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Summary of Progress to December 15, 1977

By
Robert R. Rothfus

Work Performed Under Contract No. EY-76-S-02-2641

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U.S. Department of Energy

Solar Energy

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Working-Fluid Heat Transfer

Heat transfer coefficients have been measured experimentally in falling liquid layers on the exterior of axially fluted, vertical tubes during both condensation and evaporation of R-11 at projected OTEC temperatures. Test lengths about 5 feet long were examined in three 20-inch sections to assess the effect of entrance. Two types of 40-mil flutes were studied, one with crests and rills of 40-mil diameter, the other with 40-mil crests and 60-mil rills. These tubes, of nominal 1-inch size, are the same as those in the Argonne core-test units.

Heat transfer coefficients for condensation on the 40-mil flutes have been found to be considerably higher than those previously obtained on 26-mil flutes. Condensing coefficients over the test section as a whole are almost independent of the style of applicator used to put liquid on the top of the tube. Flutes with 40-mil rills yield slightly higher coefficients than those with 60-mil rills. Part of the difference is probably due to unequal fluted-to-smooth area ratios, leaving little difference due to hydraulic effects. Mean heat transfer coefficients integrated from the experimental data to represent the case of a condenser with zero liquid load at the top are 1.6 to 2.0 times those for 26-mil flutes at low Reynolds numbers and 1.3 to 1.5 times at high Reynolds numbers. It is not yet known whether the difference between 40-mil and 26-mil flutes is due to flute geometry, entrance effects or is an artifact of the experiments.

Heat transfer coefficients in the evaporators with 40-mil flutes show the same qualitative dependence on Reynolds number as do those in evaporators with 26-mil flutes. That is, in the low Reynolds number range the coefficients are low due to incomplete wetting of the flute crests. However they increase rapidly with increased Reynolds number and exhibit a maximum in the region of laminar-turbulent transition. Over the test section as a whole, the coefficients for flutes with 40-mil rills average about 1.5 times those of flutes with 60-mil rills. This implies that it is more difficult to wet the crests of the flutes with wider rills in the upper part of the evaporator. This notion is further supported by the fact that unlike the condenser, the evaporator is sensitive to the design of the liquid applicators. Applicators which cause the crests of the flutes to be overridden with liquid at the very top of the tube produce the highest coefficients over the top few feet of the evaporator.

When data taken over individual 20-inch sections of the test length are examined, it appears that both condensation and evaporation are strongly influenced by the particular way that waves develop along the tube. From visual observations it is known that wave formations develop more slowly on fluted tubes than on smooth ones. Photographs of the experimental tubes show the wave pattern to be complex with waves of differing amplitudes and frequencies contributing to the wetting or drying of the fluted surface, and with evidence of both laminar and turbulent flow in various parts of the wave formation. Even though over the test length as a whole the heat transfer coefficients are well behaved, large unpredictable variations over the separate 20-inch sections suggest that perturbations from a source as yet unknown influence the behavior of the waves.

The way in which waves develop along the length of the tube has a particularly significant effect on the performance of the evaporator. If the applicator supplies liquid to only the rills of the flutes, wetting of the crests can take place only when the waves are sufficiently developed at some point down the tube. The data indicate that very high coefficients, comparable to those obtained in experiments with 26-mil flutes, are obtained only near the bottom of the 5 foot test length when 40-mil flutes are used. Over the upper part of the test length, however, much lower coefficients are obtained with applicators formed from truncated flutes than with those designed to override the flute crests with liquid. Moreover, the crests of 26-mil flutes appear to be more easily overridden at a given Reynolds number than the crests of 40-mil flutes. Thus, while over the short test length used in the experiments with 40-mil flutes, heat transfer coefficients only 0.3 to 0.6 those previously obtained for 26-mil flutes were observed, it is anticipated that in longer evaporators the performance will come up to the performance of 26-mil flutes, regardless of the exact design of the applicator.

In view of the experimental results, extrapolation to longer tube lengths in either evaporators or condensers is more uncertain than desirable for prototype design. It is necessary, therefore, to have firm experimental data on longer lengths. Consequently the experimental apparatus is being revised to accommodate both an evaporator and condenser of about 15-foot test length. The revised equipment will be capable of handling both R-11 and ammonia although initial experiments will be limited to R-11. In addition, to permit assessment of the effect of tilt on the heat transfer coefficients, the entire apparatus (both condenser and evaporator) is being made movable from the vertical through 2 or 3 degrees. Fluted aluminum tubes of the same design used before but of the greater length are in the process of being procured from the Aluminum Company of America.

Water-Side Heat Transfer

Heat transfer and friction have been measured experimentally in six extruded aluminum tubes of nominal 1-inch size, 8 feet long. Internal, axial flutes are specified in terms of three parameters:

AR - fluted-to-smooth area ratio

Δ - flute height in mils

Δ/D - ratio of flute height to rill diameter.

The flutes are denoted by the code (AR-Δ-Δ/D). Heat was supplied by electrical tapes. The test fluid was tap water flowing at a measured rate inside the fluted tubes.

Data were correlated in terms of the Colburn-type j-factors for heat transfer (j_H) and friction (j_F). These were expressed as functions of the bulk Reynolds number of the water in the usual way. The diameter used in the dimensionless correlation is the diameter of the smooth tube which has the same cross-sectional area as the fluted tube. At a given volumetric flow rate, the average linear velocities in the actual fluted tube and the equivalent smooth tube are the same.

Over the range of Reynolds numbers of interest to OTEC applications, the j-factors can be expressed as simple power functions of the Reynolds number (N_{Re}) as follows:

$$j_H = K_H N_{Re}^{-n_H}$$

$$j_F = K_F N_{Re}^{-n_F}$$

Flute Code (AR-Δ-Δ/D)	K_H	n_H	K_F	n_F
1.57-45-1.0	0.054	0.21	0.176	0.35
1.57-60-1.0	0.044	0.20	0.191	0.37
1.57-45-1.5	0.083	0.25	0.122	0.32
1.57-60-1.5	0.072	0.23	0.165	0.34
2.00-45-1.5	0.077	0.22	0.092	0.28
2.00-60-1.5	0.073	0.21	0.176	0.34

As a whole, these results show that heat transfer is enhanced by axial flutes more than friction is increased. The j_H for fluted tubes is greater than that for smooth tubes by a factor equal to or a bit more than the fluted-to-smooth area ratio. The j_F, however, is increased by somewhat less than the area ratio. Axial flutes are very efficient with respect to the ratio of enhancements of heat transfer coefficient and friction factor. They appear to constitute a bench-mark of performance, regardless of whether or not their use on the water side of OTEC exchangers can be justified economically.

Erosion of Flutes

The apparatus for testing erosion of flutes at water velocities of 5 and 10 feet/sec has been built, with ordinary tap water as the test fluid. Considerable problems were encountered in stabilizing the temperature of the higher velocity loop. These were eventually overcome, but at the cost of delay in starting the experiments. After several days of continuous operation, the apparatus was shut down due to failure of a section of plastic tubing. Although ready to run, the equipment has not been restarted in view of intentions to discontinue this part of the program.

Pressure Drop in Shell-Side Vapor

Distribution of Liquid Working Fluid

Since these two subjects are not independent, both are summarized in this section. Three main kinds of experiments have been performed, using hot water to simulate liquid or vapor ammonia, depending on the size scale of the equipment:

a. Pressure drop in 1/4-scale tube banks, with and without tributaries (fluid lanes) and with and without generation of fluid at each tube site (by means of porous tubes). To relate tube bundle layout to vapor-phase pressure drop.

b. Pressure drop in full scale tube bank (1-inch o.d. tubes) with and without tributaries and with and without fluid depletion at each tube site. To relate pressure drop in the liquid-supply plenum of the OTEC evaporator to the tube bundle layout and the height of the plenum.

c. Pressure drop through apertures formed by truncating the external axial flutes and surrounding them with a tight-fitting collar to simulate the bottom of a supply plenum. To establish the pressure to be maintained in the ammonia-supply plenum of the OTEC evaporator so as to furnish the correct amount of liquid to each tube.

Vapor-space pressure drop (item a) has been obtained by means of 0.218-inch o.d. porous tubes (filter cartridges). The basic bank was an in-line array on 0.375-inch centers, 4 tubes wide and about 65 tubes deep. To form a central tributary, spacers were inserted and the bank widened appropriately. Two tributaries have been studied to date, one having 0.500-inch transverse pitch and the other 0.750-inch transverse pitch. Runs have been made with and without fluid generation through the walls of the porous tubes. Pressure drops have been compared with predictions of the Gunter-Shaw equation.

As shown in the following tabulation the measured pressure drops are lower than predicted by the Gunter-Shaw equation

Pitch (Center-to-Center Distance)				$\left[\frac{\Delta p \text{ (experimentl)}}{\Delta p \text{ (Gunter-Shaw)}}\right]$	
Uniform Bank		Tributary		without	with
Transverse	Longitudinal	Transverse	Longitudinal	generation	generation
0.375"	0.375"	none		0.7	0.7
0.375"	0.375"	0.500"	0.375"	0.4	0.3
0.375"	0.375"	0.750"	0.375"	0.9	-

While over-simplified for brevity, the tabulation shows that the Gunter-Shaw equation integrates quite well to account for generation and that the influence of fluid velocity is about as predicted. On the other hand, the geometrical factors in the Gunter-Shaw equation fall far short of adequately dealing with various pitch-to-diameter ratios in both uniform banks and those split by tributaries.

Pressure drop of liquid in the supply plenum of the evaporator (item b) was experimentally studied in a bank of 1-inch o.d. smooth tubes, 1 foot long. The bank was 5 tubes wide and 21 tubes deep, but experimental sets could be pieced together to simulate a bank 42 tubes deep. The experimental liquid was hot water which could be put through the bank without depletion or caused to exit through openings in the bottom of the plenum at each tube site. The basic bank was an in-line array on 1.375-inch centers. A central tributary could be introduced by removing the middle row of tubes. The tributary thus formed had a transverse pitch of 2.75 inches.

The experimental results again show that the Gunter-Shaw equation integrates to account for depletion at each tube site and predicts the effect of fluid velocity reasonably well. But in this case, the experimental pressure drops are about 45 per cent higher than predicted, for both straight-through flow and depletion. More experiments are needed to uncover the reason for the discrepancy. Until geometrical effects can be explained, designers should allow a large contingency in pressure drop, especially when dealing with close-packed tubes having a small pitch-to-diameter ratio.

Pressure drops in apertures formed by truncated flutes (item c) were obtained using four types of openings, all 0.75 inch in length. The openings were made by turning down flutes with a rill diameter of 40 mils to a truncated height of 15 mils and 20 mils, and flutes with a rill diameter of 60 mils to the same two truncated heights. The test fluid was how water.

It has been possible to correlate the pressure drops by means of the short-tube equation

$$\frac{(\Delta p/\rho)}{\alpha(V^2/2g_c)} = \frac{64\ L}{D_e N_{Re}} + 2.0$$

where $\Delta p/\rho$ = head loss through aperture

$V^2/2g_c$ = velocity head in aperture

N_{Re} = Reynolds number in aperture

L = length of aperture

D_e = equivalent diameter of aperture (defined in the usual way as 4 × cross-section/wetted perimeter)

The effects of geometry are contained in the empirical multiplier α. The values of α for the four flutes investigated are as follows:

Rill Dia. (mils)	Aperture Depth (mils)	α
40	15	1.88
40	20	1.51
60	15	1.28
60	20	1.18

These results indicate that if the plate which forms the bottom of the supply plenum in the full-scale OTEC evaporator is at least 1 inch thick, a plenum of reasonable height (say, 2 ft) can be kept full of liquid, thus eliminating the complications of a vapor-liquid interface within the plenum. The results also imply that any applicator in the form of a non-circular, short conduit can be correlated in terms of a circular short tube modified by a simple multiplying factor.

Additional experiments have been performed to learn how tightly externally fluted tubes hold a liquid layer. A 10-foot length of tube with 40-mil flutes was held at an angle of 28° with the vertical and water was poured at room temperature from the top. The tube was then oscillated ± 15° to 17° from the vertical with a period of several seconds.

In both cases, every rill remained wet and no water separated from the tube. Wave motion was observed at all points on the periphery. In another experiment, hot water was passed through apertures formed from truncated flutes into full flutes without splashing. It was noted, however, that wave formation attains steady state more slowly on a fluted tube than on a smooth one.

Argonne Core Tests

Two heat exchangers of nominal 3.2×10^6 (maximum 4×10^6) Btu/hr capacity have been designed, fabricated and delivered to the Argonne site for core-testing. The units were thermally and hydraulically designed by Carnegie-Mellon, designed for bid by the Aluminum Company of America and finally designed and built by the Foster Wheeler Energy Company.

The exchangers are identical except for the details of the ammonia-side flutes. They both contain 240 tubes with an effective heat-transfer length of slightly more than 14 feet. Both are of vertical tube design and both can be tested as either an evaporator or a condenser. Both contain doubly-fluted tubes of nominal 1-inch size with 60-mil crest diameter. One unit (nominally the evaporator) has 40-mil rill diameter and the other (nominally the condenser) has 60-mil rill diameter.

Testing at Argonne will be monitored by Carnegie-Mellon personnel. Resultant data will be analyzed and compared with laboratory data obtained under the present contract. Arrangements for these tasks are being made currently.

Water Distribution in Headers

An analysis has been made of the effects of maldistribution of water in the headers of the heat exchangers on the thermal capacity of the units and on parasitic power losses, as well. The results, summarized in a previously submitted document from Mr. Bryant Fitch, indicate almost no effect on heat transfer performance, but an appreciable increase of power losses.

Discussions with Argonne National Laboratory have uncovered the fact that they have hydraulic loops of several thousand gpm. capacity, equipment and techniques that appear suitable for experimentation. If experiments on such a scale are projected for the future, Argonne or some comparable laboratory should plan and execute research within their particular capabilities.

Report on Vertical-Tube Evaporators

The available literature has been examined exhaustively, classified, coded and arranged in a bibliography which has been submitted as part of a previous report. In essence, this literature contained no surprises to change the projected course of research and development. At present, an evaluative narrative is being written for the purpose of presentation at the next National OTEC Conference.

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Transient Modeling and Control

Dynamic models have been developed to characterize the transient behavior of falling-film, vertical evaporators. For initial purposes a single-tube falling-film evaporator has been modeled. Transient models are being assembled into a digital computer model of an OTEC power cycle. Initial control system studies are currently in progress. By evaluating the response of the uncontrolled system, control requirements for protection of the system can be determined.