each case. How do they compare? Comment on the efficiency of the heat exchanger.

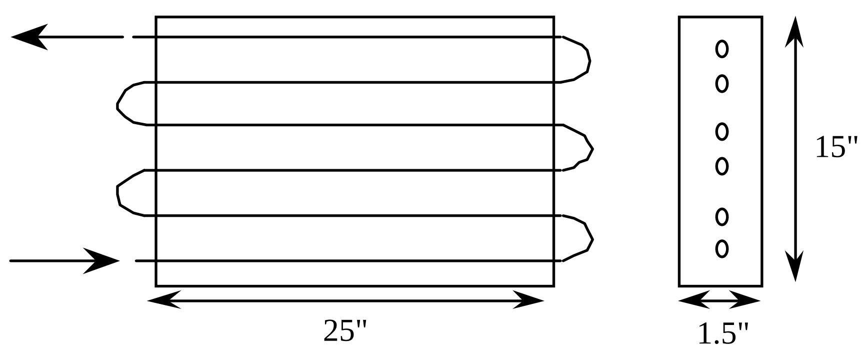
B) Calculate the U-value for the heat exchanger under the four tested conditions using the NTU method. The heat exchanger is a cross flow type with the air unmixed and the water mixed. The procedure for this calculation is outlined above. Comment on the relative magnitudes of the U-values calculated.

C) Compare the pressure drops on the air side and water side of the heat exchanger under the four tested conditions. What are the trade-offs between frictional losses, overall heat transfer coefficient, and the amount of energy delivered to the air?

D) For the fan speed of 40 Hz and high water pump speed, what is the outlet air temperature ($T_{air,out}$) for an inlet air temperature of $50^{o}F$ ($T_{air,in} = 50^{o}F$) and a water/glycol temperature drop of $10^{o}F$ ($\Delta T_{water} = 10^{o}F$)? Calculate this temperature using an energy balance on the heat exchanger.

E) Now, suppose the outlet air temperature is $5^{o}F$ less than the desired value. Think of four different ways to make the outlet temperature reach the desired value without changing any of the hardware of the system (i.e. ducts, heat exchangers, insulation, etc.)

Heat Exchanger Geometrical Analysis



Number of copper tubes passes:	6
Tube outside diameter:	5/8"
Fin length:	1.5"
Fin pitch:	6 / inch
Duct dimensions:	15" x 25"
Fin thickness:	0.04”

Heat Exchanger Data Acquisition Channel Assignments

Refer to Appendix H for sensor channels.

Reference Junction Voltage

V_{ref} should be added to all thermocouple voltage readings.

Thermocouple calibration

$$T\ (°C) = Y0 + Y1*v + Y2*v^2 + Y3*v^3 + Y4*v^4,$$

where: v is in μV.

$Y0 = 0\ °C$

$Y1 = 0.02603\ °C/\mu V$

$Y2 = -9.164\ e\ -7\ °C/\mu V^2$

$Y3 = 1.0\ e\text{-}10\ °C/\mu V^3$

$Y4 = -7.7\ e\text{-}15\ °C/\mu V^4$

Volumetric Air Flow Rate

Use the same pitot tube procedure as in previous experiments.

Air and Water Side Pressure Drop

Use the manometer that was used for measuring static pressure across the fan in the Air Handling Characterization lab to determine the air side pressure drop.

Use the Omega pressure gauge on the wall to determine the water side pressure drop.

Humidity Ratio

Use the electric psychrometer and the psychrometric chart to determine the humidity ratio of the air.

Water Volumetric Flow Rate

Measure the frequency from the Sponsler turbine flow meter (SP1/2-21DG-AN, S/N M2082), located on channel 19. The flow meter calibration is:

$$\text{Flow Rate (GPM)} = -0.2034 + 0.0087*f - 1.0e\text{-}6*f^2$$

where: f is the frequency in Hertz.

Name: ____________________

Date: ____________________

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY
Heat Exchanger Data Acquisition Sheet

Barometric Pressure ____________________ in. Hg

		40 Hz/Low	40 Hz/High	60 Hz/Low	60 Hz/High
Air Side	Air Inlet Temperature (°F)				
	Air Outlet Temperature (°F)				
	Air Static Pressure Drop Across HX (in. H_2O)				
	Air Temperature at Pitot Tube Location (°F)				
	Centerline Velocity Pressure (in. H_2O)				
	Relative Humidity at Pitot Tube Location (%)				
Water Side	Dowtherm SR-1 Inlet Temperature (°F)				
	Dowtherm SR-1 Outlet Temperature (°F)				
	Dowtherm SR-1 Inlet Pressure (psig)				
	Dowtherm SR-1 Outlet Pressure (psig)				
	Dowtherm SR-1 Rotameter Flow Rate (GPM)				
	Dowtherm SR-1 Turbine Meter Flow Rate (GPM)				

PSYCHROMETRICS: HEATING & HUMIDIFYING
or COOLING & DEHUMIDIFYING

I) Objective

The objective of this experiment is to examine the state of moist air as it enters and passes through the air handling unit. When weather conditions permit, the process investigated is cooling with dehumidification. During cooler, dryer times a heating and humidifying process is investigated. Based on measurements of air dry-bulb temperatures, humidity levels and flow rates it is possible to evaluate both the sensible and latent energy changes that the air undergoes as it passes through the process.

II) Background

A psychrometric chart provides a convenient way to look at the processes. In the charts shown below, the processes begin at state 1. The enthalpy values on the psychrometric charts are specific values, i.e. they are per unit mass (for convenience, they are customarily expressed in terms of unit mass of dry air).

Heating/humidifying:
In the heating/humidifying process the air first passes through a heat exchanger and then through the humidifier where steam at a mass flow rate of up to 25.7 lbm_w/hr and specific enthalpy h_w is sprayed into the air stream. The heating and humidification of the air is best considered by looking at the two processes sequentially. The first, from state 1 to state 2, is the sensible heating that occurs when the air passes through the heat exchanger. The second, from state 2 to state 3, is the humidification process.

During the sensible heating process the rate of energy added to the moist air, ${}_1\dot{Q}_2$, is written as:

$$ {}_1\dot{Q}_2 = \dot{m}_a\left(h_2 - h_1\right) \qquad \text{Eqn. 1} $$

where: h_1= the specific enthalpy of the moist air upstream of the heating coil
h_2= the specific enthalpy of the moist air downstream of the heating coil (and upstream of the humidifier.)
$\dot{m}_a$ = the mass flow rate of dry air through the process.

In the humidification process the energy equation is:

$$ \dot{m}_a\left(h_3 - h_2\right) = \dot{m}_w h_w \qquad \text{Eqn. 2} $$

where: h_3= the specific enthalpy of the moist air downstream of the humidifier
h_w= the specific enthalpy of the steam
$\dot{m}_w$ = mass flow rate of the steam

The rate of moisture addition to the air, $\dot{m}_w$, is determined by a water vapor mass balance:

$$\dot{m}_w = \dot{m}_a (W_3 - W_2) \qquad \text{Eqn. 3}$$

where: W_2= humidity ratio of the moist air upstream of the humidifier
W_3= humidity ratio of the moist air downstream of the humidifier

Combining these equations leads to the result:

$$\frac{h_3 - h_2}{W_3 - W_2} = h_w \qquad \text{Eqn. 4}$$

where the left side of the equation represents the slope of the humidification process on a psychrometric chart. Thus the direction of the process can be determined from the enthalpy of the steam added to the air stream and the enthalpy – moisture protractor on a psychrometric chart.

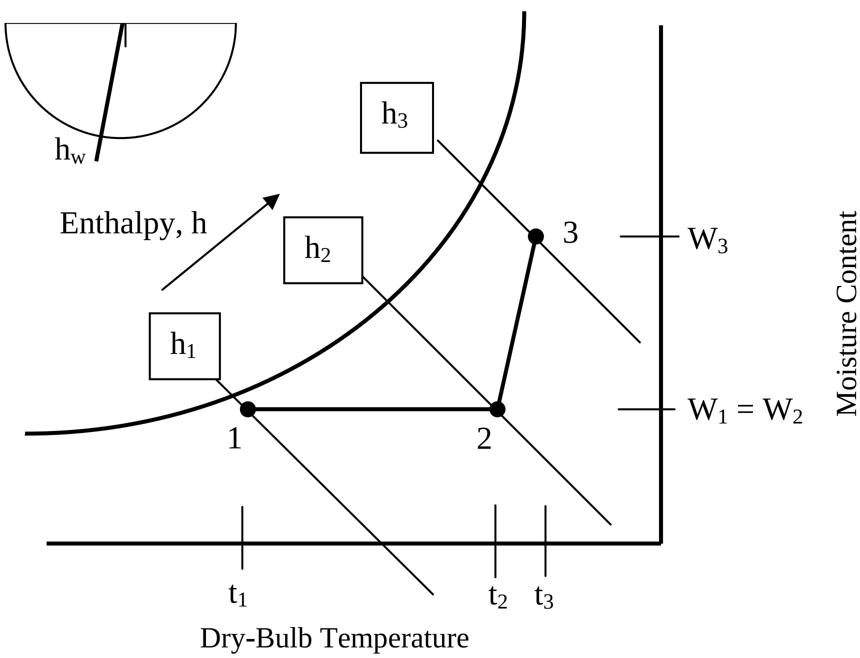


Figure 1: Heating and Humidifying

Cooling/dehumidifying

The cooling and dehumidifying process is shown in Figure 2. It begins at state 1 and ends at state 2. The refrigeration capacity required to accomplish this, $\dot{Q}_R$, is obtained from the energy balance:

$$\dot{Q}_R = \dot{m}_a \left[(h_1 - h_2) - (W_1 - W_2) h_{f,2} \right] \qquad \text{Eqn. 5}$$

where $h_{f,2}$ is the enthalpy of saturated liquid at temperature t_2. The second term in the square bracket is the enthalpy associated with the liquid condensate as it runs out of the cooling coil. This term is small compared to (h_1-h_2) which is the enthalpy difference to cool the air and condense the water. The approximation is often made where the process is divided into sensible, (S), and latent, (L), components.

$$\dot{Q}_{RS} = \dot{m}_a \left(h_2 - h_a\right) \quad \text{and} \qquad \text{Eqn. 6}$$

$$\dot{Q}_{RL} = \dot{m}_a \left(h_a - h_1\right) \qquad \text{Eqn. 7}$$

Then $\dot{Q}_R \cong \dot{Q}_{RS} + \dot{Q}_{RL}$ Eqn. 8

The sensible heat ratio for the process is then: $SHR = \dfrac{\dot{Q}_{RS}}{\dot{Q}_{RS} + \dot{Q}_{RL}}$ Eqn. 9

The rate at which moisture is removed from the air is:

$$\dot{m}_w = \dot{m}_a \left(W_1 - W_2\right) \qquad \text{Eqn. 10}$$

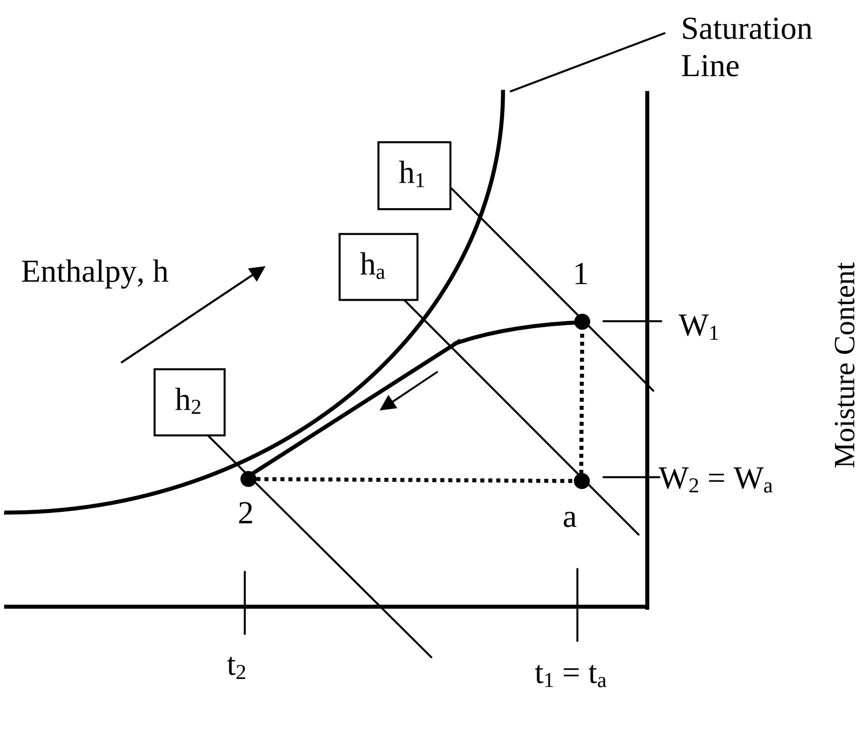


Figure 2: Cooling and Dehumidifying

A dew point hygrometer is used to measure the dew point temperature of the air. This instrument uses a thermoelectric refrigeration module to cool a highly reflective plate until condensation forms. A light source shines on the plate and when condensation occurs, the reflected intensity measured by a photosensor drops significantly. The instrument then maintains the plate at the dew point temperature through a feedback control system.

III) Procedure

Write a simple data acquisition program to measure the air dry-bulb temperatures. Set the speed of the fan to 45 Hz. Measure the velocity pressure and determine the volumetric airflow rate. Measure the dry bulb and dew point temperatures necessary to determine the heating and humidifying or cooling and dehumidifying processes. Also, measure the dry bulb and wet bulb temperatures needed to locate any mixing process at the inlet to the air handling unit.

Refer to Appendix H for channel assignments of instruments and calibration relationships.

IV) Report Requirements

A) Draw a schematic of the system and label all the equipment, processes, and state points.

B) Using the notation selected in part A, locate the air state points to describe the mixing process, (if any), and either the heating and humidifying processes or the cooling/dehumidifying process on the psychrometric chart at steady state. Clearly draw and label all the process paths on the chart.

C) Tabulate the dry bulb temperature, wet bulb temperature, dew point temperature, humidity ratio, enthalpy, relative humidity, and specific volume for each of the moist air state points.

D) Estimate the error in each value listed in part C.

E) Calculate the mass flow rates of dry air and water vapor at all state points.

F) For the heating and humidifying process do the following:

- Compare the calculated mass flow rate of the steam injected by the humidifier with the value indicated on the humidifier's key pad/digital display.
- Compare the slope of the process line for the humidifier with the value predicted by Equation 4.
- Calculate the sensible heat gain for the heating coil and fan processes.

For the cooling and dehumidifying process do the following:

- Calculate the total, sensible, and latent cooling rates across the cooling coil.
- Calculate the sensible heat ratio for the cooling/dehumidifying process.
- Determine the apparatus dew-point temperature of the coil
- Estimate the error if one neglects the condensate term in the equation for $\dot{Q}_R$.
- Calculate the rate of sensible heat added to the air from the fan.

Name ____________________ Date __________

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY
Psychrometrics Data Acquisition Sheet

Barometric Pressure ____________ in. Hg
Centerline Velocity Pressure ____________ in. H_2O
Fan Frequency ____________ Hz.

Cooling Coil Temperature (cooling and dehumidification) ________________ °F

Location	State Point	Measurement	Measurement Device	Channel	Units	Value
Power Supply for Avg. Temp. sensors	N/A	Power Supply	Power Supply	10	V	
Outdoor Air	1	Dry bulb temp	Aspirated psychrometer	N/A	°F	
	1	Wet bulb temp	Aspirated psychrometer		°F	
	1	Dry bulb temp	Vaisala		°F	
	1	Relative humidity	Vaisala		%	
	1	Dry bulb temp	Type K		°F	
	1	Dewpoint temp	Dewpoint hygrometer		°F	
Return Air	2	Dry bulb temp	Aspirated psychrometer	N/A	°F	
	2	Wet bulb temp	Aspirated psychrometer		°F	
	2	Dry bulb temp	Vaisala		°F	
	2	Relative humidity	Vaisala		%	
	2	Dry bulb temp	Type K		°F	
	2	Dewpoint temp	Dewpoint hygrometer		°F	
Mixed Air Upstream of Filters	3	Dry bulb temp	Avg. temperature sensor	11	°F	
	3	Dewpoint temp	Dewpoint hygrometer	N/A	°F	
	3	Dry bulb temp	Vaisala	N/A	°F	
	3	Relative humidity	Vaisala		%	
Mixed Air Upstream of Cooling Coil	4	Dry bulb temp	Avg. temperature sensor	11	°F	
	4	Dewpoint temp	Dewpoint hygrometer	N/A	°F	
Air Downstream of Cooling Coil	5	Dry bulb temp	Avg. temperature sensor	12	°F	
	5	Dewpoint temp	Dewpoint hygrometer	N/A	°F	
Air Upstream of HX	6	Dry bulb temp	Avg. temperature sensor	12	°F	
Air Downstream of HX	7	Dry bulb temp	Avg. temperature sensor	13	°F	
Air Downstream of Humidifier	8	Dry bulb temp	Avg. temperature sensor	14	°F	
Pitot Tube Location	9	Dry bulb temp	Vaisala	N/A	°F	
	9	Relative humidity	Vaisala		%	
	9	Dry bulb temp	Avg. temperature sensor	14	°F	
	N/A	Ref. Junction Voltage	Type T TC with Cold-Junction Compensator	15	V	
Humidifier Steam	N/A	Steam Temperature	Type T TC	16	°F	

FILTER PARTICLE SIZE REMOVAL EFFICIENCY

I) Objective

Measure the particle removal efficiency vs. particle size for two types of filters or air cleaners: an electrostatic air cleaner and a cartridge-type media filter.

II) Background

Particulate air filters are used in buildings to remove particles from air streams. Traditionally they were used to reduce the particle concentration in the HVAC system to prolong the life of the equipment and to reduce maintenance costs. Presently, these filters are primarily used to control the particle concentrations in the indoor air for improved indoor air quality.

Particles are found in a wide range of sizes. Figure 1 shows typical size ranges in microns for various particles. Those larger than about 10 microns have settling velocities larger than 1 cm/sec. These particles do not remain airborne very long and tend to settle out on the bottom of ductwork and floors of the building. Particles with smaller sizes can remain airborne for extended periods and can be transported within the building along with air currents unless physically removed.

Two types of particulate air filters are commonly used in building air handling systems; fibrous media filters and electronic air cleaners. Media filters capture large particles through the mechanisms of inertial impaction and interception when the momentum of the particle causes its path to deviate from the streamline around a fiber. This phenomenon is shown in Figure 2. The small particles have small inertia so they will follow the streamlines. However they also diffuse rapidly toward surfaces with low concentration such as surfaces of fibers where they are captured. Media filters are used in both residential and commercial air handling equipment and are found in a wide variety of forms including replaceable cartridges, bag filters and HEPA (high efficiency particulate air) filters.

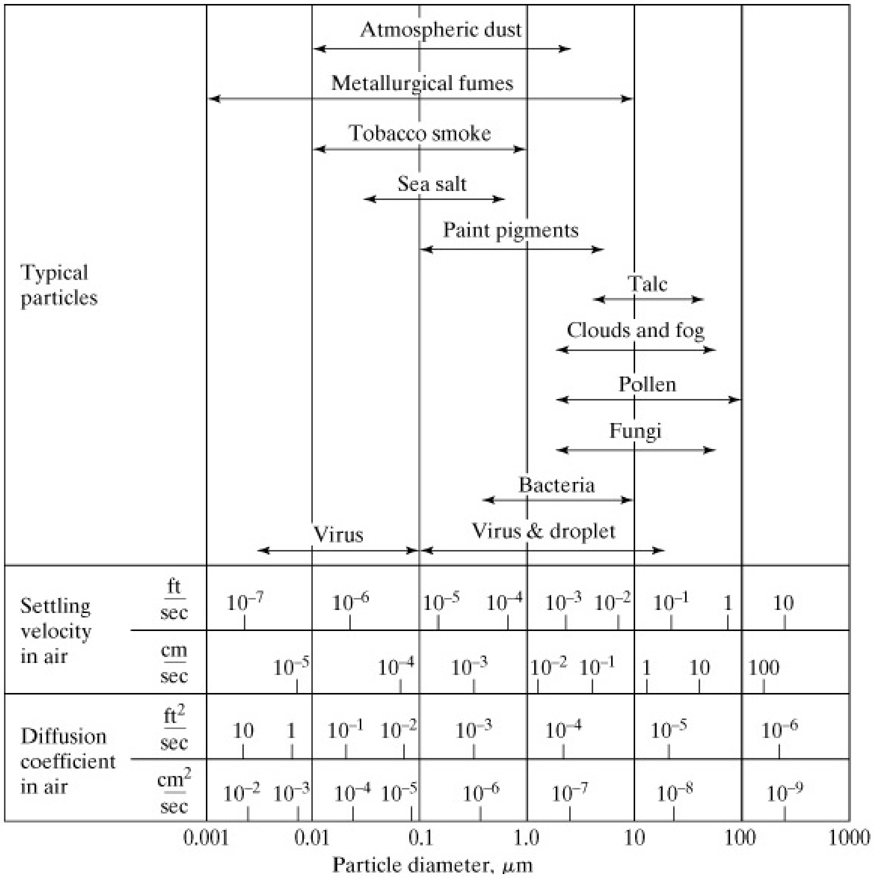


Figure 1: Typical particle size ranges and corresponding settling velocities and diffusion coefficients

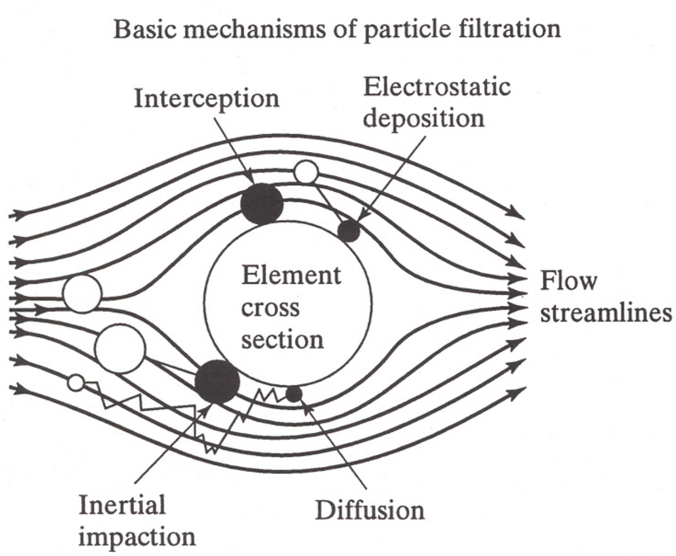


Figure 2: Particle collection mechanisms for a fibrous media filter

Electronic air cleaners capture particles by giving them an electric charge as they pass through an ion field and then capturing them in a series of oppositely charged parallel plates. This arrangement is shown in Figure 3. Large particles are given adequate charge to enable them to be captured very well. Small particles are not charged as efficiently and thus are not forced to the collecting plates as well. Very small particles are collected well because diffusion plays an important role as with fibrous media filters.

Although their particle collection mechanisms differ, fibrous media filters and electronic air cleaners have similar collection efficiency vs. particle size performance as shown in Figure 4. The larger particles are captured well because of inertial impaction or good charging efficiency. The smaller ones are also captured well because of diffusion. Particles in the middle size range are not captured well by either mechanism so that the filter collection efficiency exhibits a minimum.

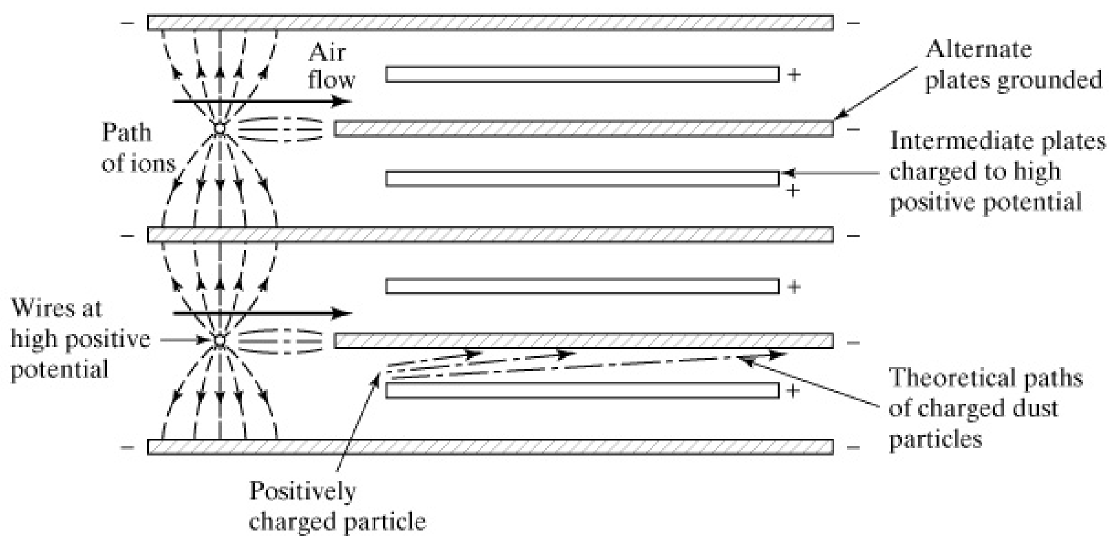


Figure 3: Schematic diagram of a two-stage electronic air cleaner

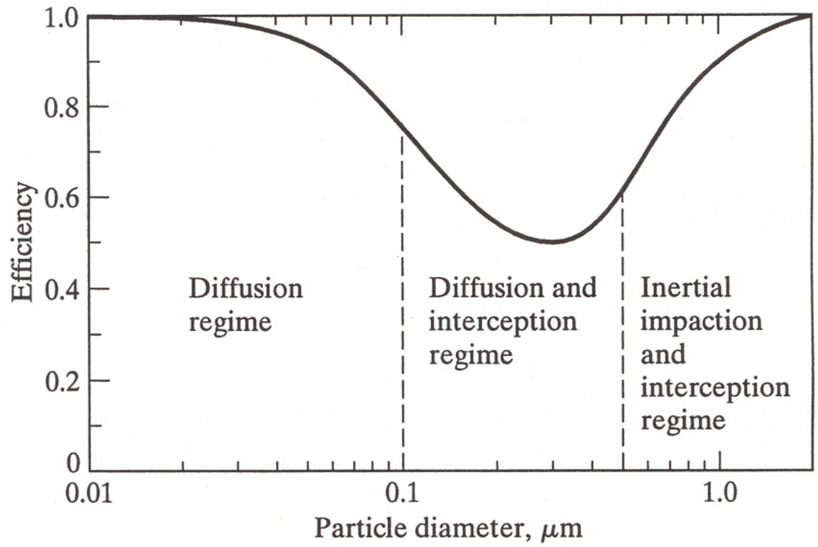


Figure 4: Typical particle removal efficiency vs. particle size for fibrous media filters and electronic air cleaners

ASHRAE has developed a standard test method for determining filtration efficiency vs. particle size such as that shown in Figure 4. This is Standard 52.2-1999. In this test method, potassium chloride particles are injected into the air duct upstream of the filter to be tested. A particle counter determines the concentration of particles vs. size both upstream and downstream of the filter under test. The ratio of upstream to downstream concentrations at a given particle size is then used to determine the particle size removal efficiency (PSE) at that particle size. For example, if the upstream concentration of 1-micron particles is C_u and the downstream concentration of 1-micron particles is C_d, the particle size removal efficiency of 1-micron particles is determined as:

$$PSE = \left(1 - \frac{C_d}{C_u}\right) \times 100\% = (1 - P) \times 100\%$$

where $P = \frac{C_d}{C_u}$ is the penetration of particles of that size through the filter.

III) Procedure

We will not perform a test according to the ASHRAE standard test method. We will conduct a similar test that can be done in the field, using ambient atmospheric air to provide the particles.

1) Close the indoor air damper and open the outdoor air damper so that all the air entering the air handling unit is outdoor air.

Baseline

2) Remove the pre-filter screens and collecting plates from the Honeywell unit. Remove the mini-pleat filters from their holder. Remove the pleated filter from the Lennox unit and close the door.

3) Adjust the fan speed so that the average velocity inside the duct near the filters is at the velocity required for isokinetic sampling. You may turn on the reheat coil if the outdoor air is very cold.

4) Measure the static pressure drop between the two aerosol sampling locations.

5) Use the particle counter supplied to measure the particle concentration vs. particle size in the air upstream. Repeat the measurements downstream. These measurements are performed with an isokinetic sampling probe and are taken near the center of the duct.

6) Repeat step 5 twice more (i.e. a total of three upstream/downstream sample pairs).

Lennox Unit

7) Insert the pleated filter into the Lennox unit.

8) Repeat steps 3 through 6 with the pleated filter installed.

Honeywell Unit

9) Remove the pleated filter from the Lennox unit and insert the collecting plates into the Honeywell unit.

10) Repeat steps 3 through 6 with the Honeywell unit turned ON.

Mini-pleat Filters

11) Remove the collecting plates from the Honeywell unit and install the mini-pleat filters.

12) Repeat steps 2 through 5 with the mini-pleat filters installed.

IV) Report Requirements

A) Describe the test facility used during these tests. Provide a schematic of the duct layout showing the filters and measurement locations.

B) List the instrumentation used in the measurements. Explain how the readings were taken. Show calculations to ensure isokinetic sampling.

C) Provide a plot of particle size removal efficiency (PSE) vs. particle size for the pleated filter. This is a semi-logarithmic plot with PSE on a vertical linear scale and particle size on a horizontal log scale. Include the results of the baseline case for comparison.

D) Provide a plot of PSE vs. particle size for the electronic air cleaner. Use the same coordinates as the plot in part C and include the results of the baseline case.

E) Provide a plot of PSE vs. particle size for the mini-pleat filters. Use the same coordinates as the plot in part C and include the results of the baseline case.

F) Show the PSE results for the pleated filter, the electronic air cleaner and the mini-pleat filters together on the same plot. Compare the PSE results you obtained for these three filters.

G) Compare the static pressure drop across the three filters tested. How does this affect the power requirement of the fan?

H) Comment on variability of the particle concentration data vs. time. How many upstream and downstream sample pairs do you recommend?

Name ______________________

Date ______________________

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY
Particle Size Removal Efficiency Data Acquisition Sheet

Condition 1: **Baseline:** Both media filters and collecting plates removed

Air Temp __________ °F $\quad$ P_{atm} __________ in. Hg

ΔP_{static} __________ in. H_2O $\quad$ Fan Power __________ W

Fan Speed __________ Hz.

Particle Size Range (µm)	C_u	C_u	C_u	C_d	C_d	C_d
0.3-0.5						
0.5-1.0						
1.0-3.0						
3.0-5.0						
5.0-10.0						
>10.0						

Condition 2: **Lennox Prefilter:** Pleated filter installed

Air Temp __________ °F $\quad$ P_{atm} __________ in. Hg

ΔP_{static} __________ in. H_2O $\quad$ Fan Power __________ W

Fan Speed __________ Hz.

Particle Size Range (µm)	C_u	C_u	C_u	C_d	C_d	C_d
0.3-0.5						
0.5-1.0						
1.0-3.0						
3.0-5.0						
5.0-10.0						
>10.0						

Name ______________________

Date ______________________

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY
Particle Size Removal Efficiency Data Acquisition Sheet p. 2

Condition 3: **Honeywell Unit:** Collecting plates installed and turned on

Air Temp __________ °F P_{atm} __________ in. Hg
ΔP_{static} __________ in. H_2O Fan Power __________ W
Fan Speed __________ Hz.

Particle Size Range (µm)	C_u	C_u	C_u	C_d	C_d	C_d
0.3-0.5						
0.5-1.0						
1.0-3.0						
3.0-5.0						
5.0-10.0						
>10.0						

Condition 4: **Mini-pleat Filter:** Mini-pleat filters in

Air Temp __________ °F P_{atm} __________ in. Hg
ΔP_{static} __________ in. H_2O Fan Power __________ W
Fan Speed __________ Hz.

Particle Size Range (µm)	C_u	C_u	C_u	C_d	C_d	C_d
0.3-0.5						
0.5-1.0						
1.0-3.0						
3.0-5.0						
5.0-10.0						
>10.0						

SOLAR RADIATION MEASUREMENTS

I) Objective

The objective of this experiment is to measure the components of solar flux using three instruments. These measurements are to be compared with each other and with predictions of the solar flux using the ASHRAE Clear Day Model. The solar energy delivered to a tilted surface will also be measured.

II) Background

Solar radiation striking a surface is composed of three components: direct, diffuse and reflected. The direct solar flux is that which is transmitted through the atmosphere without being scattered and it strikes the surface in a nearly parallel ray bundle. The solar flux measured perpendicular to this ray bundle is called the direct normal solar flux and is given the symbol, I_{DN}. The angle between the incoming direct solar rays and the surface normal is called the incidence angle, θ. The direct solar flux striking the surface is given the symbol I_D, and is related to I_{DN} by the equation:

$$I_D = I_{DN} \cos\theta$$

The diffuse solar flux is that which is scattered by the atmosphere and then strikes the surface. This radiation comes from the complete sky hemisphere and is given the symbol I_d. The reflected solar flux that strikes a surface, I_R, is reflected off surrounding surfaces before arriving at the surface. The total solar flux striking a surface, I, is the sum of the direct, diffuse and reflected solar fluxes.

$$I = I_D + I_d + I_R = I_{DN} \cos\theta + I_d + I_R$$

In Appendix D, equations are presented that allow the calculation of all components of solar flux if two components are either measured or estimated. For example, if we measure (or predict) the direct normal solar flux and the total solar flux on a horizontal surface, it is possible to calculate the direct, diffuse and reflected fluxes striking a surface pointed in any direction of the compass and at any slope from the horizontal.

Four solar flux-measuring instruments are located on the roof of Akerman Hall, a pyrheliometer, an unshaded pyranometer, a pyranometer with a shading ring, and a pyranometer mounted on a tilted surface. Respectively these measure: the direct normal solar flux, the total solar flux from the hemisphere above the pyranometer, the diffuse plus reflected solar flux from the hemisphere above the pyranometer with shading ring, and the solar flux delivered to the tilted surface. Photographs and descriptions on how these units operate are given in Appendix D.

Appendix D also presents the ASHRAE Clear Day Model which is used to predict the direct normal solar flux and the diffuse solar flux striking the horizontal on average clear days. From these it is possible to calculate all the components striking an arbitrarily oriented surface. The solar fluxes calculated using the ASHRAE model are used extensively in estimating the solar loads on buildings.

III) Basic Procedure

This lab covers a two-week period. In the first week, inspect the three measurement devices, make sure they are set up properly, record their calibration constants, and write a program to record their signals. Make sure the pyrheliometer is aligned correctly and the tracking mechanism is operating to properly follow the sun. Adjust the shading ring on the pyranometer. If time permits, you may also take some preliminary test data from the three devices.

During the second week, solar data will be collected for a number of hours with the data acquisition system.

IV) Report Requirements

Week 1: Instrumentation (Data Sheet)

A) Submit a copy of the data acquisition program and list the channel assignments.

B) Describe each piece of apparatus. List the calibration constants.

C) Provide sketches or digital photos of the four instruments. Label the important features.

D) List any other observations worthy of note.

Week 2: ASHRAE Clear Day Predictions (Formal or Informal Report)

A) Calculate the local solar time for each clock time reading for the day(s) the measurements were recorded.

B) Determine the Direct Normal solar flux from both the pyrheliometer measurements and from the measurements using the pyranometers with and without the shading ring. Compare the results of the two methods of measuring I_{DN}. Explain any discrepancies.

C) Use the ASHRAE Clear Day Model to predict the Direct Normal solar flux and the total solar flux striking the horizontal surface, I_H, for the entire test duration. (Note: I_H is the notation for the total solar flux striking the horizontal.)

D) Plot the measured and ASHRAE estimated values of I_{DN} and I_H vs. time for the duration of the measurements. Discuss what you see from the curves.

E) The solar collectors that will be tested in the next laboratory are tilted with a slope angle of $\Sigma=50°$ and face directly south. Based on the solar flux measurements, calculate the total solar flux striking the collector surface for the data point closest to solar noon. Compare this to the value measured by the tilted pyranometer.

STEADY STATE ANALYSIS OF FLAT-PLATE SOLAR COLLECTORS

I) Objective

The objective is to use steady state analysis to measure the efficiency of the flat-plate solar collectors and to measure the heating capacity of the collectors in a four hour period. The maximum efficiency days of the collectors will also be determined.

II) Background

Two flat-plate solar collector banks are on the roof of Akerman Hall. Each bank has two collectors. One bank has a single pane glass cover; the other has a double pane cover. They face south and are at a tilt angle of $\Sigma = 50°$. The experiment is a closed system. The heat transfer fluid (a mixture of ethylene glycol and water) is recirculated to the collectors from a storage tank, which is shown schematically in Figure 1. The ethylene glycol is DowTherm SR-1, manufactured by Dow Chemical. A shack next to the collectors contains the storage tank, fluid pump, flow meters, expansion tank, and flow control valves.

III) Basic Procedure

Determine what measurements are necessary for the required analysis. Write the data acquisition program to take measurements every five minutes for a four hour test interval, convert the measurements to usable quantities, and print the data for analysis.

Using a well-mixed tank (see Figure 2), set the rotameter flow rate to 1 GPM and check it at the end of the lab section and at the end of the four hour test. Measure and record the quantities that are necessary for analysis.

Quantities necessary for analysis:

Collector bank tested:

Effective area of each collector (in x in):

Indicated rotameter reading (GPM):

Percent volume composition of the water/glycol solution:

Volume of the storage unit (water heater): 42 gallons

In addition, some basic fluid properties are needed to analyze energy collection and storage, namely fluid density and specific heat. These quantities don't vary much with temperature, so use one value for each based on the percent mass composition of the water/glycol solution and the appropriate average temperature. The properties of an aqueous solution of ethylene glycol are given in Appendix F.

IV) Report Requirements

A)
Find solar noon for the test date. Plot the data points for the following quantities on the same graph using two vertical axes. Explain the reason for any differences in the shapes of the curves.

I vs. local solar time (total solar flux striking the collector surface)

$T_{out,\ coll}$ vs. local solar time (collector fluid outlet temperature)

$T_{in,\ coll}$ vs. local solar time (collector fluid inlet temperature)

B)
a) For each data point, compute the collector thermal efficiency (energy delivered/incident solar energy).

b) Plot the collector efficiency vs. $(T_{in,\ coll} - T_{amb})/I$ for the results obtained in part a).

c) Determine and draw a best fit straight line through the points plotted in part b).

d) Add the corresponding manufacturer's efficiency line to the plot.

e) What reasons might there be for any differences in the measured and manufacturer's efficiency?

f) Using the same solar collector you tested, describe the change in collector efficiency when the collector inlet fluid temperature is 50 ºF and the ambient temperature changes from 70 ºF in July to 10 ºF in January.

C)
For the entire test duration, calculate the energy that is added to the storage unit (water heater). Do this using both the lumped capacitance method and the incremental method. What percentage of energy gained at the collectors is added to the water heater? How much energy is lost from the system to the ambient?

Basic Information About the Data Acquisition Set up

The measurements for the collector are performed using thermocouples, a resistive temperature device (RTD), and a pyranometer. The function of each of these devices and the channel is listed below.

Channel	Device	Measurement
10	Pyranometer	Total solar flux striking the collectors
11	Thermistor	Reference junction temperature
12	Thermocouple	Single glazed collector inlet fluid temperature
13	Thermocouple	Single glazed collector outlet fluid temperature
14	Thermocouple	Double glazed collector inlet fluid temperature
15	Thermocouple	Double glazed collector outlet fluid temperature
16	Thermocouple	Ambient air temperature.
17	Thermocouple	Fluid temperature at the rotameter
18	Thermocouple	Fluid temperature at the storage unit inlet (dip tube tap)
19	Thermocouple	Fluid temperature at the storage unit outlet

Since the data acquisition system is used to gather this data, the signals from these channels need to be related to actual quantities (temperature, solar flux, and volumetric flow rate) that can be used to quantify the performance of the collector. The following curve fit data was found for the measurements of interest:

Thermistor: See calibration curve on page C-4.

Pyranometer:

$$I = v/C$$

where: I = solar flux in W/m^2
v = dc voltage in volts
C = calibration constant of the pyranometer.

Rotameter:

Rotameter for Single Glazed Collectors:
AFR = a * IFR + b where a = 0.995, b = -0.038

Rotameter for Double Glazed Collectors:
AFR = a*IFR + b where a = 0.768, b = -0.120

where: IFR = indicated flow rate in GPM
AFR = actual flow rate in GPM

Type T Thermocouple: Two equations are necessary:

Converting from degrees Celsius to microvolts:

$$v = Z0 + Z1 * T + Z2 * T^2 + Z3 * T^3 + Z4 * T^4$$

where:

T is temperature in °C
v is signal voltage in μV

and the coefficients are:

$Z0 = 0$ μV
$Z1 = 38.426$ μV/°C
$Z2 = 5.05e\text{-}2$ μV/°C^2
$Z3 = -8.55e\text{-}5$ μV/°C^3
$Z4 = 1.237e\text{-}7$ μV/°C^4.

Converting from microvolts to degrees Celsius:

$$T = Y0 + Y1 * v + Y2 * v^2 + Y3 * v^3 + Y4 * v^4$$

where:

T is temperature in °C
v is signal voltage in μV

and the coefficients are:

$Y0 = 0$ °C
$Y1 = 0.02583$ °C/μV
$Y2 = -6.885e\text{-}7$ °C/μV^2
$Y3 = 1.090e\text{-}10$ °C/μV^3
$Y4 = -1.70e\text{-}14$ °C/μV^4.

These equations were found by a curve fitting calibration and the manufacturer's (Omega) data.

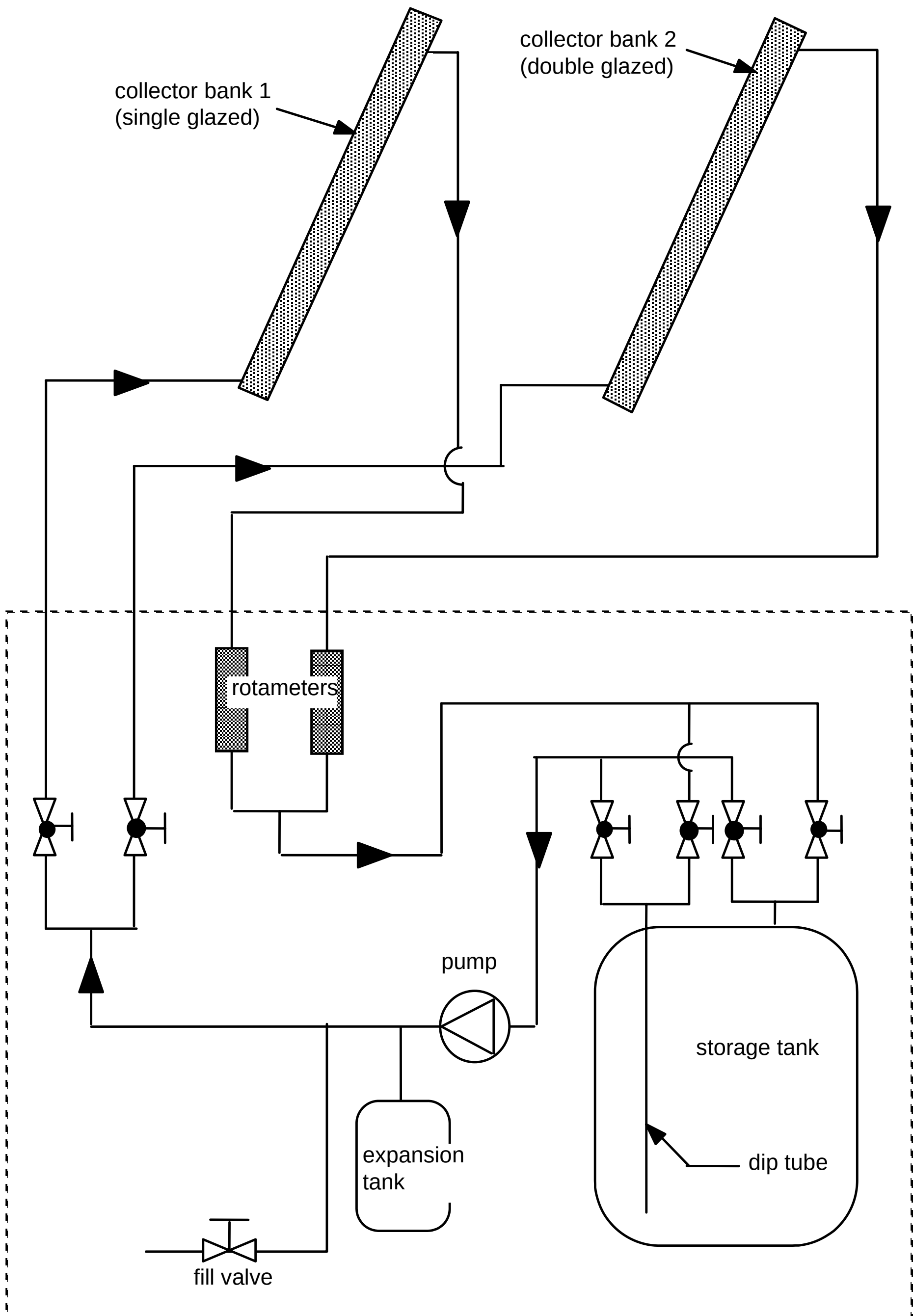
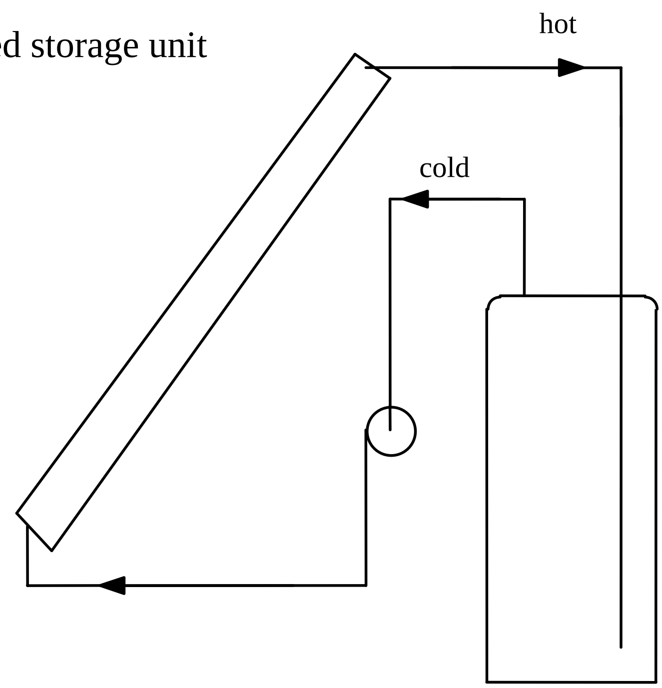


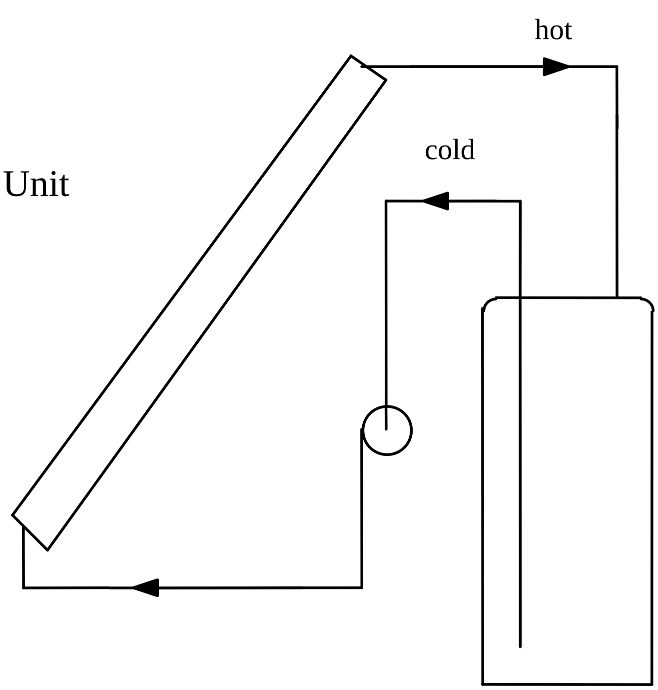
Figure 1 - Schematic of closed loop collector system

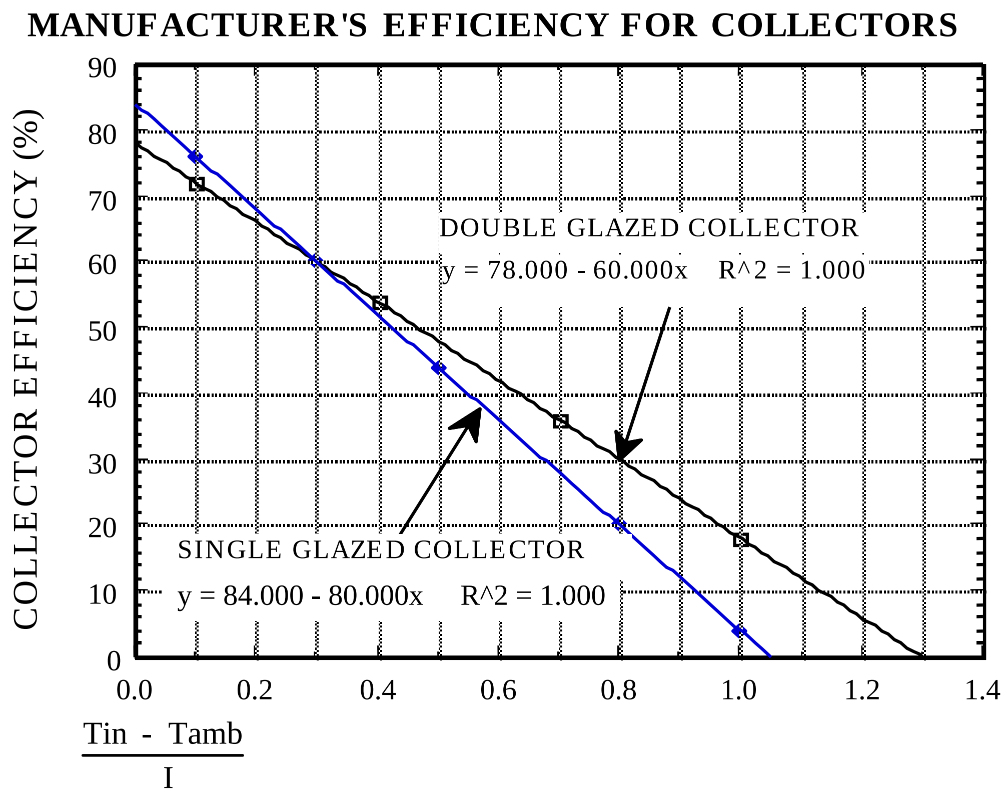
Figure 2: Schematics of two mixing schemes

Well mixed storage unit



Stratified Storage Unit





where:

T_{in} = fluid temperature at collector inlet (°F)

T_{amb} = ambient temperature surrounding the collector (°F).

I = incident solar flux (Btu/hr•ft^2)

THE WALK-IN COOLER

I) Objective

The purpose of these experiments is to observe and analyze the operating characteristics of an actual refrigeration system that would be used in a commercial application. In addition, the system is to be compared with the theoretical single stage mechanical vapor compression refrigeration cycle.

II) Background

References:

1) Thermal Environmental Engineering, 3rd. ed., Kuehn, Ramsey and Threlkeld, Chs. 3 and 4.
2) ASHRAE Fundamentals Handbook, Ch. 1.
3) ASHRAE Refrigeration Handbook

The system considered in the lab is a single stage, mechanical vapor compression refrigeration system used to provide refrigeration to an insulated enclosure called a walk-in cooler. These systems are commonly used in supermarkets and restaurants to provide refrigerated storage of food products. The four basic components are:

1) compressor
2) condenser
3) expansion valve
4) evaporator

Power to the compressor is provided by an electric motor. The heat removed from the refrigerant in the condenser can be rejected to cooling water, which is typically sent to a dry or wet cooling tower to reject the heat to ambient air. During the winter months when the building requires heating, the heat removed from the condenser can be rejected directly to the air inside the building through a finned tube condensing coil called a heat reclaim coil.

The evaporator/fan/expansion valve assembly is mounted inside the cooler. The fans blow air through the evaporator coil and circulate air inside the box. Other components in typical systems include a refrigerant filter/dryer, a liquid refrigerant receiver, a suction line/liquid line heat exchanger, and a suction line accumulator to prevent liquid refrigerant from entering the compressor. A thermostat in the cooler controls the compressor switch to maintain the interior of the box at a set temperature. The relative humidity in the cooler is usually nearly 100% to prevent dehydration of the food products. This high humidity level causes frost to form on the evaporator coil so the coil must be defrosted periodically.

III) Description of Equipment

The basic components of the system consist of a thermally conditioned space (the walk-in cooler) and the refrigeration equipment necessary to maintain the space. The working fluid in the refrigeration system is Refrigerant 22 (R-22).

The system contains three sub-groups of equipment. First, there are the components that have the purpose of manipulating the thermodynamic state of the refrigerant. Examples of this are the control and expansion valves, compressor, condensers, counter flow heat exchanger, evaporator, and evaporator fan. Second, there are components that ensure safe and proper operation of the system. The dryer, suction line accumulator, pressure relief valve, and sight glasses fall in this category. Finally, there are measuring devices to monitor the system. This instrumentation was installed by laboratory personnel and is not found in most applications. These include thermocouples for temperature measurement, pressure transducers, flow meters, and wattmeters.

Basic Information About the Data Acquisition Equipment

The measurements are performed in this lab using thermocouples, a thermistor, turbine flow meters, wattmeters, and pressure transducers. The calibration curves for these devices are given in Appendix C. The channel to which each device is assigned and the location of each device is given on p. 8-5.

Pressure Transducer assignment:

Location	Pressure Transducer Name
Discharge side of compressor	PX302-300GV
Before thermostatic expansion valve (TEV)	PX302-300GV
After TEV and before evaporator	PX302-200GV
After evaporator	PX302-100AV
Suction side of compressor	PX302-100GV

IV) Procedure

Week 1: System familiarization and steady state analysis (Data Sheet)

The system will have been running for several hours prior to class so as to achieve a steady-state condition. A 60 minute test is to be made with the pressure, temperature, flow rates, and electrical power usage recorded every 15 minutes. All these readings are taken manually from the control board. Take the first two readings with the water cooled condenser operating and the last two readings with the air cooled condenser (heat reclaim unit) operating. Between readings, carefully inspect the system and sketch all the components. Include refrigerant lines, water lines, and electrical lines for power and control signals. Complete the data sheet requirements given on the following page.

Week 2: Transient Analysis (Informal or Formal Report)

Determine the measurements that are needed to meet the requirements for the informal or formal report. Write a data acquisition program to monitor the system for the four hour time span. The system should be monitored in five minute intervals. Initially the entire system is at room temperature. Start the program and turn the system on. Then complete the required calculations outlined in the Report Requirements.

<u>V) Report Requirements</u>

Week 1: Steady State Analysis (Data Sheet)

A) Sketch the system. Label and briefly describe the purpose of all the components. Also include a brief discussion of the system used to control the temperature within the walk-in cooler.

B) Complete the data sheet provided (p. 8-5). Take two sets of readings with each of the condensing units operating. Has steady state been achieved?

C) Plot the refrigeration cycle for one set of readings using the air cooled condenser (t = 45 min) on a P-h diagram showing all the measured R-22 state points. How does this compare to the theoretical Carnot refrigeration cycle? Explain any discrepancies. P-h diagrams and thermodynamic tables for R-22 are found in Appendix E.

D) Describe how the flow meter in the refrigerant line affects the refrigeration process. You may show this graphically on a P-h plot.

E) Calculate the R-22 volumetric flow rate using an energy balance on the water cooled condenser (t = 0 min) using the indicated water volumetric flow rate. How does the calculated value compare to the indicated volumetric flow rate for the R-22? Explain any differences. You may want to plot the condenser portion of this set of measurements on a P-h diagram.

F) Use the indicated volumetric flow rate for R-22 and an energy balance on the air cooled condenser (t = 45 min) to determine the mass flow rate of air through the condenser. Convert this to a volumetric air flow rate and compare to the values obtained for the fan on the air handling unit (Air Handling System Characterization lab). Does this value seem reasonable for the fan on the air cooled condenser?

Week 2: Transient Analysis (Informal or Formal Report)

A) Sketch the system. Label and briefly describe the purpose of all the components.

B) Plot the inside cooler temperature vs. time for the four hour test interval. What is the time constant of the system?

C) Calculate the capacity of the refrigeration system at three different temperature levels inside the cooler (see below). Comment on and compare the capacity of the system when operating as a cooler, as a freezer, and at the minimum temperature that can be achieved.

D) Compare the measured electrical power into the compressor to the actual rate of energy gain by the R-22 through the compressor. Explain the difference.

E) Calculate the actual coefficient of performance (COP), the ideal COP, and the refrigerating efficiency (η_r) of the refrigeration system for all three operating conditions. Comment on the magnitudes of each.

Perform the calculations for Parts C, D, and E at three cooler temperatures to simulate various operating conditions:

1) As a cooler: 40˚ - 50˚ F
2) As a freezer: 20˚ - 30˚ F
3) At the minimum temperature achievable

Name ____________________

Date ____________________

ME 4131 THERMAL ENVIRONMENTAL ENGINEERING LABORATORY

Walk-In Cooler Data Acquisition Sheet

			water cooled condenser		air cooled condenser (heat reclaim)		
BLOCK #	CHANNEL #	TEMPERATURE LOCATIONS	t=0	t=15 min	t=30 min	t=45 min	test w/o flowmeter
0	0	1-R-22 LEAVING COMPRESSOR					
0	1	2-R-22 ENTERING WATER CONDENSER					
0	2	3-R-22 LEAVING WATER CONDENSER					
0	3	4-R-22 ENTERING HEAT RECLAIM CONDENSER					
0	4	5-R-22 LEAVING HEAT RECLAIM CONDENSER					
0	5	6-R-22 ENTERING HEAT EXCHANGER					
0	6	7-R-22 LEAVING HEAT EXCHANGER					
0	7	8-R-22 BEFORE TEV					
0	8	9-R-22 AFTER TEV AND BEFORE EVAPORATOR					
0	9	10- R-22 AFTER EVAPORATOR					
1	0	11-R-22 BEFORE HEAT EXCHANGER (SUCTION)					
1	1	12-R-22 AFTER HEAT EXCHANGER (SUCTION)					
1	2	13-R-22 ENTERING COMPRESSOR					
1	3	14-WATER ENTERING CONDENSER					
1	4	15-WATER LEAVING CONDENSER					
1	5	16- AIR ENTERING HEAT RECLAIM					
1	6	17- AIR LEAVING HEAT RECLAIM					
1	7	18-INSIDE COOLER AMBIENT					

18	19-INSIDE COOLER WALL ATTACHMENT						
19	20-INSIDE COOLER WINDOW ATTACHMENT						
20	21-OUTSIDE COOLER WALL ATTACHMENT						
21	22- OUTSIDE COOLER WINDOW ATTACHMENT						
22	23- OUTSIDE COOLER AMBIENT #1						
23	24- OUTSIDE COOLER AMBIENT #2						
	REFERENCE TEMPERATURES						
28	REFERENCE TEMPERATURE (RTD)						
29	REFERENCE TEMPERATURE (THERMISTOR)						
	PRESSURES						
30	DISCHARGE SIDE OF COMPRESSOR (PSIG)	P_1					
31	BEFORE TEV (PSIG)	P_8					
32	AFTER TEV AND BEFORE EVAPORATOR (PSIG)	P_9					
33	AFTER EVAPORATOR (PSIA)						
34	SUCTION SIDE OF COMPRESSOR (PSIG)	P_{13}					
35	PRESSURE TRANCDUCER INPUT (VOLTS)						
	BAROMETRIC PRESSURE (in Hg)						
	POWER USAGE						
38	COMPRESSOR POWER (KW)						
39	EVAPORATOR AND HEAT RECLAIM POWER (W)						
	FLOW RATES						
36	R-22 FLOW METER READING (GPM)						
37	WATER FLOW METER READING (GPM)						
	WATER FLOW -BUCKET AND WATCH (GPM)						

PERFORMANCE STUDY OF A SMALL REFRIGERATION SYSTEM

I) Objective

Design an experiment to measure the coefficient of performance (COP) of a small, vapor compression water chiller.

II) Background

The coefficient of performance (COP) of a mechanical vapor compression refrigeration system is defined as:

$$\textbf{COP} = \frac{\text{Useful refrigerating effect}}{\text{Net energy input}}$$

The net energy input includes the energy used by the compressor, the fan and/or pump. The useful refrigerating effect is the heat removed by the evaporator. The larger the COP, the better the system.

The COP of a system depends on the operating conditions. The refrigeration capacity changes with both evaporating saturation temperature and condensing saturation temperature because a change in either saturation temperature changes the refrigerant pressure. A higher pressure ratio across the compressor results in a lower volumetric efficiency, a lower mass flow rate of refrigerant, and thus less refrigerating capacity for the system and vice versa when the pressure ratio is reduced. This phenomenon is observed when the evaporator temperature is reduced in the second portion of the walk-in cooler experiments.

Thus the COP of a given refrigeration system depends on its operating conditions. `For this reason, organizations such as ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers), ARI (American Refrigeration Institute) and ANSI (American National Standards Institute) have established standard test methods for determining the capacity and other performance parameters of equipment under specified operating conditions.

For example, ANSI/ASHRAE Standard 37-1988, "Methods of Testing for Rating Unitary Air Conditioning and Heat Pump Equipment", lists several approved methods to test the piece of equipment. Each method gives a detailed sketch of the test facility requirements and locations and specifications on all measured parameters such as flow rate and temperature. Acceptable types of instrumentation are given for each measured variable.

Equations are specified as to how the measured data are to be used to compute the desired result (e.g. capacity).

In this experiment, the instrumentation has not been installed on the unit. You must assist the TA in the lab by assembling the instrumentation and installing it on the equipment. Then determine the operating conditions to use in the test. The measurements should be taken when the equipment is operating in a steady state mode.

III) Procedure

1) Obtain a copy of an ANSI/ASHRAE standard method of test for rating a piece of equipment similar to the unit in the lab.

2) Determine what parameters to measure for COP calculation.

3) Assemble and install the necessary equipment/instrumentation.

4) Determine the operating conditions that will be used when performing the test.

5) Perform the measurements under steady state conditions.

IV) Report Requirements

A) List all the components on the small refrigeration system and briefly describe the function of each.

B) List and explain the parameters required for COP determination. Give alternative measurement methods. Which method was selected and why?

C) Describe how the parameters are measured (equipment, sensors, and procedure).

D) Compute the COP using your measurements. Estimate the measurement uncertainties. Calculate the uncertainty in COP.

E) How does this method differ from the standard test rating method that was reviewed? What would need to be modified to comply with the standard method?

AIRFLOW VISUALIZATION

I) Objective

Conduct flow visualization tests to determine airflow patterns in a laboratory setting and in a scale model flow chamber.

II) Background

Knowledge of air flow direction is important for three reasons: maintenance of a prescribed pressure gradient across a barrier, capture of airborne contaminants, and assessing room ventilation.

Air flow is a relatively simple method of determining a pressure difference across a closed door or partition. Pressure differences are needed in critical applications such as between clean spaces and the ambient, and between hospital rooms and the corridor. Other applications include pressure gradients across construction barriers in a building and pressure differences created by smoke control systems. For example, consider patients with an infectious disease such as tuberculosis, which can be spread by air. These patients are placed in isolation rooms that must be maintained at a lower pressure than the surrounding rooms and corridor. The negative pressure difference allows uncontaminated air to flow into the room through cracks and openings, and ensures that no contaminated air will leak out. All the air exhausted from the room should be passed through a HEPA (High Efficiency Particulate Air) filter before being discharged. Contaminants can diffuse to regions of lower concentration and can be convected by air motion. A very small pressure differential, on the order of a few thousandths of an inch of water, is all that is needed to prevent the diffusion of contaminants upstream. It is very difficult to measure such small pressure differences unless a sophisticated instrument is used. A much less costly approach is to determine the air flow direction rather than measure the pressure difference. This can be accomplished using tufts of thread or some other mechanical means. Particles less than about 50 microns in size follow the air flow pattern very well. These can be easily generated and seen with the naked eye. Common sources are cigarette smoke, incense smoke, and particles generated from a chemical smoke stick.

The second reason flow visualization is important is to verify the proper operation of a local exhaust system. Examples include fume hoods, kitchen exhaust hoods, and exhaust systems used in industrial processes. The purpose of these local exhaust systems is to capture and remove airborne contaminants in particle or gaseous form before they mix with the remainder of the air in the space. The pressure field generated by these devices is essentially a potential field. The local air velocity caused by this potential flow field must be larger than the velocity induced by other forces, such as thermal buoyancy and cross drafts, to ensure proper contaminant removal. Visualizing the local air flow field near the entrance of these exhaust systems during normal operation allows one to determine whether the system is capturing and exhausting the contaminants as desired, or other driving forces are causing reduced capture effectiveness. Smoke particles from the sources described above are often used in these applications. The particles are exhausted from the space along with the contaminants if the system is operating properly.

The third reason flow visualization is useful is to determine the air flow patterns in a room. Typical practice in the US is to provide between 12 and 15 air changes per hour in rooms that have forced ventilation. Supply air diffusers and return grilles are selected and located in the space to provide good air mixing. However, in most commercial buildings, both the air supply and return are located in the ceiling. In this case, the space between the suspended ceiling and the roof or floor above is used for the supply and return air ducts. In many cases, the return is simply the space above the ceiling, so no return ducts are used except near the air handler. If the supply air is not well mixed with the air in the room, it can enter the return by "short circuiting" under the ceiling. This provides limited ventilation for occupants and can lead to complaints of poor indoor air quality. By visualizing the air flow pattern in a room, one can determine whether the room air is well mixed or whether short circuiting or some other problem is preventing adequate ventilation of the space. In this application, smoke is not desirable as it is a contaminant that may cause irritation to the occupants. A non-contaminating fog generator is useful since the particles generated are simply small water droplets. These are easily seen and evaporate leaving no harmful residue or odor.

Room air flow is governed by the room geometry, the Reynolds number for forced convection or momentum-driven flows, and the Grashof number for thermal buoyancy-driven flows. Most room air flows are driven by a combination of forced and natural convection so both Reynolds and Grashof numbers are important. Scale models can be used to simulate the air flow in a large room if all dimensionless governing parameters are equivalent to the values in the full scale room. All geometry features are scaled down using the same scale factor, SF. The values for the Reynolds and Grashof numbers are also set equal to their values in the full scale room.

In a full scale room:

$$Re = UL/\nu$$

where U is usually the mean velocity at the supply diffuser, and L is the characteristic length of the room. This is the diffuser opening width or some other room dimension. If air is also used in the scale model, the viscosity remains the same. However, the velocity in the scale model must increase to compensate for the reduced physical size of the model. For example, if the dimensions of the model are ${}^{1}\!/_{10}{}^{th}$ the full scale room, the velocity must increase by a factor of $\frac{1}{0.1} = 10$ to achieve the same Reynolds number. Thus if the full scale velocity is U, the full scale length is L, and the scale factor, SF, is the ratio of the model dimensions to those of the full size room, the air velocity in the model, u, is:

$$u = U/SF$$

Since typical room air velocities are very low, they are often below the range of many velocity sensors. However, in a scale model, the velocities can be much higher, which allows for easier measurement.

The thermal buoyancy must also be considered so that the Grashof number in the model is equal to the value in the full scale room. In the full scale room,

$$Gr = gL^3\Delta t/(\nu^2 T)$$

where g is gravitational acceleration, L is the characteristic length, Δt is the characteristic temperature difference, v is the air kinematic viscosity, and T is the mean absolute temperature in the room. The characteristic temperature difference is often taken as the difference between the supply air temperature and the temperature of the return air, since the return air temperature is near the mean room temperature. In the scale model, gravitational acceleration, air viscosity, and mean temperature are essentially equal to the values in the full size room. However, since the physical dimension, L, is cubed, the ratio of temperature differences is proportional to the cube of the scale factor. The temperature difference in the scale model must be $1/SF^3$ times the room temperature difference. For example, if Δt in the room is 10 ^{0}F, the value in a 1/10 scale model should be 10 ^{0}F x ($1/10^3$), or 10,000 ^{0}F. This is highly impractical. A solution is to set the Archimedes number ($Ar = Gr/Re^2$) in the model equal to that of the full scale room. Since this ratio is proportional to the ratio of buoyancy to momentum forces, matching this dimensionless number between the full size room and scale model provides reasonably good flow similarity.

III) Procedure

1) Obtain de-ionized water and liquid nitrogen. Fill the boiler and dewar and start the fogger.

2) Use the fogger or a smoke stick to determine which direction the air is flowing under the closed door between the laboratory and the hallway. Measure the room barometric pressure.

3) Using the kitchen exhaust fan and/or the air handling unit fan, change the room air pressure to reverse the flow direction under the door. Measure the room barometric pressure again.

4) Run the fogger with the kitchen exhaust fan running. Determine the air flow pattern near the unobstructed exhaust hood.

5) Repeat item #4 with someone standing near the front of the hood. Inject the fog in front of the person and determine at what point the fog is removed from the person and exhausted. Note at what point the fog moves toward the person, instead of being exhausted.

6) Use the fogger to visualize the air flow pattern in the scale model flow chamber with mechanical ventilation. Observe the flow near the supply air diffuser and the return grille. Several plexiglass partitions are available to simulate various room configurations.

IV) Report Requirements

A) Determine the pressure difference across an opening under a door with the characteristics given as follows. The opening is 4 mm high, 76 cm wide and is 4.2 cm deep. The air velocity through the opening is just sufficient to maintain a contaminant concentration on the downstream side of the slot that is a factor of 10,000 larger than the concentration of contaminant on the upstream side. Assume a diffusion coefficient of 0.15 cm^2/sec that is similar to CO_2 in air.

i) the air velocity required through the opening is:

$$V = \frac{D}{L}\ln(C_H / C_L)$$

where D is the diffusivity of the contaminant in air, L is the depth of the opening in the airflow direction, and C_H and C_L are the high and low concentration values respectively. This equation was derived assuming that the diffusion of contaminant in one direction is balanced with convection in the opposite direction. Compute the air velocity required for this example in units of m/sec.

ii) the pressure drop across the opening is given by:

$$\Delta P = f\frac{L}{d_h}\left(\frac{\rho V^2}{2}\right)$$

where f is the friction factor, L is the depth of the opening in the airflow direction, V is the air mean velocity through the hole, and ρ is the air density (assume standard air density of 1.204 kg/m^3). The opening hydraulic diameter, d_h, is given by:

2(ab)/(a+b)

where a is the height and b is the width of the rectangular opening.

The friction factor for laminar flow is:

f = 96/Re

The Reynolds number is determined as:

$$\mathrm{Re} = \frac{Vd_h}{\upsilon}$$

Assume a kinematic viscosity of 15 x 10^{-6} m^2/sec. Determine the pressure drop in Pascals and inches of water (in H_2O).

iii) what device or devices could be used to measure this pressure drop?

B) Describe the method used to change the room pressure so the airflow under the door reversed direction. Estimate the change in room pressure that was required.

C) The air flow near a local exhaust is very nearly potential flow. Consider a slot exhaust that is 2 inches wide by 6 ft long mounted in a ceiling. The total amount of air exhausted, $\dot{V}$, is 1000 CFM.

The velocity near the slot varies as:

$$V = \dot{V}/(\pi r L)$$

where $\dot{V}$ is the total volumetric flow rate, r is the distance from the line sink near the slot, and L is the slot length.

i) compute the air velocities created by this exhaust at distances of 6 inches, 1 ft, 2 ft, and 4 ft from the exhaust.

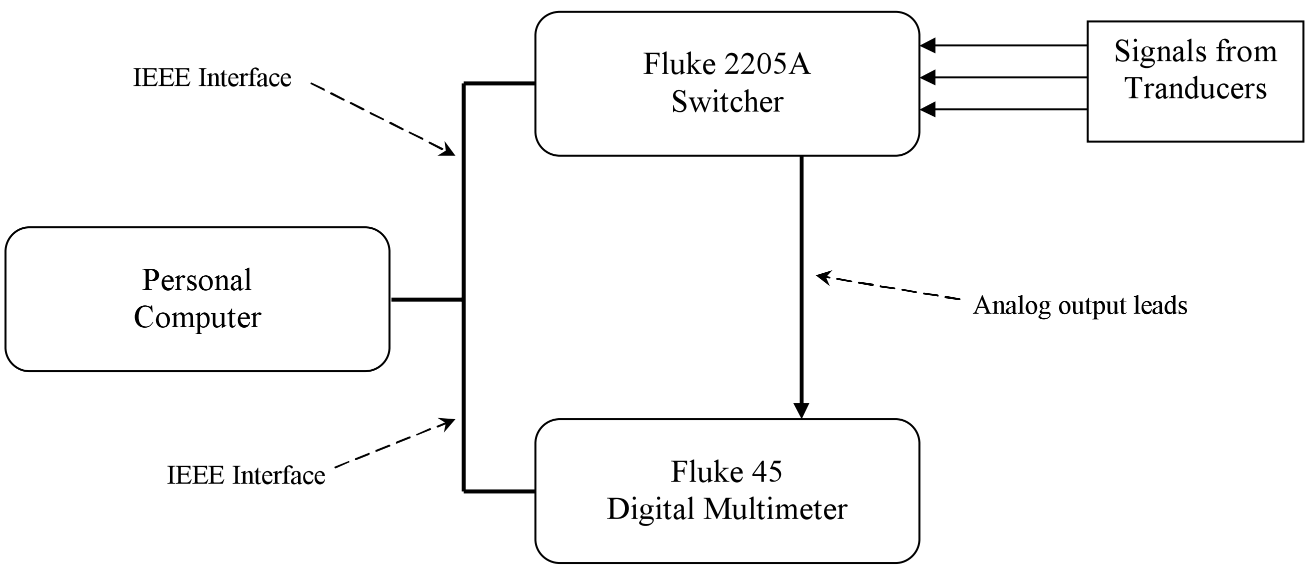
ii) what devices could be used to measure the velocity at a distance of:
a) 6 inches from the exhaust?
b) 4 ft from the exhaust?

D) Describe the flow pattern near the exhaust hood. Comment on the effect of a person blocking the air flow and the effect this would have on chemical contaminant isolation near the front of the fume hood.

E) Sketch the scale model chamber including the locations of the air supply diffuser and the return slot. Describe your observations of the air flow. Was the chamber well mixed or did you notice stratification? What effect did changing the configuration of the partitions have on the airflow? Would you characterize this room as being well ventilated or poorly ventilated?

APPENDIX A: DATA ACQUISITION

The heart of the data acquisition system used in this course is a networked personal computer connected to a Fluke 2205A channel switcher and a Fluke 45 multimeter via IEEE-488 interface buses. The channel switcher allows for the connection and switching of up to 100 input signals through the digital multimeter. Output from transducers (i.e. thermocouples, RTD's, pressure transducers, flow meters, etc.) can be connected to the switcher. These signals are converted to a digital value and sent to the computer via the IEEE interface. Alternatively, the computer may send a digital signal to the switcher or multimeter telling it to complete a given task. The computer has a Linux operating system and interfacing is done in C++ programming language. It can be used to acquire data, process the raw data into meaningful results, and to write data to disks or files for later processing.



The C compiler is a public domain or open space compiler (gcc). C++ language manuals are available for use in the lab. There are also manuals available for the multimeter, switcher, and interface bus commands if you need more information than is provided in the following pages.

To get started, log in to the computer and turn on the switcher and multimeter. Each lab section has a directory in which to store programs and files. Once the computer boots up, go to the correct directory:

type: **cd labclass/fall03wed/**
(or thurs or fri, depending on the lab section and semester)

Start up the editor:

type: **emacs 4000&**

Now the system is ready for writing a data acquisition program.

DATA ACQUISITION PROGRAMMING EXERCISE

In order to become better acquainted with the data acquisition system, write a simple C program to acquire the dc voltage from a thermocouple and the resistance from a resistance temperature device (RTD). Convert the signals to temperatures, print out the results, and store them in a data file in your group's directory.

A) Determine the commands that are required to set and switch channels.

B) Determine the commands needed to read the measurements.

C) Write a program to read in the signals and convert to temperature. Print the results to the screen and to a file in your directory.

> When measuring resistance using the switcher, the internal resistance of the switcher and wiring must be taken into account. This can be done by shorting the leads just before the RTD hook-up. The value should be approximately 930 ohms. **Record this value for use in future labs.**

Carefully read the section titled "Basic Flow of a Simple C Program". Also study the section titled "Topics in C Programming" written by Bob Hain of ME Net. There will be a test on the material next week.

BASIC FLOW OF A SIMPLE C-PROGRAM FOR DATA ACQUISITION

The following pages contain a simple but functional C program used in data acquisition. The program monitors the temperature of a Type T thermocouple with an ice bath as the reference temperature. The program is written to take a number of readings at given time intervals.

A. List the needed header files:

```
# include <ugpib.h>
# include <stdio.h>
# include <stdlib.h>
# include <math.h>
# include <time.h>
# include <unistd.h>
```

These header files contain information the computer will need to perform mathematical functions, direct output to the screen, communicate over the interface bus (ib), access the system clock, etc. These are included on all C programs written for this lab.

B. Initiate the program proper:

```
main() {
```

C. Declare *all* variables:

```
char rd[512];
int i, dvm, fluke, nap, num, a;
double volt[5], temp[5], mvolt[5], ftemp[5];
double b[] = { 8.641e-2, 25.408, -0.46794 };
time_t currentime;
struct tm  *t;
FILE *data;
```

- Note that:
  1) All statements end in a semicolon (null character)
  2) Arrays are signified by square brackets
  3) The first item of an array is indexed **zero, not one**
  4) int represents integers; double represents real numbers

- The variable rd[512] is a character string 512 in length. The instrument readings are passed in ASCII form to this character array. Getting a number out of this character string requires a little manipulation. This will be shown shortly.

- “time_t” is a certain kind of variable, a time variable. The variable name "currentime" holds values of time in seconds.

- The “struct” declaration indicates a type of entity called a “structure”. A structure is used for storage of data and is composed of one or more arrays. The individual arrays making up the structure need not be of the same variable or data type. Thus a structure can hold integer, real, character, and time values. “tm” is a specific type of structure defined by the time.h header file. “t” may be thought of as the name of one of these tm type structures (although it is actually called a pointer or memory location). “*t” is used to “point to” certain locations in the structure using a technique to be defined shortly.

- The “FILE” declaration sets up a data file named “data”.

D. Locate the instruments on the interface bus:

```
fluke = ibfind("dev3");
dvm = ibfind("dev2");

ibclr(dvm);
```

The Fluke switcher is at channel 3 on the bus, and the Fluke multimeter is at channel 2. Addresses "fluke" and "dvm" are the integer addresses assigned by the computer to these locations. Note that "dev3" and "dev2" could be used as the addresses and could be referred to throughout the program. Assigning variable names aids in keeping track of the device that is being talked to.

The multimeter is also being cleared with ibclr before being given new commands.

E. Prompt for input, print out the date, set up a data file, and begin a loop:

```
printf ( "Input the number of readings \n");
scanf("%i",&num);
printf ("Input the time in seconds between readings \n");
scanf("%I", nap);

currentime = time (&currentime);
t = localtime (&currentime);

printf ("The date is %d-%d-%d \n", t->tm_mon+1, t->tm_mday, t->tm_year+1900);
printf ("Time\t\tVoltage(mV)\tTemp(C)\tTemp(F) \n");

data = fopen("/h/whtang/labclass/fall03wed/thermocouple.dat","w");
fprintf (data,"The date is %d-%d-%d \n", t->tm_mon+1, t->tm_mday, t->tm_year +1900);
fprintf (data,"Time \t\tVoltage(mv)\tTemp (C)\tTemp (F) \n");
fclose(data);

for( a=1; a<=num; a++)  {
```

Printf is how information is printed to the screen. The **\n**, which stands for "new line" must be included, or the next piece of output will be attached to the end of this line instead of beginning a new line. This is the beginning of the outer loop of the program, and determines how many readings are taken.

The command **scanf("%i",&num)** is a way of reading in a value, in this case an integer value, and assigning it to the declared variable num. To read in a value that is of the real type or double, a slight modification to this command is needed. In this case, the following command is used: **scanf("%lf",&*variable name*).**

The function **time(),** which comes from the time.h header file, causes the computer's clock to be read and returns a value in seconds since 00:00:00 1-1-70 GMT (Greenwich Mean Time).

The **localtime()** function operates upon the argument **currentime** to return the mixed data type local time and date, which is then neatly stored in the tm structure.

The "t->tm_mon" text indicates the current month value stored in the tm structure. This is the pointing technique referred to earlier for reading from the specific location in the structure containing this month information. The "+1" is added to the current month value because months are given values zero thru 11, not 1 thru 12.

The **data=fopen** command opens a new file in a given directory and the "w" indicates it is a new file. Any information in the file is cleared away if it already exists. The effects of replacing the "w" with an "a" will be discussed later. This "a" allows an existing file to be appended, or added to, without destroying the information contained within the file.

F. Pass instructions to the instruments:

```
ibwrt(fluke, "25,",3);
```

This command is telling the switcher (fluke) to close channel 25 (with the string command (25,). (Note that here "close" has the meaning of "close the circuit" to allow signals to be transmitted.) Each device has its own set of specific commands. These commands are found in the equipment manuals. The 3 indicates the length of the character string being passed over the bus (between the double quotes including spaces and punctuation).

There are spaces after the ';' and 'r'

```
ibwrt(dvm,"vdc; trigger 2",14);
```

This command tells the multimeter to read a dc voltage and take a reading only when triggered externally. If a resistance is being read (for instance from an RTD), ohms is used in place of vdc. If a frequency is being read (from a turbine flowmeter, for example), the notation is freq. Again, all instructions must end with a semicolon.

G. Begin inner loop and read instrument(s):

```
for (i=1; i<=1; i++) {
ibtrg(dvm);
ibwrt (dvm,"val1?",5);
ibrd (dvm,rd, 30);
rd[ibcnt] = '\0';
volt[i]=atof (rd);
mvolt[i]=volt[i]*1000;
ibwrt(fluke,"+",1);
}
```

The first statement begins the loop. The second line triggers the multimeter and prepares it to take a reading. The third line signals the dvm to read the value on the main digital display. (This particular multimeter has a primary and secondary display). The fourth statement reads a 30-character long string of ASCII gibberish received over the bus. The sixth statement converts the gibberish to a real number (atof = "ASCII to float"). The fifth statement simply inserts a null character at the end of the useful gibberish, to keep the atof command from trying to convert characters it shouldn't. The final line closes the loop.

H. Algebraic manipulation:

```
temp[1]=b[0]+mvolt[1]*b[1] +
        pow(mvolt[1],2.0)*b[2];
ftemp[1]=temp[1]*1.8 + 32;
```

I. Read the internal clock and print to data file:

```
currentime = time(&currentime);
t = localtime(&currentime);

data = fopen("/h/whtang/labclass/fall03wed/thermocouple.dat","a");
fprintf (data,"%2d:%2d:%2d\t\t%.2f\t %.2f \t%.2f\n",t->tm_hour, t->tm_min,
        t->tm_sec,mvolt[1], temp[1],ftemp[1]);
fclose(data);

printf("%2d:%2d:%2d\t\t%.2f\t %.2f \t%.2f\n",t->tm_hour, t->tm_min,
        t->tm_sec, mvolt[1],temp[1],ftemp[1]);


usleep (nap*1e6);
}
}
```

In this set of statements, the internal clock is read and the data file is re-opened and appended (this is what the "a" refers to). The fprintf and printf commands print the results to the data file and the screen, respectively. The results are formatted with %2d and %.2f. %2d formats an integer argument to two places. %.2f formats floating point arguments (real numbers) to two places to the right of the decimal point. For instance, if the result is 957.374856, it is printed as 957.37. If the program is rewritten as %.3f, the result is printed as 957.375. usleep() is a function that causes the computer to rest between readings of data sets. This function takes microseconds for its argument and thus the nap time, in seconds, must be converted by a multiplicative factor of one million. Note the placement of the usleep() function inside the big loop but outside the smaller loop. The final brackets indicate the end of the outer loop and the end of the main program.

** IMPORTANT **

TO AVOID A RUN TIME ERROR IN WHICH THE STACK SIZE OVER FLOWS, BE SURE TO CLOSE A FILE IMMEDIATLY FOLLOWING THE LINES THAT OPEN AND WRITE TO THE FILE. THIS IS ESPECIALLY IMPORTANT WHEN WRITING TO FILES WITHIN LOOPS.

Save the C program by clicking "Save Buffer As". Check the directory path and

Type: programname.c

at the end of the path and press **<enter>**

The program is now ready to be compiled. The C program, which was saved as **programname.c,** must be linked to the files that contain all of the interface bus commands (Ex. ibwrt, ibrd, ibclr,etc).

There is a space after the 'c'

Type: **gcc -o programname programname.c /usr/local/lib/gpib/cib.o -lm <enter>**

Here, **gcc** is the compile command. The **-o programname programname.c** group gives the executable file the specific name **“programname”.** (Without this group, the executable program will be given the default name **a.out**.) The **c /usr/local/lib/gpib/cib.o -lm** group assures that the correct links are established.

Now run the program:

Type: **programname** **<enter>**

TOPICS IN C PROGRAMMING

By Bob Hain (ME Net)

Introduction

This document is not intended to be a text on C programming. Because many of you may not have had the opportunity to use or practice C programming, we are attempting to provide a brief description of some of the elements of C which you will need in your laboratory work. We will leave out many topics but will try to provide simple, although sometimes incomplete, explanations of some of the basic elements of C.

Why C?

The computer industry is changing rapidly. Although changes in hardware are easier to observe, changes in the software environment are no less striking. The FORTRAN and BASIC programming languages have served the scientific community for many years. These language are highly optimized for numerical calculation and are still in wide-spread use. But with the introduction of small powerful computers, software needs began to change. These computers were applied to many tasks not solely based on numerical manipulation. Two examples of such applications are the acquisition of experimental data and control of the experimental process. The FORTRAN and BASIC languages were extended to address many of these changing needs, but modern languages such as C began to spring into use. The speed with which C has developed has made it impossible for the University to introduce it early in the curriculum and to build on it throughout your education. Because of C's acceptance in industry and research institutions, we feel that you should be exposed to it. We do not expect you to become an expert in C programming. In fact, we stress that this course is about experimental techniques for heat transfer studies. An introduction to C programming falls within the scope of such a course, but it is not its main objective. We hope that you will find this experience pleasant and rewarding.

A Simple C Program

```
main()
{
}
```

It has no input, no output, and does nothing. I didn't claim it was a useful program, but it is the simplest one I could think of. What is demonstrated here are the minimum requirements of a C program. All C programs must have one function called main. The syntax of a function consists of a name followed by a set of parentheses and a set of braces. The braces delimit a group of statements (null in this case). We will encounter many braces.

The program above could have been written as:

```
main() { }
```

This is equally acceptable to the C compiler, but it is not good style. While I will not make many explicit comments about style, try to be aware of the issue.

Formatted Output

The next C program is often the first one people ever see. It is the first program presented in The C Programming Language by Brian W. Kernighan and Dennis M. Ritchie (Prentice-Hall, 1978).

```
main()
{
    printf("hello, world\n");
}
```

The output of this program is:

```
hello, world
```

While this program is only slightly more utilitarian than the last (it at least has output), it demonstrates a few more features of C programming. The printf() statement provides output to the screen. All statements must end in a semicolon! The most common error in C programming is to omit the semicolon. Such an omission causes the compiler to go berserk, reporting some sort of nonsensical error message a line or two later in the program. The first thing to do when things go wrong is to check that all your statements end with a semicolon. Another point to observe is that, ignoring all the stuff in the parentheses and the semicolon on the end, the statement reduces to printf(). This, of course, is a function. C is a very simple language that has very few built-in features. This does not imply that it is a limited language. The simplicity of C is its strength. A great amount of C programming consists of calling functions. These functions usually are written in C and serve to make programming easier. The concept of building ever more complex programs by assembling lots of simple statements is common in the computer world, and C embraces this concept.

Because output and formatting are so important in computer programming, it would be good to explain the printf() function and the related functions fprintf() and sprintf(). All three of these functions perform similar tasks. printf() formats output and writes it to the screen, fprintf() writes to a file, and sprintf() stores its output in an area (array) of memory. For now, the important thing to understand is how to specify how the output will be formatted. We will examine how this is accomplished using the printf() function as an example. The function's syntax is:

```
printf("control", arg1, arg2, ...);
```

The idea is that printf() will format the arguments according to the control string. After a look at the control string syntax, we can try an example or two. Most of the characters in a control string represent themselves, as in the "hello, world\n" example. But what about the \n part?

- \n stands for a new line
- \t stands for a tab
- \b stands for a backspace
- \0 stands for a null character (the utility of this will be explained later)

Another important character to watch out for is the % symbol. In the control string, this character introduces a conversion for one of the arguments. There is a one-to-one correspondence between the % characters and the arguments.

- %c prints a single character
- %s prints a string of characters
- %d prints the decimal value of the integer argument
- %o prints the octal value of the integer argument
- %x prints the hexadecimal value of the integer argument
- %f prints the floating point argument as [-]mmm.nnnnn
- %e prints the floating point argument as [-]m.nnnnnnE[/-]xx+
- %g uses %e or %f, whichever is shorter

Using what we already know, we can produce quite a bit of formatted output. One can embellish the output further by controlling the field width and the precision of the conversion as follows:

```
%field_width.precisionf
```

Confused yet? Well, maybe some examples will help.

```
main()
{
int i;
```

```
double f;

        i = 16;
        printf("The decimal value of i is %d\n",i);
        printf("The octal value of i is %o\n",i);
        printf("The hexadecimal value of i is %x\n",i);

        f = 100.0 / 3.0;

        printf("f = %f\n",f);
        printf("f = %e\n",f);
        printf("f = |%10.3f|\n",f);
}
```

The output of this program is:

```
The decimal value of i is 16
The octal value of i is 20
The hexadecimal value of i is 10
f = 33.333333
f = 3.333333e+01
f = |    33.333|
```

The vertical bars in the last formatting example surround the output field.

Declaration of Variables

In addition to the formatting examples, several new constructs have been added to the last program. Immediately after the first brace are two lines of code that state what variables are going to be used and what type they are. The variable i is an integer and the variable f is a double precision floating point number. Because of the way C handles mathematical functions, use double instead of float. (You don't want me to explain this point ...Trust me.) The C compiler will force you to declare all variables.

Mathematics

What do you think of a computer language that only knows how to add, subtract, multiply and divide? This may seem rather limiting at first but, as always, there is a way around this apparent limitation. The last program presented showed how the built-in divide (/) operator worked. But what about things like logs, powers and other mathematical operations?

```
#include <stdio.h>
```

```
#include <math.h>
main()
{
double f, result;

        f = sqrt(2.0);

        result = f * f;
        printf("f * f = %f\n", result);

        result = pow(f,2.0);
        printf("f raised to the power of 2 = %f\n",result);

        result = exp( 2 * log( f ));
        printf("exp( 2 * log (f)) = %f\n",result);
}
```

The output of this program is:

```
f * f = 2.000000
f raised to the power of 2 = 2.000000
exp( 2 * log (f)) = 2.000000
```

The Preprocessor

The last example is fairly self explanatory, except for those funny looking lines at the top of the program that begin with #include. These lines tell the preprocessor to include other files (squirreled away with all the compiler parts) into your file before actual compilation. Header files (can you guess why they end in .h?) contain definitions of variables, macros, and functions that might be needed by your program. In the case of math.h, the file contains the information pertinent to the use of the math functions. The stdio.h file should have been included all along, but the C compiler was cleaver enough to get it when it saw the printf() function. This omission was a little slight of hand, but I didn't want to overwhelm you in the first example. The preprocessor has some other useful features that you should keep in mind. Let's look at another example.

```
#include <stdio.h>
#include <math.h>
#define START 0
#define END 90
#define STEP 10
#define DEG2RAD (3.14159 / 180)

main()
```

```
{
double f;

      for (f = START; f <= END; f = f + STEP){
            printf("Sin of %2.0f deg. is %f\n", f, sin( f * DEG2RAD));
      }
}
```

The output of this program is:

```
Sin of 00 deg. is 0.000000
Sin of 10 deg. is 0.173648
Sin of 20 deg. is 0.342020
Sin of 30 deg. is 0.500000
Sin of 40 deg. is 0.642787
Sin of 50 deg. is 0.766044
Sin of 60 deg. is 0.866025
Sin of 70 deg. is 0.939692
Sin of 80 deg. is 0.984808
Sin of 90 deg. is 1.000000
```

In addition to the #include statements, there are several #define statements. The syntax of the define statement is:

```
#define identifier replacement-string
```

The preprocessor replaces all subsequent instances of identifier with the replacement-string.

Loops

The last example included a loop. Looping is a basic computer programming technique, regardless of the language. For C language, the most common type of loop is the for loop. Let's examine its syntax.

```
for(initializations; test; end of loop processing){
      statement_1;
      .
      .
      statement_n;
}
```

The initialization part of the loop is done before the loop is started. The test portion of the loop is actually a while test. The end of loop processing occurs at the end of each loop, but before the test. In the last example program, f was initialized to START (which had been replaced by the preprocessor with a 0). At the end of each loop, STEP (10) was added to f. Then the while test was applied: while f was <= (less than or equal to) END (90), the loop was executed again. Remember from your language studies that languages have idioms. C language is not an exception. A C idiom worth noting is:

```
for(;;){
        statement_1;
        .
        .
        statement_n;
}
```

This is a loop with no initializations, no test and no end of loop processing. It is a forever loop, and must be broken by one of the statements inside. Here is an example.

```
#include <stdio.h>

main()
{
int i;
        i = 0;
        for(;;){
                i = i + 1;
                if ( i > 3 ){
                        break;
                }
                printf("The loop is still running. i = %d\n",i);
        }
}
```

The output of this program is:

```
The loop is still running. i = 1
The loop is still running. i = 2
The loop is still running. i = 3
```

The last example also introduced the if construction and the break statement.

Arrays and Pointers

I am going to introduce several related topics at once. You will use the concepts presented here in your laboratory work. The most common communication method between the computer and the instruments you will be using is sending and receiving series of characters. Often times the series will contain characters that are not wanted and portions of the series must be removed. The model of sending and receiving characters through a common interface (the IEEE-488 bus) allows a programmer to learn to communicate with one instrument and to generalize that knowledge to communicating with other instruments. The series of characters that you send to the various instruments and the format of the character series the instruments return is dependent on the particular instrument with which you are communicating, and will be referred to as being device dependent. The basic input/output format for sending and receiving data is device independent. In the above discussion, I have avoided the term string because I wish to use that term in a very special way. Let's jump right into the worst (or best) part of the whole discussion: pointers. Because FORTRAN and BASIC do not support pointers, this will be an new concept for many of you. One of the great strengths of the C programming language is the availability of pointers. So what are they? Pointers are variables that contain the address (location in memory) of something (most likely a piece of data). Keep in mind that a pointer does not contain anything but an address. Your house or apartment has an address, and we could find you by going to that address and knocking on your door. You do not live in your address; your address is only a pointer to where you live. Let's look at an example.

```
#include <stdio.h>

main()
{
int i;
char buffer[50];
char *cp;

      i = 5;
      sprintf(buffer,"i = %d",i);

      for(cp = buffer; *cp != '\0'; cp = cp + 1 ){
            printf("%c\n",*cp);
      }
}
```

The output of this program is:

```
i

=

5
```

Oh boy! There's a lot of new things here, and a lot of funny looking characters. Everything should be familiar until the line that contains char buffer[50]. This construction states that buffer is an array of 50 characters. The square brackets make buffer an array. The next line of the program, char *cp, defines a pointer to a character. The star makes cp a pointer. Remember that cp is only the address of a place where a character can be found; it is not a character. sprintf(buffer;"i = %d",i); works like the printf statement except that the output goes into buffer and that the output will have a special character \0 appended to it. We will learn more about the reason for the \0 character soon but, for now, we know it is there and use it in the test portion of the for loop. Let's tackle that for loop. Dissecting it piece by piece. First, in the initialization portion of the loop, cp = buffer; the address of buffer is stored in cp. The statement is not intuitive, but if you understand that, internally, C knows an array by its address (not its name) it should make more sense. Also notice that there is no * in front of cp. This is because cp is a pointer; the * has a special meaning that is context dependent. If the * appears in declaration, as in char *cp it notifies the compiler that you wish to use cp as a pointer. If the * appears anywhere else in the program, as it does in the test portion of the for loop, it instructs the compiler to go to the address stored in cp and do something with whatever is at that address. In the example above, the test, *cp != '\0', should be read as "While the character stored at the address held in cp is not equal to the special character \0, continue the loop." In C parlance, the * is referred to as the indirection operator. The program first looks in cp to find the address of the character for which it is looking (an indirect means of access). The last nifty thing to observe is in the end of loop processing part of the for loop. The construct cp = cp + 1 does not add one to the value stored in cp. The compiler knows cp is a pointer and interprets this as "go to the address next door". This is referred to as pointer arithmetic and is quite useful. You can use it, as we do here, to easily access the next element of an array. The only remaining part of this example to examine is the printf statement. Here, we print one character at a time (followed by a new line). Do you know why the argument to be printf is *cp instead of cp? We want to print the character found at the address contained in cp we do not want to print the address contained in cp. The blank looking lines in the output actually contain a space, but you can't see a space unless something comes after it.

String Handling

While C does not support strings, it has a number of functions available for doing just that. This is analogous to how C handles mathematics. The string functions operate on character arrays. In general, we do not know how long a string might be, and neither do the string functions, so we must indicate the end by some means. One character that cannot be part of any string is the null character (\0). (This was something I promised to tell you about earlier.) Some string functions and sprintf automatically append the \0 character to the strings they format. Other functions like printf (when told to print a string) and strlen (string length) look for the \0 character to signal the end of the string.

```
#include <stdio.h>
#include <string.h>
#include <math.h>

main()
{
char buffer[100];
double number;

        strcpy(buffer,"123");
        strcat(buffer,"ABC");
        printf("So far the buffer contains %d characters\n",strlen(buffer));
        printf("The characters are |%s|\n",buffer);

        printf("\n");

        number = 1000.0 / 3.0;
        sprintf(&buffer[strlen(buffer)],"%f",number);
        printf("Now the buffer contains %d characters\n",strlen(buffer));
        printf("The characters are |%s|\n",buffer);

        printf("\n");

        printf("The integer at the beginning of the buffer is %d\n",
            atoi(buffer));
        printf("The floating point number at the end of the buffer is %f\n",
            atof((strchr(buffer,'C') + 1)));
}
```

The output of this program is:

```
So far the buffer contains 6 characters
The characters are |123ABC|

Now the buffer contains 16 characters
The characters are |123ABC333.333333|

The integer at the beginning of the buffer is 123
The floating point number at the end of the buffer is 333.333333
```

In order to use the string functions, we must include string.h. To use the character-to-number conversion functions, atof and atoi, we have to include math.h. With these preliminaries out of the way, let's examine the program. The first new function we encounter (strcpy) will copy the string "123" into the buffer. strcat will add the string

"ABC" to the end of the string already contained in the buffer. The buffer is printed out so you can see its contents. Now for some tricky stuff. We use sprintf to format a number and add it to the contents of the buffer. We do not want to write at the beginning of the buffer so we use the function strlen to find the end of the string already in the buffer. Because the buffer[i] is a character and the function sprintf expects a pointer to where it can start putting characters, we resort to the & operator. This operator yields the address (equivalent to a pointer) of the item that follows. In this case, &buffer[strlen(buffer)] is the address at the end of the string contained in the buffer. The buffer is printed again so you can see the contents. That explains how to put a string together piece by piece, but how can we take it apart and extract the pieces we want? You could apply some of the techniques you have already seen in the example that was presented in the section on arrays and pointers but, because you already know those tricks, we will show you some new ones. Two new functions atoi and atof will be used to convert portions of the string contained in the buffer into an integer and a floating point number. The function atoi(buffer) reads characters from the beginning of the buffer until it finds the first character that doesn't make sense as part of an integer, and converts what it had found up to that point from a string representation to an integer. In the next line, we have to do a little more work because the number we seek is not at the beginning of the buffer. We could have used our previous knowledge and said atof(&buffer[6]) (arrays start at 0) but we might not always know the place where we want to start reading. In this case, we used our knowledge that the character 'C' immediately preceded the place we expected to find the number we seek. Because strchr returns the address of the character 'C', we had to get to the next address (remember pointer arithmetic) by adding 1. The atof function could then read as much as made sense (to the end of the string in this case) and convert the result to a floating point number.

APPENDIX B: ERROR ANALYSIS

One method of error analysis that can be used for engineering applications is the root-sum-square (RSS) method. This should be familiar to you from the junior labs. This section briefly outlines the method and its consequences for the Thermal Environmental Engineering laboratory report data analysis.

Definitions:

Δ = uncertainty in precision, usually reported as a relative or percentage error, or as an absolute error

x,y,z = any measured quantities such as pressure, temperature, flow rate, etc.

w = the resultant value from the measured quantities

If:

$$w = f(x,y,z)$$

According to the RSS method, the error in w is defined by:

$$\boxed{(\Delta w)^2 = \left(\Delta x \frac{\partial w}{\partial x}\right)^2 + \left(\Delta y \frac{\partial w}{\partial y}\right)^2 + \left(\Delta z \frac{\partial w}{\partial x}\right)^2 \qquad \xleftarrow{1}}$$

The partial derivatives depend on what the function, f, is. The uncertainties, Δ, can be estimated by $\pm 1/2$ the smallest division of the measuring instrument. If enough measurements are taken, the standard deviation of those measurements can be used as the uncertainty.

<u>Example:</u>

$$w = \frac{x}{\sqrt{y}} = xy^{-1/2}$$

$$\frac{\partial w}{\partial x} = y^{-1/2} \qquad \text{and} \qquad \frac{\partial w}{\partial y} = -\frac{1}{2}xy^{-3/2}$$

therefore:

$$(\Delta w)^2 = \left(\Delta x y^{-1/2}\right)^2 + \left(\Delta y\left(-\tfrac{1}{2}\right)xy^{-3/2}\right)^2$$

Dividing both sides by w^2 ($=xy^{-1/2}$) greatly simplifies this and also defines the 'easy way' to do the root-sum-square error analysis if w results from a PRODUCT of measured quantities:

$$\left(\frac{\Delta w}{w}\right)^2 = \left(\Delta x\frac{y^{-1/2}}{xy^{-1/2}}\right)^2 + \left(\Delta y\frac{-\frac{1}{2}xy^{-3/2}}{xy^{-1/2}}\right)^2 = \left(\frac{\Delta x}{x}\right)^2 + \left(\frac{1}{2}\frac{\Delta y}{y}\right)^2$$

More generally, if:

$$w = x^a y^b z^{-c}$$

then:

$$\boxed{\left(\frac{\Delta w}{w}\right)^2 = \left(a\frac{\Delta x}{x}\right)^2 + \left(b\frac{\Delta y}{y}\right)^2 + \left(c\frac{\Delta z}{z}\right)^2 \qquad \xleftarrow{2}}$$

Comments:

1) The error in any quantity resulting from a PRODUCT of measurements can be expressed easily in relative, or %, form.
2) Unfortunately, if the function defining w contains any sums, canceling of terms cannot be done and Equation 1 must be used.
3) Partial derivatives do not need to be computed in this case.
4) The sign of the exponent doesn't matter, since it gets squared.

Back to the original example:

Suppose that: $x = 400 \pm 2$
$y = 30 \pm 1$

then:

$$\left(\frac{\Delta w}{w}\right) = \sqrt{\left(\frac{2}{400}\right)^2 + \left(\frac{1}{2}\frac{1}{30}\right)^2} = \sqrt{0.005^2 + 0.012^2}$$

$$= 0.013 = 1.3\%$$

It is easy to see which measurement contributes the most error. In this case it is the measurement of y. The error can be expressed as a relative (%) error or as an absolute error:

$$w = 73.0 \pm 1.3\%$$
$$= 73.0 \pm 0.9$$

INDEPENDENT SOURCES OF ERROR

Example: measuring the temperature of flowing water

Independent sources of error may include:

1) measurement by a thermocouple
2) actual variations in the water temperature

therefore, the total error in the water temperature is:

$$(\Delta T)^2 = \left(\Delta T_{\text{thermocouple}}\right)^2 + \left(\Delta T_{\text{actual}}\right)^2$$

USING ERROR ANALYSIS IN DESIGNING TESTS

Error analysis also is very useful in designing experiments or tests. Using the same example, suppose you want the percentage error in w to be less than 3%.

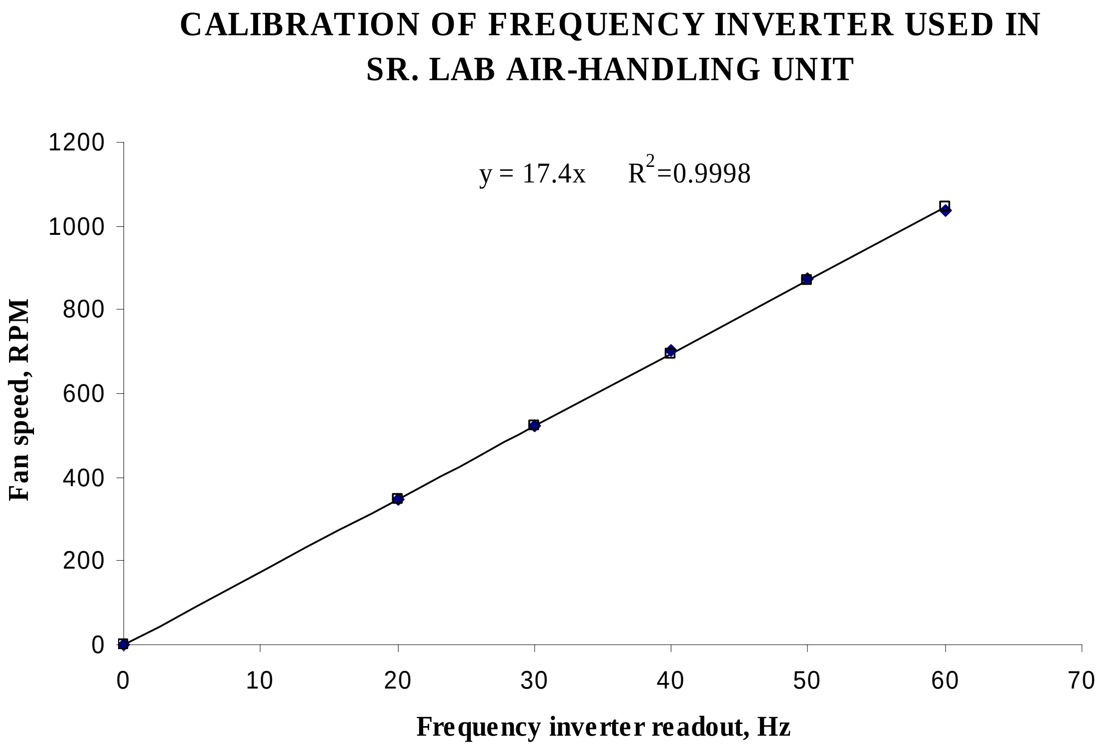
Then:

$$3\% = 0.03 \geq \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{1}{2}\frac{\Delta y}{y}\right)^2}$$

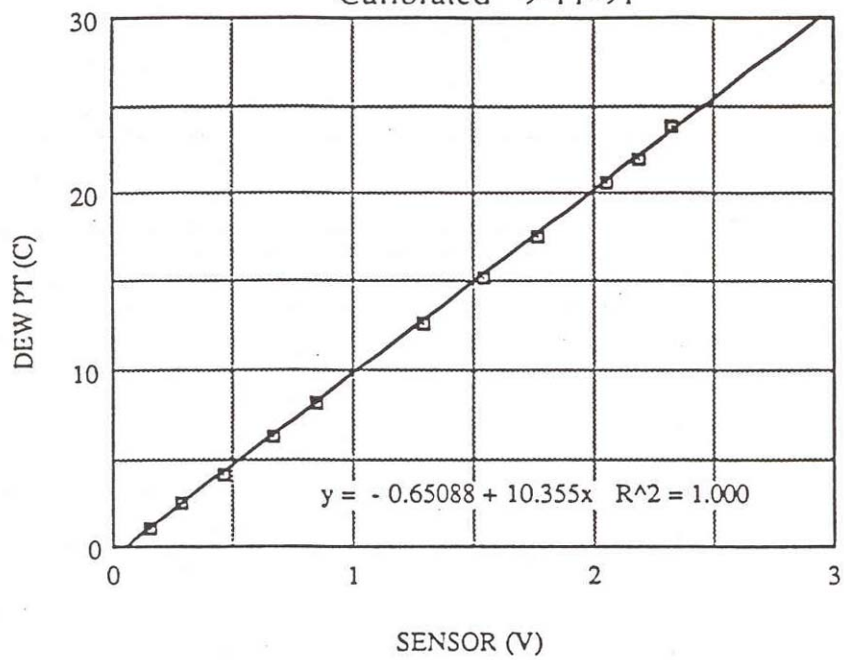
($\Delta x/x$) and ($\Delta y/y$) are the quantities that can be controlled when designing the test.

The choice of equipment determines what Δx and/or Δy are, and (sometimes) the choice of the duration of the test determines what x and/or y are. For instance, if x represents time, using electronic timing makes Δx very small and the duration of the test, x, may be short. On the other hand, if a stopwatch is used, Δx is larger. Therefore the duration of the test must be increased to make ($\Delta x/x$) sufficiently small.

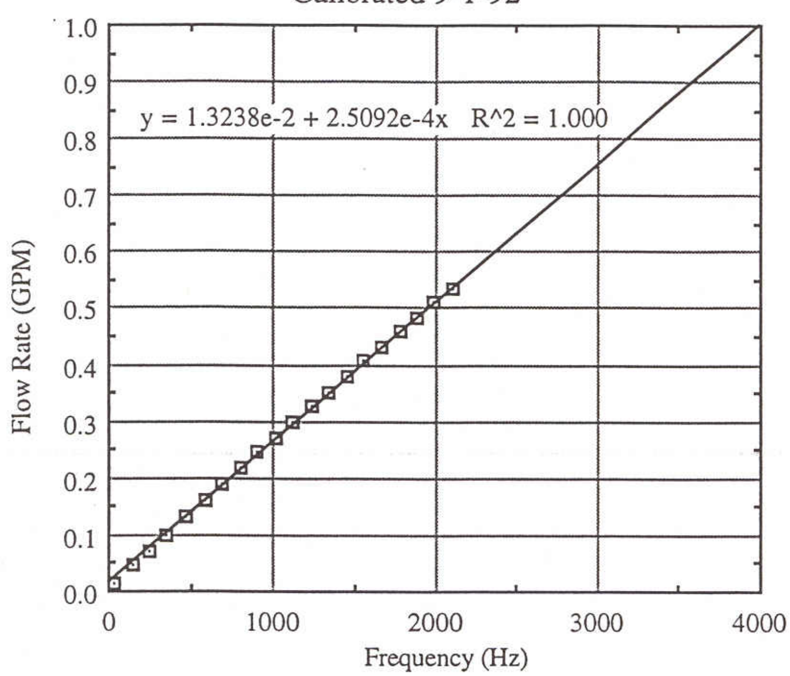
APPENDIX C: CALIBRATION CURVES

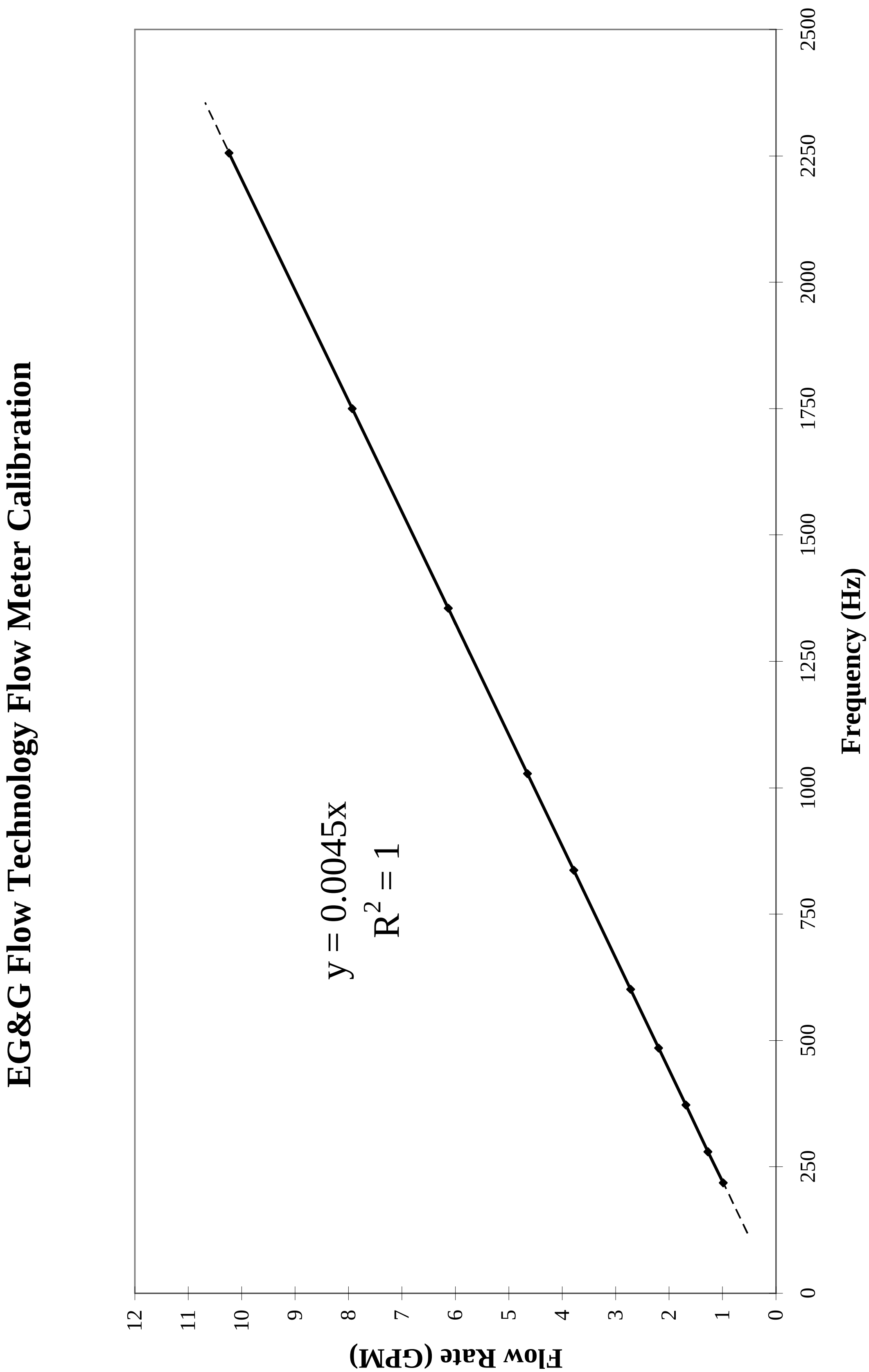


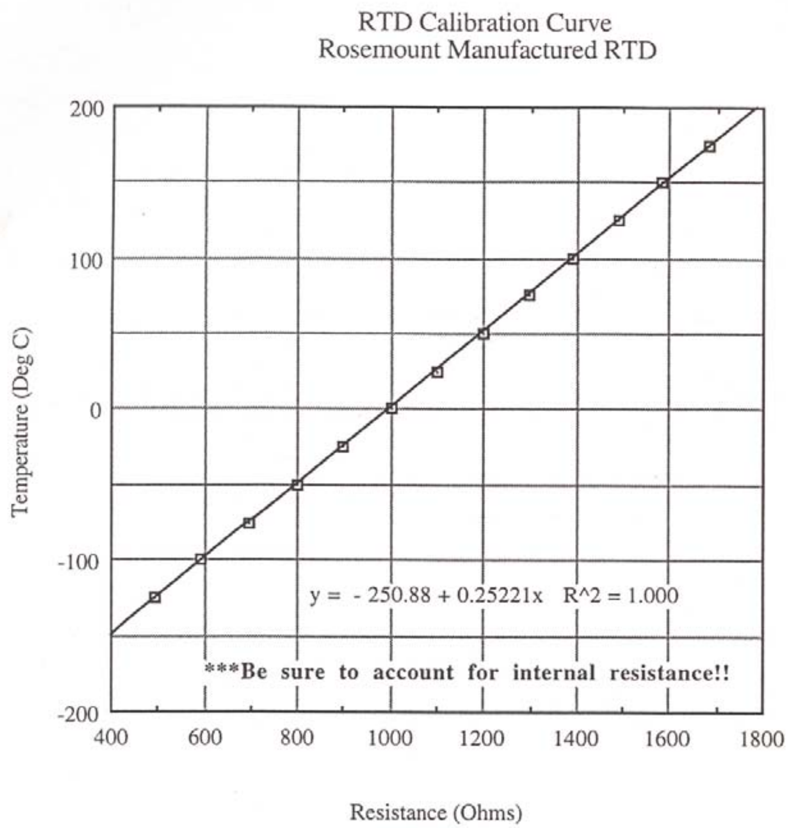
Calibration Curve for the General Eastern Dew Point Hygrometer
Model: 1100 DP S/N: 1550
Calibrated 9-11-91



Calibration Curve for the Sponsler Turbine Flow meter
Model: MF-60 S/N: M1650
Calibrated 9-1-92

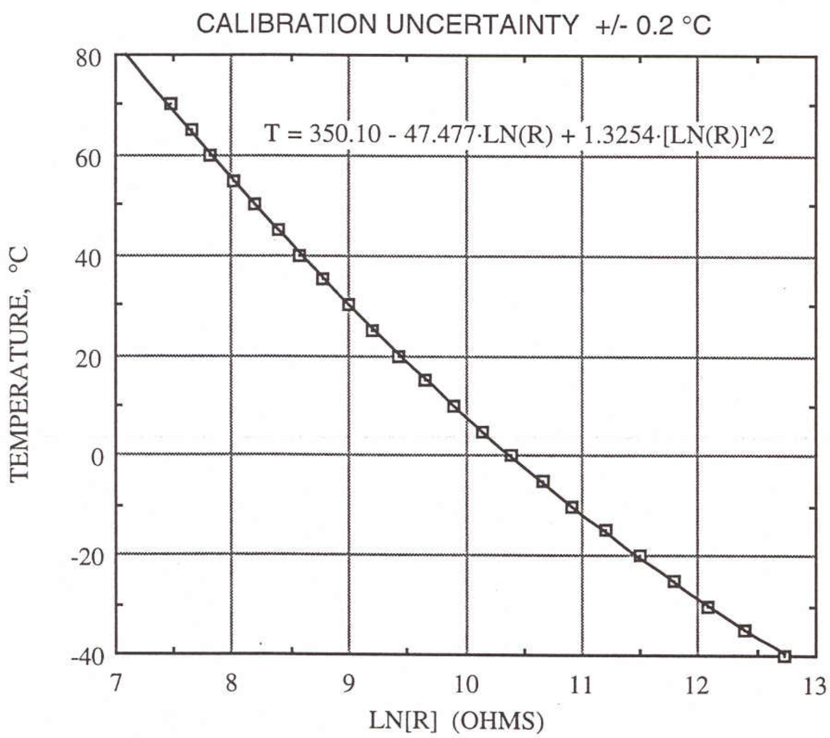



EG&G Flow Technology Flow Meter Calibration
y = 0.0045x
R2 = 1
Flow Rate (GPM)
Frequency (Hz)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
250
500
750
1000
1250
1500
1750
2000
2250
2500

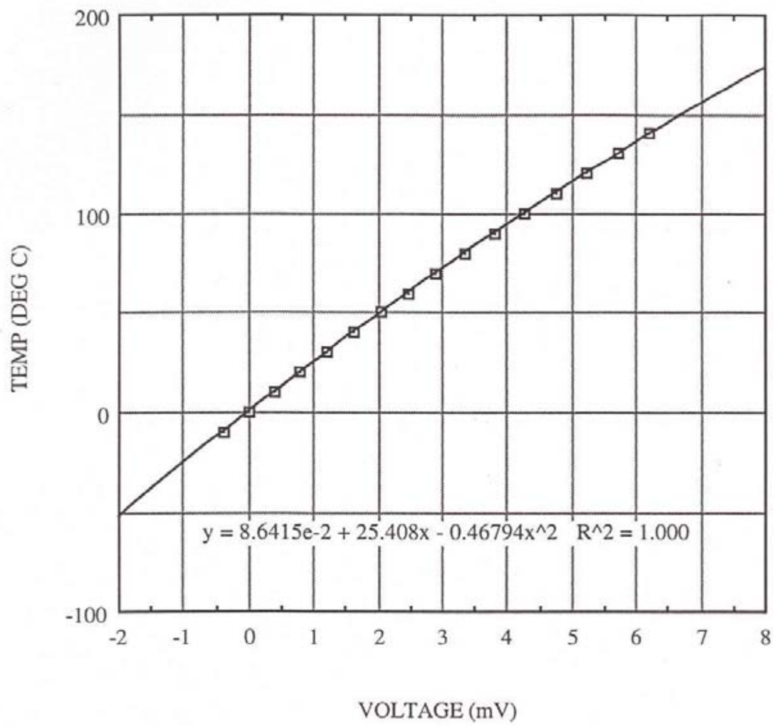


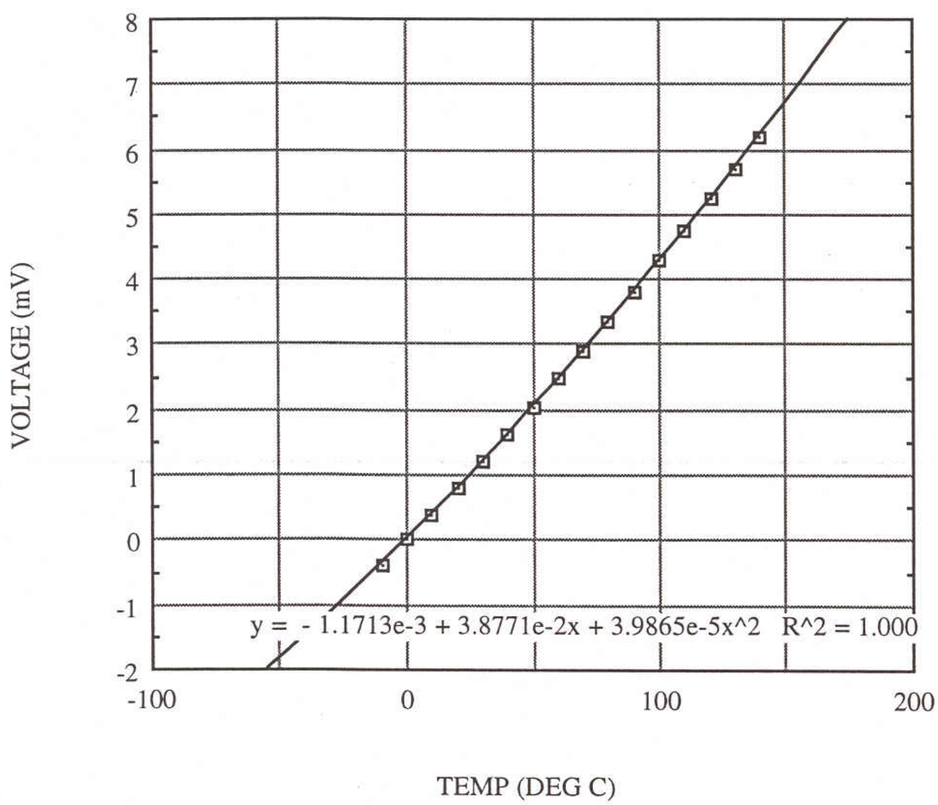
NTC THERMISTOR: TYPE DC 95 F 103 W

(Manufacturer's Calibration)

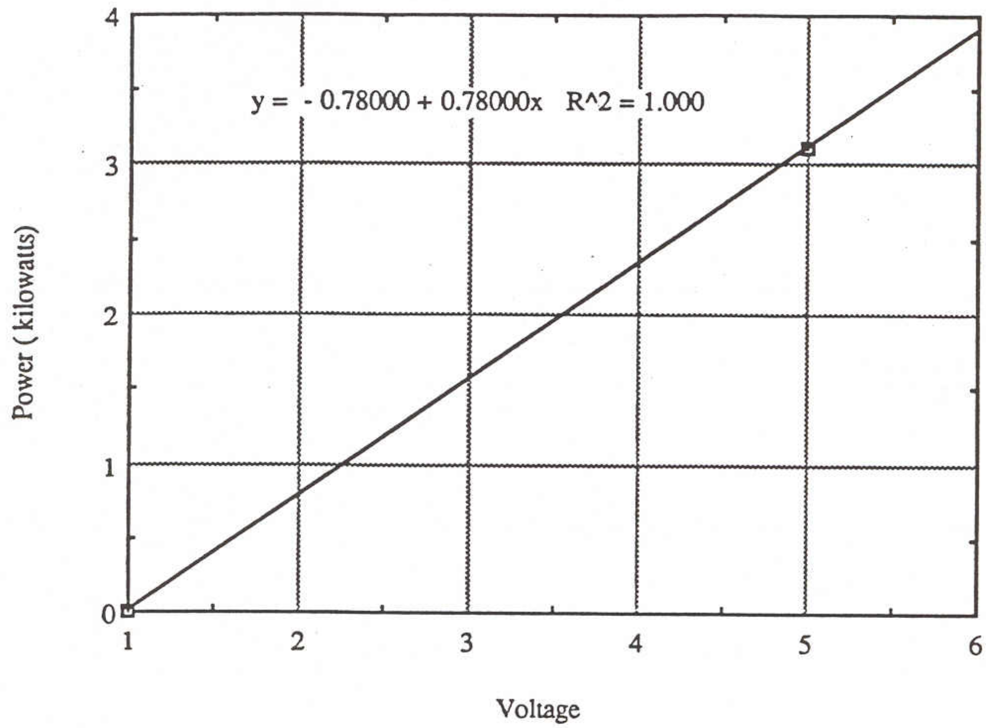


TC CALIBRATION FROM TABLES (Omega)
FOR TYPE T THERMOCOUPLE (Cu-Const)

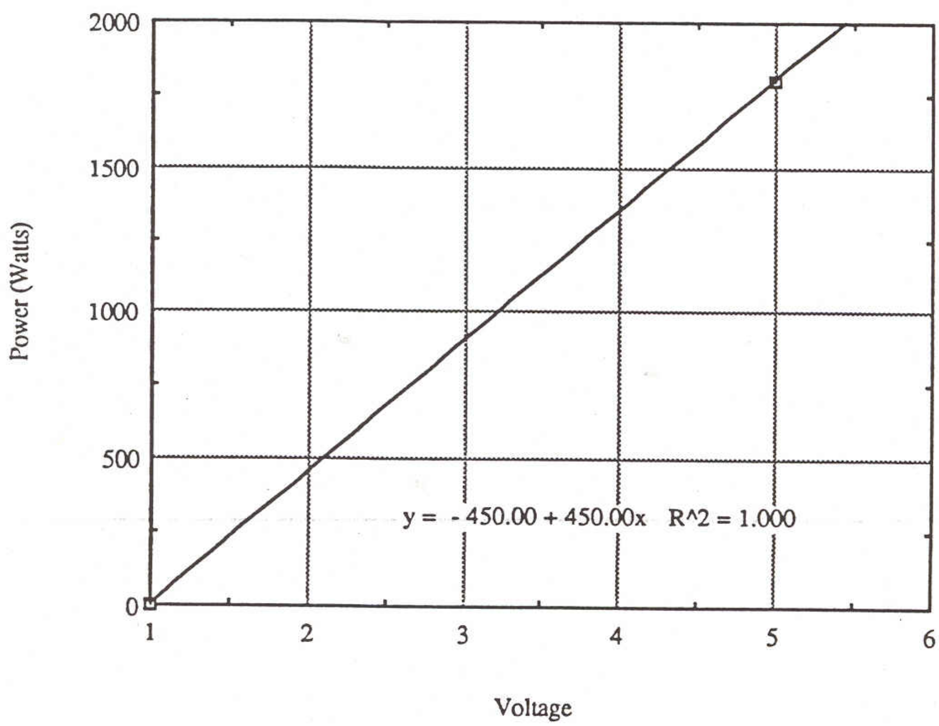


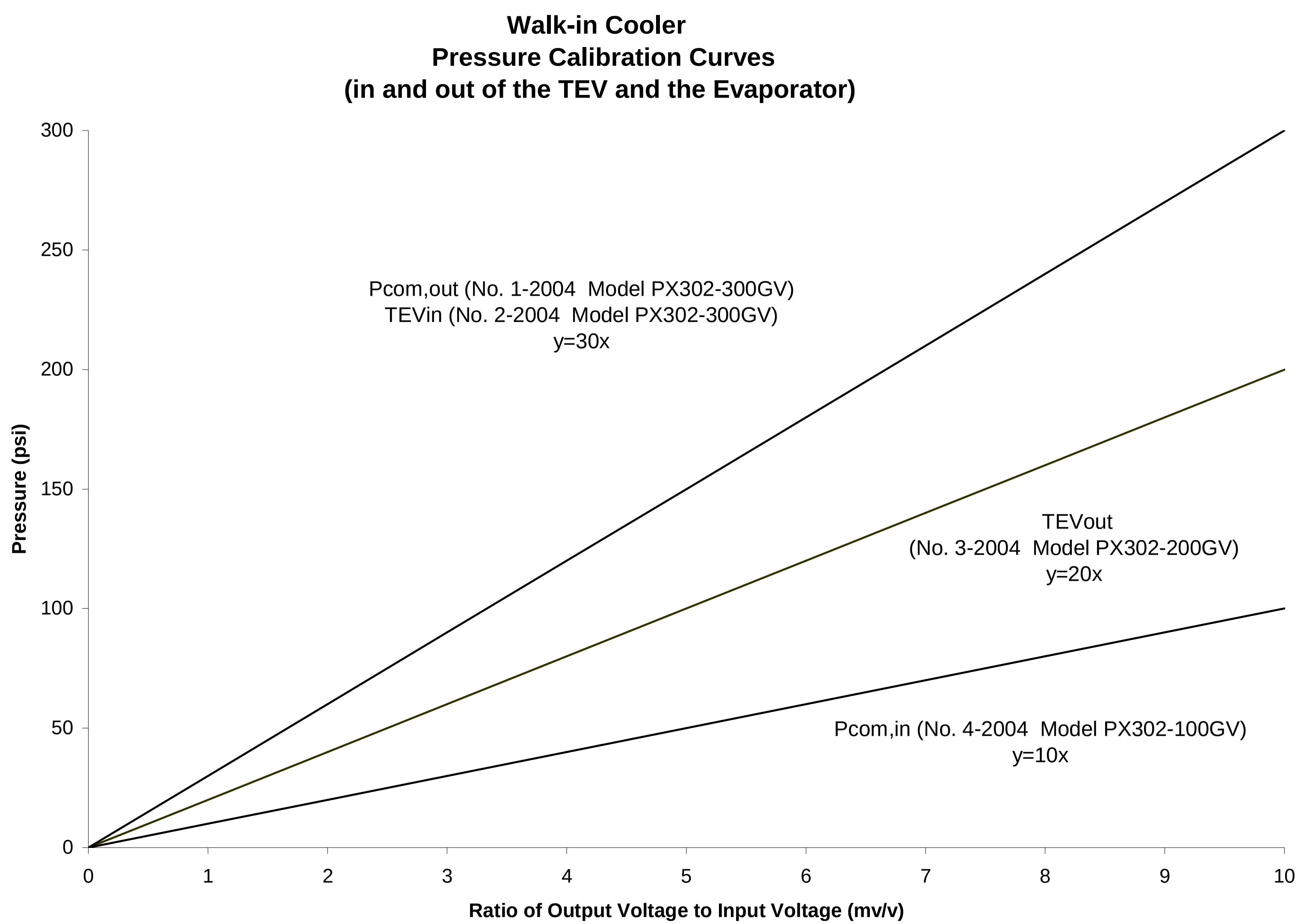


Calibration curve for Yokagawa Watt meter
3-Phase/3-wire Compressor Power

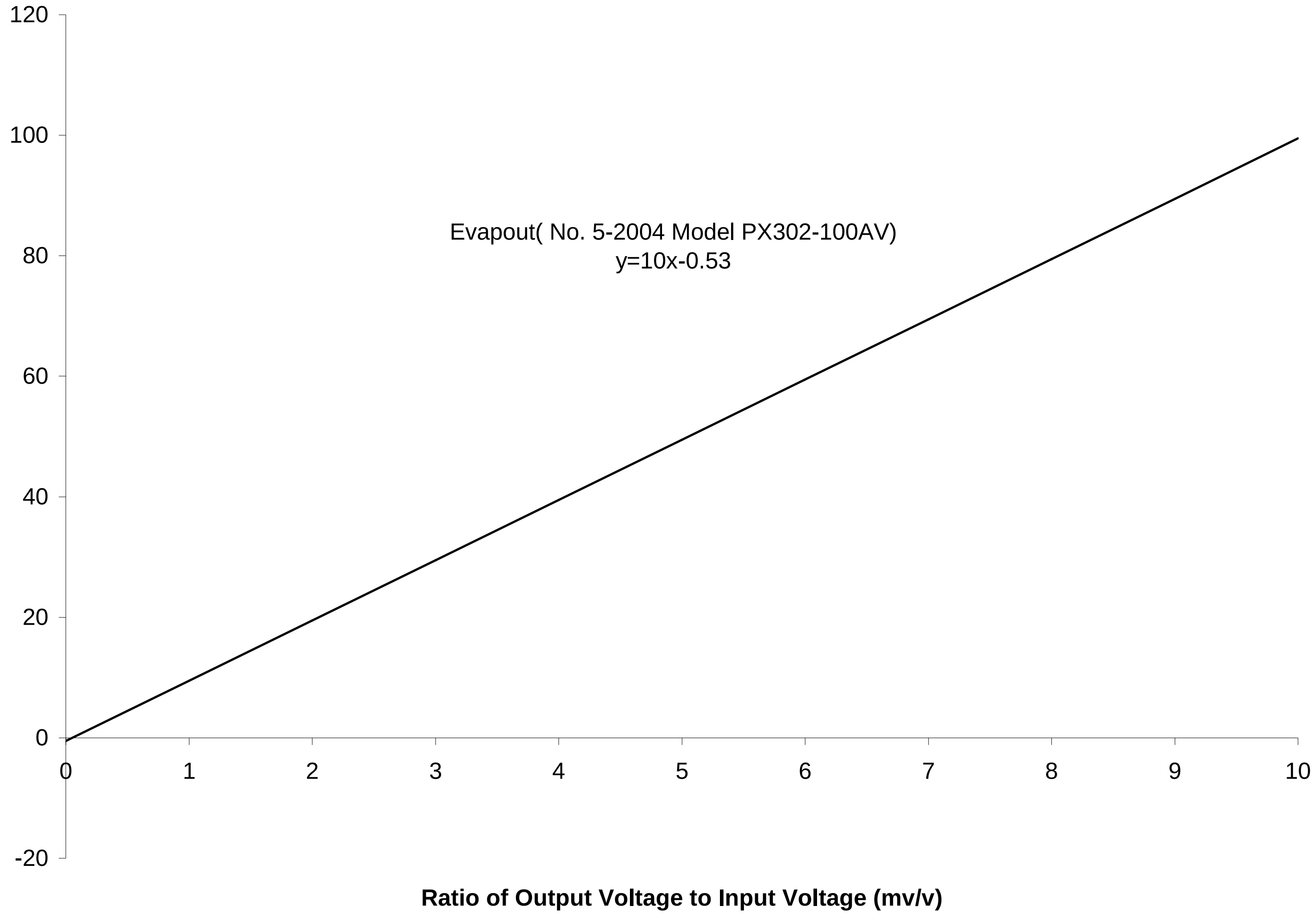


Calibration curve for Yokagawa Watt meter
1-Phase/2-Wire Evaporator and Heat Reclaim




Walk-in Cooler
Pressure Calibration Curves
(in and out of the TEV and the Evaporator)
Pressure (psi)
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Ratio of Output Voltage to Input Voltage (mv/v)
Pcom,out (No. 1-2004 Model PX302-300GV)
TEVin (No. 2-2004 Model PX302-300GV)
y=30x
TEVout
(No. 3-2004 Model PX302-200GV)
y=20x
Pcom,in (No. 4-2004 Model PX302-100GV)
y=10x

Walk-in Cooler
Pressure Calibration Curves
(after the Evaporator)



APPENDIX D: SOLAR RADIATION

The sun is the source of most energy on the earth and is a primary factor in determining the thermal environment of a locality. It is important for engineers to have a working knowledge of the earth's relationship to the sun. They should be able to make estimates of solar radiation intensity and know how to make simple solar radiation measurements. They should also understand the thermal effects of solar radiation and know how to control or utilize them.

The earth is nearly spherical with a diameter of about 7,900 miles (12.7 x 10^3 km). It makes one rotation about its axis every 24 hours and completes a revolution about the sun in a period of approximately 365 1/4 days. The earth revolves around the sun in a nearly circular path, with the sun located slightly off center of the circle. The earth's mean distance to the sun is about 9.3 x 10^7 miles (1.5 x 10^8 km). Around January 1, the earth is closest to the sun while on around July 1 it is most remote, about 3.3% farther away. Since the intensity of solar radiation incident upon the top of the atmosphere varies inversely with the square of the earth-sun distance, the earth receives about seven per cent more radiation in January than in July. The earth's axis of rotation is tilted 23.5 degrees with respect to its orbit about the sun. The earth's tilted position is of profound significance. Together with the earth's daily rotation and yearly revolution, it accounts for the distribution of solar radiation over the earth's surface, the changing length of hours of daylight and darkness, and the changing of the seasons.

Figure 1 shows the effect of the earth's tilted axis at various times of the year. Figure 2 shows the position of the earth relative to the sun's rays at the time of winter solstice. At the winter solstice (around December 22), the North Pole is inclined 23.5 degrees away from the sun. All points on the earth's surface north of 66.5 degrees north latitude are in total darkness while all regions within 23.5 degrees of the South Pole receive continuous sunlight. At the time of the summer solstice (around June 22), the situation is reversed. At the times of the two equinoxes (around March 22 and September 22), both poles are equidistant from the sun and all points on the earth's surface have 12 hours of daylight and 12 hours of darkness.

BASIC EARTH-SUN ANGLES

The position of a point P on the earth's surface with respect to the sun's rays is known at any instant if the latitude, l, and hour angle, h, for the point, and the sun's declination angle,

d, are known. Figure 3 shows these fundamental angles. Point P represents a location on the northern hemisphere.

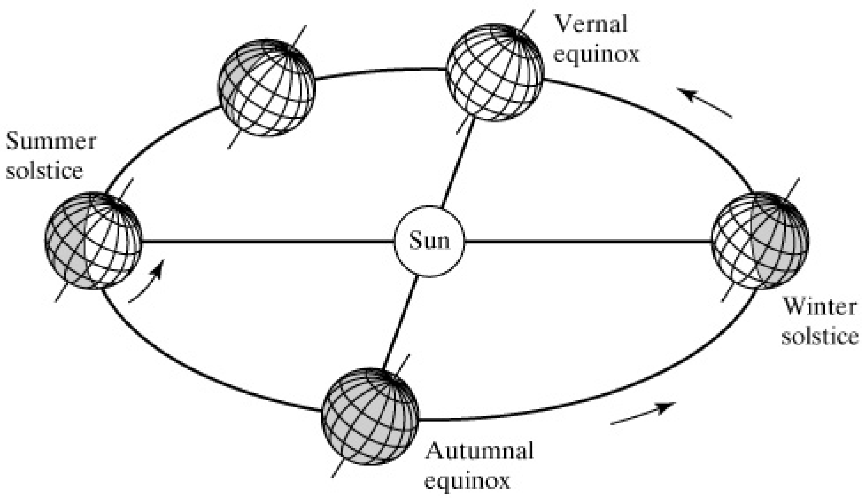


Figure 1: The earth's revolution about the sun

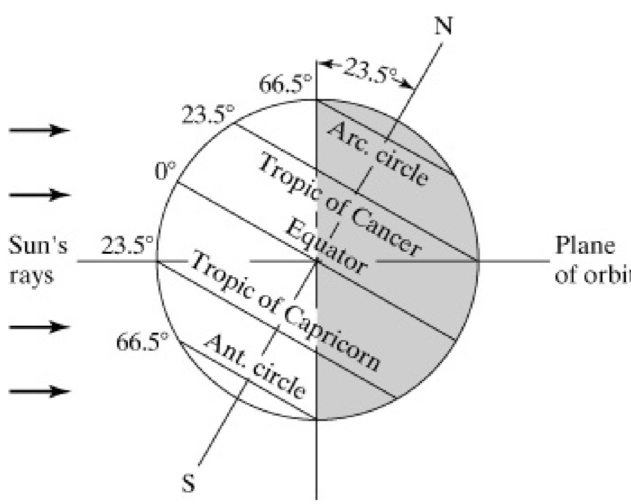


Figure 2: Position of the earth in relation to the sun's rays at time of winter solstice

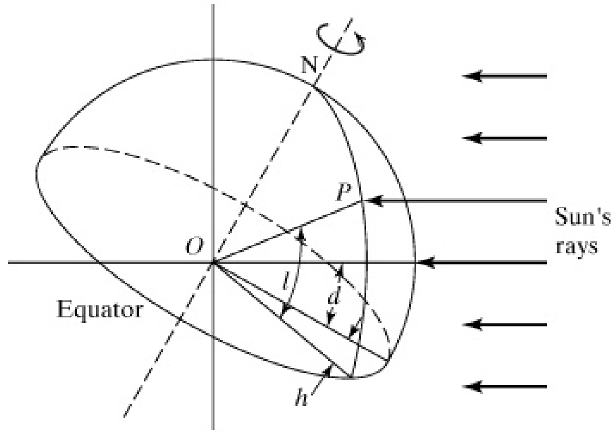


Figure 3: Latitude, hour angle, and sun's declination angle

The latitude, l, is the angular distance of the point P north (or south) of the equator. It is the angle between the line $\overline{OP}$ and the projection of $\overline{OP}$ on the equatorial plane. Point *O* represents the center of the earth. The calculation of the various solar angles, performed later in this chapter, can be simplified by the adoption of a consistent sign convention. As part of this sign convention, north latitudes are positive and south latitudes are negative.

The hour angle, h, is the angle measured in the earth's equatorial plane between the projection of $\overline{OP}$ and the projection of a line from the center of the sun to the center of the earth. At solar noon, the hour angle is zero. The hour angle expresses the time of day with respect to solar noon. One hour of time is represented by $360 \div 24 = 15$ degrees of hour angle. As part of the convention, the hour angle is negative before solar noon and positive after solar noon.

The sun's declination angle, d, is the angular distance of a sun's rays north (or south) of the equator. It is the angle between a line extending from the center of the sun to the center of the earth and the projection of this line upon the earth's equatorial plane. The declination is positive when the sun's rays are north of the equator and negative when they are south of the equator. At the time of the winter solstice, the sun's rays are 23.5 degrees south of the earth's equator (d = -23.5°). At the time of the summer solstice, the sun's rays are 23.5 degrees north of the earth's equator (d = 23.5°). At the equinoxes, the sun's declination is zero.

The declination angle throughout the year can be well approximated by a sine function:

$$d = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \quad \text{[degrees]} \qquad \text{Equation 1}$$

where n is the day of the year. The value of n for any day of the month "D" can be determined easily with the aid of Table 1.

Month	*n for the Day of the Month, D*	*Month*	*n for the Day of the Month, D*
January	*D*	July	181 + *D*
February	31 + *D*	August	212 + *D*
March	59 + *D*	September	243 + *D*
April	90 + *D*	October	273 + *D*
May	120 + *D*	November	304 + *D*
June	151 + *D*	December	334 + *D*

Table 1: Variation in "n" throughout the year for use in Equation 1

RELATIONSHIP BETWEEN CLOCK TIME AND SOLAR TIME

Solar radiation calculations must be made in terms of solar time. In a discussion of time, numerous designations may be used. We will consider here only a brief description to allow us to convert local clock time to solar time for engineering calculations.

Time reckoned from midnight at the Greenwich meridian (zero longitude) is known as Greenwich Civil Time or Universal Time. Such time is expressed on an hour scale from zero to 24. Thus, midnight is O^h and noon is 12^h. Local Civil Time is reckoned from the precise longitude of the observer. On any particular meridian, Local Civil Time is more advanced at the same instant than on any meridian further west and less advanced than on any meridian further east. The difference amounts to 1/15 hour (4 minutes) of time for each degree difference in longitude.

At a given locality, clock time generally differs from civil time. Clocks are usually set for the same reading throughout an entire zone covering about 15 degrees of longitude. The United States is divided into four time zones. The time kept in each zone is the Local Civil Time of a selected meridian near the center of the zone. Such time is called Standard Time. The four standard meridians in the United States are at west longitudes of 75 degrees (Eastern Standard Time, EST), 90 degrees (Central Standard Time, CST), 105 degrees (Mountain Standard Time, MST), and 120 degrees (Pacific Standard Time, PST). In many localities, clocks are advanced one hour beyond Standard Time in summer. In the United States, such time is called Daylight Savings Time.

Time as measured by the apparent diurnal motion of the sun is called Apparent Solar Time, Local Solar Time, or Solar Time. Whereas a civil day is precisely 24 hours, a solar day is slightly different due to irregularities of the earth's rotation, obliquity of the earth's orbit and other factors. The difference between Local Solar Time, LST and Local Civil Time, LCT is called the Equation of
Time, E.

The factors described above can be included into a single equation, which relates solar time and clock time:

$$LST = CT + \left(\frac{1}{15}\right)\left(L_{std} - L_{loc}\right) + E - DT \qquad \text{[hr]} \qquad \text{Equation 2}$$

Where:

LST = Local Solar Time [hr]

CT = Clock Time [hr]

L_{std} = Standard Meridian for the local time zone [degrees west]

L_{loc} = Longitude of actual location [degrees west]

E = Equation of Time [hr]

DT = Daylight Savings Time correction (DT = 0 if not on Daylight Savings Time, otherwise DT is equal to the number of hours that the time is advanced for Daylight Savings Time, usually 1hr)

In using Equation 2, all of the times must first be converted to decimal format from zero to 24, (e.g., a clock time of 3:45 p.m. is expressed as CT = 15.75 hr).
Values of the Equation of Time, E, are calculated by:

$$E = 0.165\sin 2B - 0.126\cos B - 0.025\sin B \qquad \text{[hr]} \qquad \text{Equation 3a}$$

where: $$B = \frac{360(n-81)}{364}$$ [degrees] Equation 3b

and n is the day of the year.

Once Local Solar Time is established, the solar hour angle, h can be calculated. By recalling that the hour angle varies at the rate of 15 degrees per hour, that h = 0 at solar noon, and that the sign convention is h < 0 before solar noon, the equation for the hour angle is determined by:

$$h = 15(LST - 12)$$ [degrees] Equation 4

DERIVED SOLAR ANGLES

Besides the three basic angles (latitude, hour angle, and sun's declination), several other angles are useful in solar radiation calculations. Such angles include the sun's zenith angle θ_H, altitude angle β, and azimuth angle ϕ. For a particular surface orientation, the sun's incidence angle θ, and surface-solar azimuth angle γ, may be defined. All of these additional angles may be expressed in terms of the three basic angles.

To an observer on the earth, the sun appears to move across the sky following the path of a circular arc from horizon to horizon. Figure 4 schematically shows one apparent solar path and defines the sun's zenith, altitude, and azimuth angles. Point P represents the position of the observer, point O is the center of the earth, and I_{DN} is a vector representing the sun's rays. The zenith angle θ_H is the angle between the sun's rays and local vertical, i.e. a line perpendicular to the horizontal plane at P. The altitude angle β is the angle in a vertical plane between the sun's rays and the projection of the sun's rays on the horizontal plane. It follows that $\beta + \theta_H = \pi/2 = 90^{O}$. The azimuth angle ϕ is the angle in the horizontal plane measured from south to the horizontal projection of the sun's rays.

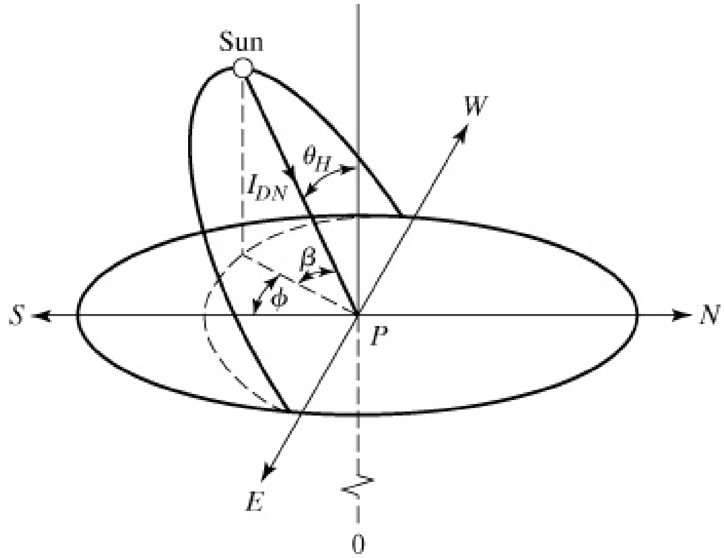


Figure 4: Definition of sun's zenith, altitude, and azimuth angles

Thus the following equations can be derived:

$$\cos\theta_H = \cos l \cos h \cos d + \sin l \sin d$$ Equation 5a

Since $\beta = 90 - \theta_H$, [degrees] Equation 5b

$$\sin\beta = \cos l \cos h \cos d + \sin l \sin d$$ Equation 6

The sun's azimuth, ϕ, is given by the relation:

$$\cos\phi = \frac{1}{\cos\beta}\left(\cos d \sin l \cos h - \sin d \cos l\right)$$ Equation 7

The sign convention used for the azimuth angle, ϕ, is negative east of south and positive west of south. Notice that this sign convention results in the hour angle, h, and the sun's azimuth angle, ϕ, always having the same sign. Since the cosine is an even function, calculating the right hand side of Equation 7 and taking the inverse cosine will not provide the information needed for the sign convention. **The user must assign the appropriate sign.**

Equations 5 - 7 allow calculation of the sun's zenith, altitude and azimuth angles if the declination, hour angle, and latitude are known. In applying these equations, attention must be given to correct signs. A summary of the sign convention is:

l: north latitudes are positive, south latitudes are negative

d: the declination is positive when the sun's rays are north of the equator, i.e. for the summer period in the northern hemisphere, March 22 to September 22 approximately, and negative when the sun's rays are south of the equator.

h: the hour angle is negative before solar noon and positive after solar noon

ϕ: the sun's azimuth angle is negative east of south and positive west of south

In calculations involving other than horizontal surfaces, it is convenient to express the sun's position relative to the surface in terms of the incidence angle, θ. The sun's angle of incidence is the angle between the solar rays and the surface normal. (Notice that for a horizontal surface, the surface normal is the local vertical and the incidence angle is equal to the zenith angle, θ_H.)

In order to evaluate the angle of incidence we need to specify the direction of the surface normal. This is done in terms of the surface tilt angle, Σ, and the surface azimuth angle, Ψ. These angles are defined in Figure 5. The surface tilt angle is the angle between the surface normal and vertical. The surface azimuth angle is the angle between south and the horizontal projection of the surface normal. The same sign convention is used for the surface azimuth angle as is used for the solar azimuth angle, i.e. Ψ is negative for a surface that faces east of south and positive for a surface that faces west of south. The azimuth angle for a horizontal surface is undefined.

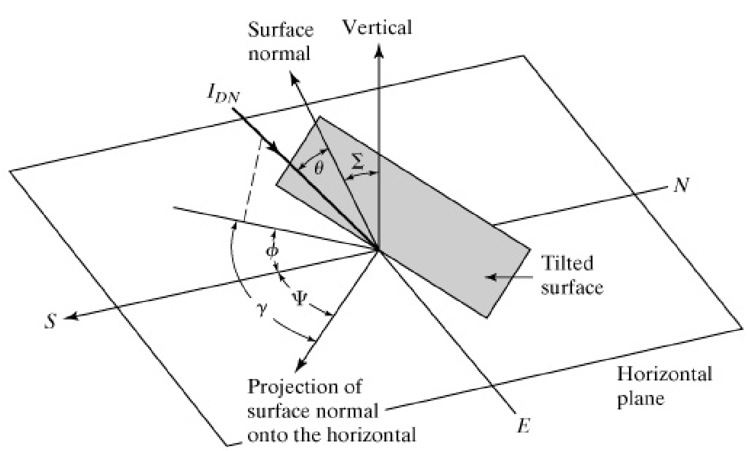


Figure 5: Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of the sun's rays to a tilted surface

It is convenient to define one additional angle, the surface-solar azimuth angle, γ. As shown in Figure 5, the surface-solar azimuth angle is defined as the angle between the horizontal projection of the solar rays and the horizontal projection of the surface normal. Examination of Figure 5 reveals that as long as one adheres to the sign conventions for the azimuth angles ϕ and Ψ, the surface-solar azimuth angle is given by the simple relation:

$$\gamma = \left|(\phi - \Psi)\right| \qquad \text{[degrees]} \qquad \text{Equation 8}$$

In Figure 5, for the tilted surface:

$$\cos\theta = \cos\beta\cos\gamma\sin\Sigma + \sin\beta\cos\Sigma \qquad \text{Equation 9}$$

If the surface is vertical (Σ=90°), then:

$$\cos\theta = \cos\beta\cos\gamma \qquad \text{Equation 10}$$

If the surface is horizontal (Σ=0), then:

$$\cos\theta = \sin\beta = \cos\theta_H \qquad \text{Equation 11}$$

Thus, as previously described, it is seen that the incidence angle for a horizontal surface is equal to the zenith angle.

ESTIMATION OF INTENSITY OF SOLAR RADIATION DURING AVERAGE CLEAR DAYS

In order to predict the solar contributions to building cooling loads it is desirable to estimate the solar intensity on typical or average clear days. An estimate of the direct normal solar flux at the earth's surface for an average clear day is:

$$I_{DN} = Ae^{-B/\sin\beta} \qquad \text{Equation 12}$$

where the coefficients *A* and *B* are empirically determined from measurements of I_{DN} made on typical clear days. The coefficients can be interpreted as:

A = Apparent direct normal solar flux at the outer edge of the earth's atmosphere

B = Apparent atmospheric extinction coefficient

The numerical values of A and B vary throughout the year because of seasonal changes in the dust and water vapor content of the atmosphere and because of the changing earth-sun distance. The ASHRAE Handbook of Fundamentals lists recommended values for the coefficients A and B for the twenty-first day of each month. These values are presented in Table 2. Also included in the table are the values of the declination angle and Equation of Time that ASHRAE lists in conjunction with the clear day coefficients. These values are for the base year 1964. A comparison of the declination angles listed for 1964 and those predicted by Equation 1 reveals that they are in good agreement. Similarly, the calculated values for the Equation of Time agree to within 0.01 hour with those for the 1964 base year. Thus, for the purpose of making HVAC calculations the approximations of Equations 1 and 3 provide acceptable values for the declination angle and Equation of Time.

	A		*B*	*C*		
	$\frac{Btu}{hr \cdot ft^2}$	$\frac{W}{m^2}$	*Dimensionless Ratios*		*Declination, deg*	*Equation of Time, hr*
January	390	1230	0.142	0.058	−20.0	−0.19
February	385	1215	0.144	0.060	−10.8	−0.23
March	376	1186	0.156	0.071	0.0	−0.13
April	360	1136	0.180	0.097	11.6	0.02
May	350	1104	0.196	0.121	20.0	0.06
June	345	1088	0.205	0.134	23.45	−0.02
July	344	1085	0.207	0.136	20.6	−0.10
August	351	1107	0.201	0.122	12.3	−0.04
September	365	1151	0.177	0.092	0	0.13
October	378	1192	0.160	0.073	−10.5	0.26
November	387	1221	0.149	0.063	−19.8	0.23
December	391	1233	0.142	0.057	−23.45	0.03

Table 2: Coefficients for average clear day solar radiation calculations for the twenty-first day of each month, base year 1964

The use of Equation 12 with the coefficients presented in Table 2 is commonly referred to as the ASHRAE Clear Day Solar Flux Model. The model also approximates the average clear day diffuse solar flux from the sky that strikes a horizontal surface, I_{dH}, by the relation:

$$I_{dH} = CI_{DN} \qquad \text{Equation 13}$$

The recommended values of the dimensionless coefficient C are listed in Table 2.

The ASHRAE Clear Day model does not give the maximum values for I_{DN} that can occur during the month, but rather are representative of conditions on average, cloudless days. For very clear atmospheres, ASHRAE points out that values of I_{DN} can be 15% higher than those calculated using Equation 12 and Table 2.

SOLAR RADIATION STRIKING A SURFACE

The solar radiation striking a surface generally consists of three components, **direct, diffuse and reflected.** The direct, or beam, solar radiation is that received from the sun without having been scattered by the atmosphere. The direct solar flux (energy/area-time) striking a surface is denoted by I_D. If the surface is perpendicular to the solar rays, the incident solar flux is equal to the Direct Normal flux, I_{DN}. From Figure 5 it can be seen that if the solar flux strikes a surface at an angle of incidence θ, the direct solar flux striking the surface is given by:

$$I_D = I_{DN} \cos\theta \qquad \text{Equation 14}$$

In the case of a horizontal surface, an additional subscript, H, is used. Thus, I_{DH} is the direct solar flux striking the horizontal. Notice that for a horizontal surface the incidence angle is equal to the zenith angle, θ_H, and therefore:

$$I_{DH} = I_{DN} \cos\theta_H = I_{DN} \sin\beta \qquad \text{Equation 15}$$

The diffuse solar radiation is that received from the sun after its direction has been changed by scattering by the atmosphere. The diffuse solar flux striking a surface is denoted by I_d for the general case and by I_{dH} for the special case of a horizontal surface. Diffuse radiation is typically of rather short wavelength, since short-wavelength radiation is scattered more by the atmosphere. Although diffuse solar radiation on clear days is usually small compared to direct radiation, it cannot be ignored in engineering calculations. During extremely cloudy days, only diffuse solar radiation may reach the ground. Because of its non-directional nature, diffuse solar radiation is more difficult to analyze than direct solar radiation, consequently less is known about it. A common approximation is that the sky is a uniform radiator of diffuse radiation. Assuming the sky to be a diffuse source, the ratio of the diffuse solar flux striking the surface to that striking the horizontal is given by:

$$\frac{I_d}{I_{dH}} = (1 + \cos\Sigma)/2 \qquad \text{Equation 16}$$

The reflected solar radiation is that which strikes a surface after the radiation is reflected from surrounding surfaces. In general, the solar radiation reflected upon a surface depends on the particular location, orientation and solar reflectance characteristics of the surrounding surfaces. One commonly occurring situation is where the solar radiation is reflected from the ground.

If the ground is horizontal and if the reflection is diffuse, an approximation for the reflected solar flux striking a surface, I_R, is given by:

$$I_R = \rho_g I_H (1 - \cos\Sigma)/2 \qquad \text{Equation 17}$$

where:

ρ_g = solar reflectance of the ground

I_H = Total solar flux striking the horizontal ground

The reflectance of the ground varies with the type of ground cover. The reflectance of browned grass is about 0.2, while that of bare soil is about 0.1. The reflectance of fresh snow cover may be as high as 0.87, with the value decreasing to less than 0.5 as the snow becomes dirty.

The total solar flux striking a surface at any instant is the sum of the three components:

$$I = I_D + I_d + I_R \qquad \text{Equation 18}$$

Notice that if any two of the solar flux values that appear in the above set of equations are known, either by **prediction or measurement**, the rest of the quantities can be evaluated. In the case of the use of the ASHRAE Clear Day model, the quantities I_{DN} and I_{dH} are predicted using Equations 12 and 13 respectively, along with the coefficients presented in Table 2.

SOLAR RADIATION MEASUREMENT

Experimental determination of the energy transferred to a surface by solar radiation requires instruments that will measure the heating effect of direct solar radiation and diffuse solar radiation. There are two general classes of solar radiation measuring devices. The instrument used to measure direct normal or beam radiation is referred to as a pyrheliometer. The other instrument, called a pyranometer, is able to measure total radiation within its hemispherical field of view. A pyranometer can also be used to measure diffuse radiation alone by shading the sensing element from the sun's direct rays.

Figure 6 is a photograph of a pyrheliometer and the required tracking device on which it is mounted. The pyreliometer consists of a long collimating tube with a detector at the far end. The aperture angle of the instrument is 5.7°, so the detector receives radiation from the sun and from an area of the sky two orders of magnitude larger than the sun. The detector consists of a multi-junction thermopile with a blackened surface. Temperature compensation is provided to minimize sensitivity to variations in the ambient temperature. The temperature of the blackened junction of the thermopile is a measure of the solar flux striking it. The output measured is a dc voltage, typically in the millivolt range, and the manufacturer, Eppley Laboratories, provides a calibration constant to convert dc voltage to solar flux.

http://www.eppleylab.com

http://www.eppleylab.com

Figure 6: An Eppley normal incidence pyrheliometer and a tracking mount

Figure 7 is a photograph of a pyranometer manufactured by Eppley Laboratories. It uses a thermopile detector, two concentric hemispherical optically ground covers to ensure a proper cosine effect and temperature compensation. This type of pyranometer measures the total solar flux coming from the hemisphere above the detector (the detector is the black disk in the center of the pyranometer). The units are usually mounted horizontally so they measure the total solar flux striking the horizontal. However, they can be mounted in any orientation. In our experiment involving solar collectors, a pyranometer is mounted with the detector in the plane of the collectors, thus measuring the total solar flux striking the collector surface.

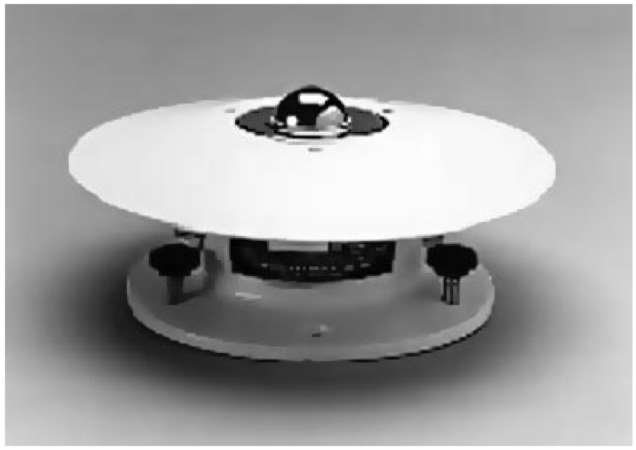


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Figure 7: An Eppley Precision pyranometer

A pyranometer can be fitted with a shading ring to block the beam or direct solar radiation. In this case, the device measures approximately the diffuse plus reflected solar flux from the hemisphere above the detector. Figure 8 is a photograph of a pyranometer with a shading ring. The design of the ring allows continuous recording of the diffuse plus reflected flux throughout the day. The position of the ring is adjusted for the changing declination angle only and can be done every few days.

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Figure 8: Pyranometer with shading ring to eliminate direct solar radiation

THERMODYNAMIC PROPERTIES OF R22 AT SATURATION (ENGLISH UNITS)

	Pressure		Liquid, Density lbm/ft^3	Vapor, Sp. Vol. ft^3/lbm	Enthalpy, Datum −40 °F, Btu/lbm		Entropy, Datum −40 °F, Btu/lbm · °R	
Temp. °F	psia	psig	$1/v_f$	v_g	Liquid h_f	Vapor h_g	Liquid s_f	Vapor s_g
-100.	2.40	*25.1	93.77	18.444	-14.6	93.4	-0.0373	0.2627
-95.	2.87	*24.1	93.31	15.588	-13.4	94.0	-0.0341	0.2602
-90.	3.42	*23.0	92.85	13.243	-12.2	94.5	-0.0309	0.2578
-85.	4.05	*21.7	92.38	11.307	-11.0	95.1	-0.0277	0.2556
-80.	4.78	*20.2	91.91	9.700	-9.8	95.7	-0.0246	0.2534
-75.	5.61	*18.6	91.43	8.360	-8.6	96.3	-0.0214	0.2513
-70.	6.55	*16.6	90.95	7.236	-7.4	96.9	-0.0183	0.2493
-65.	7.61	*14.5	90.47	6.289	-6.2	97.4	-0.0152	0.2474
-60.	8.81	*12.0	89.99	5.487	-5.0	98.0	-0.0121	0.2455
-58.	9.33	*10.9	89.79	5.201	-4.5	98.2	-0.0109	0.2448
-56.	9.88	*9.8	89.60	4.934	-4.0	98.5	-0.0097	0.2441
-54.	10.45	*8.7	89.40	4.682	-3.5	98.7	-0.0085	0.2434
-52.	11.04	*7.5	89.20	4.446	-3.0	98.9	-0.0073	0.2427
-50.	11.67	*6.2	89.01	4.224	-2.5	99.1	-0.0060	0.2421
-48.	12.32	*4.9	88.81	4.016	-2.0	99.4	-0.0048	0.2414
-46.	13.00	*3.5	88.61	3.820	-1.5	99.6	-0.0036	0.2407
-44.	13.71	*2.0	88.41	3.635	-1.0	99.8	-0.0024	0.2401
-42.	14.44	*0.5	88.21	3.461	-0.5	100.0	-0.0012	0.2395
-40.	15.21	0.5	88.01	3.297	0.0	100.3	0.0000	0.2388
-38.	16.02	1.3	87.81	3.143	0.5	100.5	0.0012	0.2382
-36.	16.85	2.2	87.60	2.997	1.0	100.7	0.0024	0.2376
-34.	17.72	3.0	87.40	2.859	1.5	100.9	0.0036	0.2370
-32.	18.62	3.9	87.20	2.729	2.0	101.1	0.0048	0.2365
-30.	19.56	4.9	86.99	2.606	2.5	101.3	0.0060	0.2359
-29.	20.05	5.4	86.89	2.547	2.8	101.5	0.0066	0.2356
-28.	20.54	5.8	86.79	2.490	3.1	101.6	0.0072	0.2353
-27.	21.04	6.3	86.68	2.434	3.3	101.7	0.0078	0.2350
-26.	21.55	6.9	86.58	2.380	3.6	101.8	0.0083	0.2348
-25.	22.08	7.4	86.48	2.327	3.8	101.9	0.0089	0.2345
-24.	22.61	7.9	86.37	2.276	4.1	102.0	0.0095	0.2342
-23.	23.15	8.5	86.27	2.226	4.4	102.1	0.0101	0.2339
-22.	23.70	9.0	86.17	2.177	4.6	102.2	0.0107	0.2337
-21.	24.26	9.6	86.06	2.130	4.9	102.3	0.0113	0.2334
-20.	24.83	10.1	85.96	2.083	5.1	102.4	0.0119	0.2331
-19.	25.42	10.7	85.85	2.038	5.4	102.5	0.0125	0.2329
-18.	26.01	11.3	85.75	1.995	5.7	102.6	0.0131	0.2326
-17.	26.61	11.9	85.64	1.952	5.9	102.7	0.0137	0.2323
-16.	27.23	12.5	85.54	1.911	6.2	102.8	0.0142	0.2321
-15.	27.85	13.2	85.43	1.870	6.4	102.9	0.0148	0.2318
-14.	28.49	13.8	85.33	1.831	6.7	103.0	0.0154	0.2316
-13.	29.14	14.4	85.22	1.792	7.0	103.1	0.0160	0.2313
-12.	29.80	15.1	85.12	1.755	7.2	103.3	0.0166	0.2310
-11.	30.47	15.8	85.01	1.719	7.5	103.4	0.0172	0.2308
-10.	31.15	16.5	84.90	1.683	7.8	103.5	0.0178	0.2305
-9.	31.84	17.1	84.80	1.648	8.0	103.6	0.0183	0.2303
-8.	32.55	17.9	84.69	1.615	8.3	103.7	0.0189	0.2301
-7.	33.27	18.6	84.58	1.582	8.5	103.8	0.0195	0.2298
-6.	34.00	19.3	84.48	1.550	8.8	103.9	0.0201	0.2296
-5.	34.74	20.0	84.37	1.518	9.1	104.0	0.0207	0.2293
-4.	35.49	20.8	84.26	1.488	9.3	104.1	0.0212	0.2291
-3.	36.26	21.6	84.15	1.458	9.6	104.2	0.0218	0.2288
-2.	37.04	22.3	84.04	1.429	9.9	104.3	0.0224	0.2286
-1.	37.84	23.1	83.94	1.400	10.1	104.4	0.0230	0.2284
0.	38.64	23.9	83.83	1.373	10.4	104.5	0.0236	0.2281
1.	39.46	24.8	83.72	1.346	10.7	104.6	0.0241	0.2279
2.	40.29	25.6	83.61	1.319	10.9	104.7	0.0247	0.2277
3.	41.14	26.4	83.50	1.294	11.2	104.8	0.0253	0.2274
4.	42.00	27.3	83.39	1.268	11.5	104.9	0.0259	0.2272
5.	42.87	28.2	83.28	1.244	11.8	105.0	0.0265	0.2270
6.	43.76	29.1	83.17	1.220	12.0	105.1	0.0270	0.2268
7.	44.66	30.0	83.06	1.196	12.3	105.2	0.0276	0.2265
8.	45.57	30.9	82.95	1.174	12.6	105.2	0.0282	0.2263
9.	46.50	31.8	82.84	1.151	12.8	105.3	0.0288	0.2261
10.	47.45	32.8	82.73	1.129	13.1	105.4	0.0293	0.2259

* Inches of mercury below one standard atmosphere (29.92 in).

THERMODYAMIC PROPERTIES OF R22 AT SATURATION (ENGLISH UNITS) p.2

Temp. °F	Pressure psia	Pressure psig	Liquid, Density lbm/ft³ $1/v_f$	Vapor, Sp. Vol. ft³/lbm v_g	Enthalpy, Datum −40 °F, Btu/lbm Liquid h_f	Enthalpy, Datum −40 °F, Btu/lbm Vapor h_g	Entropy, Datum −40 °F, Btu/lbm · °R Liquid s_f	Entropy, Datum −40 °F, Btu/lbm · °R Vapor s_g
11.	48.40	33.7	82.62	1.108	13.4	105.5	0.0299	0.2257
12.	49.38	34.7	82.50	1.087	13.7	105.6	0.0305	0.2254
13.	50.37	35.7	82.39	1.067	13.9	105.7	0.0310	0.2252
14.	51.37	36.7	82.28	1.047	14.2	105.8	0.0316	0.2250
15.	52.39	37.7	82.17	1.027	14.5	105.9	0.0322	0.2248
16.	53.42	38.7	82.05	1.008	14.7	106.0	0.0328	0.2246
17.	54.47	39.8	81.94	0.990	15.0	106.1	0.0333	0.2244
18.	55.53	40.8	81.83	0.972	15.3	106.2	0.0339	0.2242
19.	56.61	41.9	81.71	0.954	15.6	106.3	0.0345	0.2240
20.	57.71	43.0	81.60	0.937	15.8	106.4	0.0350	0.2238
21.	58.82	44.1	81.49	0.920	16.1	106.5	0.0356	0.2236
22.	59.95	45.3	81.37	0.903	16.4	106.6	0.0362	0.2233
23.	61.09	46.4	81.26	0.887	16.7	106.7	0.0367	0.2231
24.	62.25	47.6	81.14	0.871	16.9	106.7	0.0373	0.2229
25.	63.43	48.7	81.03	0.855	17.2	106.8	0.0379	0.2227
26.	64.62	49.9	80.91	0.840	17.5	106.9	0.0384	0.2225
27.	65.83	51.1	80.79	0.825	17.8	107.0	0.0390	0.2223
28.	67.06	52.4	80.68	0.810	18.1	107.1	0.0396	0.2221
29.	68.31	53.6	80.56	0.796	18.3	107.2	0.0401	0.2219
30.	69.57	54.9	80.44	0.782	18.6	107.3	0.0407	0.2217
31.	70.85	56.2	80.33	0.769	18.9	107.4	0.0413	0.2216
32.	72.14	57.4	80.21	0.755	19.2	107.5	0.0418	0.2214
33.	73.46	58.8	80.09	0.742	19.4	107.5	0.0424	0.2212
34.	74.79	60.1	79.97	0.729	19.7	107.6	0.0429	0.2210
35.	76.14	61.4	79.86	0.717	20.0	107.7	0.0435	0.2208
36.	77.51	62.8	79.74	0.704	20.3	107.8	0.0441	0.2206
37.	78.90	64.2	79.62	0.692	20.6	107.9	0.0446	0.2204
38.	80.31	65.6	79.50	0.681	20.9	108.0	0.0452	0.2202
39.	81.73	67.0	79.38	0.669	21.1	108.1	0.0457	0.2200
40.	83.18	68.5	79.26	0.658	21.4	108.1	0.0463	0.2198
41.	84.64	69.9	79.14	0.647	21.7	108.2	0.0469	0.2196
42.	86.13	71.4	79.02	0.636	22.0	108.3	0.0474	0.2195
43.	87.63	72.9	78.90	0.625	22.3	108.4	0.0480	0.2193
44.	89.15	74.5	78.77	0.615	22.6	108.5	0.0485	0.2191
45.	90.69	76.0	78.65	0.604	22.8	108.6	0.0491	0.2189
46.	92.25	77.6	78.53	0.594	23.1	108.6	0.0497	0.2187
47.	93.83	79.1	78.41	0.585	23.4	108.7	0.0502	0.2185
48.	95.43	80.7	78.28	0.575	23.7	108.8	0.0508	0.2184
49.	97.05	82.4	78.16	0.565	24.0	108.9	0.0513	0.2182
50.	98.70	84.0	78.04	0.556	24.3	109.0	0.0519	0.2180
51.	100.36	85.7	77.91	0.547	24.6	109.0	0.0524	0.2178
52.	102.04	87.3	77.79	0.538	24.9	109.1	0.0530	0.2176
53.	103.75	89.1	77.66	0.529	25.1	109.2	0.0536	0.2175
54.	105.47	90.8	77.54	0.521	25.4	109.3	0.0541	0.2173
55.	107.22	92.5	77.41	0.513	25.7	109.3	0.0547	0.2171
56.	108.99	94.3	77.28	0.504	26.0	109.4	0.0552	0.2169
57.	110.78	96.1	77.16	0.496	26.3	109.5	0.0558	0.2168
58.	112.59	97.9	77.03	0.488	26.6	109.6	0.0563	0.2166
59.	114.42	99.7	76.90	0.480	26.9	109.6	0.0569	0.2164
60.	116.28	101.6	76.78	0.473	27.2	109.7	0.0574	0.2162
61.	118.16	103.5	76.65	0.465	27.5	109.8	0.0580	0.2161
62.	120.06	105.4	76.52	0.458	27.8	109.9	0.0585	0.2159
63.	121.98	107.3	76.39	0.451	28.0	109.9	0.0591	0.2157
64.	123.92	109.2	76.26	0.444	28.3	110.0	0.0596	0.2155
65.	125.89	111.2	76.13	0.437	28.6	110.1	0.0602	0.2154
66.	127.88	113.2	76.00	0.430	28.9	110.1	0.0607	0.2152
67.	129.90	115.2	75.87	0.423	29.2	110.2	0.0613	0.2150
68.	131.94	117.2	75.74	0.417	29.5	110.3	0.0619	0.2149
69.	134.00	119.3	75.60	0.410	29.8	110.3	0.0624	0.2147
70.	136.08	121.4	75.47	0.404	30.1	110.4	0.0630	0.2145

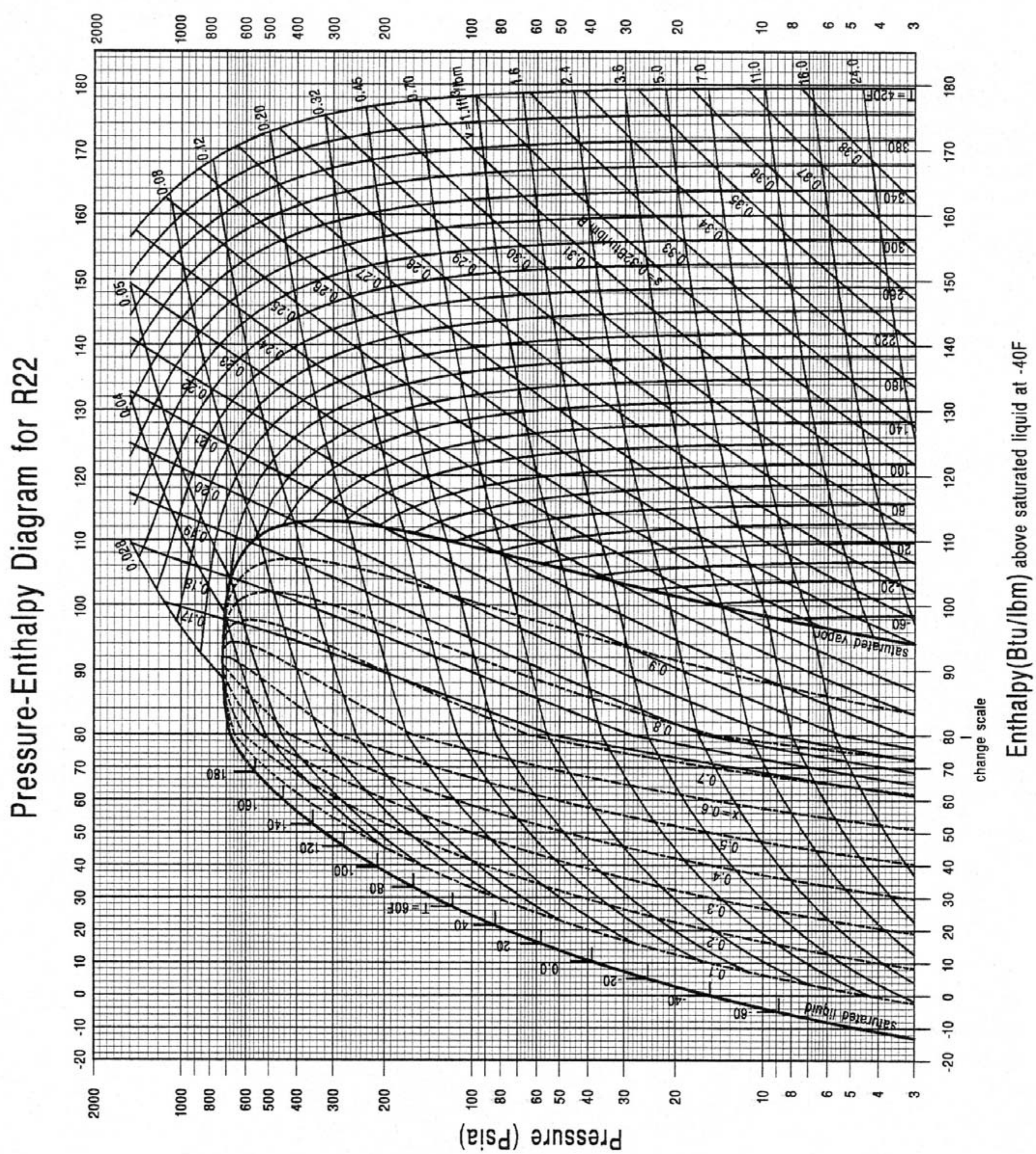
Temp. °F	Pressure psia	Pressure psig	Liquid, Density lbm/ft³ $1/v_f$	Vapor, Sp. Vol. ft³/lbm v_g	Enthalpy, Datum −40 °F, Btu/lbm Liquid h_f	Enthalpy, Datum −40 °F, Btu/lbm Vapor h_g	Entropy, Datum −40 °F, Btu/lbm · °R Liquid s_f	Entropy, Datum −40 °F, Btu/lbm · °R Vapor s_g
71.	138.19	123.5	75.34	0.398	30.4	110.5	0.0635	0.2144
72.	140.33	125.6	75.21	0.391	30.7	110.5	0.0641	0.2142
73.	142.48	127.8	75.07	0.385	31.0	110.6	0.0646	0.2140
74.	144.67	130.0	74.94	0.380	31.3	110.7	0.0652	0.2139
75.	146.87	132.2	74.80	0.374	31.6	110.7	0.0657	0.2137
76.	149.11	134.4	74.67	0.368	31.9	110.8	0.0663	0.2135
77.	151.36	136.7	74.53	0.363	32.2	110.9	0.0668	0.2134
78.	153.64	138.9	74.39	0.357	32.5	110.9	0.0674	0.2132
79.	155.95	141.3	74.26	0.352	32.8	111.0	0.0679	0.2130
80.	158.28	143.6	74.12	0.346	33.1	111.1	0.0684	0.2129
81.	160.64	145.9	73.98	0.341	33.4	111.1	0.0690	0.2127
82.	163.02	148.3	73.84	0.336	33.7	111.2	0.0695	0.2125
83.	165.43	150.7	73.70	0.331	34.0	111.2	0.0701	0.2124
84.	167.87	153.2	73.56	0.326	34.3	111.3	0.0707	0.2122
85.	170.33	155.6	73.42	0.321	34.6	111.3	0.0712	0.2120
86.	172.82	158.1	73.28	0.316	34.9	111.4	0.0717	0.2119
87.	175.34	160.6	73.14	0.312	35.2	111.5	0.0723	0.2117
88.	177.88	163.2	73.00	0.307	35.5	111.5	0.0728	0.2115
89.	180.45	165.8	72.86	0.302	35.8	111.6	0.0734	0.2114
90.	183.05	168.4	72.71	0.298	36.2	111.6	0.0739	0.2112
91.	185.67	171.0	72.57	0.294	36.5	111.7	0.0745	0.2110
92.	188.32	173.6	72.42	0.289	36.8	111.7	0.0750	0.2109
93.	191.00	176.3	72.28	0.285	37.1	111.8	0.0756	0.2107
94.	193.71	179.0	72.13	0.281	37.4	111.8	0.0761	0.2105
95.	196.44	181.7	71.98	0.277	37.7	111.9	0.0767	0.2104
96.	199.21	184.5	71.84	0.273	38.0	111.9	0.0772	0.2102
97.	202.00	187.3	71.69	0.269	38.3	112.0	0.0778	0.2100
98.	204.82	190.1	71.54	0.265	38.6	112.0	0.0783	0.2099
99.	207.67	193.0	71.39	0.261	39.0	112.1	0.0789	0.2097
100.	210.55	195.9	71.24	0.257	39.3	112.1	0.0794	0.2095
101.	213.46	198.8	71.09	0.253	39.6	112.2	0.0800	0.2094
102.	216.40	201.7	70.94	0.250	39.9	112.2	0.0805	0.2092
103.	219.36	204.7	70.78	0.246	40.2	112.2	0.0811	0.2090
104.	222.36	207.7	70.63	0.243	40.5	112.3	0.0816	0.2089
105.	225.39	210.7	70.48	0.239	40.8	112.3	0.0821	0.2087
106.	228.45	213.8	70.32	0.236	41.2	112.4	0.0827	0.2085
107.	231.53	216.8	70.17	0.232	41.5	112.4	0.0832	0.2084
108.	234.65	220.0	70.01	0.229	41.8	112.4	0.0838	0.2082
109.	237.80	223.1	69.85	0.226	42.1	112.5	0.0843	0.2080
110.	240.98	226.3	69.69	0.222	42.4	112.5	0.0849	0.2078
111.	244.20	229.5	69.53	0.219	42.8	112.5	0.0854	0.2077
112.	247.44	232.7	69.37	0.216	43.1	112.6	0.0860	0.2075
113.	250.71	236.0	69.21	0.213	43.4	112.6	0.0865	0.2073
114.	254.02	239.3	69.05	0.210	43.7	112.6	0.0871	0.2072
115.	257.36	242.7	68.89	0.207	44.1	112.7	0.0876	0.2070
116.	260.73	246.0	68.72	0.204	44.4	112.7	0.0882	0.2068
117.	264.13	249.4	68.56	0.201	44.7	112.7	0.0887	0.2066
118.	267.57	252.9	68.39	0.198	45.0	112.7	0.0893	0.2065
119.	271.04	256.3	68.23	0.195	45.4	112.8	0.0899	0.2063
120.	274.54	259.8	68.06	0.192	45.7	112.8	0.0904	0.2061
122.	281.64	266.9	67.72	0.187	46.4	112.8	0.0915	0.2057
124.	288.88	274.2	67.38	0.182	47.0	112.9	0.0926	0.2054
126.	296.26	281.6	67.03	0.177	47.7	112.9	0.0937	0.2050
128.	303.77	289.1	66.67	0.172	48.4	112.9	0.0949	0.2047
130.	311.42	296.7	66.32	0.167	49.1	112.9	0.0960	0.2043
132.	319.22	304.5	65.95	0.162	49.7	113.0	0.0971	0.2039
134.	327.16	312.5	65.59	0.157	50.4	113.0	0.0982	0.2035
136.	335.25	320.6	65.21	0.153	51.1	113.0	0.0993	0.2031
138.	343.48	328.8	64.83	0.148	51.8	112.9	0.1005	0.2027
140.	351.87	337.2	64.45	0.144	52.5	112.9	0.1016	0.2023

THERMODYNAMIC PROPERTIES OF R22 AT SATURATION (SI UNITS)

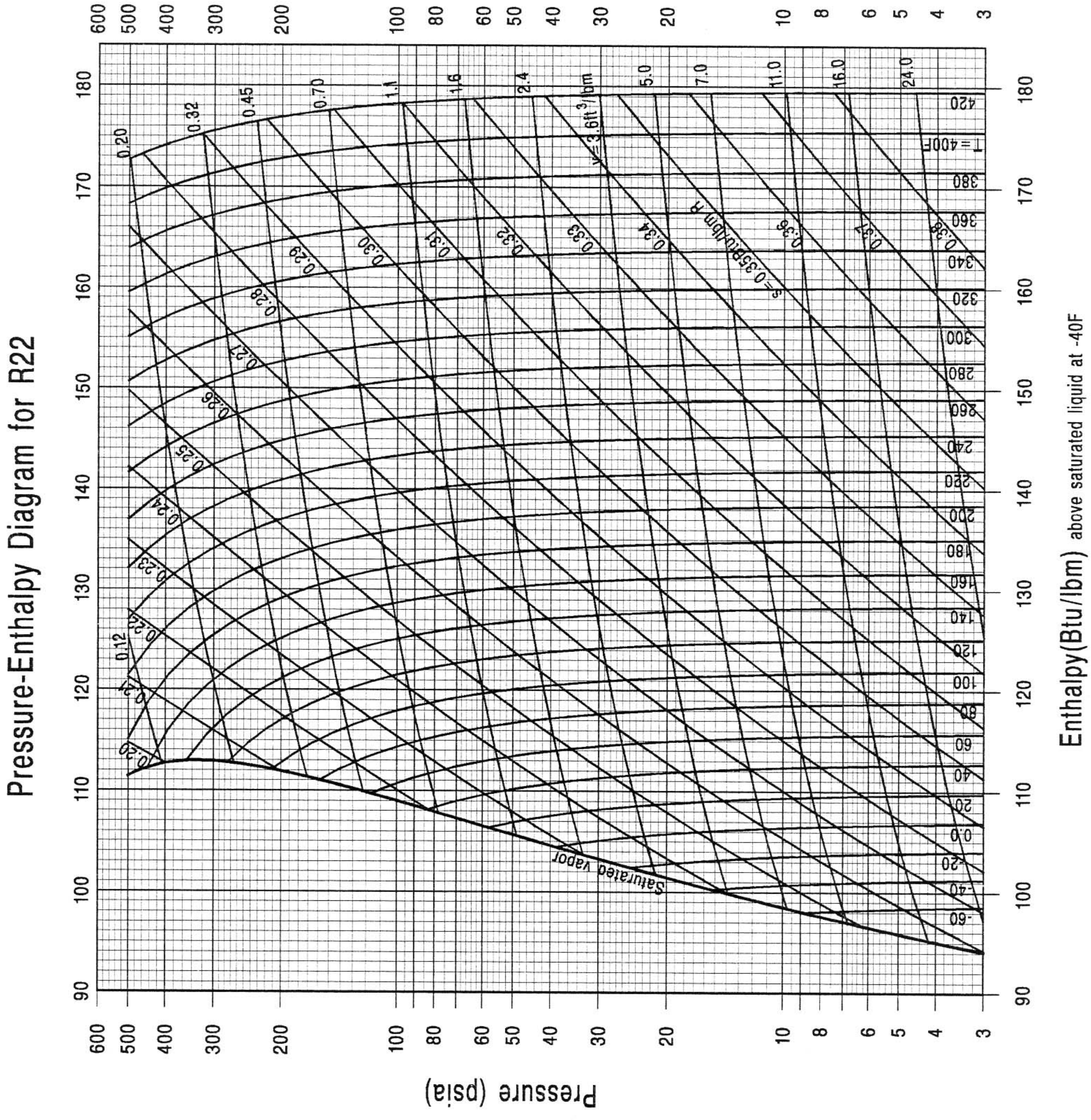
Temp. °C	Pressure MPa	Liquid Density kg/m^3 $1/v_f$	Vapor Sp. Vol. m^3/kg v_g	Enthalpy, Datum −40 °C, kJ/kg Sat. Liquid h_f	Enthalpy Sat. Vapor h_g	Entropy, Datum −40 °C, kJ/kg · K Sat. Liquid s_f	Entropy Sat. Vapor s_g
-70	0.0205	1493.2	0.94151	-30.61	218.82	-0.1401	1.0877
-68	0.0233	1487.8	0.83743	-28.63	219.80	-0.1305	1.0805
-66	0.0263	1482.5	0.74678	-26.65	220.78	-0.1209	1.0736
-64	0.0297	1477.5	0.66763	-24.66	221.76	-0.1113	1.0669
-62	0.0334	1471.6	0.59831	-22.66	222.73	-0.1018	1.0603
-60	0.0375	1466.1	0.53745	-20.65	223.70	-0.0924	1.0540
-58	0.0419	1460.6	0.48387	-18.63	224.67	-0.0829	1.0479
-56	0.0468	1455.1	0.43659	-16.60	225.64	-0.0736	1.0420
-54	0.0522	1449.6	0.39476	-14.56	226.60	-0.0642	1.0362
-52	0.0580	1444.0	0.35768	-12.51	227.56	-0.0550	1.0306
-50	0.0644	1438.4	0.32472	-10.46	228.51	-0.0457	1.0252
-49	0.0677	1435.5	0.30962	-9.42	228.98	-0.0411	1.0225
-48	0.0712	1432.7	0.29536	-8.39	229.46	-0.0365	1.0199
-47	0.0749	1429.9	0.28189	-7.35	229.93	-0.0319	1.0173
-46	0.0787	1427.0	0.26915	-6.30	230.40	-0.0273	1.0148
-45	0.0827	1424.2	0.25711	-5.26	230.87	-0.0227	1.0122
-44	0.0868	1421.3	0.24571	-4.21	231.34	-0.0182	1.0098
-43	0.0911	1418.4	0.23492	-3.16	231.81	-0.0136	1.0073
-42	0.0955	1415.6	0.22470	-2.11	232.27	-0.0091	1.0049
-41	0.1001	1412.7	0.21502	-1.06	232.74	-0.0045	1.0025
-40	0.1049	1409.8	0.20584	0.00	233.20	0.0000	1.0002
-39	0.1099	1406.9	0.19713	1.06	233.66	0.0045	0.9979
-38	0.1150	1403.9	0.18886	2.12	234.12	0.0090	0.9956
-37	0.1204	1401.0	0.18101	3.19	234.58	0.0135	0.9934
-36	0.1259	1398.1	0.17355	4.26	235.03	0.0180	0.9912
-35	0.1316	1395.1	0.16647	5.33	235.49	0.0225	0.9890
-34	0.1375	1392.2	0.15973	6.40	235.94	0.0270	0.9868
-33	0.1437	1389.2	0.15333	7.48	236.39	0.0315	0.9847
-32	0.1500	1386.2	0.14723	8.56	236.84	0.0360	0.9826
-31	0.1566	1383.3	0.14143	9.64	237.28	0.0404	0.9805
-30	0.1634	1380.3	0.13590	10.73	237.73	0.0449	0.9785
-29	0.1704	1377.3	0.13063	11.81	238.17	0.0493	0.9764
-28	0.1777	1374.2	0.12561	12.90	238.61	0.0537	0.9744
-27	0.1852	1371.2	0.12082	14.00	239.05	0.0582	0.9725
-26	0.1929	1368.2	0.11626	15.09	239.49	0.0626	0.9705
-25	0.2009	1365.1	0.11190	16.19	239.92	0.0670	0.9686
-24	0.2091	1362.1	0.10774	17.30	240.35	0.0714	0.9667
-23	0.2176	1359.0	0.10377	18.40	240.78	0.0758	0.9648
-22	0.2264	1355.9	0.09997	19.51	241.21	0.0802	0.9630
-21	0.2354	1352.8	0.09634	20.62	241.63	0.0846	0.9611
-20	0.2447	1349.7	0.09288	21.73	242.06	0.0890	0.9593
-19	0.2543	1346.6	0.08956	22.85	242.48	0.0933	0.9575
-18	0.2642	1343.5	0.08638	23.97	242.89	0.0977	0.9558
-17	0.2744	1340.3	0.08335	25.09	243.31	0.1021	0.9540
-16	0.2848	1337.2	0.08044	26.21	243.72	0.1064	0.9523
-15	0.2956	1334.0	0.07765	27.34	244.13	0.1108	0.9506
-14	0.3067	1330.8	0.07498	28.47	244.54	0.1151	0.9489
-13	0.3181	1327.6	0.07242	29.60	244.95	0.1194	0.9472
-12	0.3298	1324.4	0.06997	30.74	245.35	0.1238	0.9455
-11	0.3418	1321.2	0.06762	31.88	245.75	0.1281	0.9439
-10	0.3542	1318.0	0.06536	33.02	246.15	0.1324	0.9423
-9	0.3669	1314.7	0.06319	34.17	246.54	0.1367	0.9407
-8	0.3799	1311.5	0.06111	35.32	246.93	0.1410	0.9391
-7	0.3933	1308.2	0.05912	36.47	247.32	0.1453	0.9375
-6	0.4071	1304.9	0.05720	37.62	247.70	0.1496	0.9360
-5	0.4212	1301.6	0.05535	38.78	248.09	0.1539	0.9344
-4	0.4357	1298.3	0.05358	39.94	248.47	0.1581	0.9329
-3	0.4505	1294.9	0.05188	41.10	248.84	0.1624	0.9314
-2	0.4658	1291.6	0.05024	42.27	249.21	0.1667	0.9299
-1	0.4814	1288.2	0.04867	43.41	249.58	0.1709	0.9284

Temp. °C	Pressure MPa	Liquid Density kg/m³ $1/v_f$	Vapor Sp. Vol. m³/kg v_g	Enthalpy, Datum −40°C, kJ/kg Sat. Liquid h_f	Enthalpy, Datum −40°C, kJ/kg Sat. Vapor h_g	Entropy, Datum −40°C, kJ/kg·K Sat. Liquid s_f	Entropy, Datum −40°C, kJ/kg·K Sat. Vapor s_g
0	0.4974	1284.8	0.04715	44.59	249.95	0.1751	0.9270
1	0.5138	1281.4	0.04569	45.76	250.31	0.1794	0.9255
2	0.5307	1278.0	0.04428	46.94	250.67	0.1836	0.9241
3	0.5479	1274.6	0.04293	48.12	251.03	0.1878	0.9226
4	0.5655	1271.1	0.04163	49.30	251.38	0.1920	0.9212
5	0.5836	1267.7	0.04037	50.48	251.73	0.1963	0.9198
6	0.6021	1264.2	0.03916	51.67	252.08	0.2005	0.9184
7	0.6210	1260.7	0.03799	52.87	252.42	0.2047	0.9170
8	0.6404	1257.1	0.03686	54.06	252.76	0.2089	0.9156
9	0.6602	1253.6	0.03577	55.26	253.09	0.2131	0.9143
10	0.6805	1250.0	0.03472	56.46	253.43	0.2173	0.9129
11	0.7012	1246.4	0.03371	57.67	253.75	0.2215	0.9116
12	0.7224	1242.8	0.03273	58.88	254.08	0.2257	0.9102
13	0.7441	1239.2	0.03179	60.09	254.39	0.2298	0.9089
14	0.7663	1235.5	0.03088	61.30	254.71	0.2340	0.9076
15	0.7889	1231.9	0.03000	62.52	255.02	0.2382	0.9062
16	0.8121	1228.2	0.02914	63.74	255.33	0.2424	0.9049
17	0.8357	1224.5	0.02832	64.97	255.63	0.2465	0.9036
18	0.8598	1220.7	0.02753	66.20	255.93	0.2507	0.9023
19	0.8845	1217.0	0.02676	67.43	256.22	0.2549	0.9011
20	0.9097	1213.2	0.02601	68.67	256.51	0.2590	0.8998
21	0.9354	1209.4	0.02529	69.91	256.79	0.2632	0.8985
22	0.9616	1205.5	0.02459	71.15	257.07	0.2673	0.8972
23	0.9884	1201.7	0.02392	72.40	257.35	0.2715	0.8960
24	1.0157	1197.8	0.02326	73.65	257.62	0.2756	0.8947
25	1.0436	1193.9	0.02263	74.91	257.88	0.2797	0.8934
26	1.0720	1189.9	0.02202	76.17	258.14	0.2839	0.8922
27	1.1011	1186.0	0.02142	77.43	258.39	0.2880	0.8909
28	1.1306	1182.0	0.02085	78.70	258.64	0.2921	0.8897
29	1.1608	1177.9	0.02029	79.99	258.88	0.2963	0.8884
30	1.1916	1173.9	0.01975	81.26	259.12	0.3004	0.8872
31	1.2229	1169.8	0.01922	82.53	259.35	0.3045	0.8859
32	1.2549	1165.7	0.01871	83.81	259.58	0.3087	0.8847
33	1.2874	1161.5	0.01822	85.11	259.80	0.3128	0.8834
34	1.3206	1157.3	0.01774	86.41	260.01	0.3169	0.8822
35	1.3544	1153.1	0.01727	87.72	260.22	0.3211	0.8809
36	1.3889	1148.8	0.01682	89.00	260.42	0.3252	0.8797
37	1.4240	1144.5	0.01638	90.31	260.61	0.3293	0.8784
38	1.4597	1140.2	0.01596	91.63	260.80	0.3334	0.8771
39	1.4961	1135.8	0.01554	92.94	260.98	0.3376	0.8759
40	1.5331	1131.4	0.01514	94.27	261.15	0.3417	0.8746
41	1.5709	1126.9	0.01475	95.60	261.32	0.3458	0.8734
42	1.6093	1122.4	0.01437	96.94	261.48	0.3500	0.8721
43	1.6483	1117.9	0.01400	98.28	261.63	0.3541	0.8708
44	1.6881	1113.3	0.01364	99.63	261.77	0.3583	0.8695
45	1.7286	1108.7	0.01329	100.98	261.90	0.3624	0.8682
46	1.7698	1104.0	0.01295	102.34	262.02	0.3666	0.8669
47	1.8117	1099.3	0.01262	103.71	262.14	0.3707	0.8656
48	1.8544	1094.5	0.01229	105.08	262.25	0.3749	0.8643
49	1.8977	1089.6	0.01198	106.46	262.34	0.3791	0.8629
50	1.9419	1084.8	0.01167	107.85	262.43	0.3832	0.8616
51	1.9867	1079.8	0.01137	109.24	262.51	0.3874	0.8602
52	2.0324	1074.8	0.01108	110.65	262.58	0.3916	0.8589
53	2.0788	1069.7	0.01080	112.06	262.63	0.3958	0.8575
54	2.1260	1064.6	0.01052	113.48	262.68	0.4000	0.8561
55	2.1740	1059.4	0.01025	114.91	262.71	0.4042	0.8546
56	2.2227	1054.1	0.00999	116.34	262.73	0.4085	0.8532
57	2.2723	1048.8	0.00974	117.79	262.74	0.4127	0.8517
58	2.3227	1043.4	0.00949	119.24	262.73	0.4170	0.8503
59	2.3740	1037.9	0.00924	120.71	262.71	0.4212	0.8488
60	2.4260	1032.3	0.00900	122.18	262.68	0.4255	0.8472

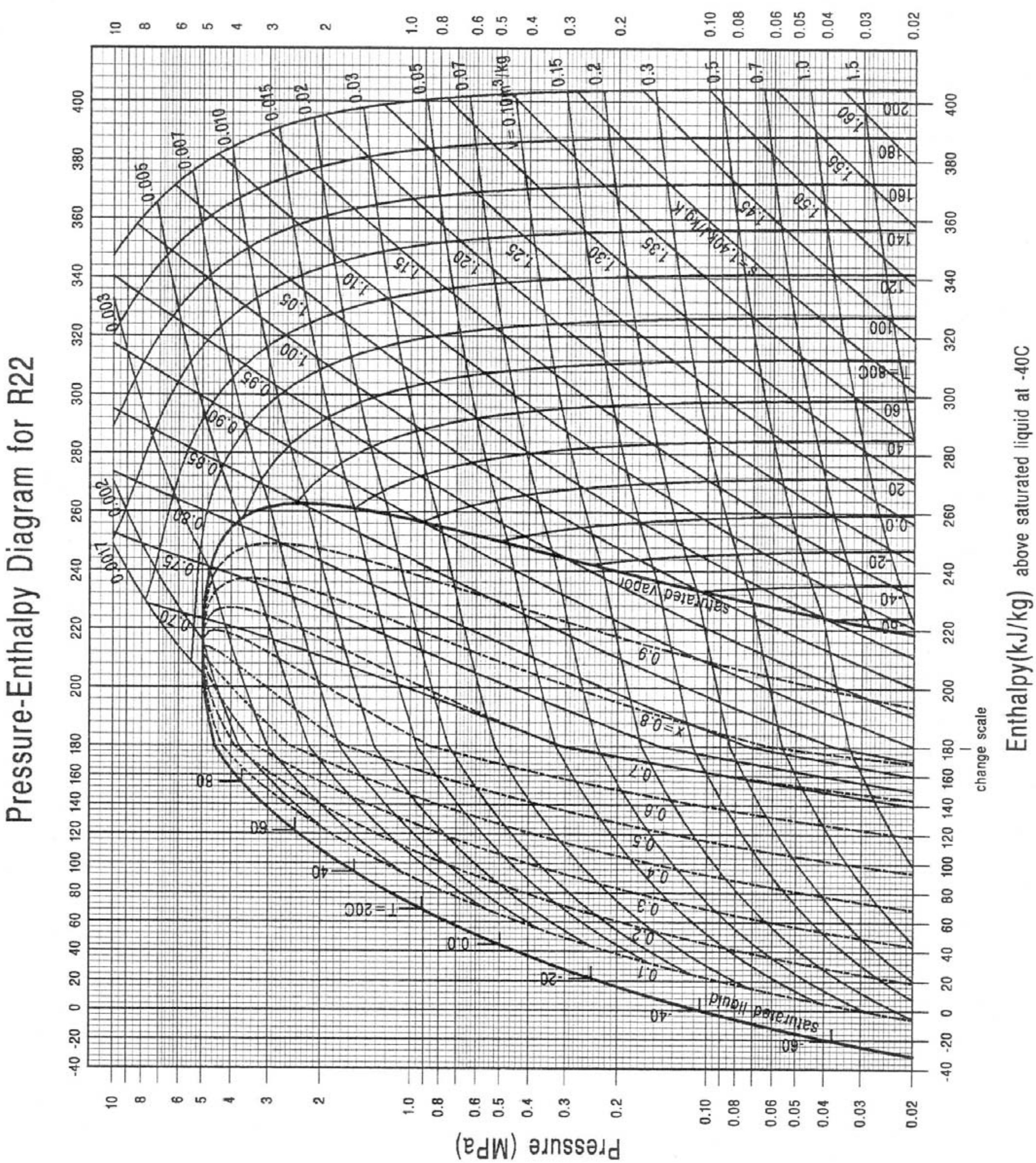
R22 P-h Diagram (English Units)



R22 P-h Diagram-Saturated Vapor Line (English Units)



R22 P-h Diagram (SI Units)



R22 P-h Diagram-Saturated Vapor Line (SI Units)

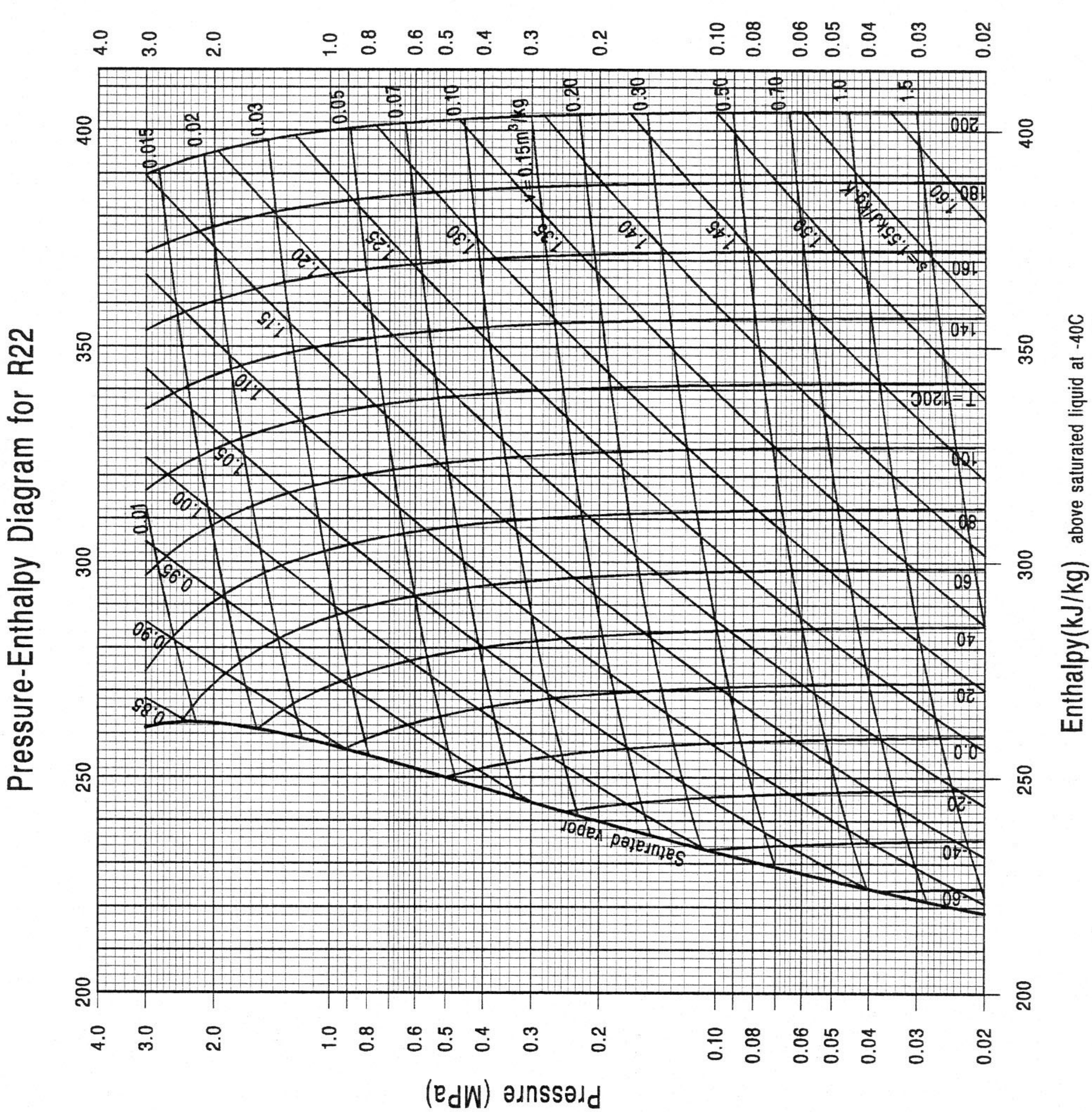
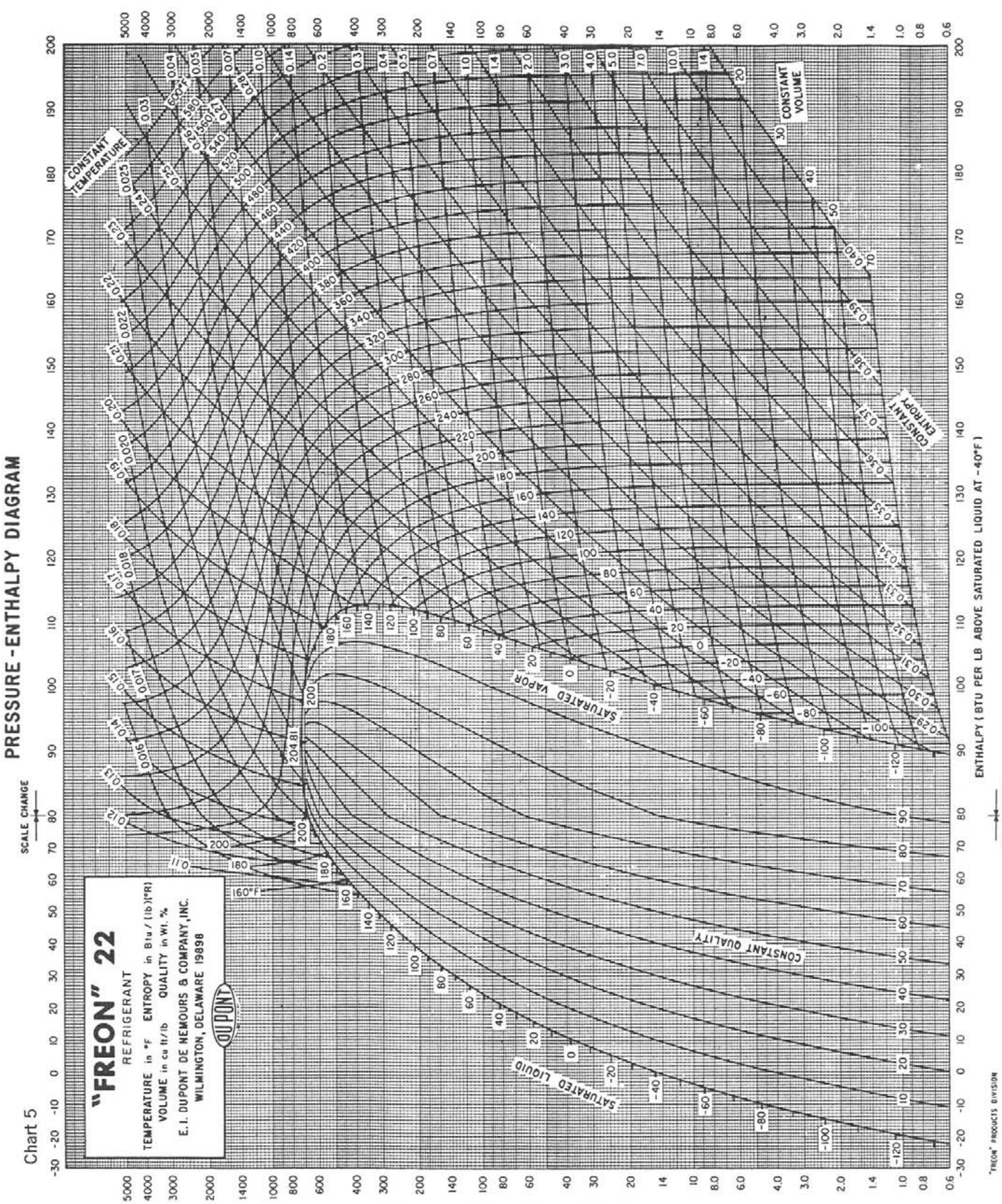


Chart 5



PRESSURE-ENTHALPY DIAGRAM
"FREON" 22
REFRIGERANT
TEMPERATURE in °F ENTROPY in Btu/(lb)(°R)
VOLUME in cu ft/lb QUALITY in Wt. %
E. I. DUPONT DE NEMOURS & COMPANY, INC.
WILMINGTON, DELAWARE 19898
CONSTANT TEMPERATURE
CONSTANT VOLUME
CONSTANT ENTROPY
SATURATED VAPOR
SATURATED LIQUID
CONSTANT QUALITY
SCALE CHANGE
ENTHALPY (BTU PER LB ABOVE SATURATED LIQUID AT -40°F)
ABSOLUTE PRESSURE (LBS. PER SQUARE INCH)
"FREON" PRODUCTS DIVISION

APPENDIX F

Properties of Aqueous Solutions of Dowtherm SR-1 (Ethylene Glycol)

Temp	Volume Percent Ethylene Glycol									
	0%		10%		20%		30%		40%	
deg F	Density	Spec. Heat	Density	Spec. Heat	Density	Spec. Heat	Density	Spec. Heat	Density	Spec. Heat
20					64.83	0.897	65.85	0.853	66.80	0.808
30			63.69	0.940	64.75	0.900	65.76	0.857	66.70	0.812
40	62.42	1.004	63.61	0.943	64.66	0.903	65.66	0.861	66.59	0.816
50	62.38	1.001	63.52	0.945	64.56	0.906	65.55	0.864	66.47	0.821
60	62.34	1.000	63.42	0.947	64.45	0.909	65.43	0.868	66.34	0.825
70	62.27	0.999	63.31	0.950	64.33	0.912	65.30	0.872	66.20	0.830
80	62.19	0.998	63.19	0.952	64.21	0.915	65.17	0.876	66.05	0.834
90	62.11	0.998	63.07	0.954	64.07	0.918	65.02	0.880	65.90	0.839
100	62.00	0.998	62.93	0.957	63.93	0.922	64.86	0.883	65.73	0.843
110	61.84	0.998	62.79	0.959	63.77	0.925	64.70	0.887	65.56	0.848
120	61.73	0.998	62.63	0.961	63.61	0.928	64.52	0.891	65.37	0.852
130	61.54	0.999	62.47	0.964	63.43	0.931	64.34	0.895	65.18	0.857
140	61.39	0.999	62.30	0.966	63.25	0.934	64.15	0.898	64.98	0.861
150	61.20	1.000	62.11	0.968	63.06	0.937	63.95	0.902	64.76	0.865
160	61.01	1.001	61.92	0.971	62.86	0.940	63.73	0.906	64.54	0.870
170	60.79	1.002	61.72	0.973	62.64	0.943	63.51	0.910	64.31	0.874
180	60.57	1.003	61.51	0.975	62.42	0.946	63.28	0.913	64.07	0.879
190	60.35	1.004	61.29	0.978	62.19	0.949	63.04	0.917	63.82	0.883
200	60.13	1.005	61.06	0.980	61.95	0.952	62.79	0.921	63.56	0.888

Units of Density are lbm/(cubic foot)
Units of Specific Heat are Btu/(lbm-degF)

Temp	Volume Percent Ethylene Glycol									
	50%		60%		70%		80%		90%	
deg F	Density	Spec. Heat	Density	Spec. Heat	Density	Spec. Heat	Density	Spec. Heat	Density	Spec. Heat
20	67.70	0.759	68.56	0.709	69.38	0.657	70.16	0.603	70.92	0.546
30	67.59	0.765	68.44	0.715	69.25	0.664	70.02	0.610	70.76	0.553
40	67.47	0.770	68.31	0.721	69.10	0.670	69.86	0.617	70.59	0.561
50	67.34	0.775	68.17	0.727	68.95	0.676	69.70	0.624	70.42	0.569
60	67.20	0.780	68.02	0.732	68.79	0.683	69.53	0.631	70.23	0.576
70	67.05	0.785	67.86	0.738	68.62	0.689	69.35	0.638	70.04	0.584
80	66.90	0.790	67.69	0.744	68.44	0.696	69.15	0.645	69.83	0.592
90	66.73	0.795	67.51	0.750	68.25	0.702	68.95	0.652	69.62	0.600
100	66.55	0.800	67.32	0.756	68.05	0.709	68.74	0.659	69.40	0.607
110	66.37	0.806	67.13	0.761	67.84	0.715	68.52	0.666	69.17	0.615
120	66.17	0.811	66.92	0.767	67.63	0.721	68.29	0.673	68.92	0.623
130	65.97	0.816	66.71	0.773	67.40	0.728	68.05	0.680	68.67	0.630
140	65.75	0.821	66.48	0.779	67.16	0.734	67.81	0.687	68.41	0.638
150	65.53	0.826	66.25	0.785	66.92	0.741	67.55	0.694	68.14	0.646
160	65.30	0.831	66.00	0.790	66.66	0.747	67.28	0.702	67.86	0.654
170	65.05	0.836	65.75	0.796	66.40	0.754	67.01	0.709	67.58	0.661
180	64.80	0.842	65.49	0.802	66.12	0.760	66.72	0.716	67.28	0.669
190	64.54	0.847	65.21	0.808	65.84	0.766	66.42	0.723	66.97	0.677
200	64.27	0.852	64.93	0.813	65.55	0.773	66.12	0.730	66.65	0.684

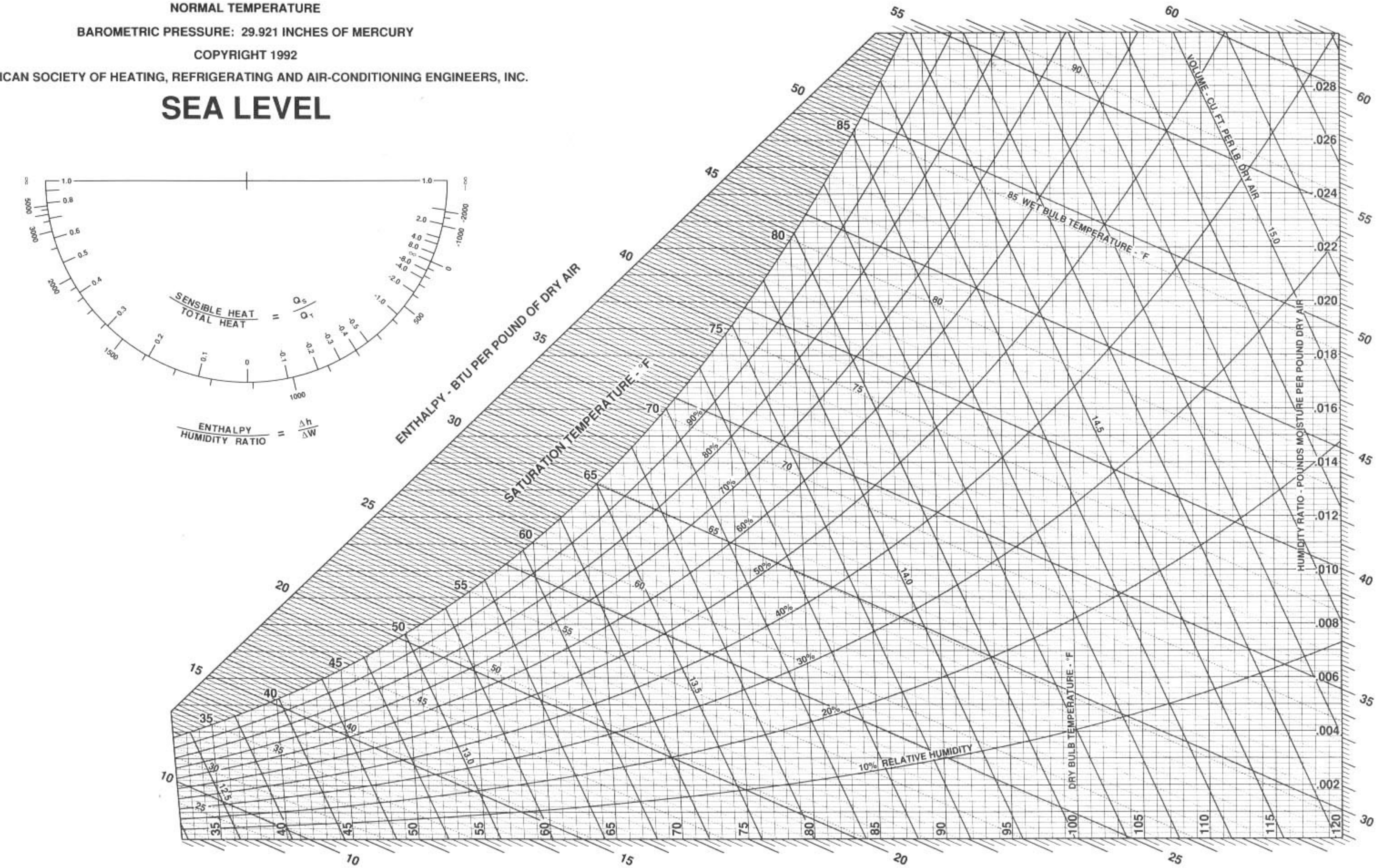
ASHRAE PSYCHROMETRIC CHART NO. 1

NORMAL TEMPERATURE

BAROMETRIC PRESSURE: 29.921 INCHES OF MERCURY

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.

SEA LEVEL



ASHRAE PSYCHROMETRIC CHART NO. 2

LOW TEMPERATURE

BAROMETRIC PRESSURE: 29.921 INCHES OF MERCURY

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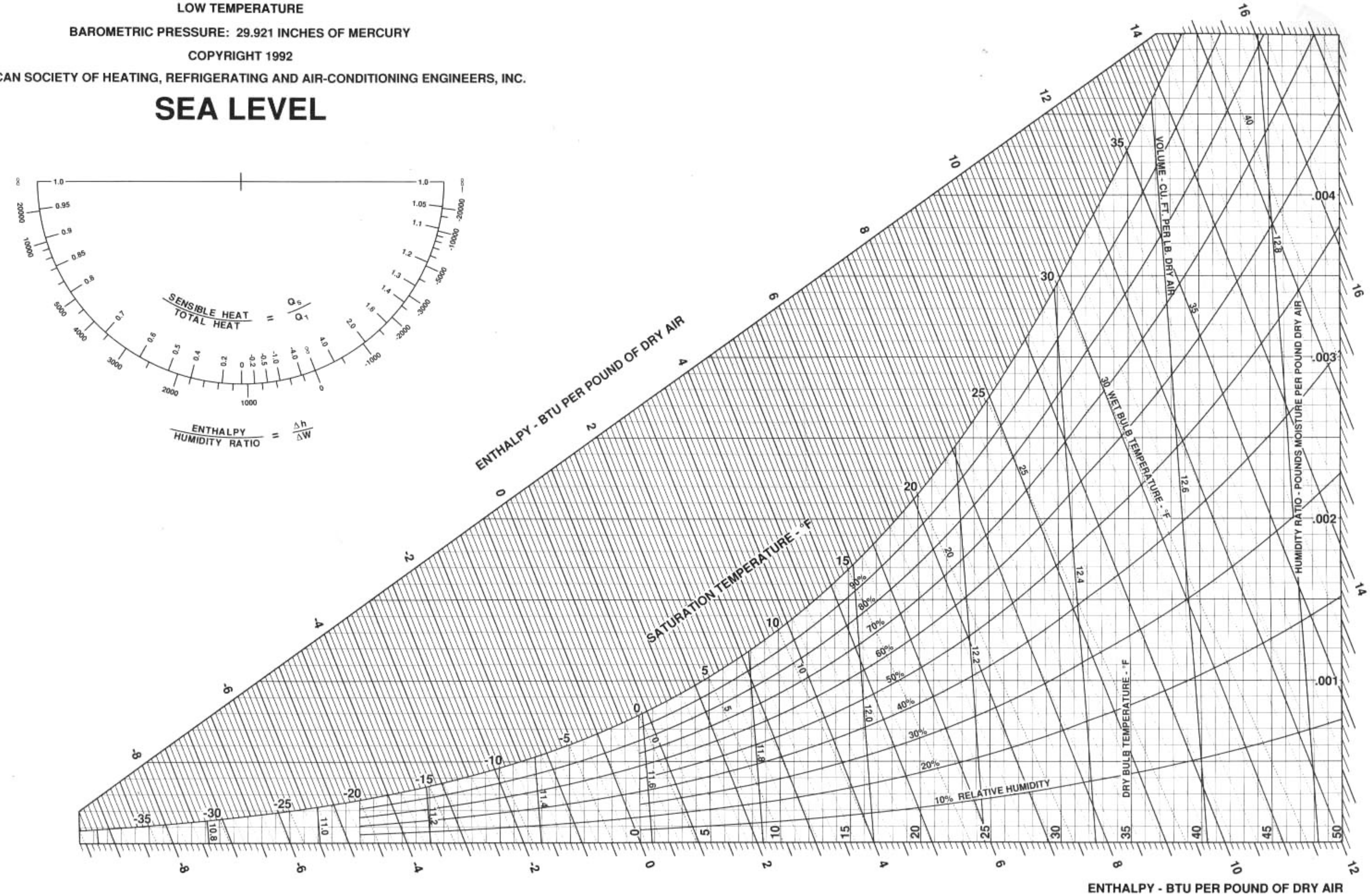
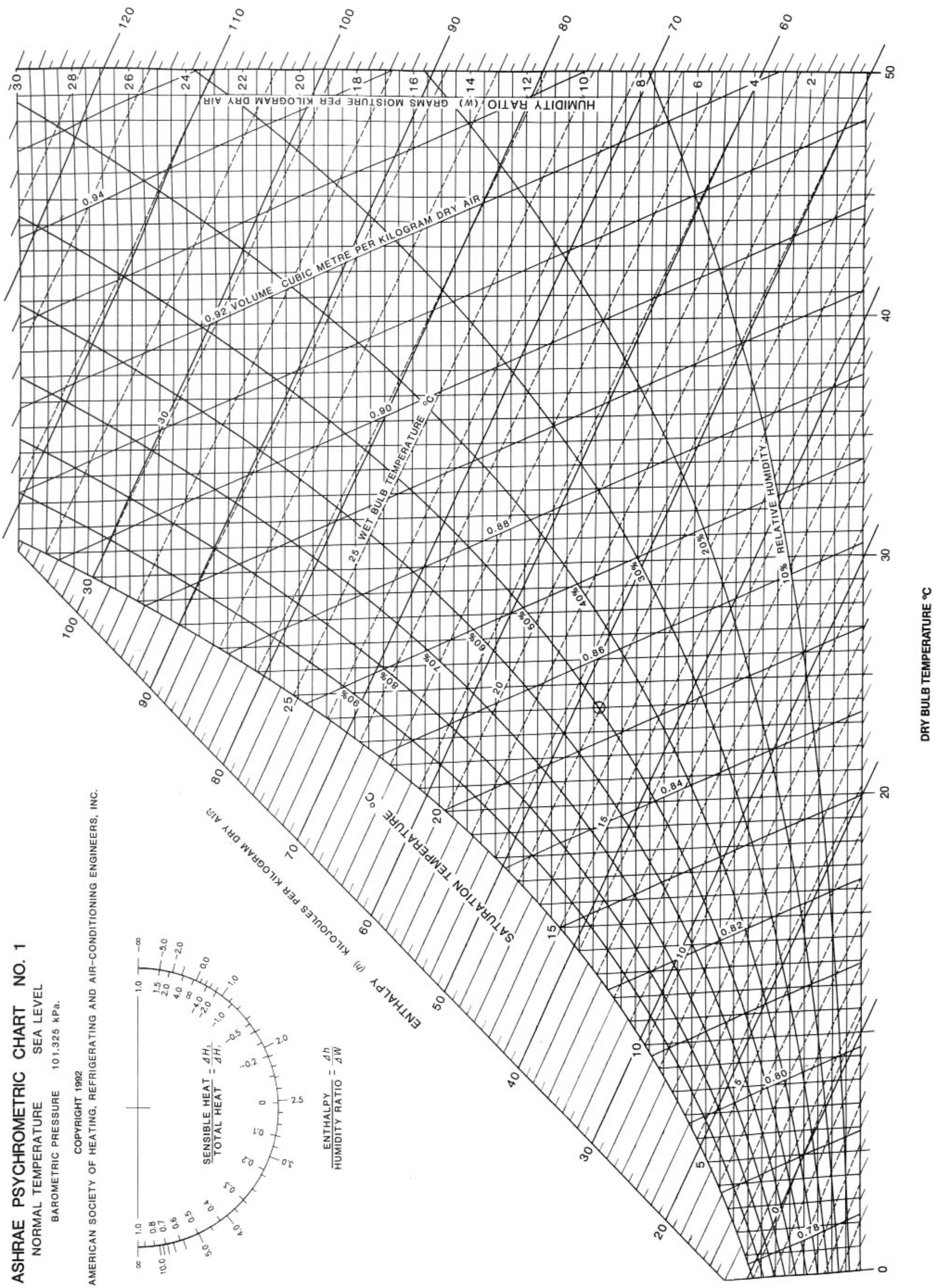
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.

SEA LEVEL





ASHRAE PSYCHROMETRIC CHART NO. 1
NORMAL TEMPERATURE SEA LEVEL
BAROMETRIC PRESSURE 101.325 kPa.
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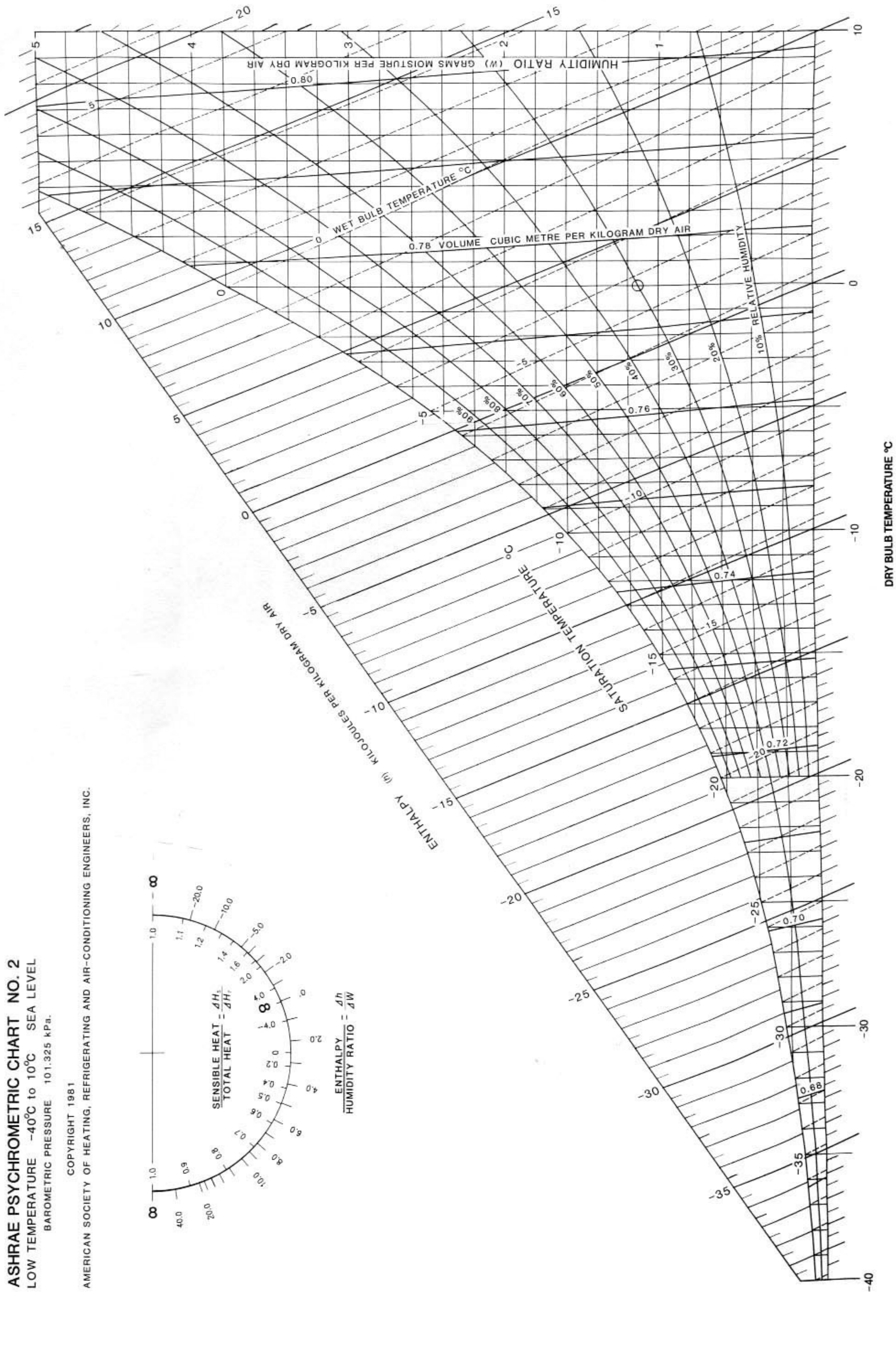
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔHt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY (h) KILOJOULES PER KILOGRAM DRY AIR
SATURATION TEMPERATURE °C
HUMIDITY RATIO (W) GRAMS MOISTURE PER KILOGRAM DRY AIR
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
WET BULB TEMPERATURE °C
RELATIVE HUMIDITY
DRY BULB TEMPERATURE °C

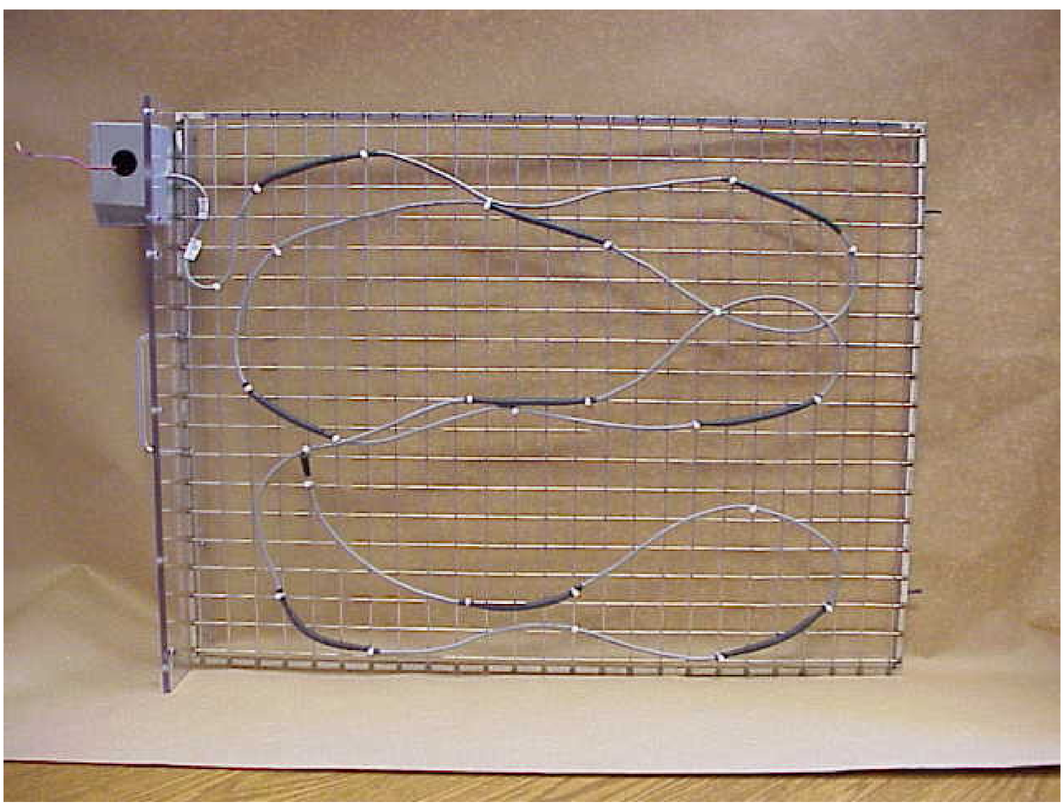

ASHRAE PSYCHROMETRIC CHART NO. 2
LOW TEMPERATURE -40°C to 10°C SEA LEVEL
BAROMETRIC PRESSURE 101.325 kPa.
COPYRIGHT 1981
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
HUMIDITY RATIO (W) GRAMS MOISTURE PER KILOGRAM DRY AIR
WET BULB TEMPERATURE °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
RELATIVE HUMIDITY
SATURATION TEMPERATURE °C
ENTHALPY (h) KILOJOULES PER KILOGRAM DRY AIR
DRY BULB TEMPERATURE °C
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔHt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW

Appendix H: Air Handling System Temperature and Flow Sensors

Channel	Sensor	Signal	Notes
10	Power supply	24VAC	Power Supply for the averaging Temp. sensors
11	Avg. Temp #1	0 – 10 VDC	Located upstream of filters
12	Avg. Temp #2	0 – 10 VDC	Located upstream of heat exchanger
13	Avg. Temp $3	0 – 10 VDC**	Located downstream of heat exchanger
14	Avg. Temp #4	0 – 10 VDC	Supply Air condition (in vertical run)
15	Thermocouple Ref.	mV DC	Reference temp for other TCs
16	Humidifier steam TC	mV DC	Temp of steam from humidifier
17	Heat Exchanger TC	mV DC	Heat Exchanger Water Inlet
18	Heat Exchanger TC	mV DC	Heat Exchanger Water Outlet
19	Flow Meter	frequency	Heat Exchanger flow meter

** May need to set the range higher than 10VDC

Each average temperature sensor consists of nine 1000 ohm platinum resistance sensors connected in such a way as to provide an output that is the average of the temperatures of the nine sensors. A temperature transmitter uses a supply voltage of 24VAC, provides the proper voltage for the sensor and conditions the output.
Output: 0 to 10 VDC corresponds to 32 to 122 deg. F (0 to 50 ºC) – Linear Output
Accuracy: Sensor: ± 0.36 º F, Transmitter accuracy: ± 0.1% of span, Total: ± 0.45 ºF



Thermocouples: All the thermocouples are Type T, Copper – Constantan. The thermocouples for the Steam Temperature, Water Inlet Temperature and the Water Outlet Temperature indicate EMF differences between the respective temperatures and a reference temperature. Channel 15 is a measure of the reference temperature with respect to the ice point (using an electronic cold junction compensator.)