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THERMAL AND HYDRAULIC PERFORMANCE OF A SIEVE-TRAY DIRECT-CONTACT HEAT EXCHANGER

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Abstract

Experiments investigating the thermal and hydraulic performance of a sieve tray direct contact heat exchanger (DCHX) were conducted using a 275° geothermal fluid as an energy source and different hydrocarbons as working fluids. The baseline performance tests with the direct contact unit were conducted with isobutane. The thermal performance of the unit met or exceeded the design goals for individual tray thermal efficiencies and pinch points. Hydraulically the column operated near recommended design fluid velocities. Following the completion of these tests, the DCHX was operated with different mixtures of hydrocarbon working fluids. Different combinations of the isobutane/hexane family were tested followed by a series with propane/isopentane fluids. The testing conducted with the direct contact unit showed that the sieve tray column is a very efficient heat exchange device although some degradation in boiling tray efficiency and column throughput were noted when mixtures were used.

INTRODUCTION

As part of the Department of Energy's Geothermal Conversion Technology effort, a specially designed sieve tray direct contact heat exchanger (DCHX) was tested with the 60kW Heat Cycle Research Facility at the Idaho National Engineering Laboratory (INEL) Raft River geothermal test site located in southern Idaho. The Heat Cycle Research Facility is used to test different components and/or concepts associated with the generation of electrical power from binary geothermal power cycles. This work was supported by the U. S. Department of Energy, Deputy Assistant Secretary for Renewable Energy, Geothermal and Hydropower Division, Contract No. DE-AC07-76IDO-1570.

The purpose of the testing of the DCHX with the facility was to evaluate the thermal and hydraulic performance of a sieve tray direct contact heat exchanger in a geothermal application. In this type of heat exchanger there are no physical boundaries such as a tube wall separating the fluids. This type of heat exchange device has significant potential when the brines being used have high levels of dissolved solids and are prone to cause scaling and corrosion of heat exchange surfaces. Although some previous testing has been done with sieve tray direct contact heat exchangers, this is the largest column tested in geothermal applications, and this effort included testing of mixed hydrocarbon fluids. Mixtures do not boil at a constant temperature for a fixed column pressure, and their use can potentially decrease the cycle irreversibility and improve performance if the countercurrent flow path can be maintained in the column. The trays in the sieve tray column are thought to help in this respect and allow for the use of working fluid mixtures in direct contact applications.

Facility and Component Description

The 60kW Heat Cycle Research Facility is a small-scale geothermal binary power plant which is similar to full-scale plants in most aspects except size. Because it is a research facility, it has been built with the flexibility to operate in different configurations utilizing various components; the basic plant cycle, though, remains the same. A flow schematic of the facility with the principle power cycle components is depicted in Figure 1. For the direct contact tests, the energy from the geothermal fluid is transferred to a hydrocarbon working fluid in the DCHX column. Since the two fluids are physically in contact with each other, it is necessary to boost both fluids to the DCHX operating pressure using a geothermal fluid boost pump and the working fluid boost and feed pumps. The geothermal fluid enters the column at the top and flows out the bottom preheating and vaporizing the working fluid which enters the bottom of the column as a liquid and leaves near the top as a vapor. The effluent geothermal fluid is then discharged to a holding pond prior to reinjection. The working fluid vapor leaving the DCHX can be expanded through a turbine which drives a generator or through a turbine bypass valve which drops the pressures of the vapor prior to its entering the condenser. (The turbine was not used during the DCHX operation as it would have required modification to match the DCHX vapor flows.) In the condenser the working fluid vapor is desuperheated and condensed, and the condensate is pumped back into the DCHX for another heat exchange cycle. In order to reduce the effect of noncondensable gases dissolved in the geothermal fluid on the cycle performance (particularly the condenser), the facility is equipped with a geothermal preflasher to remove noncondensables from the geothermal fluid before it enters the

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cycle, and a secondary vent condenser which minimizes working fluid losses when noncondensables gases are vented from the working fluid system. If measures are not taken to remove and/or minimize effects of the noncondensable gases, these gases accumulate in the condenser adding their partial pressure to the condensing pressure and inhibit the condensation process; the net result being higher condenser pressures.

The direct contact heat exchanger tested in the Heat Cycle Research Facility is a sieve tray or perforated plate column designed and built for this application by the Wahl Company of Claremont, California. This column which is approximately 1 ft in diameter and 19 ft long is schematically shown in Figure 2. The column is a vertical unit containing 20 trays and downcomers which provide for the ordered passage of flow through the column. In this application the lighter working fluid is dispersed as drops from the holes or perforations in each plate. These drops rise through the heavier geothermal fluid because of the buoyancy force on the drop, and collect and coalesce under the next tray and vessel wall. This process of drop forming and coalescing is repeated at each tray as the working fluid moves up the column, heating as it rises through the geothermal fluid. The heavier geothermal fluid flows as the continuous medium horizontally across each plate transferring heat to the working fluid, and then passes down to the next plate through a disengagement space formed by the downcomer on each plate. As indicated in Figure 2, the geothermal fluid temperature is measured in the downcomer regions at various locations as the fluid flows through the heat exchanger. Working fluid temperatures are measured at selected locations beneath the plates where the fluid has coalesced.

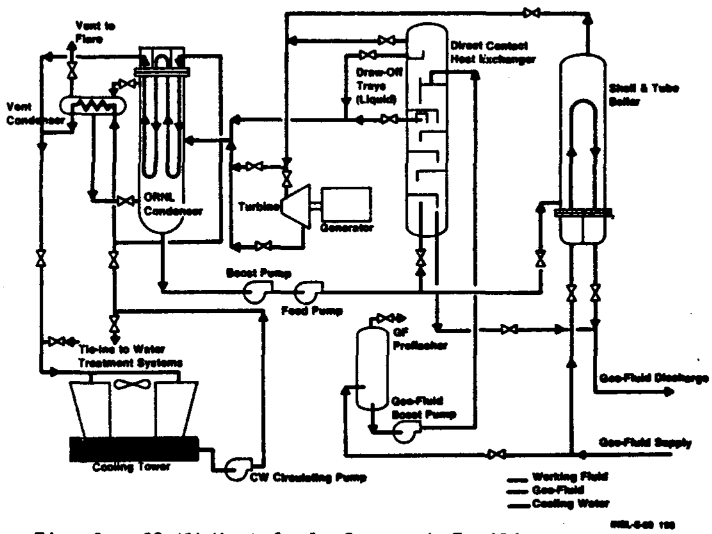

Fig. 1: 60 KW Heat Cycle Research Facility

The lower 17 trays of the column comprise the preheating section where the working fluid is heated up to the saturation temperature corresponding to the column operating pressure. These trays are spaced at 6-inch intervals and have 3-inch long downcomers. The next two trays, i.e., 18 and 19, make up the boiling section where the working fluid is vaporized. The perforations in all of the trays, or plates, have a diameter of 1/8-inch. The upper tray, number 20, is a drawoff tray not used in this testing.

Discussion of Thermal and Hydraulic Performance

The primary emphasis in baseline tests with the isobutane working fluid was on the thermal performance of the preheating trays. The main indicator of the performance of these trays is the thermal tray efficiency which is a measure of how efficiently heat is transferred during the contacting of the fluids. There are more than one specific definition of tray efficiency, the simplest being the "overall" efficiency which is the ratio of the number of ideal trays required to exchange the thermal energy to the number of actual trays required to transfer the same amount of energy. In an ideal tray the working fluid would leave at the same temperature as the geothermal fluid. This efficiency term is similar to the one proposed by Sheinbaum(2) for direct contact heat exchangers, and is a common term used in direct contact columns used for mass transfer(3). The overall efficiency can be found graphically from the construction of

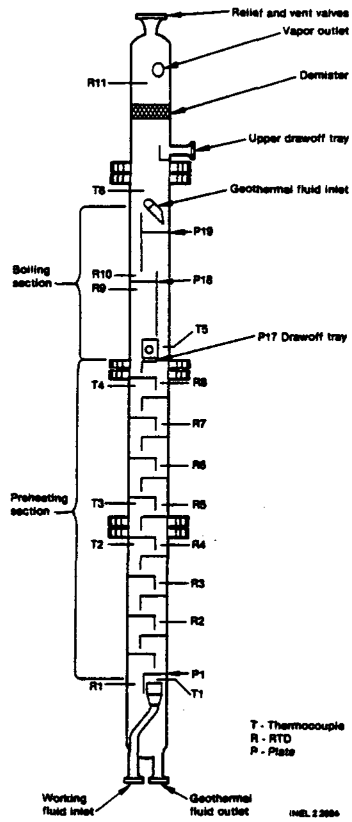

Fig. 2: Direct Contact Heat Exchanger

temperature-heat exchanged (TQ) plots for the two fluids involved in the heat transfer process. A second definition of tray efficiency that can be used is a more local term involving the conditions for an individual tray. It can be expressed as the actual heat transferred to the theoretical heat transferred in an ideal tray. In evaluating the results from the direct contact testing both of these efficiency definitions were used. The individual tray efficiency was used primarily in the baseline tests were the analysis procedure and fluid properties were incorporated into a computer program for data reduction. When mixtures were evaluated, the overall efficiency term was used because of lack of the time and resources required to modify the programs for the mixtures properties.

Another indicator of the column thermal performance is the pinch point or minimum approach temperature between the two fluids. This indicator actually reflects the tray efficiency and the number of trays available for heat transfer. If the tray efficiency is high and the column has a sufficient number of trays for boiling and preheating, then the DCHX should be able to achieve small pinch points. The volumetric heat transfer coefficients were also evaluated; however, the difficulty in defining the volumes in which heat transfer occurs makes this value hard to compare for different heaters.

The column thermal performance is to some extent affected by the column hydraulics, i.e., smaller drops heat up at a faster rate than larger drops. Any effort to reduce the drop size must be tempered by the increase in mass transfer and the increase in the potential for the drops formed to be swept along, i.e., carried under, with the geothermal fluid. The velocity at which the drops rises, or terminal velocity, is approximately proportional to the square root of the drop diameter; thus, smaller drops rise more slowly in the column. If the velocity of the continuous fluid (geothermal fluid) exceeds the terminal velocity of the drop, then the drop will be swept along in the continuous fluid stream, or mechanically entrained. This terminal velocity and the minimum flow area for the continuous fluid (usually the downcomer region), establish the maximum geothermal fluid flow rate through the column.

The prediction of the terminal rise velocity of a drop is usually based on a known drop diameter and the assumption that a drop behaves as a solid sphere as it rises. Investigators of the drop formation process in liquid-liquid systems have noted that this assumption is valid up to a certain drop diameter after which the terminal velocity no longer increases and may, in some cases, decrease. A correlation was developed by Treybal and Klee(3) for predicting this terminal velocity limit. For the conditions and fluids used in the baseline tests, this upper terminal velocity limit was approximately 0.56 ft/s in the preheating section. If the geothermal fluid velocity exceeded this value, then any drop formed would be "carried under" with the geothermal fluid stream.

Although the intent of the DCHX testing was not to investigate the different mechanisms of drop formation, it was necessary to consider the different mechanisms in interpreting the operating limits encountered in the column. At lower orifice or hole velocities, the drops are uniform in size and break off at regular intervals. As the hole velocity is increased, a point is reached where a jet will form at the orifice and the drop formation mechanism changes. While these drops are not necessarily uniform in size, there is some consistency at the lower jet velocities, and the average drop size can be predicted. As the hole velocity increases, the jet length increases, and a point is reached where the average drop size formed is at a minimum. In mass transfer applications this point is referred to as the velocity producing the maximum interfacial area(4) and is the recommended maximum hole velocity to be used in the design of a sieve tray DCHX(1). Further increases in the hole velocity produce more irregularity in the drop formation until the jet reaches a maximum length and begins to breakup in a random manner, and the drops have no uniformity in size(5).

RESULTS

Baseline Tests

The baseline performance testing with the direct contact heat exchanger consisted of bringing the column to a "flooded" condition over a range of DCHX boiling pressures using an isobutane working fluid. A "flooded" condition was considered to be that point where the carryunder of working fluid and/or the carryover of geothermal fluid were sufficient that column stability could not be maintained. For a particular boiling condition, the flow rates were increased in small increments, with data taken at each flow step until the column flooded. The data collected for each tested condition at the "near flooded" (just before flooding) condition is listed in Table 1.

The data collected was inputted into a computer program developed for the analysis of the DCHX thermal performance with an isobutane working fluid. This program, which generated a predicted temperature profile from measured flow rates and

TABLE 1: DCHX BASELINE PERFORMANCE WITH ISOBUTANE

Parameter	Test Run 1*	2	3	4	6	7
Boiler Pressure, Psia	446.7	365.0	329.4	294.2	236.3	146.2
Outlet WF Vapor Temperature, °F	249.6°	230.7°	221.0°	210.8°	190.4°	150.6°
Inlet WF Flow Rate, lb iC_4/hr	3636	6282	6904	7560	8325	8887
Inlet GF Temperature, °F	265.9°	267.7°	268.3°	268.4°	266.1°	267.6°
Outlet GF Temperature, °F	223.9°	191.1°	177.9°	165.7°	146.3°	119°
Inlet GF Flow Rate, lb GF/hr	17605	15537	14354	13334	12136	9656
Average Total Heat Load, Btu/hr x 10^6	0.743	1.204	1.311	1.404	1.470	1.437
Preheating Heat Load, x 10^6 Btu/hr	0.434	0.601	0.608	0.611	0.520	0.304
Boiling Heat Load, x 10^6 Btu/hr	0.309	0.603	0.703	0.793	0.950	1.133
Preheater Tray Efficiency	60%	70%	74%	71%	73%	71%
Boiling Tray Efficiency, Plate 18	99.6%	99.5%	99.6%	0%	0%	90%
Plate 19	92.8%	97.9%	96.7%	100%	99.4%	98.9%
Pinch Point, Predicted, °F	0.02°	0.02°	0.02°	0.05°	0.10°	0.30°
Volumetric Heat Transfer Coefficient						
Preheater Trays Btu/hr-ft^3-°F	4952	9109	10705	10354	10666	9670
Boiling Trays Btu/hr-ft^3-°F	29987	28992	27300	22957	19689	13690

*Flooding not reached

fluid temperatures at the bottom of the column, allowed the individual tray efficiency to be varied along with the mass flow ratio and the local tray carryunder. In general, the carryunder term did not have a significant effect on the results obtained unless it was made unreasonable large. The mass flow ratio was varied until the predicted column temperature profile matched the experimental measurements in the upper portion of the preheating section. This adjustment was made to compensate for instrument error or oscillations in the column in order to obtain consistent heat balances. After the mass flow ratio was corrected, the individual tray efficiency was varied until the predicted and measured column temperature profiles in the preheater section matched. Although it was possible to vary the individual tray efficiency from tray to tray, it was found that satisfactory results could be obtained if the individual tray efficiency was held constant throughout the preheating section. An example of the matching of the predicted and measured temperature profiles is shown in Figure 3 for one of the baseline test conditions. For this particular run little correction was required for instrument error, and at an individual tray efficiency of 74 percent the best match was found between predicted and measured temperature profiles. This temperature profile also graphically demonstrates the small pinch points that were obtained during the DCHX operation.

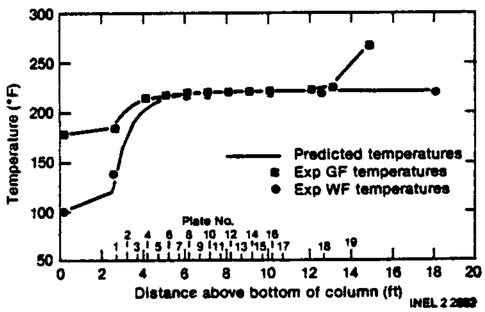

Fig. 3: DCHX Temperature Profile

The DCHX thermal performance for the baseline test runs is also summarized in Table 1. The individual tray efficiencies are given for the preheating section, along with the pinch point, heat loads, and volumetric heat transfer coefficients. Although it is difficult to identify any trends in the preheating tray efficiency, it is significant that the efficiencies obtained (except in test run 1 which was not brought to flooding) were equal to or exceeded the design value of 70 percent. Boiling tray efficiencies were calculated using a combination of temperature measurements and predicted enthalpy changes. Given the uncertainty in measuring accurately an intermediate geothermal fluid temperature between boiling trays, any significance of apparent trends in boiling tray efficiencies is questionable and the only significant conclusion is that the boiling trays had sufficient capacity for the conditions tested.

The pinch points for tests conducted were small, much smaller than could be accurately measured with the instrumentation available. In matching the preheating section temperature profile pinch points ranging from 0.02¼F to 0.30¼F were obtained. These pinch points increased as the heat load for the column increased and it would appear from those results that the pinch point is more sensitive to the heat load in the boiling section than that in the preheating section (the largest pinch point obtained occurred at the lowest preheating heat load).

The volumetric heat transfer coefficients (Uv) were defined using the heat transfer that occurred in these sections, the total volume where heat transfer could have occurred, and the log mean temperature difference. The log mean temperature differences were determined using the pinch point obtained in matching the preheating section temperature profiles. The preheating section volume was defined as the volume of the column from the top of plate 1 to the bottom of plate 18, less the volume of the downcomers. The boiling section volume was defined as the volume in the column from the top of plate 18 to the bottom of the demister. The bottom of the demister was selected, as this represents the upper limit as far as the thickness of the boiling region is concerned. (If the boiling occurred at a level above the demister, excessive carryover of water could occur and the column would be unstable.) Perhaps the most significant observation one might make from these heat transfer coefficients is that the Uv values for the preheating section are relatively constant (reflecting the fact that the preheating occurs over a fairly well defined region).

From a hydraulic standpoint, the DCHX operated near the recommended working fluid flow rates(1) which corresponds to the plate orifice velocities that produce the average drop size at the maximum interfacial area. The working fluid velocities through the plate orifices varied from 0.69 to 0.98 ft/s. These velocities generally matched or were slightly higher than the velocities predicted to produce the maximum interfacial area throughout the preheating section with the exception of plate 17. The upper preheating tray (number 17) was designed to also serve as a drawoff tray allowing working fluid near the saturation temperature to be removed from the column. In order to accomplish this, the hole area in this plate was reduced by about 60 percent. This reduced area producing orifice velocities ranging from 1.71 to 2.03 ft/s. For those runs which approached a "flooded" condition, this velocity exceeded that predicted to produce the maximum jet length (corresponds to irregular jet breakup and a lack of uniformity in drop formation). It is not known whether the hydraulic working fluid limits in these tests were imposed by the operation at the velocity producing the maximum interfacial area in the lower portion of the preheating section, or if they were imposed by the irregular breakup of the orifice jet in plate 17 with the formation of a number of very small drops.

In comparing spray and sieve tray direct contact device, the sieve tray column is reputed to have a thermal advantage, but is said to have a lower mass throughput capacity than a spray tower of similar dimensions[1]. To compare the throughput capacity relative to spray towers, the superficial velocities of the sieve tray DCHX in the baseline tests with isobutane were compared to those of the DSS column[6] and the 500kW column[7] both of which are spray tower units. This comparison, shown graphically in Figure 4, is somewhat inconclusive. The throughput of the sieve tray DCHX compares favorably with the relative capacity of the 500kW spray tower, however, this spray tower was never brought to a "flooded" condition so that an increment in capacity performance could be estimated. A comparison with the high temperature cycle test performance of the DSS spray tower indicates the sieve tray DCHX had a throughput advantage. When compared to the low temperature cycle test performance of the DSS unit, the spray tower had an advantage. This point represents the probable operating limit for the DSS column and indicates that the spray column has, as reputed, a throughput advantage over the sieve tray column.

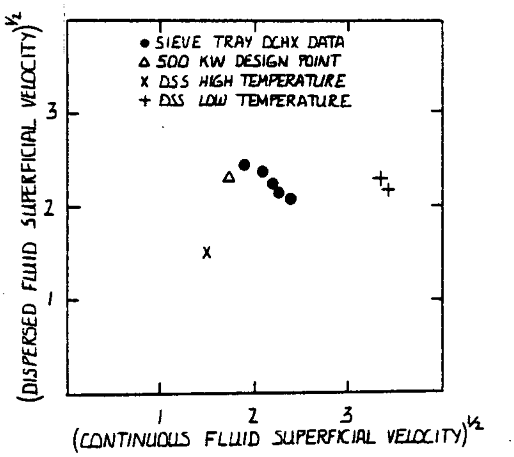

Fig. 4: DCHX Throughput Comparison

Mixed Working Fluids

Following the completion of the baseline tests with isobutane, the second sequence of tests was conducted with working fluids consisting of different mixtures of hydrocarbons. The first fluid tested was a 0.95 isobutane/0.05 hexane (mass fraction) followed by 0.90 iC_4/0.10C_6 and 0.85 iC_4/0.15 C_6. The plant was then drained and filled with propane which was tested briefly to get a reference data point. Isopentane was then added to the plant working fluid system and the mixture adjusted to a 0.95 C_3/0.05 iC_5 composition. After testing this mixture, 0.90 C_3/0.10 iC_5 and 0.85 C_3/0.10 iC_5 fluids were tested.

The mixture tests showed that these hydrocarbon mixtures could be preheated and vaporized in a sieve tray DCHX. The thermal performance of the column, in terms of the minimum approach temperature or pinch point obtained, with mixtures was not at the same level as with the isobutane working fluid. This does not mean that the thermal performance with mixtures was poor as pinch points from 0.3¼ to 2.3¼F were obtained (the higher pinch point corresponded to those mixtures having the highest concentration of the minor component). It merely accentuates the level of thermal performance obtained in the baseline tests with isobutane.

As indicated previously, the evaluation of the tray efficiency in the mixtures tests was not done with the computer program developed for the baseline tests. In these cases the overall efficiencies were determined using column T-Q plots for each set of conditions. An example of one of these T-Q plots and the determination of the overall tray efficiency is shown in Figure 5 for a 90% iC_4, 10% C_6 mixture. This figure also shows that this particular fluid reached its "bubble point" (where the first bubble formed) well within the preheating section of trays. (These mixtures do not boil at a constant temperatures for a fixed column pressure.) In fact, the upper 8 of the 17 preheating trays were being used for boiling. This was typical of all the working fluid mixtures tested, the results of which are summarized in Table 2. These results which also include corresponding results for the pure fluids tests, show the trend of the number of trays required for boiling increasing as the concentration of the minor component was increased. This occurred for both families of mixtures tested. These results also show that the overall preheating tray efficiency appears to be quite independent of the fluid used, but for the trays in which boiling occurred, the overall tray efficiencies were not as high with mixtures as they were for isobutane. When the preheating trays were used for boiling, their efficiencies were lower than when used for preheating, and were lower than the efficiencies of the trays designed for boiling.

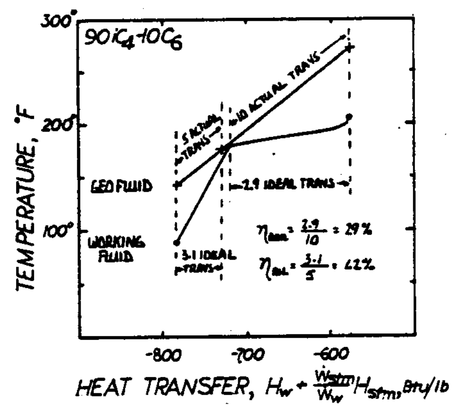

Fig. 5: Mixture T-Q Plot

In the mixture tests, the throughput capacity of the sieve tray column was reduced considerably. As the concentration of the minor component in the mixture increased, the maximum throughput for the

TABLE 2: DCHX PERFORMANCE FOR MIXTURES

Test Run	Working Fluid	Column Pressure (psia)	Outlet WF Temperature °F	Flow Rate (lbm/hr) Work Flow	Flow Rate (lbm/hr) Geofluid	Tray Efficiency % Preheat (Overall)	Tray Efficiency % Boiling (Overall)	Tray Efficiency % Trays 18, 19	Number of Trays with Boiling
1	Isobutane (IC_4)	446	250	3636	17605	33	--	100,98	2
2	Isobutane (IC_4)	365	231	6282	15537	49	--	99,98	2
3	Isobutane (IC_4)	329	221	6984	14354	54	--	100,98	2
4	Isobutane (IC_4)	294	211	7569	13334	55	--	100	1
5	Isobutane (IC_4)	236	190	8325	12136	55	--	99	1
6	Isobutane (IC_4)	146	151	8887	9656	55	--	90,99	2
MX1	0.95 IC_4/0.05 C_6	222	202	5220	8520	60	62	50(18+19)	3
MX4	0.95 IC_4/0.10 C_6	195	208	3190	4900	62	29	42(18+19)	10
MX6	0.95 IC_4/0.10 C_6	247	225	3110	5860	46	21	48(18+19)	10
MX7	0.85 IC_4/0.15 C_6	166	204	2200	3730	47	23	52(18+19)	12
PRP 6	Propane (C_3)	484	182	4600	4750	82	--	98(18+19)	2
MX11	0.95 C3/0.05 IC5	439	186	4380	4690	66	45	54(18+19)	4
MX14	0.90 C3/0.10 IC5	393	183	2370	2800	50	26	*	8

*Could not determine because of local temperature inconsistencies.

column decreased. The hydraulic limit in the mixture tests is thought to be imposed by the section of the column doing the boiling since the throughput of the column appears to vary inversely with the number of preheating trays in which boiling occurs. These trays are not designed for handling large quantities of vapor flow; they are closely spaced and have relatively short downcomers leaving little space for the boiling to occur. The entrainment of liquid brine in the vapor, "weeping" of brine through the plate perforations, and the "venting" of working fluid up the downcomer are suspected of contributing to, if not causing, the breakdown of the column hydraulics when boiling occurs in the preheating trays.

CONCLUSIONS

The sieve tray direct contact heat exchanger tests confirmed that this type of column is an excellent heat exchange device particularly when a single component working fluid was used. The thermal performance of the preheating trays appeared to be independent of the type of working fluid used provided the flow rates were above certain levels. The individual tray efficiencies for these trays were at or near the design goal of 70 percent at the higher flows, and the overall efficiencies were generally around 50 percent for both pure fluids and mixtures. The pinch points obtained with the sieve tray column were small, particularly in the baseline tests with isobutane where pinch points of 0.3°F and less were obtained. In the mixtures tests the pinch points were higher although they were still less than 2.3°F. The efficiencies of the trays used for boiling were not as high with mixtures as they were with isobutane. For all the pure fluids tests, two boiling trays were more than adequate for the boiling heat duty. This was not the case with mixtures, and as the concentration of the minor component increased, the number of trays designed for preheating but required to do boiling also increased.

In the baseline tests the column was operable at the working fluid flow rates predicted to produce the maximum interfacial droplet area (minimum average drop size) from the sieve plate orifices (the recommended operating point for this type of column). The geothermal fluid flow rates encountered in the baseline tests corresponded to the terminal velocity of a drop with a diameter of 1-32 inch (a common droplet size used for specifying the continuous fluid velocity in these types of columns). In the mixtures tests the throughputs dropped considerably. The primary cause for this decrease is felt to be the result of boiling in the upper preheating trays which were not designed for this type of duty. When compared to spray tower direct contact columns, the sieve tray compares favorably though the spray towers appear to have a throughput advantage.

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