Heat Transfer to Water in an Annulus

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A limited number of measurements were made of the heat transfer coefficient from an electrically heated rod to water flowing in an annulus. Tests were performed at Reynolds numbers ranging from 5,000 to 22,000 (based on equivalent diameter), water temperatures of 70° and 125°F., and relatively high heat fluxes of 52,000 to 208,000 B.t.u./(hr.) (sq. ft.). The annulus dimensions were 0.625 in. I.D. and 0.840 in. O.D. The coefficients varied as the 0.8 power of the velocity; they were 20% higher than predicted by use of Colburn's equation for flow inside pipes with the equivalent diameter. Over the range of conditions studied, it was found that the thermal boundary layer was fully developed in 1⅛ in. ($L_h/D_e=5$).

In the course of a study of heat transfer to water flowing parallel to a bundle of rods (which will be reported separately), a few measurements were made under annular-flow conditions by means of the heated test rod developed for the general study. These measurements were made at high heat fluxes and moderate Reynolds numbers. Since the literature contains only a limited amount of data for annular-flow heat transfer, it seemed worth while to present the results of these tests, in spite of their limited scope (including the use of a single geometry and the absence of pressure - drop measurements). Tests were made at Reynolds numbers (D_eG/μ) ranging from 5,000 to 22,000; at heat fluxes from 52,000 to 208,000 B.t.u./(hr.) (sq.ft); at water temperatures 70° and 125°F.; and at a single ratio of $D_2/D_1 = 1.34$. Three different heater rods were tested.

Equipment and Procedure

Figure 1 shows a diagram of the annulus test section. A vertical glass tube, 16 in. long and with a measured I.D. of 0.840 ± 0.001 in. enclosed the middle section of the 0.625-in. O.D. heater rod (for rods 15 and 19; for rod 20 the glass tube was 17 in. long and 0.865 ± .001 in. I.D.). The rod was centered in the tube by means of two perforated aluminum collars, which had about 50% free-flow area. For rod 15 the bottom collar was 3½ in. below the bottom of the heated section; for rod 19 this distance was 2 in.; and for rod 20 it was 3¾ in. Standard ¾-in. pipe tees formed inlet and outlet headers for the water, which flowed upward; the tees were connected to the glass tubes by heavy-wall rubber tubing and were sealed at the outer end by rubber stoppers through which the heater rod passed.

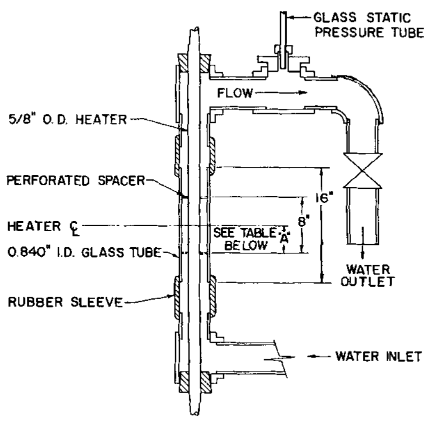
Figure 2 gives a flow diagram of the system. For convenience, an available overhead 1,000-gal. storage tank of a laboratory-waste-water-treatment system, which contained deionized water, was used as a feed tank. To obtain the required flow rate, an air pressure between 38 and 39 lb./sq.in. gauge was maintained automatically in the upper part of this tank; the flow rate was adjusted by means of a throttling valve in the tank discharge line, which was connected to the test section by means of rubber hose. The water leaving the test section discharged to the atmosphere through a throttling valve, which was adjusted to give a convenient pressure reading in an open-ended vertical glass tube inserted in the discharge line, which served as an indication of the uniformity of flow rate. The flow rate was measured by the time required to fill a calibrated 5-gal. bottle, and the temperature of the discharge water was measured to 0.2°C. with a glass thermometer. The flow-rate measurement was reproducible to better than 2%.

An ice bath was used for the reference junction for all thermocouple measurements. The water temperature was raised appreciably by the heat from the test rod; the temperature rise was about 5°F. at a velocity of 3 ft./sec. and a power input of 1,650 watts. A proportionate part of this temperature rise was subtracted from the measured outlet temperature of the water to obtain the appropriate water temperature for calculating ΔT. Since both the temperature rise and ΔT are proportional to the power input, the percentage correction in ΔT is independent of power; it amounted to about 2% for a thermocouple at the midpoint of a 4-in. heated section. The thermocouple voltages were read with a Leeds and Northrup type K-2 potentiometer and D.C. (No. 2430) galvanometer. The surface thermocouples were calibrated in flowing water against a chromel-alumel thermocouple that had been calibrated in an oil bath against Anshutz precision thermometers.

The test element was heated with D.C. current from a Westinghouse type R.A. arc welder. This unit was rated to supply 200 amp. at 40 volts. The maximum power input obtainable with the heaters used (close to 1-ohm resistance) was approximately 3.2 kw., corresponding to a current of 56.5 amp. and a voltage drop of 56.5 volts across the heater. The power input was measured with a Weston model 310 Wattmeter, which had scales of 1,000, 2,000, and 4,000 watts graduated in divisions of 10, 20, and 40 watts. Independent calibration of this meter by the vendor and by an outside laboratory showed the maximum error on any scale to be less than ¼ of 1% of full scale value. The meter readings required no correction, since the voltage leads were connected directly to the ends of the heating coil.

The cooling water was at room temperature, except for one set of measurements made with rod 15 and water at 125°F. In that test the inlet stream was preheated continuously with steam by means of a Heliflow heat exchanger suitably connected.

After a smooth flow rate had been established and the system was visually free of air bubbles, power was applied to the heater (at 825, 1,650, or 3,200 watts, for a 4-in.



DIMENSION "A" FOR HEATERS TESTED	
HEATER ROD	"A"
NO. 15	5 1/2"
NO. 19	4"

Fig. 1. Diagram of annulus test section.

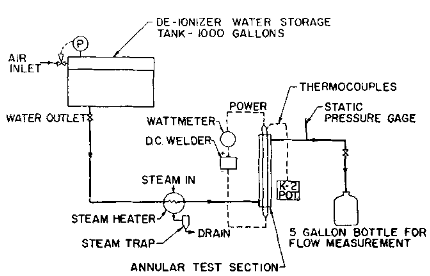


Fig. 2. Flow diagram for annular-flow heat transfer tests.

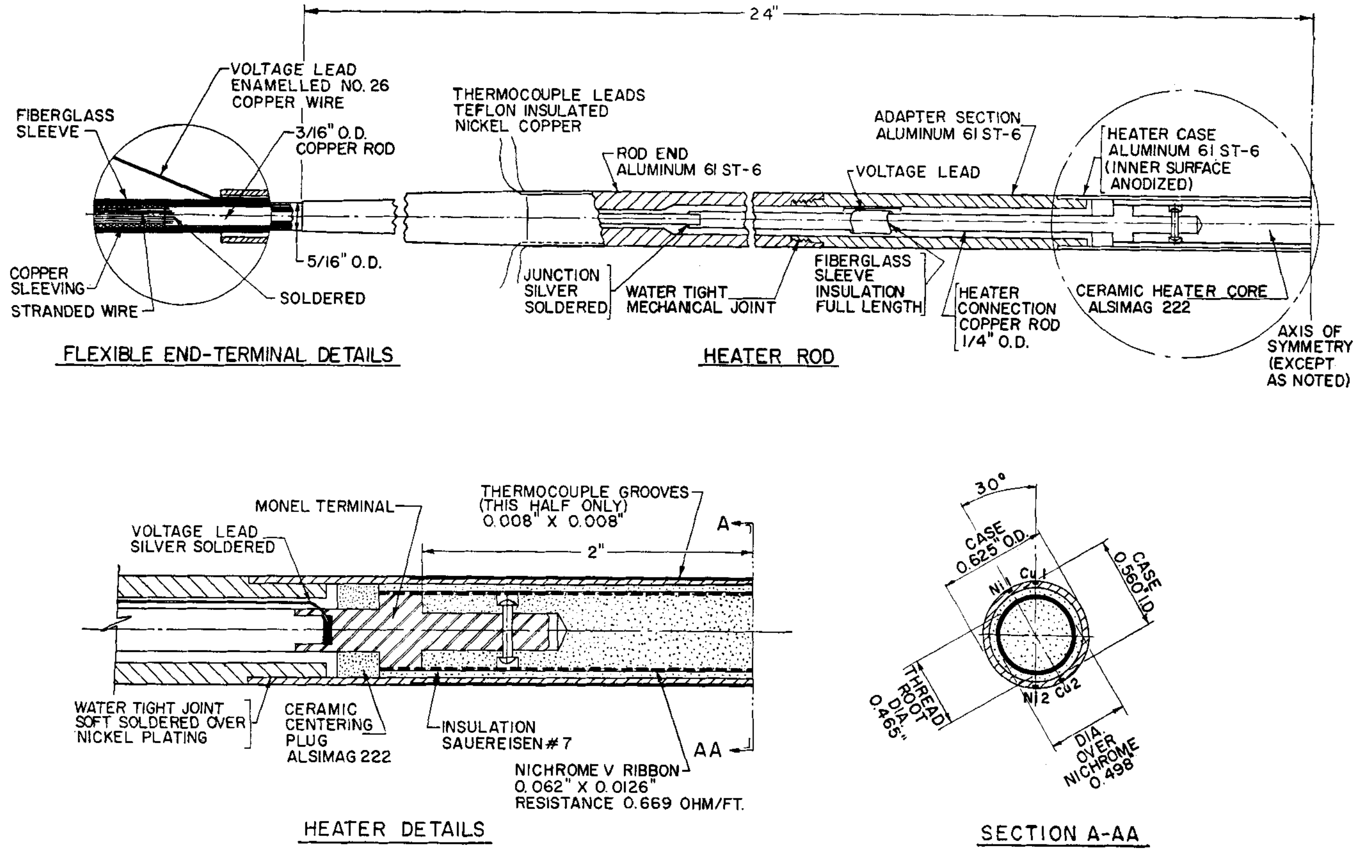


Fig. 3. Construction of heater rod 15.

heated length). Thermocouple readings were then taken until a steady state was indicated by the absence of a trend. Generally three sets of consecutive readings were sufficient, and an average of the last two sets was taken as the result. Table 1 gives a typical data sheet.

Description of Heater Rod

The construction of the heated test rod is shown in Figure 3. Heat was generated in a nichrome resistance element wound on a threaded ceramic core and encased in an aluminum jacket from which it was insulated electrically by a 31-mil layer of Sauereisen (type 7) refractory ce-

Table 1.—Typical Data Sheet (Test A3-Rod 15)

Time	Cold junction, °C.	Thermocouple reading, mv. CuNi 1	CuNi 2	Outlet water temp., °C.	Flow rate	Air pressure, lb./sq. in. gauge	Wattmeter Read.	Scale	Factor	Power, watts
9:05	—0.2	0.374	0.374	19.75	125 sec. ≈ 5.15 gal.	39	OFF			
9:11		0.374	0.375	19.75						
9:25							805	75 Par.	1.0	805
9:27		1.020	0.943	21.5			810			810
9:28		1.025	0.945	21.5			810	75 Par.	1.0	810
9:30		1.029	0.948	21.5	127 sec. ≈ 5.15 gal.	39	810	75 Par.	1.0	810
9:33		1.027	0.947	22.0			810	75 Par.	1.0	810
9:35							1,650			1,650
9:37		1.624	1.444	23.2			1,640	75 Par.	1.0	1,640
9:38	—0.2	1.645	1.471	23.2		38	1,650			1,650
9:41		1.647	1.470	23.5			1,650	75 Par.	1.0	1,650
9:42		1.652	1.488 1.496	23.2	128 sec. ≈ 5.15 gal.		1,650			1,650
9:48		1.659	1.514				1.650	75 Par.	1.0	1,650
9:50		1.661	1.518				1,650			1,650
9:55		1.124	0.990	22.2	67 sec. ≈ 5.15 gal.		1,650	75 Par.	1.0	1,650
9:59	—0.2	1.126	0.986				1,650			1,650
10:01		1.126	0.985	22.0			1,650	75 Par.	1.0	1,650
10:03							840	75 Par.	1.0	840
10:05		0.768	0.699	22.0			840	75 Par.	1.0	840
10:08		0.770	0.700	22.0			840	75 Par.	1.0	840
10:09		0.770	0.700	22.0	66 sec. ≈ 5.15 gal.		840			840

ment. The core was made of Alsimag 222, a ceramic which can be machined quite easily and which does not change its dimensions upon subsequent heating to high temperatures. The core was doubly threaded in order to use two nichrome windings in parallel, which was a convenient way of reducing the resistance without changing the type of nichrome ribbon used (nichrome V, cross section 0.062×0.0126 in., resistance 0.669 ohm/ft.). The heated section was 4 in. long, and the heater resistance was 0.919 ohm. The ceramic core was extended for ¼ in. at each end with a cylindrical Monel terminal piece of the same O.D. and threaded continuously with the ceramic core. The ends of the nichrome windings were anchored to the Monel pieces by peening the thread walls down over the nichrome ribbon. The Sauereisen cement was brushed on as a paste, air-dried at room temperature overnight, ground on a lathe to the I.D. of the aluminum jacket, then baked overnight at 120°C.

The aluminum jacket was a 6-in. length of commercially available 61ST-6 tubing of 0.625 in. O.D. and 32-mil wall thickness. It was anodized on the inside to provide additional electrical insulation, and was fastened by soft-soldering to two hollow aluminum end pieces of equal length. Aluminum surfaces to be soldered were first nickel plated.

Separate power leads and voltage leads were fastened to the Monel terminal pieces and were carried out through the hollow aluminum end pieces.

Two copper-nickel thermocouples were attached to the surface of heater rod 15, with both junctions at the midlength of the heated section and 180° apart on the circumference. For each thermocouple the two wires were inserted in separate grooves and were insulated from the jacket metal except at the tip, where a junction was made by swaging ¼ in. of exposed wire into the groove with cold solder, then smoothing the surface. The thermocouple circuit was completed by the jacket. The grooves were 8 mils wide by 8 mils deep and 30° apart and extended back for 2 in. from the junction. Beyond this point the wires were cemented to the surface of the rod. The copper wire was 7 mils in diameter and the nickel wire was 3.5 mils in diameter; both were insulated with an integral Teflon coating. Void space in the grooves not occupied by the wires was filled in with Pliobond cement.

Heater rod 19 was similar to rod 15, except that it was provided with a single thermocouple mounted as nearly flush with the surface as was feasible. This was done to determine whether the 8-mil depth of the rod-15 thermocouples caused any significant difference in reading. The rod-19 thermocouple was installed by squeezing the wires into slits only 1 to 2 mils deep made with a razor blade. Then a ⅛-in. band of nickel less than ½-mil thick was plated around the circumference over the wire tips to anchor them and ensure electrical and thermal contact. (This method of installation did not prove rugged enough for general use.) The thermocouple junction was located ⅞ in. below the midlength of the heated section.

Heater rod 20 had an 8-in. heated length and was copper jacketed. It was provided with six thermocouples spaced axially along the rod. Each thermocouple required only a single groove, for a nickel wire, since the copper jacket completed the thermocouple circuit. The nickel wires were 45° apart on the circumference.

The surface of the heater rods is believed to have been equivalent to that of a smooth tube. In a long series of experiments (not annular flow), coefficients measured with rod 15 showed no trend, indicating that the surface remained smooth. This was confirmed by physical appearance.

RESULTS AND DISCUSSION

The results of the heat transfer measurements are listed in Table 2. For heater rod 15 the readings of the two thermocouples were averaged to calculate the temperature difference between the heated surface and the water. The two thermocouples consistently differed by about 10%; from other work with this heater rod it was concluded that this difference was probably due to a peripheral variation in heat flux, caused by a variation in thickness or thermal conductivity of the layer of Sauereisen insulation. Since there was an estimated drop of as much as 1500°F. across this layer, relatively small differences in thermal resistance could cause an uneven flux pattern. In several measurements the glass outer sleeve was rotated 180° as a means of detecting any annulus eccentricity not disclosed by the measurement of the dimensions. No significant changes were observed.

The heat ransfer results are believed to be accurate to ±8%.

The effect of heated length on heat transfer coefficient was investigated in tests made with rod 20. This rod had an 8-in. heated length, with six thermocouples spaced axially along the rod from 1⅛ to 6 in. past the upstream end. The upstream unheated length was 3¾ in., and the jacket diameter was 0.865 in. I.D. (compared with 0.840 in. in the other tests). Tests were made at two velocities with room-temperature water, the heat flux being varied at the lower velocity.

Figure 4 gives a plot of h vs. heated length. The measured heat

TABLE 2.—MEASURED HEAT TRANSFER COEFFICIENTS FOR ANNULAR FLOW

Test	Heater rod	Outlet water temp., °F.	Water velocity, ft./sec.	Heat flux, B.t.u./(hr.)(sq. ft.)	Corrected† ΔT, °F.	h, B.t.u. (hr.)(sq. ft.)(°F.)
A3	15	70.8	3.15	50,600	50.1	1,010
		73.8	3.13	103,000	97.5	1,060
		71.6	6.06	52,400	27.8	1,880
		71.6	5.98	103,000	55.2	1,870
		73.4*	6.06	105,500	55.4	1,900
A6	15	75.8*	6.68	104,600	44.9	2,330
		126.2	6.91	104,300	36.0	2,900
		126.2	6.91	103,600	35.0	2,960
		130.6	6.91	199,800	69.0	2,900
A4	19	74.3	3.21	51,200	44.9	1,140
		76.3	3.21	104,300	86.5	1,210
		69.2	6.37	50,900	28.8	1,770
		73.8	6.26	104,300	51.4	2,030
		73.8*	6.37	103,000	54.9	1,880
		73.4*	12.52	102,700	31.1	3,300
A17	20	80.6	2.82	38,200	39.7	960
		82.9	2.82	62,600	62.9	995
		86.0	2.82	100,800	94.5	1,070
A15	20	75.3	5.98	98,900	55.4	1,790

*For these tests the glass outer tube was rotated 180° compared with the unstarred tests.

†For rod 15 the reported ΔT is based on an average of two thermocouples; for rod 20, an average is taken for six thermocouples; rod 19 had a single thermocouple.

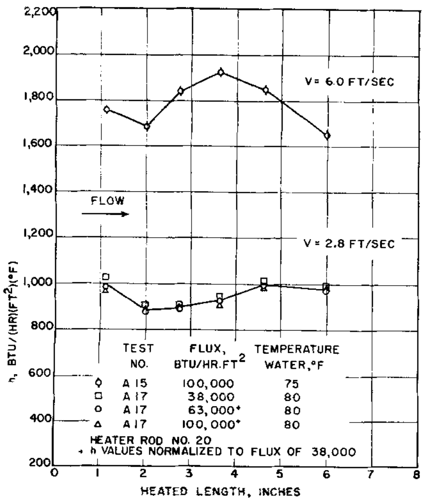


Fig. 4. Effect of heated length.

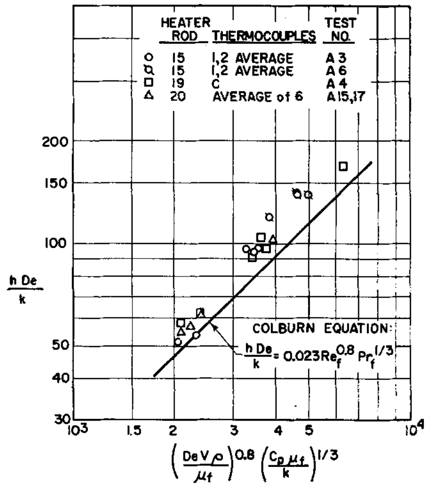


Fig. 5. Annular-flow heat transfer data compared with Colburn equation.

transfer coefficients increased with increasing flux, as would be expected from the effect of increased film temperature and reduced viscosity. To place the data for the lower velocity on a comparable basis, the values in Figure 4 have been "normalized" to a constant film temperature by use of the relation that h is inversely proportional to $\mu_f^{0.467}$, derived from the Colburn equation [Equation (1)].

The values of h show no consistent trend with heated length. The average deviation of a single value from the mean of the six values was less than 5% at each velocity. It appears that for a heated length greater than 1⅛ in. ($L_h/D_e > 4.7$, where L_h is heated length) the thermal boundary layer was fully developed within the accuracy of the experiments. Likewise, for $L/D_e > 20$ the hydraulic boundary layer was fully developed.

(A measurement was also made at a heated length of ⅝ in. in one test, which indicated a higher value of h; however, it was calculated that axial heat conduction would be sufficient to lower the surface temperature significantly at this point. For this reason, the value is not reported.)

Rod 15 had a 2-in. heated length upstream of the thermocouples, and for rod 19 this distance was 1⅛ in. Consequently, all the results represent a fully developed thermal boundary layer.

These results are not in agreement with those reported by McAdams *et al.*(*1*) for annular heat transfer to water. They report the results of a test, over an 11.5-in. heated length, in which the coefficient dropped almost linearly by 35%, in going from 2 to 10 in. (corresponding to a range of 4 to 19 for L_h/D_e). The heated rod was 0.25 in. in diam., the jacket was 0.77 in. I.D., the velocity was 1 ft./sec., water temperature was 270°F. ($Re = 17{,}600$, based on D_e), and there was an upstream unheated section 3 in. long.

The data in Table 2 are plotted in Figure 5 for comparison with the modified Colburn equation, which is recommended by Perry for annular heat transfer(*2*):

$$\frac{hD_e}{k} = 0.023\left(\frac{D_eG}{\mu_f}\right)^{0.8}\left(\frac{C_p\mu_f}{k}\right)^{1/3} \quad (1)$$

On the average, the experimental values fall about 20% above the straight line representing Equation (1). The values obtained with heater rod 19 (squares) fall quite close to a straight line parallel to the Colburn equation. The other values show somewhat more scatter, particularly at the low velocities, but are in general agreement with the rod-19 results. This was taken to indicate that the method of mounting the thermocouples used on heater rods 15 and 20 did not introduce any significant error into the measured surface temperatures.

Perry(*2*) gives the following dimensional equation for heat transfer to water in turbulent flow inside tubes:

$$h = \frac{160\,(1 + 0.012\,t_f)\,(V_s)^{0.8}}{(D')^{0.2}} \quad (2)$$

When one applies this equation to the conditions of Table 2, using D_e, values of h are calculated which, on the average, are 6% higher than the experimental values. Equation (2), which is confined to water, is perhaps a better basis of comparison than Equation (1), which represents the average behavior of a large variety of fluids over a wide range of conditions.

It is concluded that the present results, within their limited scope, indicate that annular-flow heat transfer can be predicted by the accepted equations for flow inside tubes, by means of the equivalent diameter.

ACKNOWLEDGMENT

The results reported in this paper were obtained during work performance by the Walter Kidde Nuclear Laboratories, Inc., under Contract AT(30-1)-1374 for the United States Atomic Energy Commission. The permission of the A.E.C. to publish this paper is hereby gratefully acknowledged.

The authors are indebted to Mr. George G. Bartolomei for construction of the heated test rods.

NOTATION

C_p = specific heat of water at bulk temperature, B.t.u./(lb.) (°F.)
D_1 = outside diameter of rod, ft.
D_2 = inside diameter of annulus jacket, ft.
D_e = equivalent diameter, ft. = 4x flow area/wetted perimeter = $D_2 - D_1$
D' = diameter, in.
G = mass velocity of water = $V\rho$, lb./(hr.) (ft.²)
h = heat transfer coefficient, B.t.u. /(hr.) (ft.²) (°F.)
k = thermal conductivity of water at bulk temperature, B.t.u./(hr.) (ft.) (°F.)
L = upstream length, ft.
L_h = upstream heated length, ft.
T = temperature, °F.
T_f = average film temperature, °F.
ΔT = temperature difference from rod surface to bulk water, °F.
V = water velocity, fps.
V_s = water velocity, fps., based on $\rho = 62.3$ lb./ft.³
μ = viscosity of water at bulk temperature, lb./(ft.) (hr.)
μ_f = viscosity of water at average film temperature, lb./(ft.) (hr.)
ρ = density of water at bulk temperature, lb./ft.³
Re = Reynolds number, D_eG/μ
$Re_f = D_eG/\mu_f$

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