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FILM COEFFICIENTS OF HEAT TRANSFER
FOR HELIUM AT 2,000° TO 2,500° F
IN TURBULENT FLOW

By N. H. Coates and A. F. Galli

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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H.C. \$ 1.00; MN 50

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UNITED STATES DEPARTMENT OF THE INTERIOR
Stewart L. Udall, Secretary

BUREAU OF MINES
Walter R. Hibbard, Jr., Director

The work upon which this report is based was done in part under an agreement between the Bureau of Mines, U.S. Department of the Interior, and the U.S. Atomic Energy Commission.

This publication has been cataloged as follows:

Coates, Neil H

Film coefficients of heat transfer for helium at 2,000° to 2,500° F in turbulent flow, by N. H. Coates and A. F. Galli. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1966]

22 p. illus., tables. (U. S. Bureau of Mines. Report of investigations 6856)

Based on work done in cooperation with the U. S. Atomic Energy Commission.

1. Helium. I. Galli, Alfred F., jt. auth. II. Title. (Series)

TN23.U7 no. 6856 622.06173

U. S. Dept. of the Int. Library

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FILM COEFFICIENTS OF HEAT TRANSFER FOR HELIUM AT 2,000° TO 2,500° F IN TURBULENT FLOW

by

N. H. Coates¹ and A. F. Galli²

ABSTRACT

The Bureau of Mines determined average film coefficients of heat transfer for helium flowing through smooth, water-cooled tubes at Reynolds numbers of 5,000 to 25,000, helium inlet temperatures of 1,600° to 2,600° F, average temperature difference across the helium film of 800° to 1,300° F, and heat flux to 215,000 Btu/(hr)(sq ft). Since helium was the only gas used, the ranges of values for physical properties of the fluid are limited--thermal conductivity from 0.15 to 0.20 Btu/(hr)(sq ft)(° F/ft), viscosity from 0.082 to 0.104 lb/(ft)(hr), and Prandtl number from 0.63 to 0.68. Four equations, three of them dimensionless, correlate these coefficients with other properties of the helium--bulk temperature, film temperature, dimensionless parameters based on temperature, and the ratio of wall temperature to bulk temperature.

$$\frac{h_i D_i}{k_b} = 0.020 \left(\frac{D_i G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4}$$

$$\frac{h_i D_i}{k_f} = 0.0197 \left(\frac{D_i G}{\mu} \right)_f^{0.8} \left(\frac{C_p \mu}{k} \right)_f^{0.4}$$

$$\frac{h_i D_i}{k_b} = 0.0215 \left(\frac{D_i G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4} \left(\frac{\mu_w}{\mu_b} \right)^{0.14}$$

$$h_i = 0.0198 \frac{G^{0.8}}{D_i^{0.2}}$$

Values of the average inside film coefficient of heat transfer determined from these equations agree within 10 percent.

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INTRODUCTION

In cooperation with the Atomic Energy Commission, the Bureau of Mines undertook development of a nuclear process-heat system that utilizes flowing helium at 2,500° F and 250 psig as the heat carrier. Nuclear process heat could possibly reduce the cost of producing synthesis gas from coal and also serve effectively in chemical processing.

Essential to this work was the development of an exchanger for transferring heat from the reactor to the process stream. No information was available in the literature, however, on high-temperature helium film coefficients needed to design such an exchanger.

This report gives results of tests conducted to determine these coefficients. It should be noted that the equations derived in this report for helium are not necessarily applicable to all gases; also, the correlations apply only for fully developed thermal and hydraulic flow conditions and are not suitable for entrance accelerating regions.

DATA CORRELATION METHOD

The heat transfer tests were designed to give data amenable to the "Wilson," or graphical, method (10, 15)³ of interpreting overall heat transfer coefficients. The overall heat transfer coefficient based on the inside area of the pipe or tube is given by the equation

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{D_i x}{D_{av} k} + \frac{D_i}{D_o h_o}}, \quad (1)$$

where h_i = inside film coefficient, helium,
 h_o = outside film coefficient, water or air,
 D_i , D_{av} , D_o = inside, average, and outside pipe diameters,
 x = pipe wall thickness,
 and k = thermal conductivity of pipe.

Since the velocity of the coolant in these tests was kept uniform and its physical properties were little affected by temperature and pressure changes, h_o is constant. Neglecting thermal expansion of the pipe, D_i , D_o , D_{av} , and x are constants for a given exchanger, and k for type 304 stainless steel over the temperature range of the experiments can also be considered constant. Hence, the resistance terms for the metal wall and the outside film can be combined into one constant, R_1 :

---

³Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

$$R_1 = \frac{D_1 x}{D_{av} k} + \frac{D_1}{D_o h_o}. \quad (2)$$

Therefore

$$U_1 = \frac{1}{\frac{1}{h_1} + R_1}, \quad (3)$$

or

$$\frac{1}{U_1} = \frac{1}{h_1} + R_1. \quad (4)$$

For a gas flowing inside smooth, circular pipe in turbulent flow, the convective heat transfer coefficient, h_1 , is usually given by the relationship

$$h_1 = \frac{n C_p G^{0.8}}{D_1^{0.2}} \quad (5)$$

where n = a constant that depends on the physical properties of the gas,
 G = mass velocity of the gas,
 D_1 = inside diameter of the pipe,
 and C_p = heat capacity.

For helium and the test exchanger, C_p and $D_1^{0.2}$ are constant. Therefore,

$$h_1 = C G^{0.8} \quad (6)$$

and

$$\frac{1}{U_1} = \frac{1}{C G^{0.8}} + R_1 \quad (7)$$

where C is a constant.

Tests were conducted with helium at various flow rates, temperatures, and pressures, and these data were utilized to calculate Q , the rate of heat transfer. Values of Q were then substituted into the formula $Q = U_1 A \Delta t$ to obtain values for U_1 . A plot of $1/U_1$ (as ordinate) versus $1/G^{0.8}$ from equation 7 gives a straight line with a slope of $1/C$. The vertical intercept of this line, K , represents R_1 , the sum of the resistance of the metal wall and the outside film. The vertical distance from the intercept to any point on the line gives the approximate helium film resistance for the particular velocity. The constant C is determined from the graph; h_1 is calculated from equation 6.

TEST EXCHANGER AND PROCEDURE

Forty-one runs were made with maximum helium flow rates (2,000 to 8,000 std cu ft/hr) attainable at 100, 175, and 250 psig and exchanger-inlet temperatures of 1,600° and 2,200° F. The test exchanger, instruments, and recycle system are shown in figures 1 to 3. Specified temperatures were achieved and conditions were maintained steady for 1 hour before each test. Tests lasted for 2 hours, with data taken at 15-minute intervals. All conditions were kept constant during each test. Temperatures were determined by high-velocity

FIGURE 1. - Test Exchanger.

FIGURE 2. - Instrumentation Diagram.

FIGURE 3. - Flowsheet for Test System.

thermocouple before each test, but not during stabilizing and test periods because flow of gas through the thermocouple significantly altered conditions in the exchanger. Helium temperature was measured again after each test. Water and air rates to the shell side of the exchanger were maintained constant throughout.

In establishing the correlations in this paper, all graphical "best fits" of results were obtained by the least squares method.

Relatively few data exist on the properties of helium at 1,500° to 2,500° F. Moreover, available data at lower temperatures are inconsistent.

A detailed literature survey was made, therefore, in order to choose the most accurate values for the viscosity, thermal conductivity, and specific heat of helium. Results of this survey are given in appendix A. Appendix B lists data and results from heat transfer tests in tabular form, and appendix C is a detailed breakdown of data calculations for an individual run. Symbols used in the paper are identified in the "Nomenclature" section, appendix D.

DERIVATION OF COEFFICIENT EQUATIONS

Figure 4 is a Wilson plot of the data. Figure 5 gives helium film coefficients, calculated from U_1 values obtained from figure 4, as a function of mass flow rate of helium. The slope of this line is 0.8, thus proving the validity of the exponent 0.8 in equation 7.

Values for helium film coefficients were subsequently compared with those determined from equations derived by various other investigators for helium at lower temperatures. These investigators have advanced different equations for gas film coefficients. For example, heat transfer data for fluids in turbulent flow in smooth tubes at moderate temperature differences, with all physical properties evaluated at the bulk temperature, can be correlated by the following equation (11):

$$\frac{h_1 D_1}{k_b} = 0.023 \left(\frac{D_1 G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4} \quad (8)$$

For air and other gases, however, Drexel and McAdams (4) suggest that equation 8 be modified as follows:

$$\frac{h_1 D_1}{k_b} = 0.021 \left(\frac{D_1 G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4} \quad (9)$$

Desmon and Sams (3) have shown that increasing the temperature difference across the film decreases the film coefficient; hence, equations like 8 and 9 must be modified. One equation (18) used to correlate heat transfer data for large temperature differences is

$$\frac{h_1 D_1}{k_f} = 0.021 \left(\frac{D_1 G}{\mu} \right)_f^{0.8} \left(\frac{C_p \mu}{k} \right)_f^{0.4} \quad (10)$$

All physical properties for the fluid are evaluated at a film temperature calculated from the equation $t_f = (t_w + t_b)/2$.

Another method of correlating heat transfer data for large temperature differences is that developed by Sieder and Tate (17), in which a dimensionless factor (μ_w/μ_b) is introduced into an equation in which the fluid physical properties are evaluated at the bulk temperature. An equation of this type is

$$\frac{h_1 D_1}{k_b} = 0.023 \left(\frac{D_1 G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4} \left(\frac{\mu_w}{\mu_b} \right)^{0.14} \quad (11)$$

FIGURE 4. - Wilson Plot.

FIGURE 5. - Helium Film Coefficient as Function of Mass Flow of Helium.

Other investigators (1, 14) have used a dimensionless factor T_w/T_b in place of μ_w/μ_b to give the following equation:

$$\frac{h_1 D_1}{k_b} = 0.023 \left(\frac{D_1 G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4} \left(\frac{T_w}{T_b} \right)^{-0.5}. \quad (12)$$

The exponent of T_w/T_b term is not constant; it varies for different gases. The value of -0.5 shown in equation 12 was suggested by Davenport and coworkers (2) as applying to helium. Barnes (1) states that the exponent for air is -0.4, helium -0.185, and carbon dioxide -0.27. Humble and coworkers (6) suggest a value of -0.55 for air.

Results from the Bureau of Mines tests were compared with those of all four types of correlations discussed; that is, those using bulk temperature, film temperature, dimensionless parameters based on temperature, and the ratio of wall temperature to bulk temperature. Figure 6 shows a correlation of heat transfer data in which the quantity $(N_{Nu})_b / (N_{Pr})_b^{0.4}$ is plotted as a function of the film Reynolds number. The slope of the line is 0.8, the exponent of the Reynolds number; the resulting empirical correlation is

$$\frac{h_1 D_1}{k_b} = 0.020 \left(\frac{D_1 G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4}. \quad (13)$$

All of the data are within the two dashed lines that represent 10-percent deviation from the solid line. The experimental curve is slightly lower than those reported by other investigators, but it agrees, within the spread of data, with equation 9 for air (4) and an equation for helium (18).

In the second correlation, physical properties of the fluid are evaluated at the average film temperature. This correlation is shown in figure 7. The solid line representing the best fit to the data is given by the equation

$$\frac{h_1 D_1}{k_f} = 0.0197 \left(\frac{D_1 G}{\mu} \right)_f^{0.8} \left(\frac{C_p \mu}{k} \right)_f^{0.4}. \quad (14)$$

The dotted lines indicate a 10-percent deviation from this equation.

The third correlation, figure 8, involves use of viscosity, a temperature dependent parameter, μ_w/μ_b . The solid line on figure 8, representing the best fit to the data, is given by the equation

$$\frac{h_1 D_1}{k_b} = 0.0215 \left(\frac{D_1 G}{\mu} \right)_b^{0.8} \left(\frac{C_p \mu}{k} \right)_b^{0.4} \left(\frac{\mu_w}{\mu_b} \right)^{0.14}. \quad (15)$$

The dotted lines again represent a 10-percent deviation from this equation.

Equations 13-15 all represent the experimental data with the same degree of accuracy, and the similar data spread makes each as good as the others.

FIGURE 6. - Heat Transfer Correlation Based on Fluid Properties Evaluated at Bulk Stream Temperature (t_b).

This is probably due to the relatively small changes in physical properties of helium. The specific heat is constant, and the thermal conductivity and viscosity increase at approximately the same rate, so the conductivity-to-viscosity ratio is almost constant. The Prandtl number therefore is nearly constant at 0.63 to 0.68.

A correlation based on equation 12 also was attempted, but it was discarded because of its extremely poor fit of ± 17 percent. The exponent of the parameter T_w/T_b was approximately -0.39, but this value does not agree with published values for helium.

FIGURE 7. - Heat Transfer Correlation Based on Fluid Properties Evaluated at Film Temperature (t_f).

The data were also correlated within 10 percent by the following dimensional equation:

$$h_1 = 0.0198 \frac{G^{0.8}}{D_1^{0.2}}. \quad (16)$$

Heat transfer data were also obtained for a 1/2-inch air-cooled exchanger, but wide variation in the air film coefficients made the Wilson plot a curve instead of a straight line; thus the helium film coefficients could not be accurately evaluated.

FIGURE 8. - Heat Transfer Correlation Based on Viscosity Ratio Parameter.

CONCLUSIONS

Film coefficients of heat transfer were determined experimentally for helium with high film temperature differences in turbulent flow inside smooth, round pipes. Four standard types of heat transfer equations correlated the results with other properties of the helium--bulk temperature, film temperature, dimensionless parameters based on temperature, and the ratio of wall temperature to bulk temperature. Thus, the film coefficients of heat transfer can be evaluated by the standard heat transfer equations in the literature for gases in forced convection.

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APPENDIX A. - TRANSPORT PROPERTIES OF HELIUM¹Viscosity

The most extensive investigation of helium viscosity, that of Trautz and Zink (19), covered the temperature range 0° to 1,500° F. Hilsenrath and Touloukian (5) developed an empirical equation based on the work of three other investigators. Johnston and Grilly (7) and van Itterbeek and Rietveld (20) also present data. Wilson (21) surveyed helium viscosity data in the literature and concluded the best data were accurate to 3 percent. Other investigators, using the Hilsenrath-Touloukian data, attained values within 3 percent of Wilson's. The effect of pressure on helium viscosity was found to be negligible. Figure 9 shows the data used in this report.

Thermal Conductivity

Thermal conductivity values for helium given in the literature agree well for low temperatures, but not for elevated temperatures. Keys (8) and Hilsenrath and Touloukian (5) give the lowest values, but they have few data to support their curves above 600° F. Mann and Blais (9) obtained data from 1,200° to 2,000° F, and Wilson (21) correlated data from several sources for temperature below 600° F; these data were used by Samuels (16) and agree with the theoretical work of Nicklin (13). Wilson (21) also obtained a curve for thermal conductivity which falls between the two other sets of data, but his curve was obtained by extrapolation of low-temperature data. The Samuels thermal conductivity values were used in this Bureau of Mines study, primarily because they were based on the most experimental data.

Fewer data are available on the effect of pressure on the thermal conductivity of helium. Wilson's experimental data (21) cover the pressure range 14.7 to 2,500 psia for 100° to 600° F and show the thermal conductivity to change less than 5 percent. Theoretical methods fail to express adequately the effect of pressure on thermal conductivity. Since the pressure range for our heat transfer study covers 100 to 250 psig, the use of thermal conductivity data for atmospheric pressure should introduce no errors in our correlations. Figure 10 shows data used in this report.

Specific Heat

Abundant data in the literature give the specific heat of helium as 1.242 Btu/(lb)(° F), (5, 8, 12-13, 19, 21) and this value changes very little with changes in temperature and pressure. The value used in our calculations is 1.242 Btu/(lb)(° F).

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¹Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

FIGURE 9. - Helium Viscosity.

FIGURE 10. - Thermal Conductivity of Helium.

APPENDIX B. - DATA AND CALCULATION SUMMARY

TABLE B-1. - Data from heat transfer tests with helium

(D_i = 0.0455 ft; L = 3.0 ft; A = 0.429 sq ft)

Run	Air			Water			Pres- sure, psig	Helium				
	Flow, lb/hr	Temperature, ° F		Flow, lb/hr	Temperature, ° F			Flow		Temperature, ° F		
		Inlet	Exit		Inlet	Exit		Std cu ft/hr	Lb/hr	Air cooler exit	Water cooler exit	Water cooler inlet
1	482	94	230	1,668	72.0	102.2	100	3,945	41.7	523	824	1,790
2	283	108	335	1,669	72.8	102.0	100	3,700	39.1	580	875	1,872
3	303	101	306	1,675	73.1	100.3	100	3,400	35.9	541	873	1,893
4	288	98	283	1,673	69.0	94.3	100	3,000	31.7	511	834	1,902
5	287	98	268	1,664	70.2	93.4	100	2,610	27.6	474	813	1,932
6	290	98	242	1,666	73.2	93.0	100	2,190	23.1	425	772	1,915
7	294	96	219	1,663	69.4	86.2	100	1,800	19.0	372	737	1,913
8	289	99	383	1,669	71.7	107.8	100	3,370	35.6	690	1,133	2,487
9	288	98	384	1,673	74.9	109.4	100	3,200	33.8	686	1,154	2,520
10	288	96	364	1,675	72.2	104.0	100	2,870	30.3	650	1,139	2,542
11	289	91	320	1,666	73.4	102.0	100	2,400	25.4	591	1,091	2,592
12	288	102	407	1,671	64.7	101.7	175	6,450	68.2	729	976	1,760
13	285	109	390	1,667	69.0	109.5	175	6,450	68.2	686	916	1,709
14	284	104	380	1,668	70.9	109.4	175	6,000	63.4	665	902	1,712
15	285	103	367	1,664	68.9	105.0	175	5,480	57.9	645	895	1,725
16	283	106	344	1,670	74.2	108.3	175	5,080	53.7	606	847	1,695
17	283	108	337	1,671	71.0	104.0	175	4,480	47.4	580	842	1,773
18	286	100	308	1,661	67.4	95.9	175	4,020	42.5	522	790	1,681
19	285	103	320	1,660	68.0	97.2	175	4,020	42.5	554	833	1,745
20	284	105	485	1,663	70.1	123.4	175	5,700	60.2	852	1,196	2,374
21	283	110	489	1,668	72.5	122.0	175	5,520	58.3	846	1,199	2,332
22	285	102	478	1,664	66.9	112.5	175	4,980	52.6	825	1,216	2,370
23	285	104	454	1,668	70.0	111.6	175	4,500	47.6	796	1,198	2,364
24	284	107	300	1,696	75.5	102.2	175	3,480	36.7	517	804	1,791
25	284	105	276	1,693	75.0	98.6	175	3,000	31.7	475	769	1,777
26	289	95	251	1,693	74.0	95.0	175	2,430	25.7	416	751	1,858
27	289	92	410	1,666	76.6	113.0	175	3,980	42.1	775	1,194	2,346
28	289	93	355	1,673	75.3	109.0	175	3,170	33.5	665	1,099	2,445
29	285	104	481	1,668	71.0	114.8	250	7,850	83.0	711	960	1,664
30	284	105	477	1,669	71.0	103.9	250	7,730	81.7	697	945	1,646
31	284	105	458	1,669	69.0	105.5	250	6,820	72.1	730	997	1,673
32	290	88	293	1,668	69.5	100.4	250	4,350	46.0	586	834	1,730
33	290	87	261	1,669	70.0	96.2	250	3,580	37.8	515	771	1,697
34	290	87	230	1,668	70.4	91.8	250	2,820	29.8	440	707	1,665
35	290	89	453	1,668	68.0	123.9	250	6,520	68.9	907	1,201	2,274
36	289	90	443	1,668	72.6	124.4	250	6,000	63.4	885	1,207	2,297
37	290	89	432	1,670	74.8	123.0	250	5,500	58.1	869	1,197	2,305
38	290	90	413	1,668	74.8	120.5	250	5,000	52.8	824	1,164	2,319
39	290	87	390	1,667	74.0	114.2	250	4,500	47.6	781	1,150	2,276
40	290	89	366	1,668	73.5	111.2	250	4,000	42.3	737	1,101	2,290
41	289	105	346	1,668	73.0	106.0	250	3,480	36.8	681	1.053	2,250

TABLE B-2. - Results from heat transfer tests with helium

 $(D_1 = 0.0455 \text{ ft}; L = 3.0 \text{ ft}; A = 0.429 \text{ sq ft})$

Run	Water-cooled section				Helium			
	Δt_m , ° F	Q , 1,000 Btu/hr	U_1 , Btu/(hr) (sq ft)(° F)	$100/U_1$	Mass velocity, lb/(hr)(sq ft)	$\frac{10,000}{G^{0.8}}$	Film coefficient, Btu/(hr) (sq ft)(° F)	Average temper- ature (t_b), ° F
1	1,158	50.37	101.3	0.987	25,583	2.976	122.4	1,307
2	1,224	48.73	87.5	1.143	23,994	3.133	116.3	1,373
3	1,232	45.56	86.1	1.161	22,049	3.352	108.7	1,383
4	1,214	42.33	81.3	1.231	19,455	3.705	98.4	1,368
5	1,211	38.60	74.2	1.347	16,926	4.143	88.0	1,373
6	1,173	32.99	65.6	1.525	14,202	4.766	76.5	1,344
7	1,153	27.94	56.4	1.772	11,673	5.577	65.3	1,325
8	1,635	60.25	86.0	1.163	21,854	3.376	107.9	1,810
9	1,659	57.72	81.1	1.234	20,752	3.519	103.6	1,837
10	1,661	53.27	74.7	1.339	18,612	3.839	94.9	1,842
11	1,648	47.65	67.4	1.484	15,564	4.429	82.3	1,842
12	1,249	66.84	124.7	.802	41,828	2.008	181.4	1,368
13	1,157	67.57	128.3	.779	41,828	2.008	181.4	1,312
14	1,175	64.22	127.4	.785	38,910	2.128	171.2	1,307
15	1,173	60.07	119.4	.838	35,538	2.288	159.3	1,304
16	1,132	56.94	117.2	.854	32,944	2.482	146.8	1,271
17	1,228	55.14	104.6	.956	29,053	2.688	135.6	1,370
18	1,105	47.33	99.9	1.001	26,070	2.931	124.3	1,325
19	1,151	48.47	98.3	1.017	26,070	2.931	124.3	1,289
20	1,590	88.64	130.0	.769	36,964	2.217	164.3	1,785
21	1,576	82.56	122.1	.819	35,797	2.275	160.2	1,765
22	1,612	75.88	109.6	.902	32,295	2.470	147.5	1,793
23	1,597	69.39	101.3	.987	29,182	2.679	136.0	1,781
24	1,144	45.28	91.6	1.092	22,568	3.289	110.8	1,297
25	1,086	39.94	85.7	1.167	19,455	3.705	98.4	1,273
26	1,136	35.55	73.0	1.370	15,759	4.385	81.3	1,304
27	1,610	60.64	87.8	1.139	25,810	2.955	123.3	1,770
28	1,590	56.38	82.7	1.209	20,557	3.545	102.8	1,772
29	1,189	73.06	143.2	.698	50,907	1.716	212.3	1,312
30	1,172	71.60	142.4	.702	50,129	1.738	209.7	1,295
31	1,220	60.92	116.4	.859	44,228	1.921	189.7	1,335
32	1,443	51.54	105.2	.951	28,210	2.760	132.0	1,282
33	1,090	43.73	93.4	1.071	23,216	3.216	113.3	1,234
34	1,035	35.70	80.4	1.244	18,288	3.893	93.6	1,186
35	1,591	92.41	135.0	.741	42,282	1.995	182.7	1,738
36	1,601	86.40	125.8	.795	38,910	2.128	171.2	1,752
37	1,594	80.49	117.7	.850	35,667	2.282	159.7	1,751
38	1,581	76.23	112.4	.890	32,425	2.462	148.0	1,742
39	1,558	67.01	100.3	.997	29,182	2.679	136.0	1,713
40	1,532	62.88	95.7	1.045	25,940	2.943	123.8	1,696
41	1,488	55.04	86.3	1.159	22,568	3.291	110.7	1,652

TABLE B-2. - Results from heat transfer tests with helium--Continued

(D₁ = 0.0455 ft; L = 3.0 ft; A = 0.429 sq ft)

Run	Helium--Continued		Dimensionless numbers			
	Viscosity, lb/(ft)(hr)	Thermal conductivity, Btu/(hr)(sq ft)(° F/ft)	Reynolds number (N _{Re}) _b	Nusselt number (N _{Nu}) _b	Prandtl number (N _{Pr}) _b	$\frac{(N_{Nu})_b}{(N_{Pr})_b^{0.4}}$
1	0.1060	0.2040	10,930	27.30	0.651	32.42
2	.1090	.2105	10,016	25.14	.648	29.89
3	.1095	.2110	9,162	23.44	.647	27.90
4	.1090	.2100	8,121	21.32	.648	25.35
5	.1090	.2105	7,065	19.02	.648	22.62
6	.1080	.2075	5,983	16.77	.649	19.94
7	.1070	.2060	4,964	14.42	.650	17.13
8	.1260	.2515	7,892	19.52	.621	23.64
9	.1270	.2540	7,435	18.56	.626	22.39
10	.1275	.2545	6,642	16.97	.625	20.47
11	.1275	.2545	5,554	14.71	.625	17.74
12	.1090	.2100	17,460	39.30	.648	46.73
13	.1070	.2045	17,787	40.36	.651	47.93
14	.1065	.2040	16,624	38.18	.651	45.34
15	.1060	.2040	15,255	35.53	.651	42.20
16	.1050	.2010	14,291	33.23	.653	39.42
17	.1090	.2100	12,128	29.38	.648	34.93
18	.1070	.2060	11,086	27.45	.650	32.60
19	.1055	.2025	11,243	27.93	.652	33.13
20	.1250	.2490	13,455	30.02	.627	36.17
21	.1240	.2475	13,135	29.45	.628	35.48
22	.1250	.2500	11,755	26.85	.627	32.35
23	.1250	.2490	10,622	24.85	.627	29.94
24	.1060	.2030	9,687	24.83	.652	29.45
25	.1050	.2010	8,431	22.27	.653	26.42
26	.1060	.2040	6,764	18.53	.651	22.01
27	.1240	.2480	9,471	22.62	.628	27.25
28	.1240	.2480	7,543	18.86	.628	22.72
29	.1065	.2040	21,749	47.24	.651	56.10
30	.1060	.2030	21,518	47.00	.652	55.75
31	.1075	.2070	18,745	41.70	.650	49.58
32	.1050	.2020	12,224	29.73	.653	35.27
33	.1030	.1975	10,256	26.10	.655	30.92
34	.1015	.1930	8,198	22.07	.657	26.12
35	.1230	.2450	15,641	33.93	.630	40.83
36	.1240	.2460	14,277	31.67	.629	38.11
37	.1240	.2460	13,087	29.54	.629	35.55
38	.1240	.2450	11,819	27.49	.630	33.08
39	.1220	.2425	10,883	25.52	.631	30.67
40	.1220	.2405	9,714	23.42	.632	28.15
41	.1200	.2365	8,557	21.30	.634	25.57

TABLE B-2. - Results from heat transfer tests with helium--Continued

(D_i = 0.0455 ft; L = 3.0 ft; A = 0.429 sq ft)

Run	Av helium tempera- ture, ° F	Av water tempera- ture, ° F	t _w , ° F	t _f , ° F	K _f , Btu/(hr) (sq ft)(° F/ft)	μ _f , lb/ (ft)(hr)	(N _{Nu}) _f	(N _{Pr}) _f	(N _{Pr}) _f ^{0.4}
1	1,307	87	297	667	0.1611	0.0870	34.57	0.675	0.8546
2	1,373	87	405	889	.1704	.0917	31.05	.673	.8534
3	1,383	86	356	870	.1714	.0920	28.86	.671	.8524
4	1,368	82	306	837	.1640	.0886	27.30	.675	.8546
5	1,373	82	285	829	.1630	.0880	24.56	.675	.8546
6	1,344	83	263	804	.1603	.0866	21.71	.675	.8546
7	1,325	78	239	782	.1587	.0860	18.72	.677	.8557
8	1,810	90	441	1,125	.1936	.1018	25.36	.657	.8453
9	1,837	90	469	1,153	.1970	.1031	23.93	.654	.8438
10	1,842	89	462	1,152	.1968	.1030	21.94	.654	.8438
11	1,842	90	362	1,102	.1903	.1003	19.68	.659	.8463
12	1,368	84	485	927	.1730	.0925	47.71	.668	.8509
13	1,312	89	447	880	.1691	.0910	48.81	.673	.8534
14	1,307	89	401	854	.1662	.0894	46.87	.672	.8530
15	1,304	87	392	848	.1656	.0891	43.77	.673	.8534
16	1,271	90	328	800	.1600	.0859	41.75	.671	.8524
17	1,370	88	381	876	.1677	.0901	36.79	.672	.8530
18	1,325	82	326	826	.1618	.0874	34.95	.675	.8546
19	1,289	83	336	813	.1618	.0874	34.95	.675	.8546
20	1,785	95	448	1,117	.1920	.1010	38.94	.658	.8459
21	1,765	95	492	1,129	.1937	.1018	37.63	.657	.8453
22	1,793	91	528	1,161	.1975	.1034	33.98	.654	.8438
23	1,781	91	522	1,152	.1966	.1028	31.48	.654	.8438
24	1,297	89	298	798	.1599	.0867	31.53	.678	.8560
25	1,273	87	240	757	.1550	.0840	28.89	.677	.8557
26	1,304	85	233	769	.1563	.0850	24.19	.680	.8570
27	1,770	95	577	1,174	.1997	.1043	28.09	.653	.8434
28	1,772	92	420	1,096	.1911	.1006	24.48	.658	.8459
29	1,312	93	490	901	.1720	.0922	56.16	.670	.8520
30	1,295	88	475	885	.1696	.0910	56.26	.671	.8524
31	1,335	87	569	952	.1768	.0943	48.82	.667	.8504
32	1,282	85	328	805	.1609	.0870	37.33	.676	.8550
33	1,234	83	285	760	.1560	.0848	33.05	.679	.8565
34	1,186	81	237	712	.1507	.0822	28.26	.682	.8580
35	1,738	96	528	1,132	.1942	.1021	42.81	.657	.8453
36	1,752	97	536	1,144	.1957	.1027	39.80	.656	.8448
37	1,751	98	539	1,145	.1960	.1028	37.07	.656	.8448
38	1,742	97	493	1,118	.1930	.1014	34.89	.657	.8453
39	1,713	94	519	1,116	.1933	.1017	32.01	.658	.8459
40	1,696	92	456	1,076	.1888	.0997	29.84	.660	.8470
41	1,652	90	434	1,043	.1854	.0981	27.17	.661	.8474

TABLE B-2. - Results from heat transfer tests with helium--Continued

(D_i = 0.0455 ft; L = 3.0 ft; A = 0.429 sq ft)

Run	$\frac{(N_{Nu})_f}{(N_{Pr})_f^{0.4}}$	$(N_{Re})_f$	$(N_{Re})_f^{0.8}$	$(N_{Re})_b^{0.8}$	μ_w , lb/(ft)(hr)	μ_b , lb/(ft)(hr)	$\frac{\mu_w}{\mu_b}$	$\left(\frac{\mu_w}{\mu_b}\right)^{0.14}$	$\frac{(N_{Nu})_b}{(N_{Pr})_b^{0.4} \left(\frac{\mu_w}{\mu_b}\right)^{0.14}}$
1	40.45	13,380	2,001	1,702	0.0653	0.1060	0.6160	0.9348	34.68
2	36.38	11,905	1,822	1,587	.0721	.1090	.6615	.9440	31.66
3	33.86	10,905	1,699	1,478	.0726	.1095	.6630	.9444	29.54
4	31.94	9,986	1,583	1,339	.0653	.1090	.5991	.9311	27.23
5	28.74	8,752	1,425	1,200	.0642	.1090	.5890	.9291	24.35
6	25.40	7,462	1,254	1,051	.0627	.1080	.5806	.9272	21.51
7	21.88	6,176	1,078	906	.0618	.1070	.5776	.9264	18.49
8	30.00	9,768	1,555	1,312	.0743	.1260	.5897	.9292	25.44
9	28.36	9,158	1,477	1,252	.0764	.1270	.6016	.9317	24.03
10	26.00	8,222	1,355	1,142	.0760	.1275	.5961	.9305	22.00
11	23.25	7,060	1,200	990	.0759	.1275	.5953	.9304	19.07
12	56.07	20,575	2,823	2,475	.0757	.1090	.6945	.9506	49.16
13	57.19	20,914	2,860	2,512	.0737	.1070	.6888	.9495	50.48
14	54.95	19,803	2,738	2,380	.0708	.1065	.6648	.9448	47.99
15	51.29	18,171	2,556	2,222	.0704	.1060	.6642	.9447	44.67
16	48.98	17,450	2,474	2,109	.0663	.1050	.6314	.9381	42.02
17	43.13	14,672	2,154	1,849	.0693	.1090	.6358	.9389	37.20
18	40.90	13,572	2,023	1,721	.0653	.1070	.6103	.9336	34.92
19	40.90	13,572	2,023	1,741	.0672	.1055	.6370	.9392	35.27
20	46.03	16,652	2,383	2,011	.0742	.1250	.5936	.9306	38.87
21	44.52	16,000	2,308	1,971	.0768	.1240	.6194	.9355	37.93
22	40.27	14,211	2,099	1,804	.0792	.1250	.6336	.9485	34.11
23	37.31	12,916	1,945	1,663	.0783	.1250	.6264	.9370	31.95
24	36.84	11,844	1,815	1,545	.0648	.1060	.6113	.9338	31.54
25	33.76	10,538	1,653	1,383	.0607	.1050	.5781	.9267	28.51
26	28.23	8,436	1,383	1,159	.0603	.1060	.5689	.9245	23.81
27	33.31	11,259	1,742	1,517	.0821	.1240	.6621	.9443	28.86
28	28.94	9,298	1,495	1,265	.0733	.1240	.5911	.9295	24.44
29	65.92	25,122	3,312	2,951	.0757	.1065	.7108	.9536	58.83
30	66.00	25,065	3,306	2,926	.0749	.1060	.7066	.9528	58.51
31	57.41	21,340	2,906	2,620	.0802	.1075	.7460	.9601	51.64
32	43.66	14,754	2,163	1,861	.0666	.1050	.6343	.9387	37.57
33	38.59	12,457	1,890	1,617	.0638	.1030	.6194	.9355	33.05
34	32.94	10,123	1,600	1,352	.0606	.1015	.5970	.9308	28.06
35	50.64	18,843	2,631	2,267	.0786	.1230	.6390	.9396	43.58
36	47.11	17,239	2,450	2,107	.0793	.1240	.6395	.9397	40.56
37	43.88	15,786	2,283	1,966	.0796	.1240	.6419	.9402	37.81
38	41.28	14,550	2,139	1,821	.0770	.1240	.6210	.9359	35.35
39	37.84	13,056	1,962	1,696	.0787	.1220	.6451	.9408	32.60
40	35.23	11,838	1,814	1,549	.0750	.1220	.6148	.9346	30.12
41	32.06	10,467	1,644	1,399	.0738	.1200	.6150	.9347	27.36

APPENDIX C. - SAMPLE CALCULATIONS

Operating Data, Run 31

Helium flow.....	std cu ft/hr..	6,820
Helium pressure.....	psia..	264.3
Helium temperature, outlet of air section.....	° F..	730
Airflow.....	lb/hr..	284
Air temperature, ° F:		
Inlet.....		105
Outlet.....		458
Water flow.....	lb/hr..	1,669
Water temperature, ° F:		
Inlet.....		69.0
Outlet.....		105.5

Helium Temperatures at Inlets to Water and Air Sections

$$\text{Average temperature of air} = \frac{105 + 458}{2} = 282^\circ \text{ F}$$

$$\text{Specific heat of air (C}_p\text{)} = 0.24 \text{ Btu}/(\text{lb})(^\circ \text{ F})$$

$$\text{Heat removed by air} = (284)(0.24)(458-105) = 24,060 \text{ Btu/hr}$$

$$\text{Weight rate of water} = 1,669 \text{ lb/hr}$$

$$\text{Heat removed by water} = (1,669)(1.0)(105.5-69.0) = 60,919 \text{ Btu/hr}$$

$$\text{Weight rate of helium} = 6,820 \left(\frac{4}{378.4} \right) = 72.1 \text{ lb/hr}$$

$$\Delta t \text{ of helium in air section} = \frac{24,060}{(72.1)(1.25)} = 267^\circ \text{ F}$$

$$\Delta t \text{ of helium in water section} = \frac{60,919}{(72.1)(1.25)} = 676^\circ \text{ F}$$

Calculated helium temperature at

$$\text{Inlet to air section} = 730 + 267 = 997^\circ \text{ F}$$

$$\text{Inlet to water section} = 997 + 676 = 1,673^\circ \text{ F}$$

Overall Coefficients of Heat Transfer for Water and Air SectionsIn water-cooled section

$$\text{Length of exchanger} = 3.0 \text{ ft}$$

$$\text{Inside surface area per foot of length} = 0.143 \text{ sq ft/ft}$$

$$A_1 = 3.0 (0.143) = 0.429 \text{ sq ft}$$

$$\Delta t_1 = 1,673 - 105.5 = 1,567.5^\circ \text{ F}$$

$$\Delta t_2 = 997 - 69.0 = 928^\circ \text{ F}$$

$$\Delta t_m = \frac{1,567.5 - 928}{2.3 \log \frac{1,567.5}{928}} = 1,220^\circ \text{ F}$$

$$U_1 = \frac{q}{A_1 \Delta t_m} = \frac{60,919}{(0.429)(1,220)} = 116.4 \text{ Btu}/(\text{hr})(\text{sq ft})(^\circ \text{ F})$$

In air-cooled section

$$\text{Length of exchanger} = 3.833 \text{ ft}$$

$$\text{Inside surface area per foot of length} = 0.143 \text{ sq ft/ft}$$

$$A_1 = 3.833 (0.143) = 0.548 \text{ sq ft}$$

$$\Delta t_1 = 997 - 458 = 539^\circ \text{ F}$$

$$\Delta t_2 = 730 - 105 = 625^\circ \text{ F}$$

$$\Delta t_m = \frac{625 - 539}{2.3 \log \frac{625}{539}} = 581^\circ \text{ F}$$

$$U_1 = \frac{24,060}{(0.548)(581)} = 75.6 \text{ Btu/(hr)(sq ft)(}^\circ \text{ F)}$$

$$\text{Average helium temperature } (t_b) = \frac{997 + 1,673}{2} = 1,335^\circ \text{ F}$$

$$\text{Average water temperature} = \frac{69.0 - 105.5}{2} = 87^\circ \text{ F}$$

$$\text{Overall heat transfer resistance} = \frac{1}{116.4} = 0.008591 \text{ (hr)(sq ft)(}^\circ \text{ F)/Btu}$$

$$\text{Helium film resistance} = \frac{1}{189.7} = 0.005271 \text{ (hr)(sq ft)(}^\circ \text{ F)/Btu}$$

$$\text{Fraction of } \Delta t \text{ across helium film} = \frac{0.005271}{0.008591} = 0.6135$$

$$\text{Helium film } \Delta t = 0.6135 (1,335 - 87) = 766^\circ \text{ F}$$

$$\text{Tube wall temperature } (t_w) = 1,335 - 766 = 569^\circ \text{ F}$$

$$\text{Average film temperature } (t_f) = \frac{1,335 + 569}{2} = 952^\circ \text{ F}$$

APPENDIX D. - NOMENCLATURE

- A = Heat transfer surface, sq ft
 C = Slope of line on Wilson plot
 C_p = Specific heat at constant pressure, Btu/(lb)(° F)
 D = Diameter of tube or pipe, ft
 G = Mass velocity of gas, lb/(hr)(sq ft)
 h = Average film coefficient of heat transfer, Btu/(hr)(sq ft)(° F)
 k = Thermal conductivity of pipe, Btu/(hr)(sq ft)(° F/ft)
 K = Intercept on Wilson plot
 L = Length, ft
 n = Constant based on physical properties of gas
 Q = Heat flow, Btu/hr
 R_1 = Resistance to heat flow, (hr)(sq ft)(° F)/Btu
 t = Temperature, ° F
 T = Absolute temperature, ° R
 U = Overall heat-transfer coefficient, Btu/(hr)(sq ft)(° F)
 x = Pipe wall thickness, ft
 μ = Viscosity, lb/(ft)(hr)

Dimensionless Numbers

- $C_p \mu / k$ = Prandtl number (N_{Pr})
 DG / μ = Reynolds number (N_{Re})
 hD / k = Nusselt number (N_{Nu})

Subscripts

- av = Average
 b = Bulk
 f = Film
 i = Inside of pipe or tube
 m = Log mean
 o = Outside of pipe or tube
 w = Wall