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Heat transfer studies of a hydrocarbon oil.

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HEAT TRANSFER STUDIES OF A HYDROCARBON OIL

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HEAT TRANSFER
STUDIES OF A HYDROCARBON OIL

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LIST OF SYMBOLS

Symbol	Quantity	Units
A	Heat transfer surface	sq.ft.
C_p	Specific heat	B.t.u./(lb.)(deg.F.)
D	Diameter of pipe	ft.
f	Friction factor	none
g	Acceleration due to gravity	ft./hr.^{2}
G	Mass velocity	lb./(hr.)(sq.ft.)
h	Heat transfer coefficient	B.t.u./(hr.)(sq.ft.)(deg.F)
k	Thermal conductivity	B.t.u./(hr.)(sq.ft.)(deg.F/ft.)
L	Length of path of heat conduction	ft.
N	Length of test section	ft.
dN	Differential length of pipe	ft.
dP	Differential pressure drop due to friction	lb./sq.ft.
Q	Quantity of heat transferred	B.t.u./hr.
t_1	Fluid entrance temperature	deg.F
t_2	Fluid exit temperature	deg.F

LIST OF SYMBOLS (Concluded)

Symbol	Quantity	Units
t_3	Refrigerant entrance temperature	deg.F
t_4	Refrigerant exist temperature	deg.F
V	Velocity of fluid in pipe	ft./hr.
w	Weight rate of flow	lb./hr.
z	viscosity	Centipoise
Δt	Temperature difference	deg.F
ρ	Density of fluid	lb./cu.ft.
μ_f	Viscosity of film	lb./(hr.)(ft.)
μ_b	Bulk Viscosity	lb./(hr.)(ft.)

Symbols are according to the system recommended by the Council of the American Institute of Chemical Engineers.

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I. INTRODUCTION

This study of heat transfer of a hydrocarbon oil was made for the investigation of cooling phenomena in the upper viscous and lower turbulent range. All data reported or discussed in this dissertation are cooling data on "Eocene", a refined kerosene. The primary object of the research was the observation of the characteristics in the cooling of a hydrocarbon oil in the critical region.

Previous workers in the same field have reported cooling data correlated in numerous ways. However, it was found that the most satisfactory correlation of the date obtained in this research was by means of an equation of the Dittus and Boelter type [1]. Although this type of equation does not represent the data perfectly, it does give a far better presentation of the results than other methods attempted.

The studies reported in this presentation were made on a liquid heat exchanger designed by Browne and Finger [2] amd constructed by Browne [3] and Donahew [4]. In order to attain the temperatures desired, it was found necessary to install a three-quarter ton ice machine for the cooling of the refrigerant liquid. In the installation of this refrigeration unit, several minor changes were made in the original piping layout.

As the heat exchanger was operated and lower temperatures were sought, it was found necessary to resort to insulation for the successful maintenance of relatively low temperatures. The range of pipe temperatures reported varied from 60°F to 20°F. Consequently, it followed that the test liquid temperatures were higher than the corresponding pipe temperatures. It was also logical that the refrigerant liquid temperature be considerably lower than the pipe temperatures.

In the insulation of the exchanger, cork was used for the refrigerant reservoir and hair felt for the piping.

All temperatures were measured by means of thermocouples read with a type "K" potentiometer. The use of such an arrangement made possible the reading of temperature differences to three significant figures. Whether such accuracy was justified in all cases is problematical. However, this accuracy frequently made data having small temperature differences valuable.

All the data presented in this study were obtained using "Eocene" as both test liquid and cooling liquid.

II. THEORETICAL

An examination of the literature for a means of correlating heat transfer data led to the conclusion that the most satisfactory method would be the use of dimensionless groups [4-16]. It was decided to use an equation of the type suggested by Dittus and Boelter:

$$\frac{hD}{k} = 0.026 \left(\frac{DG}{\mu}\right)^{0.8} \left(\frac{C_p\mu}{k}\right)^{0.3}$$

This equation is recommended by them for cooling data [I].

Since an equation of this type can be converted by proper mathematical manipulation into types that are used for both turbulent and viscous flow, the use of this type of equation followed [I6].

The equation consists of the following dimensionless groups:

Prandtl number	$C\mu/k$
Nusselt Number	hD/k
Reynolds Number	DG/μ

The Prandtl number contains terms that are properties only. Since this fact is true, it would seem that the Prandtl number would be of no significance except in cases in which the properties have a marked variation. Furthermore it would seem logical that the greatest property variation would occur at the film. Hence, in the correlation of these data an average film viscosity was used. The film temperature was found by taking the arithmetic mean temperature between that of the pipe and the average test liquid temperature [16].

The Nusselt number contains only conductivity terms and thereby indicates its value in the study of heat transfer through films.

The Reynolds number is a flow term and would seem to become more important as turbulence is increased. However, since it is concerned with flow rather than with heat conduction or property change, the use of a viscosity at an average test liquid temperature would seem to coincide with the purpose of the group.

Since this equation contains a flow group, a conduction group, and a property change group, all the activity occurring in both the viscous and turbulent regions should be adequately expressed.

III. APPARATUS

FIGURE I.

HEAT EXCHANGER WITHOUT INSULATION

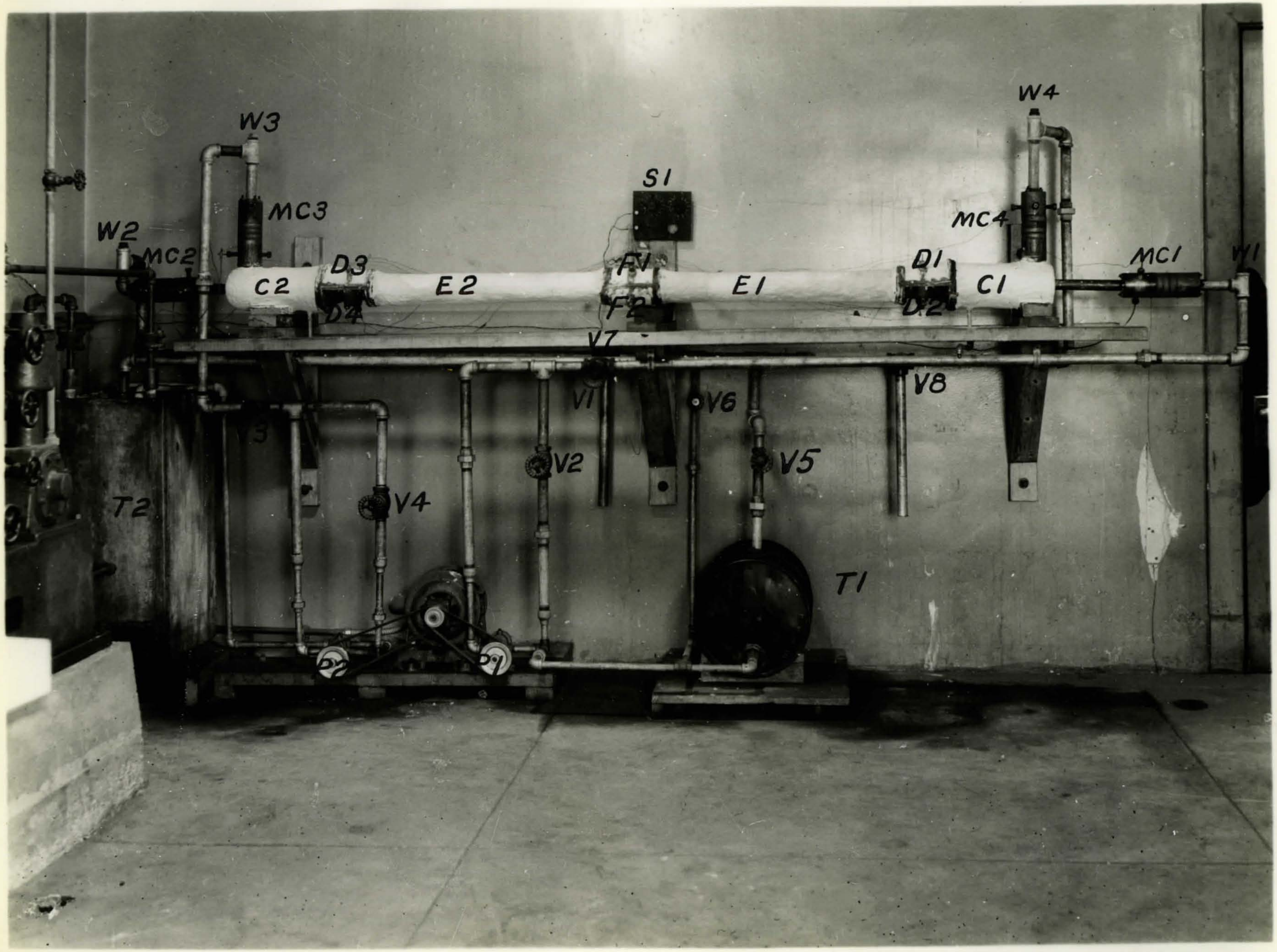

W3
S1
W4
MC3
MC4
W2
MC2
D3
D1
MC1
W1
C2
E2
F1
E1
C1
D4
F2
D2
V7
V1
V6
V8
V3
V2
V5
V4
T2
T1
P2
P1

FIGURE II.

HEAT EXCHANGER WITH INSULATION AND ADDITIONS

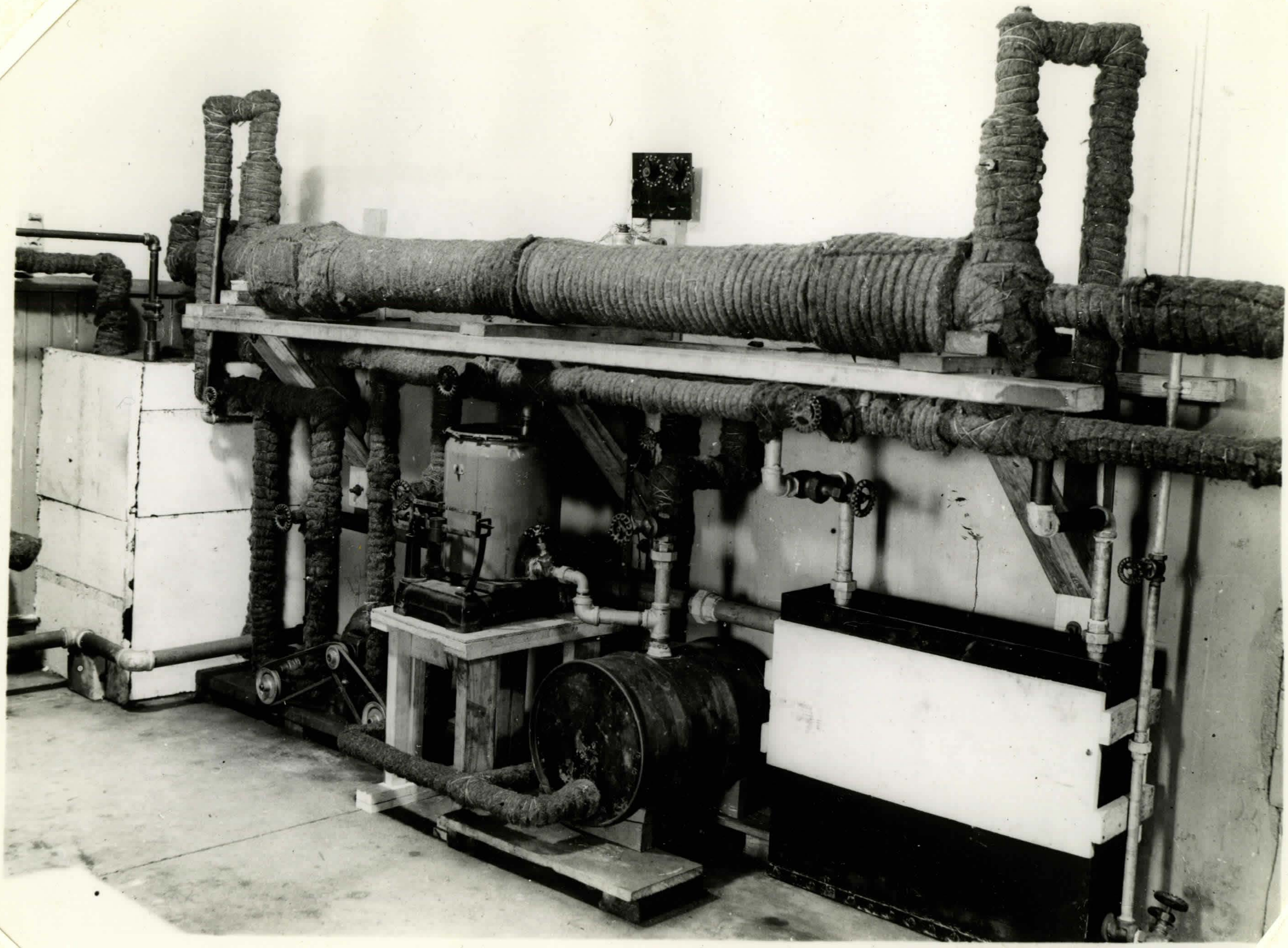
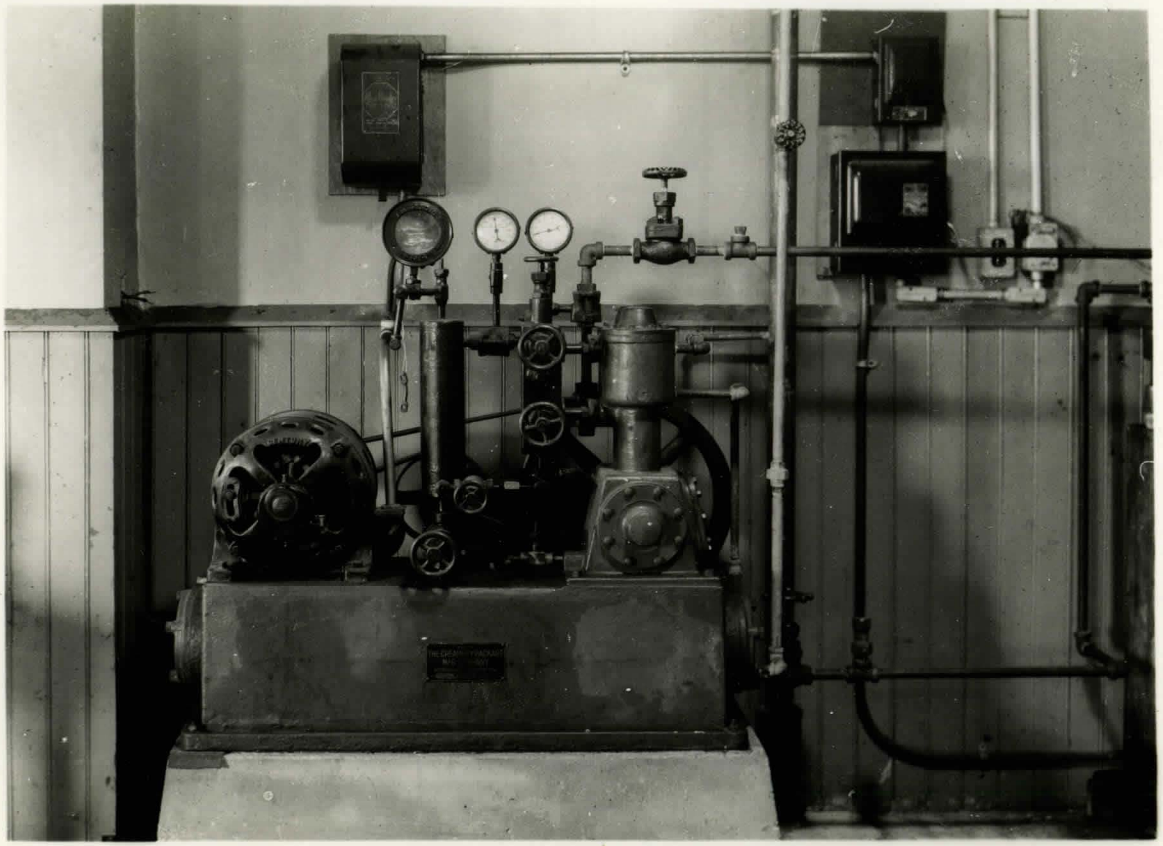


FIGURE III.

AMMONIA COMPRESSOR



With the apparatus used in this investigation, the means are provided for the determination of temperatures and rates of flow in order that the heat transfer coefficients and various related dimensionless groups may be calculated. The equipment consists of the heat exchanger proper and the accessories.

The entire apparatus is shown in Figures I., II., and III., pages 15, 17, and 19, and is described with reference to the figures in the following discussion.

HEAT EXCHANGER

The heat exchanger proper includes the test section, the calming and mixing chambers, and the thermocouples. The test section consists of a standard one inch brass pipe within a cast iron shell. This brass pipe is a single length 9 feet, 6 inches long. The test section includes a calming section of 23 inches, a test length of 6 feet, and an exit section of 19 inches. The cast iron annular shell is composed of an inlet and outlet section for the refrigerant, C 1 and C 2; and several sleeves. Sections E 1 and E 2 are two 30 inch sleeves. The sections marked D and F are split sleeves through which the thermocouple junctions are installed.

The calming sections installed in the inlet and outlet sections of the refrigerant system are for the purpose of preventing turbulence in the vicinity of the thermocouple junctions at the pipe ends. These calming sections also bring about streamline flow of the refrigerant after it has passed through the mixing chambers.

The purpose of the calming section is the elimination of the turbulence of the liquid after passage through the mixing chamber. The calming section has a cross made of sheet copper, inserted in the brass pipe between the test section and the mixing chamber at the entrance end of the test liquid system.

The mixing chambers consist of slotted copper plates and steel collars bolted together. The mixing chambers in the test line, MC 1 and MC 2, and in the refrigerant line, MC 3 and MC 4, effect a mixing so that an average temperature of the liquid immediately after the chamber may be obtained by a single thermocouple placed in the center of the stream.

In order that heat transfer may be reduced to a minimum between the refrigerant and the test liquid in the refrigerant inlet and outlet sections inner steel sleeves are provided. These sleeves forming an annular space around the ends of the brass pipe extend to the centers of the cast iron sleeves, D 1, D 2, D 3, and D 4. This annular space around each end of the brass pipe is packed with rock wool. In order that undesirable conduction between the cast iron shell and the test section might be minimized, asbestos strips are placed between the surfaces making contact. Such conduction, however, is of minor importance since the areas of contact are small and relatively distant from the test section.

For the measurement of temperatures, sixteen thermocouples are installed in the heat exchanger. One thermocouple is located in each of the four mixing chambers and twelve are attached to the brass test section. Those couples fastened to the brass pipe are arranged in the following order: four thermocouples ninety degrees apart at each end and at the center of the test section. The thermocouples are made of No. 28 B & S gage iron and constantan wires welded together at one end and led to a cold junction behind the heat exchanger. From the cold junction connection is made to two dials by means of copper leads. The dials have sixteen terminals so that any thermocouple of the group may be connected to the potentiometer with a proper dial setting.

The thermocouples are installed in the mixing chambers through one-eighth inch copper tubing, centered in one-half inch steel bolts. These junctions are located in the center of the liquid stream. The copper tubing extending from the bolts protects the junction and holds it in the proper position.

The thermocouples for measuring the pipe temperature pass through copper tubing within one-half inch steel bolts in the split sleeves. Each junction is soldered to the pipe at one end of a one-sixteenth inch by one inch slot cut in the pipe. The slots are filled with litharge and glycerine cement, and the surface smoothed to conform with the surface of the pipe.

ACCESSORIES

Reservoirs are provided for the test and refrigerant liquids. The test liquid reservoir, T 1, is a ten-gallon steel drum placed in a horizontal position. A by-pass line around this reservoir is provided so that a control of the test liquid temperature can be maintained. The refrigerant reservoir is a rectangular tank, T 2, having a capacity of about thirty gallons. The expansion coils of the ammonia compressor are located in this tank.

Originally the rate of flow was determined by means of an open tank into which the test liquid was allowed to flow for a measured amount of time with subsequent weighing of the collected liquid. However, it was found with the attainment of temperatures even a few degrees below room temperature that this method of rate determination added too much heat to the system. In order to correct this fault a five gallon covered tank was insulated with hair felt and mounted on a small platform scale. This arrangement is shown in Figure II., page 17. The tank was provided with an exit line near the bottom. The exit line containing a valve emptied into an up-turned one-inch elbow that led to the test liquid reservoir, T 1. A line from the three-way valve, V 7, extended through the cover of this tank in such a way that it in no way hindered the vertical movement of the tank on the platform scale. By means of this installation the test liquid could be collected over a measured period of time, weighed, and returned to the system without the introduction of a too great amount of heat.

The test liquid is taken from the return line by means of the three-way valve, V 7. In the refrigerant line a similar three-way valve, V 8, is provided. The period of time over which the test liquid was collected was measured with a stop watch. This period varied from thirty to sixty seconds.

Two pumps, P 1 and P 2, are provided for the circulation of the test and refrigerant liquids. P 1 is in the test liquid line, and P 2 is in the refrigerant line. These pumps are bronze gear pumps, having a rated capacity of six gallons per minute at a speed of 1000 R.P.M. A constant-speed, electric motor drives the pumps.

The rate of flow of the two liquids is controlled by means of the valves, V 1, V 2, V 3, and V 4. Valves V 2 and V 4 are in the by-pass lines.

A three-quarter-ton ammonia compressor was installed for the attainment of lower temperatures. The expansion coils of the compressor were located in the refrigerant reservoir. The refrigeration was controlled manually by means of the adjustment of a needle-point expansion valve in the liquid ammonia line.

As a means of checking the thermocouple readings, four thermometer wells are provided, W 1, W 2, W 3, and W 4. The wells are made of quarter-inch copper tubing plugged at one end and sealed in a drilled one-inch standard cast-iron plug.

The thermocouple readings were taken with a Leads and Northrup Type K potentiometer and a wall galvanometer. In order that vibration of the galvanometer be reduced to a minimum, it was mounted on a large concrete slab supported by four rubber cushions.

It was found very early in the operation of the heat exchanger that temperatures even a few degrees below room temperature could not be reached and held with any success without the use of insulation. At first the test section alone was insulated; however, with operation at lower temperatures, it was found necessary to cover the entire apparatus. The refrigerant reservoir was covered with sheet-cork and Celotex. A layer of asbestos fiber mixed with plaster of paris and water was molded around the cast iron shell containing the test section in order that this section might be brought more nearly to a uniform size. The test section was then covered with two inches of hair felt. The rest of the heat exchanger was covered with a one-inch thickness of hair felt.

With the insulation of the entire heat exchanger, it was found that the time required to bring the apparatus to equilibrium was increased greatly because of the lower temperatures attained. In order to shorten this time as well as to economize on the use of the refrigerant stored in the refrigerant reservoir, it was decided to install a cooling bank in the test liquid line. This bank consists of six 1-inch pipes between two headers. This additional piece of apparatus was placed in the line leading to the test section as is shown in Figure II., page 17. The installation was accomplished by installing two tees with a valve between them in the test liquid line. Connection was made between the tees and the ends of the headers. A valve was also placed in the entrance line leading to the bank. This bank of pipes was placed in a galvanized iron tank to which a water connection was made at the bottom and an overflow drain connection made at the top. With this arrangement city water could be used for cooling prior to the circulation of the refrigerant.

OPERATION

In the preparation of the heat exchanger for a run, the operation differs somewhat from its operation after equilibrium has been reached and thermocouple readings have been taken. Before the refrigerant is circulated, the test liquid is circulated and allowed to pass through the cooling bank. After the test liquid has been cooled as much as possible by means of the cooling bank, it is by-passed across the bank, and the refrigerant circulation begun.

In the normal operation of the heat exchanger the pump, P 1, draws the test liquid from the reservoir, T 1, Valves, V 1 and V 2, control the rate of flow. The liquid then passes to the mixing chamber, MC 1, where its temperature is measured. From the mixing chamber the liquid goes through the test section and then to the mixing chamber, MC 2, where the temperature is again measured. The liquid then passes to either valves, V 5, V 6, or V 7. V 7 is the three-way valve which is used to divert the liquid for rate of flow determinations. V 6 is a valve in the by-pass line around the test liquid reservoir. Valves, V 5 and V 6, are both used in regulation of the quantity of liquid by-passing the test liquid reservoir.

In the refrigerant system, the liquid is taken from the refrigerant by pump, P 2, and then passed, with the rate of flow controlled by valves, V 3 and V 4, to the mixing chamber, MC 3. In the mixing chamber the temperature is measured. The liquid then passes through the annular space around the test section and to mixing chamber, MC 4. The temperature is again determined and the liquid returned to the refrigerant reservoir, T 2.

Before any data are taken on the apparatus, the refrigerant and test liquids are circulated until the desired temperatures are obtained and the apparatus has come to equilibrium. Equilibrium conditions are attained when the refrigerant and test liquid entrance temperatures have become constant.

When the apparatus had come to equilibrium, the cold junctions of the thermocouples were brought to 32°F. in an ice bath. The potentiometer circuit was balanced, and the thermocouple readings made and recorded. These thermocouple readings were in millivolts and, consequently, required a conversion to degrees Fahrenheit. The temperatures indicated by the thermometers in the thermometer wells were also recorded. The rate of flow of the test liquid was determined by collecting a portion of the liquid over a period of thirty to sixty seconds and weighing the collected material. This rate determination was made after the thermocouple and temperature readings had been recorded. After the test liquid taken from the system had been returned, the valves were again adjusted for another rate of flow, and equilibrium conditions were again sought.

MATERIALS

In this study of heat transfer, both refrigerant and test liquids were Eocene. Since the refrigerant liquid served merely to cool the test liquid and thereby produce a transfer of heat, its properties were not examined. The properties of the test liquid were examined rather closely. The physical properties of the Eocene used in the calculation of the results are listed in Table I., page 33. The density was determined with a Westphal balance. The specific heat was determined by measuring the temperature rise of a weighed amount of Eocene when a measured quantity of electricity was introduced. Viscosities were determined at several temperatures by means of a Hoepler viscosimeter, and a smooth curve was drawn through the points to indicate the variation of the viscosity with a temperature change, Curve I., page 34. The value of the thermal conductivity that was used in the calculations was taken from the literature[1].

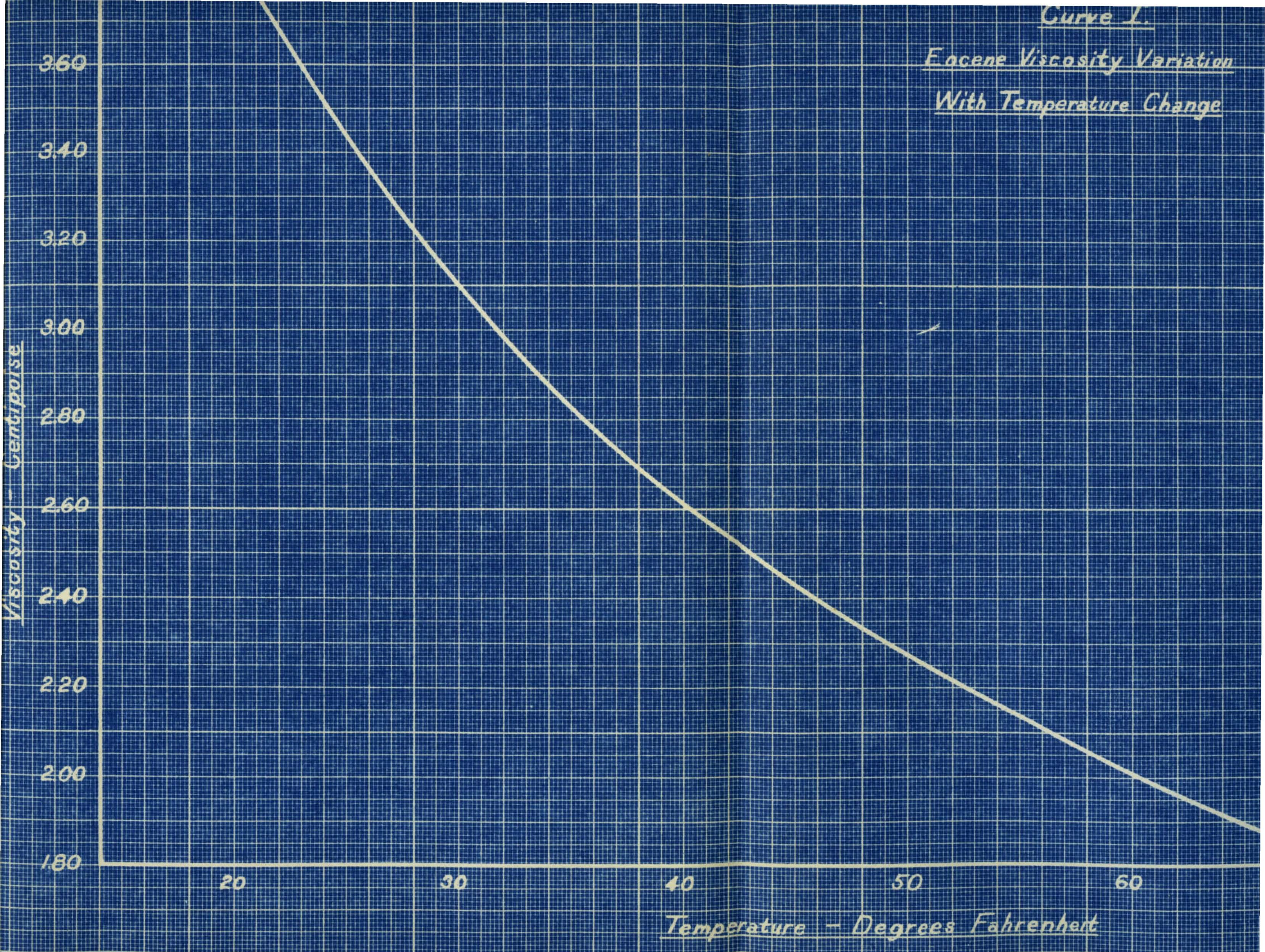
TABLE I.

PHYSICAL PROPERTIES OF EOCENE (60°F.)

Density	50.1	lb./cu.ft.
Specific Heat	0.504	B.T.U./(lb.)(°F.)
Thermal Conductivity	0.0875	B.T.U./(hr.)(sq.ft.)(°F./ft.)

DISTILLATION RANGES OF EOCENE

Percent Distilled	New Sample	Used Sample
0	320	332
10	357	368
20	376	384
30	386	407
40	398	424
50	424	439
60	448	455
70	466	471
80	484	490
90	509	510


Curve I.
Eocene Viscosity Variation
With Temperature Change
Viscosity - Centipoise
3.60
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
20
30
40
50
60
Temperature - Degrees Fahrenheit

IV. DATA AND RESULTS

The experimental data and the calculated results are reported in the Table II, page 37 The test liquid inlet and outlet temperatures are recorded directly from the thermocouple readings. The average pipe temperature is the readings of the twelve thermocouples attached to the pipe. Δt_1 is the difference between the test liquid inlet temperature and the average pipe temperature. Δt_2 is the difference between the test liquid outlet temperature and the average pipe temperature. The logarithmic mean temperature difference is the logarithmic mean of Δt_1 and Δt_2. The test liquid Δt is the drop in temperature in the test liquid by passage through the test section. The weight of the test liquid per minute was either determined directly or by a simple multiplication. The weight of the test liquid per hour was obtained by multiplying the weight of the test liquid per minute by sixty. The average test liquid temperature is an arithmetic average of the inlet and outlet temperatures of the test liquid - the temperature at which the bulk viscosity was found. The film temperature was found by averaging the pipe temperature with the average test liquid temperature. The film

TABLE II

HEAT TRANSFER DATA

Run No.	Test Liquid Inlet Temp.	Test Liquid Outlet Temp.	Average Pipe Temp.	Δt_1	Δt_2	Log Mean Δt
Units	°F	°F	°F	°F	°F	°F
1	56.438	53.046	39.638	16.800	13.408	15.056
2	57.997	55.019	39.546	18.451	15.473	16.935
3	54.223	51.211	37.365	16.858	13.846	15.318
4	59.300	54.154	38.865	20.435	15.289	17.756
5	64.067	58.827	34.870	29.197	23.957	26.518
6	54.292	50.138	29.923	24.369	20.215	22.250
7	61.167	56.612	39.382	21.785	17.230	19.438
8	55.400	52.285	34.008	21.392	18.277	19.814
9	60.567	57.997	47.380	13.187	10.617	11.868
10	59.200	56.992	47.768	11.432	9.224	10.299
11	50.312	48.407	34.712	15.600	13.695	14.642
12	55.607	53.011	28.573	27.034	24.438	25.740
13	60.867	49.377	19.452	41.415	29.925	35.395
14	57.650	54.638	25.899	31.751	28.379	30.250
15	55.365	52.458	23.038	32.327	29.420	30.882
16	52.215	50.588	36.877	15.338	13.711	14.524
17	56.231	54.223	35.512	20.719	18.711	19.717
18	56.889	54.500	38.135	18.754	16.365	17.550
19	59.867	56.231	38.114	21.753	18.117	19.899
20	58.031	55.607	29.343	28.688	26.264	27.486
21	56.231	54.263	32.321	23.910	22.041	22.986
22	55.019	53.600	35.817	19.202	17.783	18.502
23	54.050	53.081	38.642	15.408	14.439	14.933
24	53.774	52.665	38.145	15.629	14.520	15.084
25	56.715	54.535	37.569	19.146	16.966	18.052
26	54.673	52.631	37.288	17.385	15.343	16.359
27	58.827	56.715	36.870	21.957	19.845	20.905
28	54.085	52.250	34.781	19.304	17.469	18.390
29	54.050	52.215	35.577	18.473	16.638	17.557
30	54.812	52.873	34.473	20.339	18.400	19.373

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Inlet Temp.	Test Liquid Outlet Temp.	Average Pipe Temp.	Δt_1	Δt_2	Log Mean Δt
Units	^oF	^oF	^oF	^oF	^oF	^oF
31	54.742	52.907	33.666	21.076	19.241	20.165
32	55.123	53.184	32.459	22.664	20.725	21.702
33	50.830	50.035	36.855	13.975	13.180	13.587
34	62.833	61.400	45.801	17.032	15.599	16.321
35	61.067	57.788	46.811	14.256	10.977	12.558
36	62.267	58.862	46.167	16.100	12.695	14.345
37	62.733	59.100	47.085	15.648	12.015	13.766
38	64.000	59.600	47.339	16.661	12.261	14.363
39	65.400	61.533	46.352	19.048	15.181	17.067
40	66.600	61.833	45.686	20.914	16.147	18.447
41	65.933	60.200	32.757	33.167	27.443	30.249
42	62.300	57.546	32.181	30.119	25.365	27.702
43	60.767	56.785	32.373	28.394	24.412	26.380
44	59.567	55.607	33.643	25.924	21.964	23.910
45	57.892	54.396	34.574	23.318	19.822	21.544
46	57.096	53.566	35.077	22.019	18.489	20.233
47	56.127	52.977	35.691	20.436	17.286	18.836
48	55.780	52.250	34.505	21.275	17.745	19.476
49	55.780	51.869	34.644	21.136	17.225	19.133
50	54.950	50.796	35.323	19.627	15.473	17.485
51	54.673	50.415	36.116	18.557	14.299	16.352
52	54.569	50.277	36.902	17.667	13.375	15.437
53	66.700	61.100	35.747	30.953	25.353	28.088
54	65.167	60.933	37.045	28.122	23.888	25.974
55	63.833	60.200	38.599	25.234	21.601	23.394
56	63.033	60.000	41.519	21.514	18.481	19.976
57	62.133	59.500	42.930	19.203	16.570	17.872
58	61.333	59.167	44.522	16.811	14.645	15.719
59	60.767	58.862	47.175	13.592	11.687	12.628
60	61.533	59.833	49.749	11.784	10.084	10.923

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Inlet Temp.	Test Liquid Outlet Temp.	Average Pipe Temp.	Δt_1	Δt_2	Log Mean Δt
Units	^oF	^oF	^oF	^oF	^oF	^oF
61	53.462	50.035	42.523	10.939	7.512	9.117
62	59.733	54.569	27.551	32.182	27.018	29.482
63	42.593	40.896	27.327	15.266	13.569	14.399
64	46.573	43.700	30.996	15.577	12.704	14.089
65	49.689	47.681	34.285	15.404	13.396	14.375
66	53.973	51.973	42.766	10.731	9.207	9.948
67	44.011	42.280	30.511	13.500	11.769	12.613
68	42.246	41.138	33.835	8.411	7.303	7.843
69	42.731	41.173	32.692	10.039	8.481	9.237
70	42.731	40.654	29.404	13.327	11.250	12.157
71	40.066	38.093	26.981	13.085	11.112	12.069
72	38.577	37.227	26.324	12.253	10.903	11.562
73	32.727	31.654	20.750	11.977	10.904	11.430
74	52.423	51.523	48.269	4.154	3.254	3.601
75	41.623	33.004	29.459	12.164	3.545	6.989
76	45.396	42.593	33.558	11.838	9.135	10.374
77	48.235	46.019	38.543	9.692	7.476	8.535
78	41.692	40.377	27.396	14.296	12.981	13.626
79	44.046	41.900	29.785	14.261	12.115	13.156
80	45.362	42.350	28.434	16.928	13.916	15.370
81	42.315	40.516	26.670	15.645	13.846	14.724
82	50.381	49.240	43.769	6.612	5.471	6.022
83	49.239	47.167	36.223	13.016	10.944	11.948
84	48.997	47.681	39.788	9.209	7.893	8.533
85	43.354	40.827	26.912	16.442	13.915	15.141
86	40.931	39.477	24.800	16.131	14.677	15.390
87	39.388	36.915	22.342	16.996	14.573	15.751
88	38.508	36.085	21.200	17.308	14.885	16.063
89	48.753	45.120	36.984	11.769	8.136	9.839
90	50.969	43.215	29.404	22.565	13.811	15.791

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Inlet Temp.	Test Liquid Outlet Temp.	Average Pipe Temp.	Δt_1	Δt_2	Log Mean Δt
Units	°F	°F	°F	°F	°F	°F
91	50.242	46.296	38.023	12.219	8.273	10.011
93	38.439	35.566	24.247	14.192	11.319	12.699
94	37.330	34.700	25.250	12.080	9.450	10.709
95	38.715	36.535	26.600	12.115	9.935	10.987
96	39.027	37.192	27.846	11.181	9.346	10.234
97	44.046	38.162	22.965	22.081	15.197	15.752
98	46.607	43.354	23.277	23.330	20.077	21.659
99	44.981	40.100	28.088	15.993	12.012	13.905
100	40.723	37.296	26.358	14.365	10.938	12.571
101	41.173	38.335	26.358	14.815	11.977	13.343
102	40.827	38.231	18.292	22.535	19.939	21.207
103	38.300	36.984	15.765	22.535	21.219	20.274
104	29.542	28.712	18.880	10.662	9.832	10.239
105	38.854	33.835	17.046	21.808	16.789	19.186
106	36.050	33.869	20.300	15.750	13.569	14.632
108	38.404	36.466	26.635	11.769	9.831	10.769
109	39.477	37.158	25.942	13.535	11.216	12.338
110	37.989	36.223	25.631	12.358	10.592	11.450
111	38.369	35.600	24.765	13.604	10.835	12.168
112	37.642	34.769	21.927	15.715	12.842	14.228
113	36.638	33.558	20.646	15.992	12.912	14.395
114	36.050	32.900	19.434	16.616	13.466	14.983
115	31.377	29.715	19.538	11.839	10.177	10.986
116	34.112	32.000	21.200	12.912	10.800	11.823
117	36.500	34.215	22.792	13.708	11.423	12.528
118	37.711	34.077	21.442	16.269	12.635	14.372
119	36.673	33.176	20.715	15.958	12.461	14.134
120	35.739	32.450	20.300	15.439	12.150	13.727
121	36.362	32.934	19.781	16.581	13.153	14.798
122	36.984	33.385	20.335	16.649	13.050	14.774

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Inlet Temp.	Test Liquid Outlet Temp.	Average Pipe Temp.	Δt_1	Δt_2	Log Mean Δt
Units	°F	°F	°F	°F	°F	°F
129	20.854	20.231	16.561	4.293	3.670	3.973
130	33.038	28.400	17.220	15.818	11.180	13.362
131	32.104	28.643	16.942	15.162	11.701	13.666
132	32.865	29.508	17.393	15.472	12.115	13.725
133	32.865	29.715	16.042	16.823	13.673	15.674
134	33.489	29.231	15.800	17.689	13.431	15.459
135	32.104	29.785	15.627	16.477	14.158	15.285
136	31.862	28.989	14.554	17.308	14.435	15.825
137	32.000	28.989	13.100	18.900	15.889	17.348
138	32.069	28.608	12.789	19.380	15.819	17.489
139	32.000	28.712	13.031	18.969	15.681	17.270
140	32.000	28.330	12.407	19.593	15.923	17.691
141	32.727	28.196	11.957	20.770	16.235	18.407
142	32.242	29.093	12.580	19.662	16.513	17.068
143	34.215	29.750	13.550	20.665	16.200	18.339
144	34.215	29.992	13.100	21.115	16.892	18.922
145	36.327	26.566	12.442	23.885	14.124	18.576
146	32.000	29.923	12.546	19.454	17.469	19.295
147	32.761	30.477	11.854	20.907	18.623	19.740
148	31.688	28.643	15.038	16.650	13.605	15.074
149	32.277	28.781	12.580	19.697	16.201	17.482
150	32.208	28.192	11.508	20.700	16.684	18.617
151	35.219	25.492	12.269	22.950	13.223	17.639
152	37.123	26.239	12.615	24.508	13.624	18.070
153	36.604	25.596	13.100	23.504	12.694	17.421
154	35.323	27.396	12.927	22.396	14.469	18.142
155	34.077	28.643	12.442	21.635	16.201	18.783
156	34.458	28.123	11.473	22.985	16.650	18.335

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Inlet Temp.	Test Liquid Outlet Temp.	Average Pipe Temp.	Δt_1	Δt_2	Log Mean Δt
Units	^oF	^oF	^oF	^oF	^oF	^oF
157	33.004	29.162	11.681	21.323	17.481	19.335
158	32.484	29.469	11.196	21.288	18.273	19.795
159	31.550	28.261	10.954	20.596	17.307	18.900
160	31.377	27.950	10.747	20.630	17.203	18.861
161	31.204	27.950	10.503	20.701	17.447	19.024
162	31.100	27.500	10.712	20.388	16.788	18.526
163	29.369	26.773	11.992	17.377	14.781	16.041
164	27.915	25.665	11.439	16.476	14.226	15.321
165	26.324	24.212	11.888	14.436	12.324	12.749
166	25.354	23.346	11.785	13.569	11.561	12.536
167	25.250	23.277	12.407	12.843	10.870	11.827
168	25.492	23.380	12.685	12.807	10.695	11.718
169	25.838	23.761	12.927	12.911	10.834	11.840
170	26.670	24.385	12.165	14.505	12.220	13.328
171	27.569	25.077	11.508	16.061	13.489	14.277
172	28.643	25.942	11.715	16.928	14.227	15.536
173	29.577	26.393	11.508	18.069	14.885	16.423
174	30.303	25.492	10.816	19.487	14.676	16.965
175	31.481	26.946	10.123	21.358	16.823	18.996

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Δt	Weight Test Liquid per Min.	Weight Test Liquid per Hr.	Average Test Liquid Temp.	Bulk Viscosity z_b	Bulk Viscosity Absolute μ_b
Units	°F	Lbs. per Min.	Lbs. per Hr.	°F	Centipoises	Lbs./(hr.)(ft.)
1	3.392	19.25	1155.0	54.742	2.15	5.20
2	2.978	29.87	1792.5	56.508	2.10	5.08
3	3.012	17.25	1035.0	52.717	2.20	5.32
4	5.146	9.13	547.5	56.727	2.09	5.06
5	5.240	25.25	1515.0	61.447	1.97	4.77
6	4.154	14.00	840.0	52.215	2.21	5.35
7	4.555	32.38	1942.5	58.890	2.04	4.94
8	3.115	12.00	720.0	53.843	2.17	5.25
9	2.570	32.38	1942.5	59.282	2.03	4.91
10	2.208	15.63	937.5	58.096	2.06	4.99
11	1.905	32.00	1920.0	49.360	2.29	5.54
12	2.596	17.19	1031.3	54.309	2.16	5.23
13	1.490	8.25	495.0	55.122	2.13	5.15
14	3.012	17.00	1020.0	56.144	2.11	5.11
15	2.907	21.00	1260.0	53.912	2.17	5.25
16	1.627	31.00	1860.0	51.402	2.24	5.42
17	2.008	16.75	1005.0	55.227	2.13	5.15
18	2.389	19.25	1155.0	55.695	2.12	5.13
19	3.636	16.63	997.5	58.049	2.06	4.99
20	2.424	11.63	697.5	56.819	2.09	5.06
21	1.869	14.56	873.8	55.297	2.13	5.15
22	1.419	17.81	1068.8	54.310	2.16	5.23
23	0.969	24.63	1477.5	53.566	2.18	5.28
24	1.109	31.63	1897.5	53.220	2.19	5.30
25	2.180	33.38	2002.5	55.625	2.12	5.13
26	2.042	26.63	1597.5	53.652	2.18	5.28
27	2.112	24.56	1473.8	57.771	2.07	5.01
28	1.835	21.63	1297.5	53.168	2.19	5.30
29	1.835	18.00	1080.0	53.133	2.19	5.30
30	1.939	17.19	1031.3	53.843	2.17	5.25

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Δt	Weight Test Liquid Per Min.	Weight Test Liquid per Hr.	Average Test Liquid Temp.	Bulk Viscosity z_b	Bulk Viscosity Absolute μ_b
Units	^oF	Lbs. per Min.	Lbs. per Hr.	^oF	Centipoises	$\frac{Lbs.}{(hr.)(ft.)}$
31	1.835	15.50	930.0	53.825	2.17	5.25
32	1.939	14.00	840.0	54.154	2.16	5.23
33	0.795	33.00	1980.0	50.433	2.27	5.49
34	1.433	33.00	1980.0	62.117	1.96	4.74
35	3.279	31.88	1912.5	59.428	2.06	4.99
36	3.405	24.88	1492.5	60.565	2.00	4.84
37	3.633	24.00	1440.0	60.917	1.99	4.82
38	4.400	18.38	1102.5	61.800	1.97	4.77
39	3.867	14.50	870.0	63.467	1.93	4.67
40	4.767	12.38	742.5	64.217	1.91	4.62
41	5.733	8.88	532.5	63.067	1.94	4.69
42	4.754	11.00	660.0	59.923	2.01	4.86
43	3.982	12.88	772.5	58.776	2.04	4.94
44	3.960	15.50	930.0	57.587	2.07	5.01
45	3.496	17.00	1020.0	56.144	2.11	5.11
46	3.530	18.38	1102.5	55.331	2.13	5.15
47	3.150	20.50	1230.0	54.552	2.15	5.20
48	3.530	23.13	1387.5	54.015	2.16	5.23
49	3.911	26.13	1567.5	53.825	2.17	5.25
50	4.154	27.25	1635.0	52.873	2.19	5.30
51	4.258	31.88	1912.5	52.544	2.20	5.32
52	4.292	32.00	1920.0	52.423	2.21	5.35
53	5.600	8.00	480.0	63.900	1.92	4.65
54	4.234	9.50	570.0	63.050	1.94	4.69
55	3.633	13.25	795.0	62.017	1.96	4.74
56	3.033	15.75	945.0	61.517	1.98	4.79
57	2.633	19.13	1147.5	60.816	1.99	4.82
58	2.166	22.25	1335.0	60.260	2.01	4.86
59	1.905	29.25	1755.0	59.815	2.02	4.89
60	1.700	32.13	1927.5	60.683	1.99	4.82

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Δt	Weight Test Liquid per Min.	Weight Test Liquid per Hr.	Average Test Liquid Temp.	Bulk Viscosity z_b	Bulk Viscosity Absolute μ_b
Units	^oF	Lbs. per Min.	Lbs. per Hr.	^oF	Centipoises	Lbs. / (hr.)(ft.)
61	3.427	32.88	1973.0	51.749	2.23	5.40
62	5.164	18.75	1125.0	57.151	2.08	5.03
63	1.697	31.38	1883.0	41.745	2.55	6.17
64	2.873	26.63	1598.0	45.137	2.43	5.88
65	2.008	29.25	1755.0	48.685	2.31	5.59
66	1.524	29.25	1755.0	52.735	2.20	5.32
67	1.731	18.63	1118.0	43.146	2.50	6.05
68	1.108	15.38	922.5	41.692	2.55	6.17
69	1.558	11.75	705.0	41.952	2.54	6.15
70	2.077	8.13	487.5	41.693	2.55	6.17
71	1.973	6.38	382.5	39.080	2.65	6.41
72	1.350	27.63	1658.0	37.902	2.69	6.51
73	1.073	36.75	2205.0	32.191	2.97	7.19
74	0.900	24.00	2040.0	51.973	2.22	5.37
75	8.619	26.00	1560.0	37.314	2.72	6.58
76	2.803	20.88	1253.0	43.995	2.47	5.98
77	2.216	30.63	1838.0	47.127	2.36	5.71
78	1.315	19.38	1163.0	41.035	2.58	6.24
79	2.146	25.75	1545.0	42.973	2.50	6.05
80	3.012	12.38	742.0	43.856	2.47	5.98
81	1.799	15.25	915.0	41.416	2.56	6.20
82	1.141	15.50	930.0	49.811	2.28	5.52
83	2.072	18.50	1110.0	48.203	2.33	5.64
84	1.316	13.38	802.5	48.339	2.33	5.64
85	2.527	8.63	517.5	42.091	2.54	6.15
86	1.454	9.75	585.0	40.204	2.61	6.32
87	2.423	11.00	660.0	38.127	2.69	6.51
88	2.423	14.25	855.0	37.297	2.72	6.58
89	3.633	28.75	1725.0	46.937	2.37	5.74
90	7.754	5.25	315.0	47.092	2.36	5.72

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Δt	Weight Test Liquid per Min.	Weight Test Liquid per Hr.	Average Test Liquid Temp.	Bulk Viscosity Z_b	Bulk Viscosity Absolute μ_b
Units	^oF	Lbs. per Min.	Lbs. per Hr.	^oF	Centipoises	$\frac{\text{Lbs.}}{(\text{hr.})(\text{ft.})}$
91	3.946	8.13	487.5	48.269	2.33	5.64
93	2.873	9.75	585.0	37.003	2.74	6.63
94	2.630	9.75	585.0	36.015	2.78	6.73
95	2.180	14.25	855.0	37.625	2.71	6.56
96	1.835	13.00	780.0	38.110	2.69	6.51
97	5.884	6.00	360.0	41.104	2.57	6.22
98	3.253	6.00	360.0	44.981	2.43	5.88
99	3.981	9.13	547.5	42.091	2.54	6.15
100	3.427	12.75	765.0	39.010	2.65	6.41
101	2.838	19.75	1186.0	39.754	2.62	6.34
102	2.596	17.35	1028.0	39.529	2.63	6.36
103	1.316	16.25	975.0	37.642	2.71	6.56
104	0.830	28.00	1680.0	29.127	3.15	7.62
105	5.019	28.25	1695.0	36.345	2.77	6.70
106	2.181	30.75	1845.0	34.960	2.82	6.82
108	1.938	17.88	1073.0	37.435	2.72	6.58
109	2.319	14.25	855.0	38.318	2.68	6.49
110	1.766	11.63	697.5	37.106	2.73	6.61
111	2.769	9.50	570.0	36.985	2.73	6.61
112	2.873	8.88	532.5	36.206	2.97	7.19
113	3.080	7.75	465.0	35.098	2.82	6.82
114	3.150	7.13	427.5	24.475	2.85	6.90
115	1.662	27.50	1650.0	30.546	3.06	7.41
116	2.112	26.50	1590.0	33.056	2.92	7.07
117	2.285	21.38	1283.0	35.358	2.80	6.78
118	3.634	15.25	915.0	35.894	2.78	6.73
119	3.497	12.63	757.5	34.925	2.84	6.85
120	3.289	10.63	637.5	34.095	2.87	6.95
121	3.428	8.75	525.0	34.648	2.84	6.87
122	3.599	6.63	397.5	35.185	2.82	6.82

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Δt	Weight Test Liquid Per Min.	Weight Test Liquid Per Hr.	Average Test Liquid Temp.	Bulk Viscosity z_b	Bulk Viscosity Absolute μ_b
Units	^oF	Lbs. Per Mind.	Lbs. Per Hr.	^oF	Centi-poises	$\frac{Lbs.}{(hr.)(ft.)}$
129	0.623	25.25	1515.0	20.543	3.811	9.223
130	4.638	31.50	1890.0	30.719	3.051	7.383
131	3.461	25.25	1515.0	30.274	3.078	7.336
132	3.357	13.38	802.5	31.187	3.024	7.318
133	3.250	19.75	1185.0	31.290	3.020	7.308
134	4.258	21.00	1260.0	31.360	3.016	7.299
135	2.319	23.73	1483.5	30.945	3.039	7.354
136	2.873	14.00	840.0	30.426	3.068	7.425
137	3.011	15.50	930.0	30.495	3.064	7.415
138	3.461	16.00	960.0	30.339	3.073	7.437
139	3.288	15.50	930.0	30.356	3.072	7.434
140	3.670	14.73	883.5	30.165	3.083	7.461
141	4.535	12.73	763.5	30.459	3.067	7.422
142	3.149	11.50	690.0	30.668	3.054	7.391
143	4.465	9.50	570.0	31.983	2.980	7.212
144	4.223	8.25	495.0	32.104	2.970	7.187
145	9.761	7.13	427.5	31.447	3.005	7.272
146	2.077	9.31	558.8	30.967	3.038	7.352
147	2.284	9.31	558.8	31.619	2.992	7.241
148	3.045	24.75	1485.0	30.166	3.083	7.461
149	3.496	12.00	720.0	30.529	3.062	7.410
150	4.016	7.25	435.0	30.200	3.080	7.454
151	9.727	1.88	112.5	30.356	3.072	7.434
152	10.884	2.25	135.0	31.681	2.994	7.246
153	11.008	2.50	150.0	31.100	3.028	7.328
154	7.927	4.25	255.0	31.360	3.014	7.294
155	5.434	6.63	397.5	31.360	3.014	7.294
156	6.335	7.31	438.8	31.291	3.019	7.306

HEAT TRANSFER DATA (Continued)

Run No.	Test Liquid Δt	Weight Test Liquid per Min.	Weight Test Liquid per Hr.	Average Test Liquid Temp.	Bulk Viscosity Z_b	Bulk Viscosity Absolute μ_b
Units	^{o}F	Lbs. per Min.	Lbs. per Hr.	^{o}F	Centi-poises	$\frac{Lbs.}{(hr.)(ft.)}$
157	3.842	9.13	547.5	31.083	3.028	7.328
158	3.015	8.63	517.5	30.977	3.040	7.357
159	3.289	10.75	645.0	29.906	3.100	7.502
160	3.427	11.75	705.0	29.664	3.113	7.534
161	3.254	11.63	697.5	29.577	3.120	7.550
162	3.600	16.00	960.0	29.300	3.135	7.587
163	2.596	23.75	1425.0	28.071	3.210	7.768
164	2.250	32.00	1920.0	26.790	3.300	7.986
165	2.112	36.00	2160.0	25.268	3.412	8.257
166	2.008	36.00	2160.0	24.350	3.483	8.429
167	1.973	35.00	2100.0	24.264	3.490	8.446
168	2.112	28.25	1695.0	24.436	3.475	8.410
169	2.077	26.00	1560.0	24.800	3.448	8.344
170	2.285	18.75	1125.0	25.528	3.400	8.228
171	2.492	13.75	825.0	26.323	3.337	8.076
172	2.701	10.25	615.0	27.293	3.266	7.904
173	3.184	9.00	540.0	27.985	3.220	7.792
174	4.811	7.25	435.0	27.898	3.223	7.800
175	4.535	3.00	180.0	29.214	3.139	7.596

HEAT TRANSFER DATA (Continued)

Run No.	Film Temp.	Film Viscosity z_f	Film Viscosity Absolute μ_f	Q	h	$\frac{hD}{k}$
Units	^oF	Centipoises	$\frac{Lbs.}{(hr.)(ft.)}$	B.T.U. per Hr.	B.T.U. per (hr.)(sq. ft.)(^oF)	None
1	47.190	2.36	5.71	1971	79.4	79.2
2	48.027	2.34	5.66	2695	96.5	96.3
3	45.041	2.43	5.88	1570	62.0	61.9
4	47.796	2.34	5.66	1419	48.5	48.4
5	48.159	2.33	5.64	3995	91.5	91.3
6	41.069	2.57	6.22	1760	48.0	47.9
7	49.136	2.30	5.57	4470	139.2	139.0
8	43.926	2.47	5.98	1130	34.6	34.5
9	53.331	2.18	5.28	2520	128.8	128.6
10	52.932	2.19	5.30	1042	61.4	61.3
11	42.036	2.54	6.15	1842	76.4	76.2
12	41.441	2.56	6.20	1350	31.8	31.7
13	37.287	2.72	6.58	2870	49.2	49.1
14	41.022	2.58	6.24	1545	31.0	30.9
15	38.475	2.67	6.46	1848	36.3	36.2
16	44.140	2.46	5.95	1525	63.6	63.5
17	45.370	2.42	5.86	1020	31.3	31.2
18	46.915	2.37	5.74	1390	48.0	47.9
19	48.082	2.33	5.64	1825	55.6	55.5
20	43.081	2.50	6.05	851	18.7	18.7
21	43.809	2.48	6.00	822	21.6	21.5
22	45.064	2.43	5.88	763	25.0	24.9
23	46.104	2.40	5.81	720	29.2	29.1
24	45.683	2.35	5.69	1060	42.6	42.5
25	46.597	2.38	5.76	2200	73.9	73.7
26	45.470	2.42	5.86	1640	60.9	60.8
27	47.321	2.36	5.71	1568	45.5	45.4
28	43.975	2.47	5.98	1200	39.6	39.5
29	44.355	2.46	5.95	998	34.4	34.3
30	44.158	2.46	5.95	1010	31.6	31.5

HEAT TRANSFER DATA (Continued)

Run No.	Film Temp.	Film Viscosity z_f	Film Viscosity Absolute μ_f	Q	h	$\frac{hD}{k}$
Units	°F	Centipoises	$\frac{Lbs.}{(hr.)(ft.)}$	B.T.U. per Hr.	B.T.U. per (hr.)(sq. ft.)(°F)	None
31	43.746	2.48	6.00	859	25.8	25.7
32	43.307	2.49	6.03	821	22.9	22.8
33	43.644	2.48	6.00	793	35.4	35.3
34	53.959	2.17	5.25	1430	53.1	53.0
35	53.119	2.19	5.30	3160	152.4	152.1
36	53.366	2.18	5.28	2560	108.0	107.8
37	54.001	2.17	5.25	2640	116.3	116.1
38	54.570	2.15	5.20	2445	103.2	103.0
39	54.910	2.14	5.18	1695	60.1	60.0
40	54.952	2.14	5.18	1784	58.6	58.5
41	47.912	2.34	5.66	1539	30.8	30.7
42	46.052	2.40	5.81	1581	34.6	34.5
43	45.575	2.41	5.83	1550	35.7	35.6
44	45.615	2.41	5.83	1854	47.1	47.0
45	45.359	2.42	5.86	1797	50.5	50.4
46	45.204	2.43	5.88	1960	58.7	58.6
47	45.122	2.43	5.88	1950	62.8	62.7
48	44.260	2.46	5.95	2470	77.0	76.8
49	44.235	2.46	5.95	3090	98.0	97.8
50	44.098	2.46	5.95	3420	118.6	118.3
51	44.330	2.46	5.95	4110	152.4	152.1
52	44.663	2.44	5.90	4150	163.0	162.7
53	49.824	2.28	5.52	1352	29.2	29.1
54	50.048	2.28	5.52	1214	28.3	28.2
55	50.308	2.27	5.49	1453	37.7	37.6
56	51.518	2.23	5.40	1441	43.8	43.7
57	51.874	2.22	5.37	1520	51.6	51.5
58	52.386	2.21	5.35	1458	56.2	56.1
59	53.495	2.18	5.28	1682	80.8	80.6
60	55.216	2.13	5.15	1650	91.5	91.3

HEAT TRANSFER DATA (Continued)

Run No.	Film Temp.	Film Viscosity z_f	Film Viscosity Absolute μ_f	Q	h	$\frac{hD}{k}$
Units	°F	Centipoises	$\frac{\text{Lbs.}}{(\text{hr.})(\text{ft.})}$	B.T.U. per Hr.	B.T.U. per (hr.)(sq. ft.)(°F)	None
61	47.136	2.36	5.71	3408.0	226.50	226.30
62	42.351	2.53	6.12	2928.0	60.19	60.12
63	34.536	2.85	6.90	1611.0	67.78	67.71
64	38.067	2.69	6.51	2314.0	99.53	99.42
65	41.485	2.56	6.20	1776.0	74.88	74.80
66	47.751	2.28	5.52	1348.0	82.12	82.03
67	36.829	2.74	6.63	975.4	46.87	46.82
68	37.764	2.70	6.53	515.2	39.71	39.76
69	37.322	2.72	6.58	553.6	36.32	36.28
70	35.549	2.79	6.75	510.3	25.23	25.20
71	33.031	2.92	7.07	380.4	19.10	19.08
72	32.113	2.97	7.19	1128.0	59.13	59.06
73	26.471	3.32	8.03	1192.0	63.23	63.16
74	50.121	2.27	5.49	925.3	152.20	152.00
75	33.387	2.90	7.02	6777.0	587.60	586.90
76	38.777	2.66	6.44	1770.0	103.40	103.30
77	42.835	2.51	6.07	2053.0	145.70	145.60
78	34.216	2.86	6.92	770.8	34.28	34.25
79	36.379	2.76	6.68	1671.0	76.98	76.89
80	36.145	2.77	6.70	1137.0	44.44	44.39
81	34.043	2.87	6.95	829.6	34.15	34.11
82	46.790	2.37	5.74	534.3	53.78	53.72
83	42.213	2.53	6.12	1186.0	58.80	58.73
84	44.064	2.46	5.95	532.3	37.80	37.76
85	34.502	2.85	6.90	659.1	26.38	26.35
86	32.502	2.95	7.14	428.7	16.88	16.86
87	30.235	3.08	7.45	806.0	31.01	30.98
88	29.249	3.14	7.60	1044.0	39.39	39.35
89	41.961	2.54	6.15	3159.0	194.60	194.30
90	38.248	2.68	6.49	1231.0	47.25	47.19

HEAT TRANSFER DATA (Continued)

Run No.	Film Temp.	Film Viscosity Z_f	Film Viscosity Absolute μ_f	Q	h	$\frac{hD}{k}$
Units	°F	Centipoises	$\frac{\text{Lbs.}}{(\text{hr.})(\text{ft.})}$	B.T.U. per Hr.	B.T.U. per (hr.)(sq. ft.)(°F)	None
91	43.146	2.50	6.05	969.5	58.08	59.02
93	30.625	3.06	7.41	847.1	40.43	40.38
94	30.633	3.06	7.41	775.4	43.89	43.84
95	32.113	2.97	7.19	939.4	51.82	51.76
96	32.978	2.92	7.07	721.4	42.72	42.67
97	32.035	2.98	7.21	1068.0	41.08	41.03
98	34.129	2.87	6.95	590.2	16.52	16.50
99	35.090	2.82	6.82	1099.0	47.88	47.83
100	32.684	2.94	7.11	1321.0	63.70	63.63
101	33.056	2.92	7.07	1695.0	76.99	76.90
102	28.911	3.16	7.65	1345.0	38.44	38.40
103	26.704	3.31	8.01	373.4	11.16	11.15
104	24.004	3.51	8.49	702.8	41.60	41.55
105	26.696	3.31	8.01	4288.0	135.40	135.40
106	27.630	3.24	7.84	2028.0	84.00	83.91
108	62.035	1.96	4.74	1048.0	58.98	58.92
109	32.130	2.97	7.19	999.3	49.09	49.03
110	31.369	3.01	7.28	620.8	32.86	32.82
111	30.875	3.04	7.36	795.5	39.62	39.58
112	29.067	3.15	7.62	771.1	32.84	32.81
113	27.872	3.23	7.82	721.8	30.39	30.36
114	26.955	3.29	7.96	678.7	27.45	27.42
115	25.042	3.51	8.49	1382.0	76.25	76.16
116	27.128	3.28	7.94	1692.0	86.76	86.66
117	29.075	3.15	7.62	1478.0	71.48	71.39
118	28.668	3.18	7.70	1676.0	70.67	70.59
119	27.820	3.23	7.82	1335.0	57.25	57.18
120	27.198	3.27	7.91	1057.0	46.66	46.60
121	27.215	3.27	7.91	907.1	37.15	37.11
122	27.760	3.23	7.82	721.0	29.58	29.55

HEAT TRANSFER DATA (Continued)

Run No.	Film Temp.	Film Viscosity z_f	Film Viscosity Absolute μ_f	Q	h	$\frac{hD}{k}$
Units	°F	Centipoises	Lbs. / (hr.)(ft.)	B.T.U. per Hr.	B.T.U. per (hr.)(sq. ft.)(°F)	None
129	18.552	4.00	9.67	475.7	72.66	72.51
130	23.970	3.52	8.51	4418.0	200.62	200.62
131	23.608	3.54	8.57	2642.7	117.34	117.34
132	24.290	3.49	8.44	1357.8	60.04	59.97
133	23.666	3.54	8.57	1941.1	75.15	75.06
134	23.580	3.55	8.59	2704.0	106.14	106.02
135	23.286	3.57	8.64	1733.9	68.83	68.75
136	22.490	3.64	8.81	1216.3	46.64	46.58
137	21.798	3.70	8.95	1411.3	49.37	49.31
138	21.564	3.72	9.01	1674.6	58.10	58.03
139	21.694	3.71	8.98	1541.2	54.15	54.09
140	21.296	3.74	9.06	1634.2	56.05	55.99
141	21.208	3.75	9.07	1101.1	36.30	36.26
142	21.624	3.71	8.99	1036.2	36.84	36.80
143	22.767	3.62	8.76	1282.7	42.44	42.39
144	22.602	3.63	8.78	1042.9	33.45	33.41
145	22.445	3.64	8.81	2103.1	68.70	68.62
146	21.757	3.71	8.98	584.9	18.40	18.33
147	21.737	3.71	8.97	643.2	19.77	19.75
148	22.602	3.63	8.78	2279.0	91.74	91.14
149	21.555	3.72	9.01	1239.8	43.03	42.98
150	20.854	3.78	9.15	880.5	28.70	28.67
151	21.313	3.74	9.05	551.5	18.97	18.95
152	22.148	3.67	8.88	723.7	24.25	24.22
153	22.100	3.68	8.89	832.2	28.99	28.95
154	22.144	3.67	8.88	1018.8	34.08	34.04
155	21.901	3.69	8.93	1088.7	35.17	35.13
156	21.382	3.74	9.05	1400.9	46.37	46.31

HEAT TRANSFER DATA (Continued)

Run No.	Film Temp.	Film Viscosity z_f	Film Viscosity Absolute μ_f	Q	h	$\frac{hD}{k}$
Units	°F	Centipoises	$\frac{\text{Lbs.}}{(\text{hr.})(\text{ft.})}$	B.T.U. per Hr.	B.T.U. per (hr.)(sq. ft.)(°F)	None
157	21.392	3.74	9.05	1060.2	33.27	33.23
158	21.087	3.77	9.12	786.4	24.11	24.08
159	20.430	3.82	9.24	1069.2	54.40	54.34
160	20.206	3.84	9.29	1217.7	39.18	39.13
161	20.040	3.86	9.34	1143.9	36.49	36.45
162	20.006	3.86	9.34	1741.8	57.05	56.99
163	20.032	3.86	9.34	1864.5	70.53	70.45
164	19.115	3.94	9.54	2177.3	86.04	85.94
165	28.578	3.18	7.70	2299.2	109.43	109.31
166	18.068	4.04	9.78	2186.0	105.81	105.69
167	18.336	4.02	9.72	2088.2	107.14	107.02
168	18.561	4.00	9.67	1804.3	93.43	93.33
169	18.864	3.97	9.60	1633.1	83.69	83.60
170	18.847	3.97	9.60	1295.6	58.99	58.92
171	18.916	3.96	9.58	1036.2	44.04	43.90
172	19.504	3.90	9.45	837.2	32.70	32.66
173	19.747	3.88	9.40	866.6	32.02	31.98
174	19.357	3.92	9.49	1054.8	37.73	37.69
175	19.669	3.89	9.41	411.2	13.14	13.13

HEAT TRANSFER DATA (Continued)

Run No.	$\frac{C_p \mu_f}{k}$	$\left(\frac{C_p \mu_f}{k}\right)^{0.3}$	$\frac{\frac{hD}{k}}{\left(\frac{C_p \mu_f}{k}\right)^{0.3}}$	$\frac{DG}{\mu_b}$
Units	None	None	None	None
1	32.9	2.85	27.8	3240.0
2	32.6	2.84	33.9	5140.0
3	33.9	2.88	21.5	2840.0
4	32.6	2.84	17.0	1580.0
5	32.5	2.84	32.1	4630.0
6	35.8	2.93	16.4	2290.0
7	32.1	2.90	49.1	5730.0
8	34.4	2.89	11.9	2000.0
9	30.4	2.79	46.2	5760.0
10	30.5	2.79	21.9	2740.0
11	35.4	2.92	26.1	5050.0
12	35.7	2.92	10.8	2870.0
13	37.9	2.98	16.5	1400.0
14	35.9	2.93	10.6	2910.0
15	37.2	2.96	12.2	3500.0
16	34.3	2.89	22.0	5000.0
17	33.8	2.87	10.9	2840.0
18	33.1	2.86	16.8	3280.0
19	32.5	2.84	19.5	2910.0
20	34.9	2.90	6.44	2010.0
21	34.6	2.89	7.43	2470.0
22	33.9	2.88	8.66	2980.0
23	33.5	2.87	10.2	4080.0
24	32.8	2.85	14.9	5220.0
25	33.2	2.86	25.8	5690.0
26	33.8	2.87	21.2	4410.0
27	32.9	2.85	15.9	4290.0
28	34.4	2.89	13.7	3570.0
29	34.3	2.89	11.9	2970.0
30	34.3	2.89	10.9	2860.0

HEAT TRANSFER DATA (Continued)

Run No.	$\frac{C_p \mu_f}{k}$	$\left(\frac{C_p \mu_f}{k}\right)^{0.3}$	$\frac{hD/k}{\left(\frac{C_p \mu_f}{k}\right)^{0.3}}$	$\frac{DG}{\mu_f}$
Units	None	None	None	None
31	34.6	2.89	8.88	2580.0
32	34.7	2.90	7.87	2340.0
33	34.6	2.89	12.2	5260.0
34	30.2	2.78	19.1	6090.0
35	30.5	2.79	54.5	5580.0
36	30.4	2.79	39.1	4450.0
37	30.2	2.78	41.8	4350.0
38	30.0	2.77	37.2	3370.0
39	29.8	2.77	21.7	2710.0
40	29.8	2.77	21.1	2340.0
41	32.6	2.84	10.8	1650.0
42	33.5	2.87	12.0	1980.0
43	33.6	2.87	12.4	2280.0
44	33.6	2.87	16.4	2710.0
45	33.8	2.87	17.5	2910.0
46	33.9	2.88	20.4	3120.0
47	33.9	2.88	21.8	3450.0
48	34.3	2.89	26.6	3870.0
49	34.3	2.89	33.9	4350.0
50	34.3	2.89	41.0	4490.0
51	34.3	2.89	52.7	5240.0
52	34.0	2.88	56.5	5230.0
53	31.8	2.82	10.3	1500.0
54	31.8	2.82	9.99	1770.0
55	31.6	2.82	13.3	2440.0
56	31.1	2.80	15.6	2870.0
57	30.9	2.80	18.4	3470.0
58	30.8	2.80	20.1	4000.0
59	30.4	2.79	28.9	5230.0
60	29.7	2.77	33.0	5830.0

HEAT TRANSFER DATA (Continued)

Run No.	$\frac{C_p \mu_f}{k}$	$\left(\frac{C_p \mu_f}{k}\right)^{0.3}$	$\frac{hD/k}{\left(\frac{C_p \mu_f}{k}\right)^{0.3}}$	$\frac{DG}{\mu_f}$
Units	None	None	None	None
61	32.9	2.85	79.4	5320
62	35.3	2.91	20.7	3260
63	39.7	3.02	22.4	4450
64	37.5	2.97	33.5	3960
65	35.7	2.92	25.6	3570
66	31.8	2.82	29.1	4810
67	38.2	2.98	15.7	2690
68	37.6	2.97	13.4	2180
69	37.9	2.98	12.2	1670
70	38.9	3.00	8.4	1150
71	40.7	3.04	6.3	869
72	41.4	3.06	19.3	3710
73	46.3	3.16	20.0	4470
74	31.6	2.82	53.9	5540
75	40.4	3.03	193.5	3450
76	37.1	2.96	35.0	3050
77	35.0	2.90	50.1	4690
78	39.9	3.02	11.3	2720
79	38.5	2.99	25.7	3720
80	38.6	2.99	14.8	1810
81	40.0	3.03	11.3	2150
82	33.1	2.86	18.8	2450
83	35.3	2.91	20.2	2870
84	34.3	2.89	13.1	2070
85	39.7	3.02	8.7	1230
86	41.1	3.06	5.5	1350
87	42.9	3.09	10.0	1480
88	43.8	3.11	12.7	1890
89	35.4	2.91	66.6	4380
90	37.4	2.96	15.9	802

HEAT TRANSFER DATA (Continued)

Run No.	$\frac{C_p \mu_f}{k}$	$\left(\frac{C_p \mu_f}{k}\right)^{0.3}$	$\frac{\frac{hD}{k}}{\left(\frac{C_p \mu_f}{k}\right)^{0.3}}$	$\frac{DG}{\mu_b}$
Units	None	None	None	None
91	34.9	2.90	20.0	1260
93	42.7	3.08	13.1	1290
94	42.7	3.08	14.2	1270
95	41.4	3.06	16.9	1900
96	40.7	3.04	14.0	1750
97	41.5	3.06	13.4	843
98	40.0	3.03	5.5	892
99	39.3	3.01	15.9	1360
100	40.9	3.05	20.9	1740
101	40.7	3.04	25.3	2720
102	44.1	3.11	12.3	2360
103	46.1	3.16	3.5	2170
104	48.9	3.21	12.9	3210
105	46.1	3.16	42.9	3690
106	45.2	3.14	26.8	3940
108	27.3	2.70	21.9	2380
109	41.4	2.06	16.0	1920
110	41.9	3.14	10.7	1540
111	42.4	3.08	12.9	1260
112	43.9	3.11	10.6	1080
113	45.0	3.13	9.7	993
114	45.9	3.15	8.7	924
115	48.9	3.21	23.7	3240
116	45.7	3.15	27.5	3280
117	43.9	3.11	23.0	2760
118	44.4	3.12	22.6	1980
119	45.0	3.13	18.3	1610
120	45.6	3.15	14.8	1340
121	45.6	3.15	11.8	1110
122	45.0	3.13	9.4	849

HEAT TRANSFER DATA (Continued)

Run No.	$\frac{C_p \mu_f}{k}$	$\left(\frac{C_p \mu_f}{k}\right)^{0.3}$	$\frac{\frac{hD}{k}}{\left(\frac{C_p \mu_f}{k}\right)^{0.3}}$	$\frac{DG}{\mu_b}$
Units	None	None	None	None
129	55.69	3.34	21.8	2393.1
130	49.01	3.21	62.3	3729.1
131	49.37	3.22	36.4	2963.9
132	48.62	3.21	18.7	1597.5
133	49.35	3.22	23.3	2362.1
134	49.47	3.22	32.9	2514.9
135	49.79	3.23	21.3	2938.6
136	50.74	3.25	14.3	1648.2
137	51.56	3.26	15.1	1826.7
138	51.87	3.27	17.8	1880.6
139	51.72	3.27	16.6	1822.4
140	52.16	3.28	17.1	1725.1
141	52.24	3.28	11.1	1498.6
142	51.76	3.27	11.3	1360.1
143	50.43	3.24	10.4	1151.5
144	50.57	3.25	10.3	993.2
145	50.75	3.25	21.1	858.4
146	51.66	3.27	5.6	1107.2
147	51.69	3.27	6.0	1124.2
148	50.57	3.25	28.2	2899.6
149	51.90	3.27	13.1	1415.5
150	52.72	3.29	8.7	850.2
151	52.15	3.28	5.8	220.5
152	51.13	3.26	7.4	271.4
153	51.23	3.26	8.9	298.2
154	51.14	3.26	10.5	509.3
155	51.44	3.26	10.8	793.9
156	52.11	3.27	14.1	874.9

HEAT TRANSFER DATA (Concluded)

Run No.	$\frac{C_p \mu_f}{k}$	$\left(\frac{C_p \mu_f}{k}\right)^{0.3}$	$\frac{\frac{hD}{k}}{\left(\frac{C_p \mu_f}{k}\right)^{0.3}}$	$\frac{DG}{\mu_b}$
Units	None	None	None	None
157	52.11	3.27	10.1	1088.5
158	52.52	3.28	7.3	1024.8
159	53.25	3.30	16.5	1252.5
160	53.53	3.30	11.9	1363.3
161	53.78	3.31	11.0	1345.8
162	53.79	3.31	17.2	1843.4
163	53.78	3.31	21.3	2672.4
164	54.92	3.33	25.9	3502.4
165	44.37	3.12	35.0	3810.9
166	56.31	3.35	31.5	3648.3
167	55.97	3.27	32.7	3622.2
168	55.70	3.34	27.9	2936.3
169	55.31	3.33	25.1	2723.6
170	55.31	3.33	17.7	1991.9
171	55.19	3.33	13.2	1488.3
172	55.42	3.32	9.8	1133.6
173	54.13	3.31	9.7	1009.5
174	54.67	3.32	11.3	812.5
175	54.22	3.31	4.0	345.2

viscosity was read from the curve at this temperature. The viscosities in centipoises were converted to absolute viscosities by multiplying by 2.42.

The quantity of heat transferred per hour was calculated as the product of the temperature decrease of the test liquid, the specific heat, and the weight rate of flow per hour. The film coefficient, h, was calculated by means of Newton's law, $Q/\theta = h A \Delta t$, in which Q/θ is the quantity of heat transferred per hour, A is the heat transfer area, and Δt is the temperature differential. In this case the area of heat transfer was taken as the inside area of the six feet test section. The logarithmic mean temperature drop was also used in this calculation.

The film coefficient, physical properties, and characteristics were used to calculate the Nusselt and Prandtl groups. The Reynolds number was calculated directly from the weight rate of flow and the bulk viscosity as $4w/\pi D \mu_b$.

The data of Run No. 61 are used in the following sample calculation:

Δt_1:	$\Delta t_1 = t_1 - t$
	$= 53.462 - 42.523$
	$\Delta t_1 = 10.939^{o}F$
Δt_2:	$\Delta t_2 = t_2 - t$
	$= 50.035 - 42.523$
	$\Delta t_2 = 7.512^{o}F$
Log Mean Δt	$\Delta t_m = \dfrac{t_1 - t_2}{\ln \dfrac{t_1}{t_2}}$
	$= \dfrac{10.939 - 7.512}{2.303 \log \dfrac{10.939}{7.512}}$
	$\Delta t_m = 9.117^{o}F$
Test Liquid Δt	$\Delta t = t_1 - t_2$
	$= 53.462 - 50.035$
	$\Delta t = 3.427^{o}F.$
Weight Rate of Flow	$W = w \times 60$
	$= 32.88 \times 60$
	$W = 1973.0$ lbs./hr.
Average Test Liquid Temperature	$t_a = (t_1 + t_2)/2$
	$= (53.462 + 50.035)/2$
	$t_a = 51.749^{o}F.$

Absolute Viscosity	$\mu = z \times 2.42$
	$\mu_b = 2.23 \times 2.42$
	$\mu_b = 5.40$ lbs./(hr.)(ft.)
	$\mu_f = 2.36 \times 2.42$
	$\mu_f = 5.71$ lbs./(hr.)(ft.)
Film Temperature	$t_f = (t + t_a)/2$
	$= (42.523 + 51.749)/2$
	$t_f = 47.136^{\circ}$F.
Heat Transferred	$Q = W \times \Delta t \times C_p$
	$= 1973.0 \times 3.427 \times 0.504$
	$Q = 3408.0$ B.T.U. per hr.
Film Coefficient	$Q = h \times A \times \Delta t_m$
	$h = Q/(A \times \Delta t_m)$
	$= 3408.0/(1.65 \times 9.117)$
	$h = 226.50$ B.T.U./(hr.)(sq.ft.)($^{\circ}$F.)
Nusselt Number	$Nu = hD/k$
	$= 226.5 \times 0.0874/0.0875$
	$Nu = 226.30$

Prandtl Number

$$Pr = C_p\mu_f/k$$
$$= 0.504 \times 5.71/0.875$$
$$= 32.9$$
$$Pr^{0.3} = 32.9^{0.3}$$
$$= 2.85$$

Ratio of Nusselt to Prandtl Number to 0.3 power

$$\frac{hD/k}{(C_p\mu_f/k)^{0.3}} = \frac{226.3}{2.85}$$
$$= 79.4$$

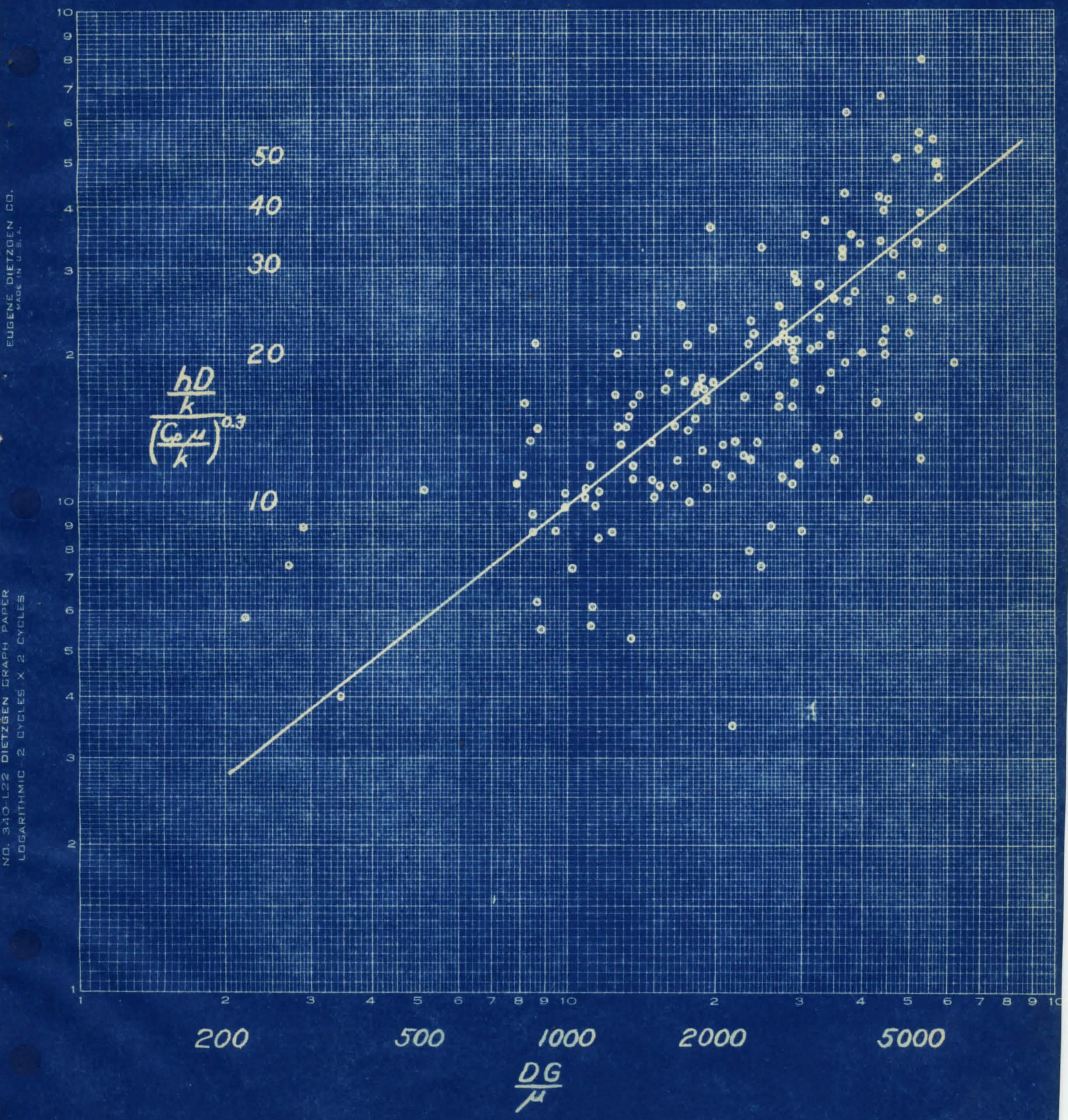
Reynolds Number

$$Re = (4 \times W)/(\pi \times D \times \mu_b)$$
$$= \frac{4 \times 1973.0}{3.1416 \times 0.0874 \times 5.40}$$
$$Re = 5320$$

The experimental data are shown graphically by Curve II., page 65. The straight line through the points is an arbitrary line that seemed to best represent the median locus. In this correlation $(hD/k)(C_p\mu_f/k)^{0.3}$ is plotted logarithmically against DG/μ_b. This method of plotting employs the type equation recommended by Dittus and Boelter [17].

Curve II.

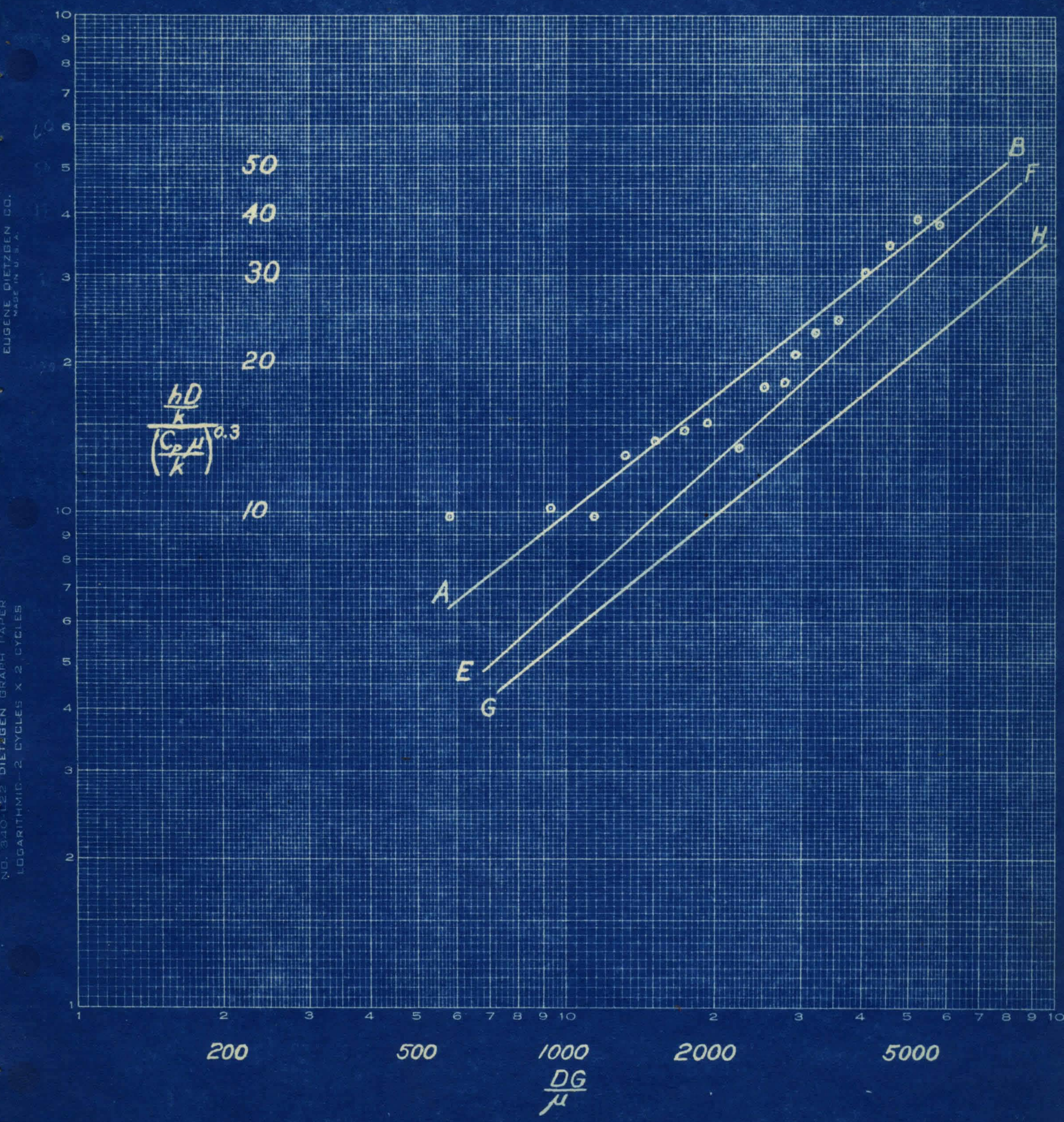
Cooling Data Correlation



CONCLUSIONS

Curve III.

Grouping and Comparison of Heat Transfer Data



The logarithmic plot of the ratio of the Nusselt to the Prandtl numbers to the 0.3 power against the Reynolds number indicates that this type of equation can be used for the correlation of cooling heat transfer data in the viscous and critical ranges.

The data of Sherwood and Petrie[1] gave a slope to the empirical curve greater than 0.8. A plot of the first sixty runs of this data using bulk viscosity throughout the calculations gave a slope to the line of 0.915[17]. The equation of the curve representing the data in this study is as follows:

$$\frac{hD}{k} = 0.0387 \left(\frac{C_p \mu_f}{k}\right)^{0.3} \left(\frac{DG}{\mu_b}\right)^{0.801}$$

This equation was obtained by grouping the data and drawing the best straight line through the points. In the grouping of the data, Reynolds numbers were collected in groups of ten beginning with the smallest and continuing through to the highest value. The line A-B on Curve III., page 67, was assumed to be the best line through all the points.

A comparison with previous work is also given in Curve III., page 67. The line E-F is a plot of the equation determined by Groth[17]. The line

G-H is the plot of the equation of Dittus and Boelter[1]. The three lines, A-B, E-F, and G-H, have slopes that are very nearly the same, and the lines are fairly close together. These facts would seem to indicate that the temperatures at which the data were taken have very little influence on the location of the curves.

From the plot of the data it is indicated that the use of this type of equation is sufficiently accurate for Reynolds numbers above 1000. Below this figure the correlation is not as successful.

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