THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

85-HT-49

Evaluation of the Flooding Limits and Heat Transfer of a Direct Contact Three Phase Spray Column

P. GOODWIN[1], M. COBAN[1], and R. BOEHM[2]
Department of Mechanical and Industrial Engineering
University of Utah
Salt Lake City, Utah

ABSTRACT

A study of the flooding limits of a large spray column used as a three-phase direct contact heat exchanger is reported. Flooding is defined here as pentane being carried out with cooled water. The spray column had a diameter of 0.61 m (24 in) and a height of 6.1 m (20 ft), although only half of this height was used in typical operation. Normal pentane was utilized as the dispersed phase fluid which was injected at approximately 30 C (85 F). Water at approximately 85 C (185 F) was used as the continuous phase. The pentane vaporized in contact with the water, and this vapor and water vapor flowed from the top of the column, and the cooled water exited from the bottom of the column. Vessel pressure and each fluid's flow rate were varied during the course of the experiments. Plots of heat transfer performance and flooding conditions are given.

INTRODUCTION

Of the various types of direct contactors available, the spray column is clearly the simplest in construction. While the possible shortcomings of these devices have been pointed out many times (e.g. backmixing and end effects [1], both of which can lead to decreased performance), the low cost of the device is a very appealing attribute. This is especially true when large duties, and thus large devices, are required for a given application.

Heat transfer performance of spray columns is most often stated in terms of the volumetric heat transfer coefficient, U_v, which is given by:

$$U_v = Q_{net}/(LMTD \cdot V) \qquad (1)$$

where Q_{net} is the net heat transfer to the working fluid, $LMTD$ is the normal definition of the log mean temperature difference and V is the active volume of the column (usually taken as the volume of the continuous fluid with entrained dispersed fluid).

One of the most widely reported performance aspects of the spray column is that the volumetric heat transfer coefficient increases directly with the holdup (defined as the fraction of the active volume that is made up of the dispersed phase). It is most economical to operate at the highest holdup possible as this will yield the maximum performance per unit volume of equipment. At high holdups, however, the condition of flooding can occur, and this is usually associated with a decrease in performance. Flooding is the situation where the dispersed phase is swept backward by the continuous phase. A small number of approaches have been given in the literature to predict flooding and these show significant disagreement (see discussion below). There is no question, however, that this is an undesirable condition for operation. In fact, it is suggested [2] that regular operation should never occur at conditions greater than 90% of the flooding holdup so that uncertainties in the flooding limit will not cause poor performance and/or dispersed fluid loss in the exit of the continuous fluid. Some workers suggest even lower fractions.

Prediction of the flooding limit is difficult, but very important. The need to estimate the conditions at flooding originates during the design of the contactor because this situation sets the diameter of the device. This has been covered for mass transfer applications in classical texts (e.g. [3]). There is enough similarity between flow fields in the (usually) isothermal flows encountered in liquid/liquid mass transfer and the nonisothermal flows encountered in liquid/liquid heat transfer to design heat transfer devices from mass transfer experience.[4] Unfortunately when phase change occurs in a heat transfer application there is not a body of knowledge in the mass transfer literature to draw upon for defining the flooding limit.

Three of the often cited approaches for predicting flooding in non-phase-change systems are those of Minard and Johnson [5], Sakiadis and Johnson [6] and Richardson and Zaki [7]. A comparison of results predicted by the three techniques has recently been given by Wright [8]. He has shown that great discrepancy exists between the three methods.

---

[1] Graduate Research Assistant in Mechanical Engineering.

[2] Professor of Mechanical Engineering. Currently on Sabbatical Leave at Sandia National Laboratories, Livermore, California. Fellow of the ASME.

Presented at the National Heat Transfer Conference
Denver, Colorado—August 4-7, 1985

If the situation is confused for predicting the flooding limit of non-phase-change systems, there is an absence of approaches for the corresponding boiling case. Studies of boiling (usually called "three-phase") applications are quite limited, and very few of these have addressed the flooding conditions.

Among the earliest and most comprehensive reports of performance of three-phase spray columns is that of Sideman and Gat. [9] They used a column 70 mm (2.75 in) in diameter and about 300 mm (12 in) high to evaporate pentane with water. They were able to measure holdup by quickly isolating the vessel from the flow loop and measuring the decrease of water level after the pentane evaporated completely. The data indicated that a maximum was found in the variation of the volumetric heat transfer coefficient, but the physical flooding conditions were not reached.

Blair, et al. [10] studied the evaporation of Refrigerant 113, whose liquid density is higher than that of water, in a device similar to that used by Sideman and Gat. Holdup was not measured. Although "carryover" conditions were reported, which is in effect a kind of flooding, the density difference effects on the physical situation make comparison difficult. Like comments apply to the data reported by Jacobs, et al. [11] for a larger, but somewhat similar configuration.

Correlations for heat transfer in three-phase configurations are limited. In most cases data is presented that actually applies only to the boiling portion of the tower. Examples of this are the results of Sideman and Gat [9] noted earlier and a compilation of the few other sources of data given by Jacobs and Boehm. [4]

Few heat transfer correlations for liquid-liquid systems are found in the literature either. Most of the existing data have been plotted and correlated against holdup and volume flow ratio. [4]

If spray columns are to be considered for low temperature boiler applications like solar pond power plants and electricity generation from waste heat streams, their maximum performance has to be understood. Clearly the paucity of data relevant to the heat transfer and flooding limits is a great impediment. It was within this context that the present study was initiated.

EXPERIMENTAL DESIGN AND PROCEDURE

Quite simply, the experimental apparatus consisted of a tower and two flow loops, one each for water and pentane. A schematic of the system is shown in Figure 1.

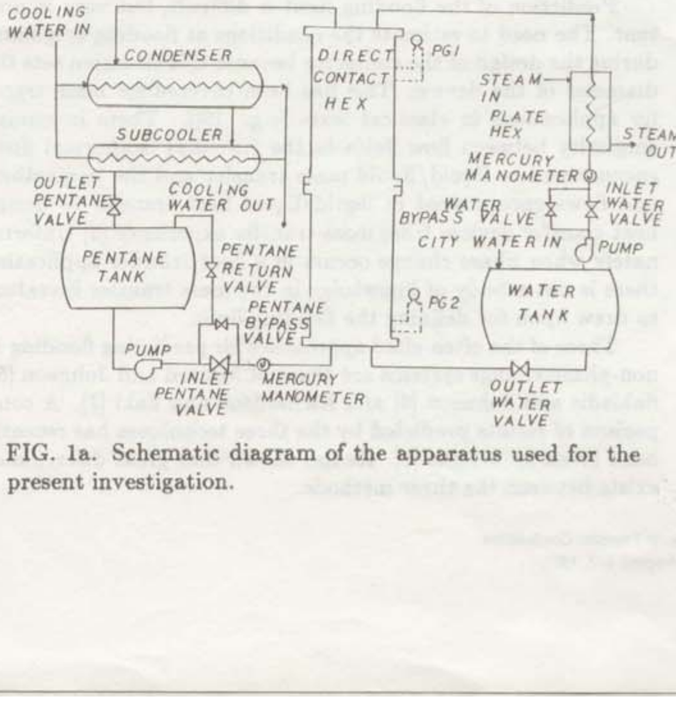

FIG. 1a. Schematic diagram of the apparatus used for the present investigation.

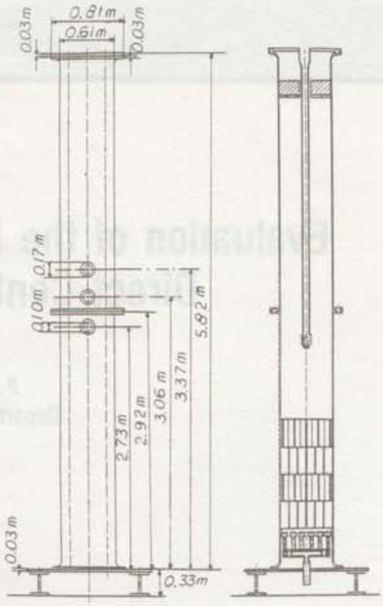

FIG. 1b. Diagram of spray column used for this work. The active water level was kept near the half-way point, and hot water was injected below this level from the pipe extending from the top of the vessel.

The tower was designed from conventional 0.61 m (24 in) pipe. While it was anticipated that a typical maximum working height of the tower would be on the order of 3.05 m (10 ft), the actual height of the vessel was set at 6.1 m (20 ft). A benefit of doing this is to allow other configurations to be evaluated later that may need a greater height than the initial configuration.

Normal pentane was selected as the working fluid as it would yield absolute vessel pressures that were moderate, but not too high. In specific, pressures of approximately 2-3 atm result when typical inlet water temperatures of 85 C (185 F) are used. Normal pentane is also one of the more desirable fluids to use in a direct contact power plant for this level of inlet temperature. [12,13] Because of the flammability aspect of this fluid, all electrical components and wiring were designed to be explosion proof. To simplify the system, it was decided not to control the pentane inlet temperature to the column. This omission later caused minor problems when the ambient temperature was very high, with premature boiling of the pentane a possibility. This variation in pentane temperature was reduced somewhat as needed with temporary localized cooling on the inlet pipe.

Orifice plates were used to measure the flowrates of the hot water and the liquid pentane. Known flow measurement accuracy resulted from this decision. Large flowrate ranges could be accommodated quite inexpensively by changing the plates. Pressure transmitters were connected in parallel with manometers to indicate the pressure drops.

Temperature measurement was accomplished with the use of shielded Chromel-Alumel thermocouples. 24 units were used to determine temperatures throughout the system, including the inlet and outlet stream temperatures as well as the temperatures at various locations within the column. All thermocouple outputs, as well as the pressure transmitter outputs, were recorded on a Fluke Datalogger.

A small shed was located about 15 m (50 ft) from the experiment. All electrical instrumentation was located in the shed. The location of the shed was set to minimize open sparks in too close a proximity to possible pentane vapors.

The heat exchange functions of the loops were accomplished by three devices. On the water side, a plate heat exchanger (93.4 square feet, 100 psig, 33 plates) was used. Steam, from an adjacent utility power plant, at approximately 6 atm and 150 C was used to heat the water. To condense the pentane, two shell and tube heat exchangers were used (the nameplates on the exchangers indicated their areas are 124.1 sq ft and 219 sq ft). One of these latter two devices served essentially as a desuperheater and the other served as a condenser. Cooling water from the adjacent steam power plant was used to condense the pentane.

The water and the pentane were stored in 1900 liter (500 gal) galvanized storage tanks. A line was installed on the bottom of the pentane tank so that condensed water could be drained as needed. Both the overall level within the pentane tank as well as the underlying water level could be determined by viewing through a dual sight gauge arrangement. The top of the water tank was outfitted with a line so that fluid could be drained as desired. An additional line was connected to the water tank to allow the installation of a pressure relief valve to vent water if the system overpressured.

Pumping was accomplished by centrifugal, explosion proof pumps. Construction of the pumps is stainless steel. Since the required pentane flowrate varied over a very large range, a bypass line, with a valve, was installed between the exit of the pump and the pentane storage.

Three 10 cm (4 in) diameter windows were installed in the tower, one above the other near the location of the interface. Level was controlled manually by viewing the interface through the windows and adjusting appropriate valves.

In a typical run, the final adjustments were made to achieve the desired settings for flowrates, vessel pressure and level, and water inlet temperature. Note that the pentane inlet temperature was not controlled, but localized cooling using a water stream on the inlet pipe and pump regions was used to combat possible cavitation or premature boiling (e.g. in the inlet nozzles) when needed.

Flooding conditions, if present, could be determined during a run by briefly cracking a small valve on the top of the water storage tank. The resulting sound of venting pentane vapor, if present, was a very effective approach to this determination.

Data analysis took place after each day's operation. The analysis technique involved simple energy balances on each of the fluids as well as on the column as a whole. Both calibrations and calculated estimates of heat loss from the vessel were used in predicting the net heat transfer between the fluids. Of particular interest was the generation of values for the volumetric heat transfer coefficient, U_v, which is defined in Eq. (1). V was calculated from the average height noted in the viewing windows.

RESULTS AND DISCUSSION

Among the most basic data that resulted from the experiment is information on the temperature distribution along the column. While details of this are available for each of the approximately 100 data cases from this work, only one representative example will be shown here. See Figure 2. In this figure, the temperatures that were actually read are shown as data points. The vertical line just past the 3 m mark denotes the observed active level during the run. It should be noted that the 85 C (approximately) water inlet temperature is considerably higher than is the temperature at the top of the active level. Since the inlet temperatures were held constant, the vessel pressure had the single largest effect on the temperature distributions in the column. Note that for each case, though, a relatively uniform temperature distribution is demonstrated.

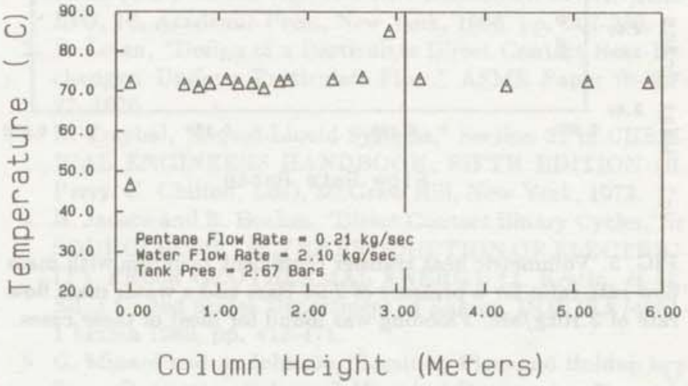

FIG. 2. Measured temperature data throughout the column for a typical run. A vertical line above 3 m indicates the active level, so temperatures above this height are for vapor. The high temperature just below 3 m is the water inlet temperature.

Of fundamental interest is the variation of the overall volumetric heat transfer coefficient, as defined by Eq. (1). This is shown for a series of cases in Figures 3, 4, and 5. Cases for two pressures and two water flowrates are given as parameters, while the pentane flowrate is taken as the independent variable of each figure. "Flow Rate Ratio" used in the figures is defined as as the ratio of the mass flow rate of pentane divided by the corresponding value for water. Since each data point represents a separate steady-state run, points where multiple runs are shown at the same values of the parameters indicate the kind of repeatability in the demonstrated in the experiment. (See more discussion on this point below.) Figure 4 shows both flooded and nonflooded cases. In the other two figures (3 and 5), all points represent cases with no flooding. During the performance of the experiment, it was noted that pressures above 3.2 atm (47 psia) could not be attained for the ranges of other parameters used here. (Implications of this pressure limitation are discussed again later.) It should also be noted that the maximum in the U_v vs. flow ratio curves shown by Sideman and Gat [9] is not noted here, but physical carrying out of working fluid (flooding) not attained by them was found here.

During the data gathering, readings were taken every 2 minutes. After approximately 20 minutes had elapsed from a small change in one of the variables, steady-state conditions appeared to have been achieved. Data readings continued for several more periods. Then the complete set of data for the steady-state conditions was reduced and plotted. Repeat runs were taken on different days. The resulting high values, low values and best estimate values are shown in Figures 3-5. The error bands ranged from 8-20% depending upon the particular run. A specific analysis was carried out to determine to what extent the U_v values were affected by the variation of the pentane inlet temperature. For a range of 15 C in pentane inlet temperatures the resulting error band varied between 7 and 10 percent. The bulk of the data fell within this range of pentane temperature variations, but some cases were higher.

From the experiments, the variation of the flooding limit with the two mass flow rates and the vessel pressure has been determined. See Figures 6-8, where maps of data points from the experiment are shown plotted against water mass flow rate and mass flow ratio. As before, points shown as a circle denote where pentane was detected with the water exiting the column (flooding). For higher pentane flow rates the possibility of flooding decreases. If there is a point at which higher pentane flows will result in flooding, these points could not be demonstrated in these evaluations. The effect of pressure on the flooding limit is summarized in Figure 9. As shown, the chance of flooding decreases for constant mass flow rate ratio for increased pressure. Operational limits were encountered, so vessel pressures above 3.2 atm (47 psia) could not be attained for lower mass flow rate ratios. This was due to the pentane saturation pressure effects relative to the temperature conditions used here. The pressure at the flooding point varies approximately as the inverse of the pentane flow rate.

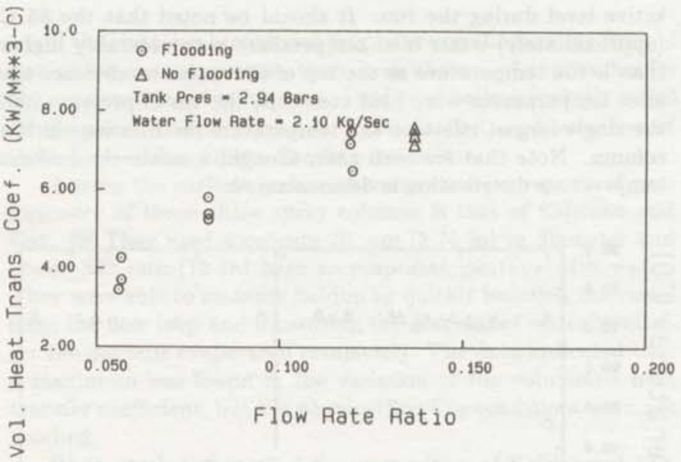

FIG. 3. Volumetric heat transfer coefficient variation with mass flow rate ratio for a pressure of 2.94 Bars and a water mass flow rate of 2.10kg/sec. Flooding was found for most of these cases.

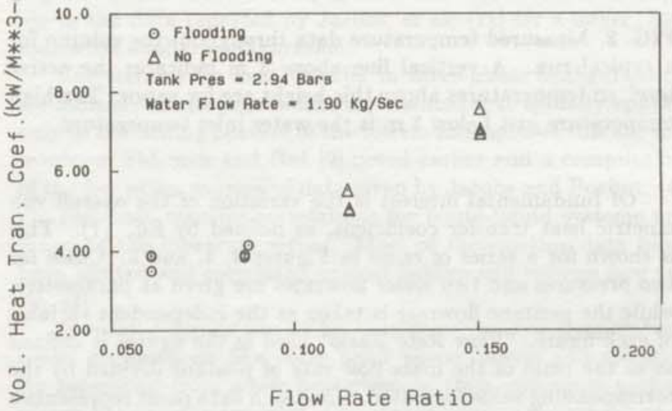

FIG. 4. Volumetric heat transfer coefficient variation with mass flow rate ratio for a pressure of 2.94 Bars and a water mass flow rate of 1.90 kg/sec. Cases where flooding occurred are also shown.

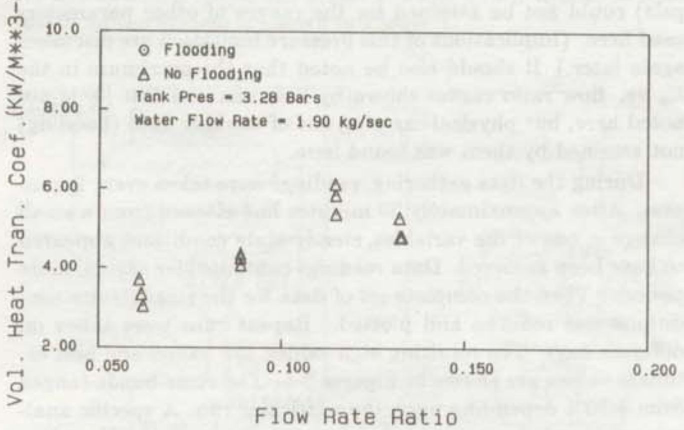

FIG. 5. Volumetric heat transfer coefficient variation with mass flow rate ratio for a pressure of 3.28 Bars and a water mass flow rate of 1.90 kg/sec are shown. Flooding was not found in any of these cases.

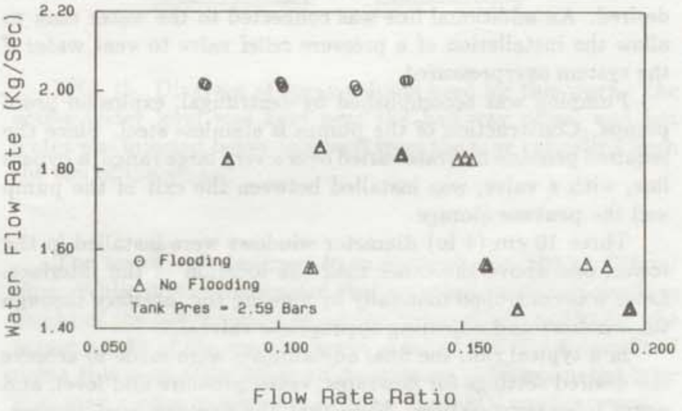

FIG. 6. Map of mass flow rates investigated at 2.59 Bars, showing flooding and no flooding cases.

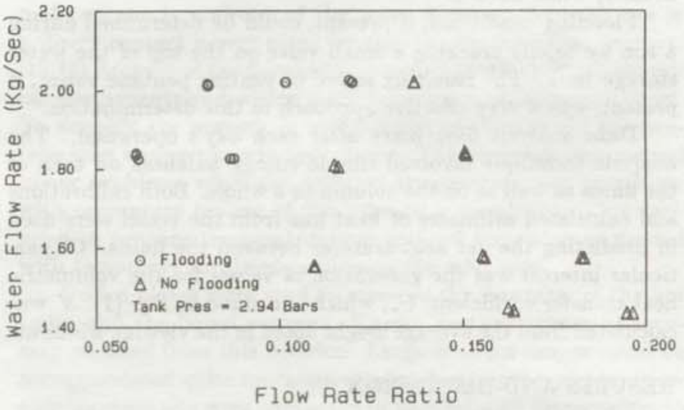

FIG. 7. Map of mass flow rates investigated at 2.94 Bars, showing flooding and no flooding cases.

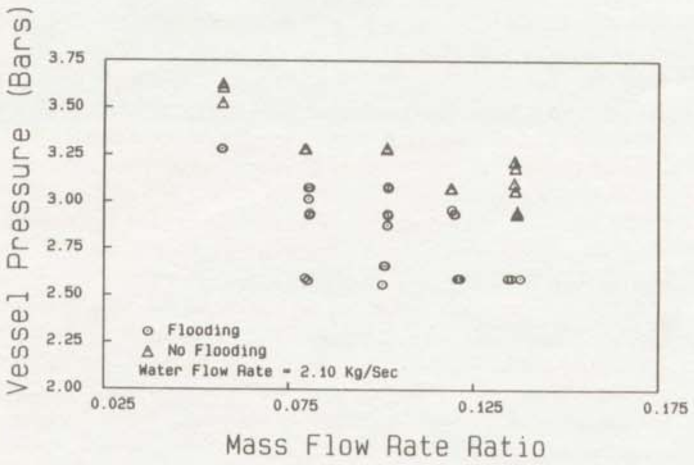

FIG. 8. Map of mass flow rates investigated at 3.28 Bars, showing flooding and no flooding cases.

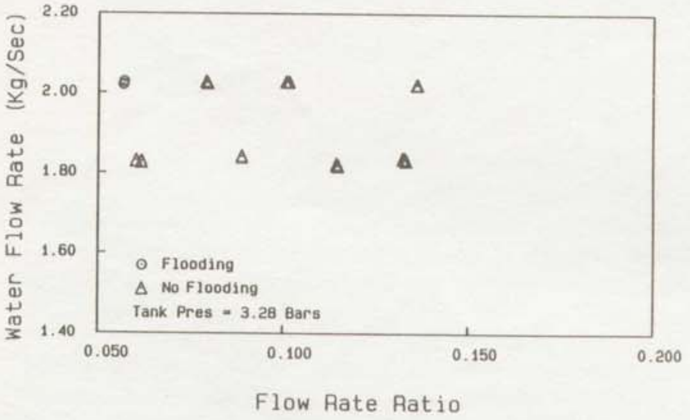

FIG. 9. Map of vessel pressure vs. mass flow ratio for a water mass flow rate of 2.10 kg/sec, showing flooding and no flooding cases.

CONCLUSIONS

1. A 0.61 m (24 in) diameter tower direct contact heat exchanger has been built and operated using water at 85 C as the heat source. Pentane was injected in the bottom of the column, was vaporized by the water and left at the top of the tower. An active column height of 3.05 m (10 ft) was used in a spray column configuration.
2. It is found that the controlled variable that most influences the temperature profiles within the column is the vessel pressure. An increasing vessel pressure results in an increasing vessel temperature. As was found in previous studies of direct contact boilers, the temperature profile is fairly flat throughout the column.
3. As expected, the variation of the volumetric heat transfer coefficient showed an increasing trend when plotted against the pentane mass flow rate. Conditions where pentane came out with the water (flooding) were easily identified in the experimental procedure. Uncertainties in the data for U_v were estimated to be between 8 and 20%.
4. Detailed studies of the vessel pressure effects on the flooding limit are given here for the first time. It is found that the pressure at the flooding point varies with the inverse of the pentane flow rate, at constant water flow and inlet temperature. Unfortunately the pentane inlet temperature could not be controlled closely in the present work, and this variable introduces an uncertainty, estimated to be between 7 and 10%, in the results.

LITERATURE CITED

1. S. Sideman, "Direct Contact Heat Transfer between Immiscible Liquids," in ADVANCES IN CHEMICAL ENGINEERING, 16, Academic Press, New York, 1966, pp. 207-286.
2. R. Letan, "Design of a Particulate Direct Contact Heat Exchanger: Uniform Particulate Flow," ASME Paper 76-HT-27, 1976.
3. R. Treybal, "Liquid-Liquid Systems," Section 21 in CHEMICAL ENGINEERS HANDBOOK, FIFTH EDITION (R. Perry, C. Chilton, Eds), McGraw Hill, New York, 1973.
4. H. Jacobs and R. Boehm, "Direct Contact Binary Cycles," in SOURCEBOOK ON THE PRODUCTION OF ELECTRICITY FROM GEOTHERMAL ENERGY (J. Kestin, et al., Ed.,) United States Department of Energy, DOE/RA/4051-1 March 1980, pp. 413-471.
5. G. Minard and A. Johnson, "Limiting Flow and Holdup in a Spray Extraction Column," Chemical Engineering Progress, 48, February 1952, pp. 62-74.
6. B. Sakiadis and A. Johnson, "Generalized Correlation of Flooding Rates," Industrial and Engineering Chemistry, 46, June 1954, pp. 1229-1239.
7. J. Richardson and W. Zaki, "Sedimentation and Fluidization, Part I," Transactions of the Institute of Chemical Engineers, 32, 1954, pp 35-53.
8. J. Wright, "Sizing of Direct-Contact Preheater/Boilers for Solar Pond Power Plants," SERI/TR-252-1401, Solar Energy Research Institute, May 1982.
9. S. Sideman and Y. Gat, "Direct Contact Heat Transfer with Change of Phase," AIChE Journal,12, March 1966, pp 296-303.
10. C. Blair, R. Boehm, and H. Jacobs, "Heat Transfer Characteristics of a Direct Contact Volume Type Boiler," ASME Paper 76-HT-26, 1976.
11. H. Jacobs, S. Plass, A. Hansen, and R. Gregory, "Operational Limitations of Direct Contact Boilers for Geothermal Applications," ASME Paper 77-HT-5, 1977 .
12. J. Wright, "Direct-Contact Preheater/Boilers for Solar Pond Power Plants," SERI/TP-252-1968, Solar Energy Research Institute, December 1983.
13. A. Sonn and R. Letan, "Thermal Analysis of a Solar Pond Power Plant Operated with a Direct Contact Boiler," Journal of Solar Energy Engineering, 1982, pp 262-269.

ACKNOWLEDGEMENTS

The partial support of this work by a grant from the Solar Energy Research Institute is greatly appreciated. Special thanks also go to Utah Power and Light Company for assisting with the experimental facilities. The assistance of H. Jacobs with the early phases of this work was very valuable. F. Lindbeck, L. Stegen, J. Bossard, J. Oliva, F. Perkins and E. Esparza assisted with the construction of the apparatus. The typing of the paper was performed by Tracey Lamee.