AN INVESTIGATION OF THE EFFECT OF VARYING VISCOSITY AND VELOCITY ON THE TRANSFER OF HEAT UNDER CONDITIONS OF STRAIGHT LINE FLOW IN CIRCULAR PIPES.

Thesis

by

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INTRODUCTION

The factors affecting heat transfer to or from a moving liquid in pipes have been fairly well investigated for the case in which the liquid is in turbulent motion. An empirical equation expressing the relation between these factors and the film coefficient has been derived [1] and is found to check reasonably well with experimental measurements.

The equation is: $h_L = \frac{23.3\ K\ (v)^{0.794} (J)^{0.794}}{D^{0.206}}$

Where: h_L is the film coefficient in B. T. U. per hr. per sq. ft. of film surface per degree F. temp. diff.

K is the thermal conductivity of the stationary liquid.

v is the average mass velocity of the liquid.

J is the fluidity of the liquid relative to water at 68°F.

D is the inside diameter of the pipe in inches.

The rate of heat transfer is given in terms of h_L by the equation: $Q/\theta = h_L\ A\ \Delta t$

Where: Q/θ is the heat transfer in B. T. U. per hr.

A is the area of film surface.

Δt is the temperature drop across the film in degrees F.

[1](Walker, Lewis and McAdams, Principles of Chem.Eng., p. 140.)

The above equations do not hold for velocities below which the flow is not turbulent. As heat interchange between liquids flowing at less than the critical velocity is common practice in oil refineries and other industries it was thought that some data on the effect of varying the factors involved would be of interest. Strose and Whitmore,[2] working with sugar and molasses solutions, derived an empirical equation for the film coefficient for natural convection:

$$h = 33.6(J)^{0.314}(\Delta t)^{0.412}$$

His apparatus consisted of a 12 inch depth of liquid in a 10 gallon drum heated by a 3/8 inch steam coil. While these conditions are similar to those obtained in straight line flow the equation is not known to be applicable to it.

As shown by the investigations made above the critical velocity, the film coefficient is affected by the thermal conductivity of the liquid, the velocity, the fluidity and the density. Strose and Whitmore found it to be dependent upon the temperature drop in the case of natural convection. The ideal manner of investigating these factors is to arrange an apparatus in which any one factor may be varied at will, all other conditions remaining the same. This is, however, impractical for with all suitable liquids the viscosity, density and heat conductivity vary with the temperature. It is possible to vary the velocity and temperature independently and the viscosity and other properties may be determined as a function of the temperature so that some useful information may be gained.

[2](Walker, Lewis and McAdams, p. 139.)

It was decided to investigate the variation in heat transfer to an oil with variations of viscosity and velocity in a straight double tube cooler. Preliminary calculations were made showing that Mobiloil - A [3] possessed properties that rendered it satisfactory for the work contemplated. A similar oil, (Zerolene No. 7) was obtained and used. It proved similar to Mobiloil - A in all respects and seemed satisfactory. A double tube cooler was designed and built but was found to be too short to give a sufficient temperature drop to measure accurately. The difficulty was due to failure to make adequate allowance for the effect of the liquid films when the preliminary design was made. As not enough time remained to rebuild the apparatus

[3](Walker, Lewis and McAdams,p.83.)

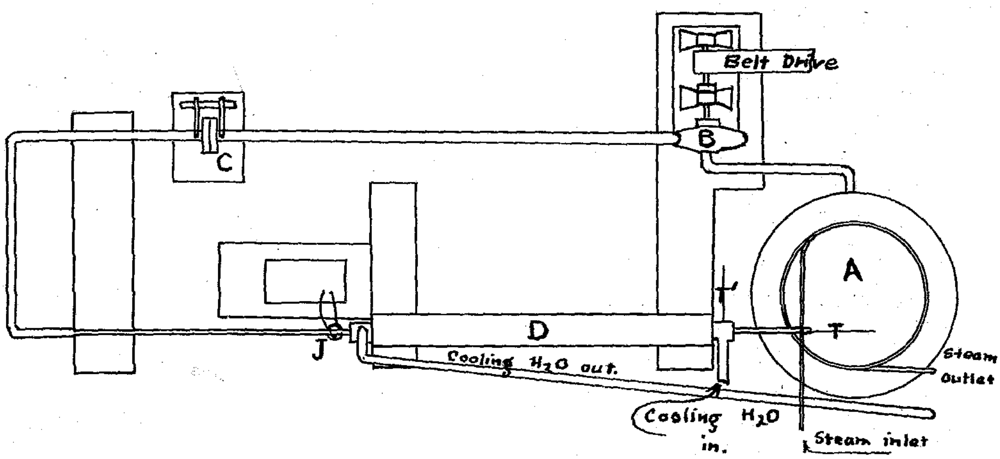
with a longer cooling tube no results were obtained.

APPARATUS.

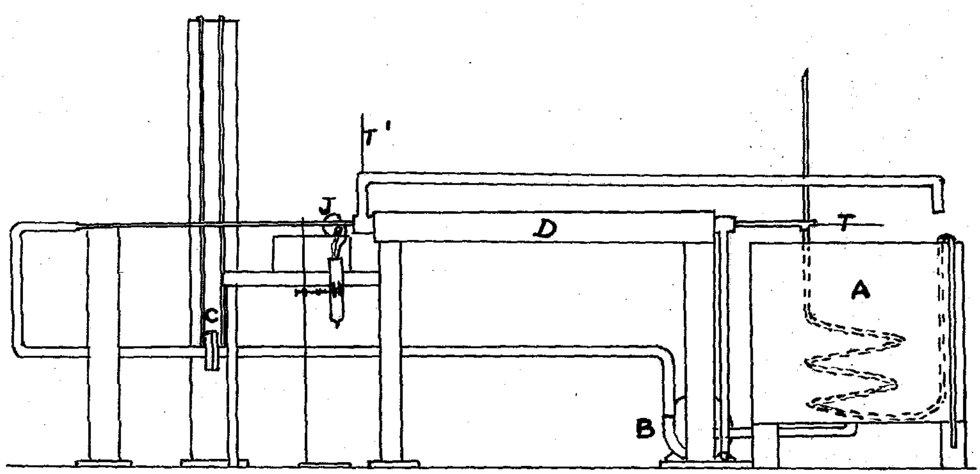
Fig. 1 shows a diagram of the apparatus built. Oil is heated by steam coils in the reservoir, A, from which it is pumped by means of the centrifugal pump, B, through the connecting pipes and the double tube cooler, D, and discharged back into A. C is a standard orifice with a manometer attached for the purpose of measuring the velocity of the oil in the apparatus. J is a multiple thermocouple for measuring the temperature of oil entering the cooler. The cooler, D, consists of a 6 ft. length of 3/8 inch brass pipe, having an internal diameter of 0.492 inches, 3 ft. of which are inclosed within a 1 inch W. I. pipe through which cooling water may be circulated directly from the water supply of the building. The thermometer, T, is to measure the temperature of the oil coming from the cooler. The thermometers, T' T', are to measure the temperature of the ingoing and outgoing cooling water. The rate of flow of cooling water was to be determined by weighing the discharge over a period of time.

Some preliminary runs with this apparatus showed that the cooling surface was not large enough and that the thermocouple, as made, did not give a true indicacation of the temperature of the oil flowing past the

FIGURE 1



FLOOR PLAN.



SIDE ELEVATION

junctures.

CALIBRATION OF THE THERMOCOUPLE.

The thermocouple, which consisted of four copper-constantan junctures in series, was fastened in the pipe with alumdum cement mixed with sodium silicate in such a way that the hot junctures just projected within the inner surface of the pipe. The hot junctures consisted of one very small twist of wire held together with solder. The cold junctures were twisted several times and soldered. They were immersed in melting ice in a vacuum flask and leads were run to a potentiometer equipped with an ordinary dry cell. When oil was pumped through the pipe it was found to leak out through the cement fastenings along the wires. This leakage was not great enough to cause difficulty and should have had the effect of bringing the entire juncture more nearly to the temperature of the oil within.

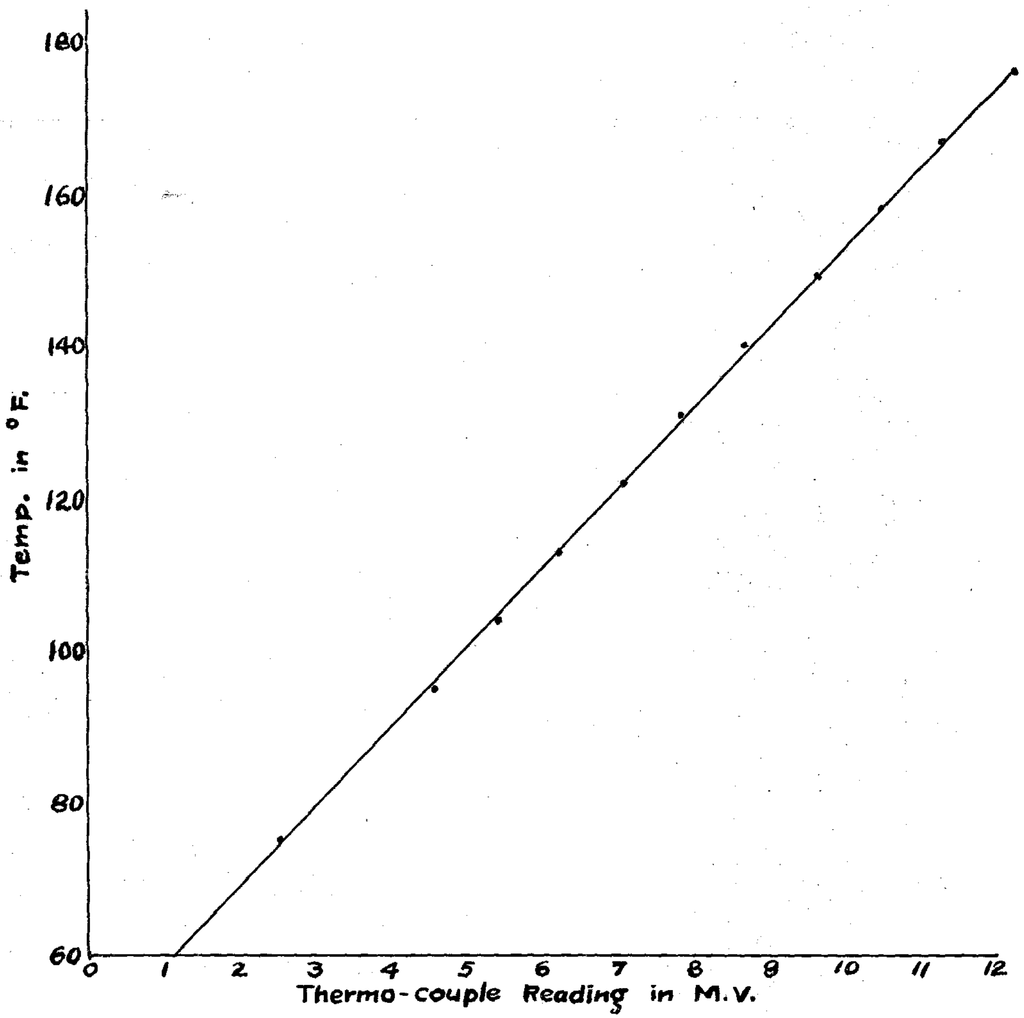
The thermocouple was first calibrated against the temperature of the oil as shown by the oil thermometer, T. The cooling jacket was free from water and the heat loss through this section neglected. The thermocouple was later removed from the pipe and standarized, along with the thermometer used to measure the temperature of the oil, against a centrigrade thermometer of known accuracy. The results of this calibration were found to be:

Standard thermometer °C.	°F.	Oil therm.	Potentiometer read'g.m.v.
24.0	75.2	75.5	2.55
35.0	95.0	95	4.60
40.0	104.0	104	5.45
45.0	113.0	113	6.20
50.0	122.0	122	7.05
55.0	131.0	131	7.85
60.0	140.0	139.5	8.70
65.0	149.0	149.	9.63
70.0	158.0	158	10.50
75.0	167.0	167	11.32
80.0	176.0	176	12.25

Fig. 2 shows the potentiometer readings plotted against the temperature in degrees F. The oil thermometer checks the standard thermometer as closely as it can be read and may be considered accurate enough for the purpose.

The following table gives some results of the calibration of the thermocouple in the pipe against the oil discharge temperature. It is a composite of several different runs made at different times.

FIGURE 2



CALIBRATION OF MULTIPLE THERMOCOUPLE.

Oil Temp. °F.	Thermocouple readings. Milivolts.	Actual temp. corresponding to thermocouple rdg. (Fig. 2).
87.5	3.08	80 °F.
109	4.10	91
124.5	5.50	106
134.5	5.90	110
138	6.67	118
142	6.90	121
148	7.65	128
155	7.70	128
164.5	8.52	137
171.5	9.25	144

The temperatures shown by the thermocouple are below the true temperatures of the oil and are further not reproducible at different times. It would seem that the reason for this is that the junctures are not immersed completely in the oil and that heat flows through the cement and connecting wires faster than through the oil. The fact that the thermocouple readings drop still lower when cooling water is turned into the jacket would indicate that the cement used is a poor heat insulator.

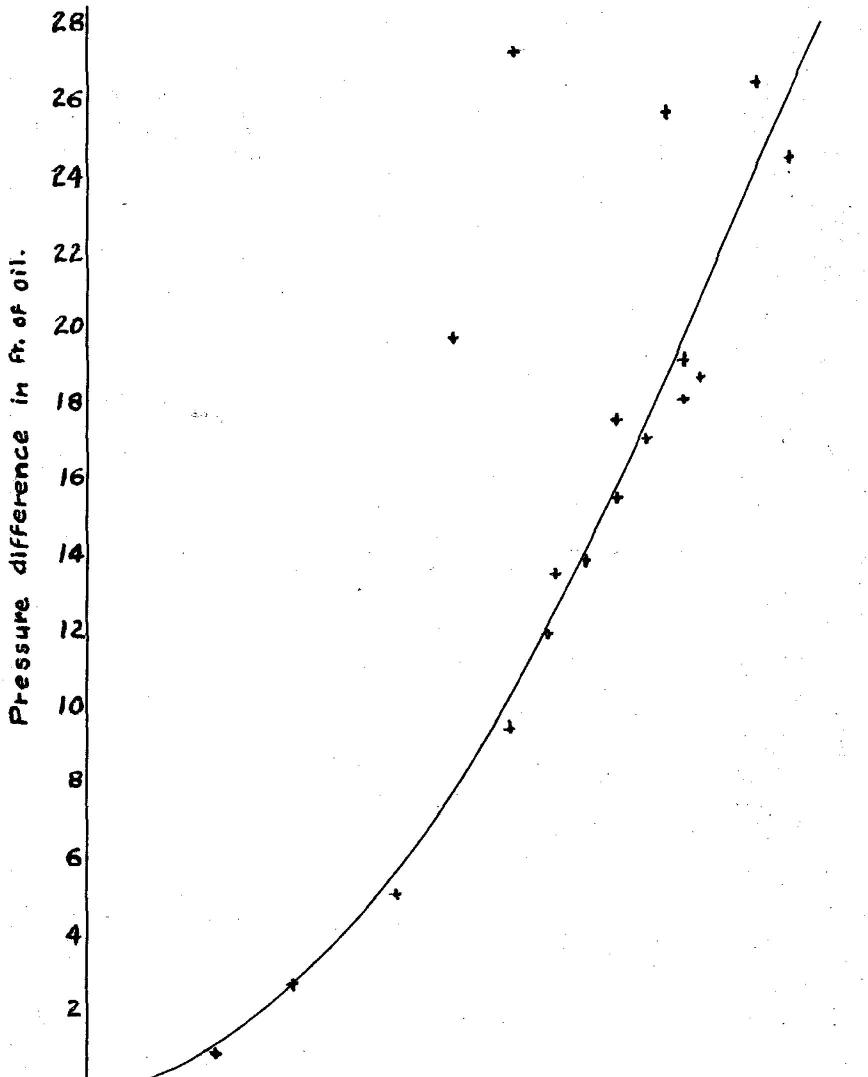
CALIBRATION OF THE ORIFICE.

The standard orifice used to measure the flow of oil consisted of a thin brass plate with a sharp edged opening of about 0.25 inch in diameter inserted in a section of 1 inch iron pipe, extending 4 ft. before and 2 ft. behind the orifice. Glass tubes ran up on both sides of the orifice to the top of a manometer tube containing mercury. The rate of flow was measured by collecting the discharge from the cooler in a small pail of known volume, measuring with a stop-watch the time required to fill it. The difference in level of the oil in the glass tubes was measured and the readings corrected accordingly. Fig. 3 shows the results of this calibration. The results are not consistant and apparently the method of timing the flow would prove satisfactory for regular runs.

HEAT TRANSFER OBTAINED.

As previously stated the chief difficulty with the apparatus as built was that the cooling surface was not great enough to give appreciable drop in temperature. At high velocities the temperature drop could not be measured on the thermometer used. A run was made at very low velocity and a small drop was observed. The oil in the reservoir was heated up and pumped through the apparatus for twenty minutes without cooling water in the jacket and the temperatures noted. Then the cooling water was turned on very slowly and two readings taken at ten minute intervals. The results are

FIGURE 3



STANDARD ORIFICE CALIBRATION CURVE.

tabulated below.

Time	Oil temp. °F.	Thermo-couple	Temp.of t.c. °F.	Cooling water Temp. in	out	Oil Velocity ft/sec.
2:10	136.5					
2:20	132.5					
2:30	128	4.45	94			
2:40	120	3.75	87	72	75	0.54
2:50	114.5	3.50	84.5	70	72	0.45

Fig. 4 gives a graphical representation of the temperatures obtained from which it can be seen that the temperature drop of the oil is from 4 to 5 °F.

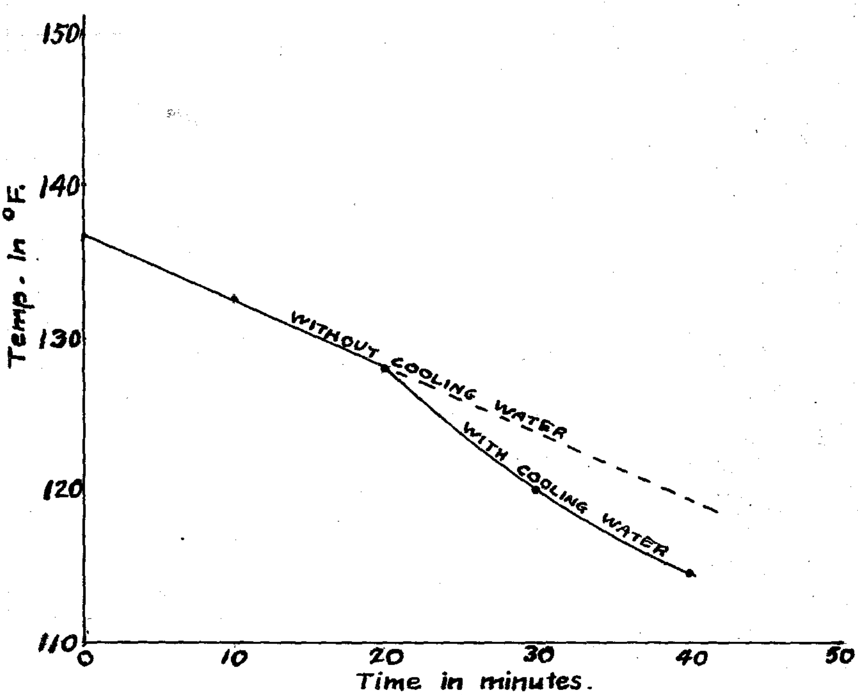
DESIGN OF NEW APPARATUS.

From the work done it is apparent that to obtain the results desired from an apparatus of this sort it will be necessary to:

1. Have a greater cooling surface.
2. Provide a better means of obtaining the temperature of the oil entering the cooler without disturbing conditions of straight line flow.

As the temperature drop of 4 or 5 degrees found experimentally was at relatively low velocity and at a fairly high temperature difference it is not expected that the drop over the entire range of conditions at which the apparatus would be run would be so great. However at higher velocities the rate of heat transfer is greater and

FIGURE 4



RESULTS OF COOLING TEST.

it may be expected that a drop of 2°F. through a 3 ft. section of pipe will not be above the average. As it is desirable to have a relatively large temperature drop, (perhaps 20°F.) a cooler of the same sized pipe would need to be about 10 times as long as the one built, or about 30 ft. This would require much more pipe and possibly a larger pump and oil reservoir.

The temperature of the entering oil might be measured by means of thermocouple junctures, the wires of which were introduced through separate holes in the pipes and then joined within so that they lay along the surface of the pipe parallel to the direction of the flow. This would insure the junctures being entirely within the oil. It would also probably cause some turbulence but should not materially affect the results where the cooler is so long. If such a thermocouple failed a thermometer might be installed 50 pipe diameters (25 inches) from the cooler and provision made to insert a thermometer at the entrance to determine the heat loss from the bare pipe by separate experiment, and correct for it in regular runs.

An orifice to measure the flow does not seem necessary.

VISCOSITY AND DENSITY OF ZEROLENE NO. 7.

The viscosity of Zerolene No. 7 was determined over a range of temperatures from 17.5°C to 96.7°C. by means of an Engler viscosimeter with which it was found possible to check values to within two per cent. The thermometer used was an ordinary centrigrade thermometer which could be estimated to 0.1°. A stem correction was made for higher temperatures.

Correction = N(t - t')0.000154

Where: N = Exposed thread in degrees.

t = Temperature read.

t' = Temp. of stem, which was assumed to be the mean between t and 20°C.

The viscosimeter was standardized against water at 20°C. The values for viscosity in Engler degrees were converted to absolute units by means of a viscosity conversion chart.[4]

The viscosities obtained are as follows:

[4](H. G. Hevitt, Chem. and Met. 23:1171 (1920).)

Temp. (corr)	Engler viscosity	Density (Fig. 6)	Abs. visc. Eng. units
63.5 F.	100.5	0.927	0.424
69.2	71.8	0.926	0.330
85.1	33.4	0.922	0.148
92.6	19.8	0.918	0.085
104.4	15.7	0.915	0.066
111.8	11.8	0.912	0.052
122.5	8.61	0.909	0.038
131.3	6.54	0.905	0.028
139.8	5.19	0.901	0.022
150.0	4.18	0.897	0.0175
158.6	3.52	0.894	0.0144
168.0	2.91	0.890	0.0109
175.0	2.62	0.887	0.0098
185.3	2.28	0.883	0.0081
198.0	2.02	0.879	0.0066
207.0	1.84	0.874	0.0057

Fig. 5 shows the viscosities plotted against the temperature on semi-logarithmic paper.

The density was determined with a hydrometer. As it varies but slowly with the temperature the latter was not corrected for the exposed stem. Fig. 6 shows the specific gravity plotted as a function of the temperature.

From the values of density and viscosity obtained for

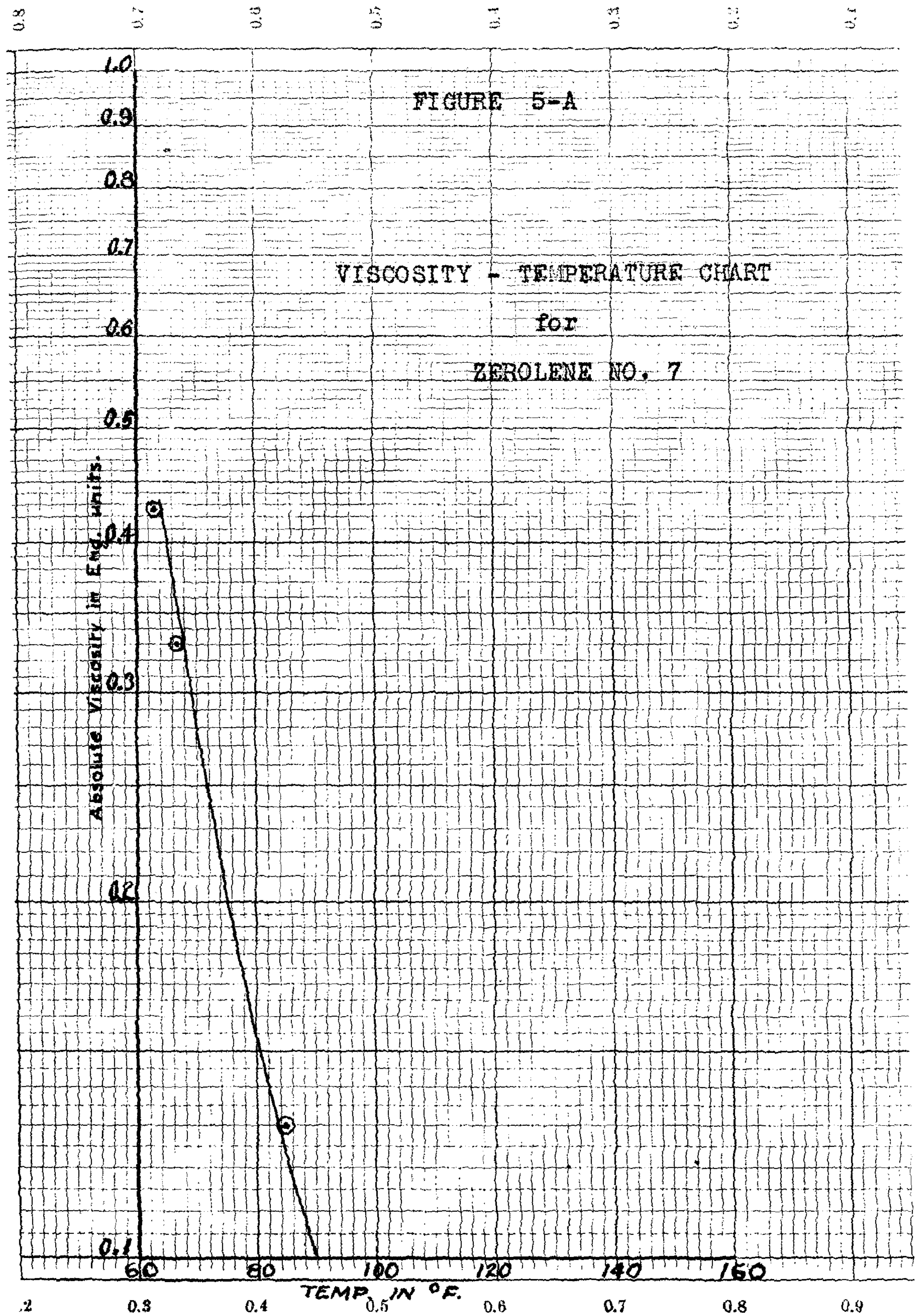
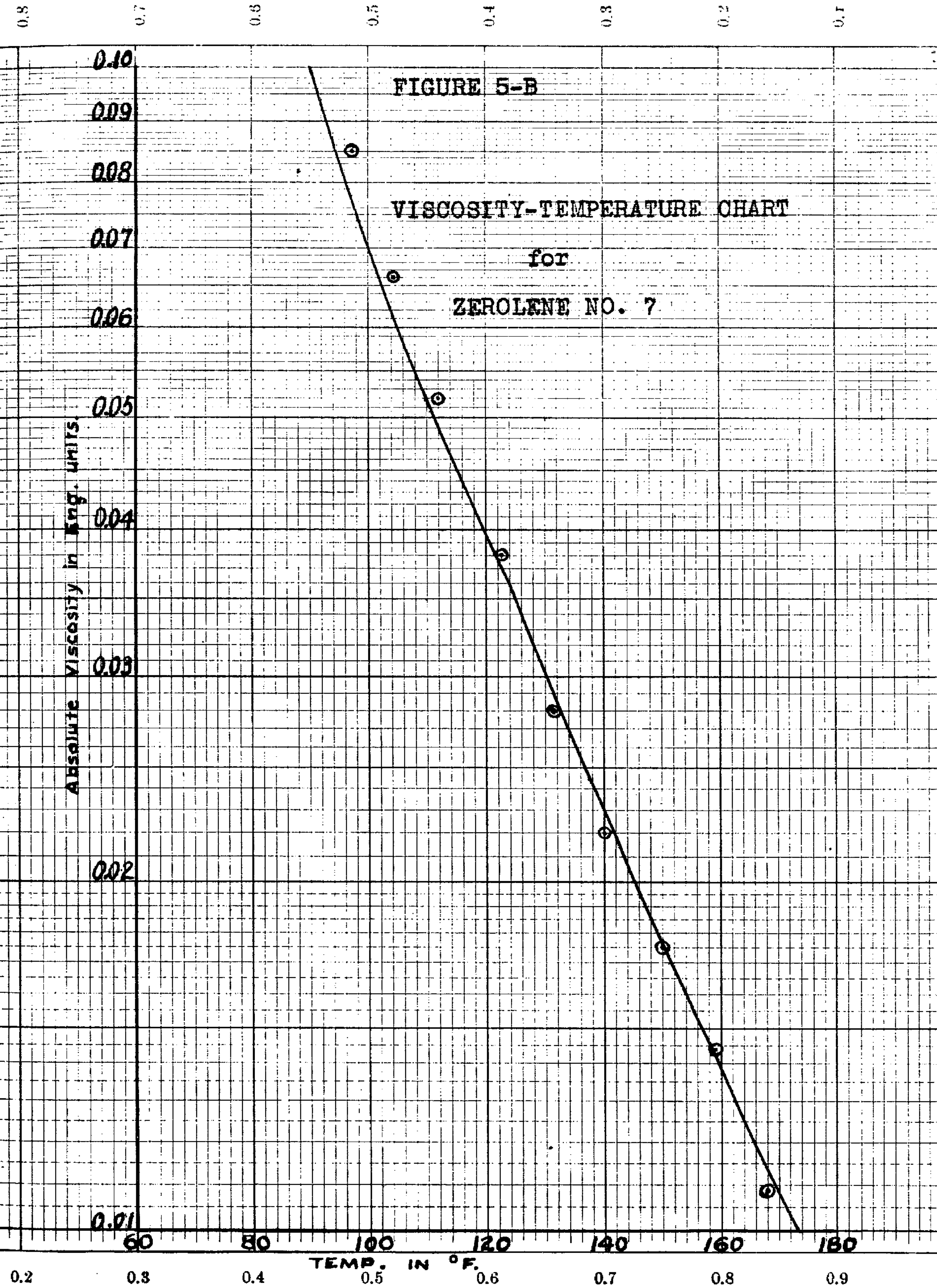


FIGURE 5-A

VISCOSITY - TEMPERATURE CHART
for
ZEROLENE NO. 7

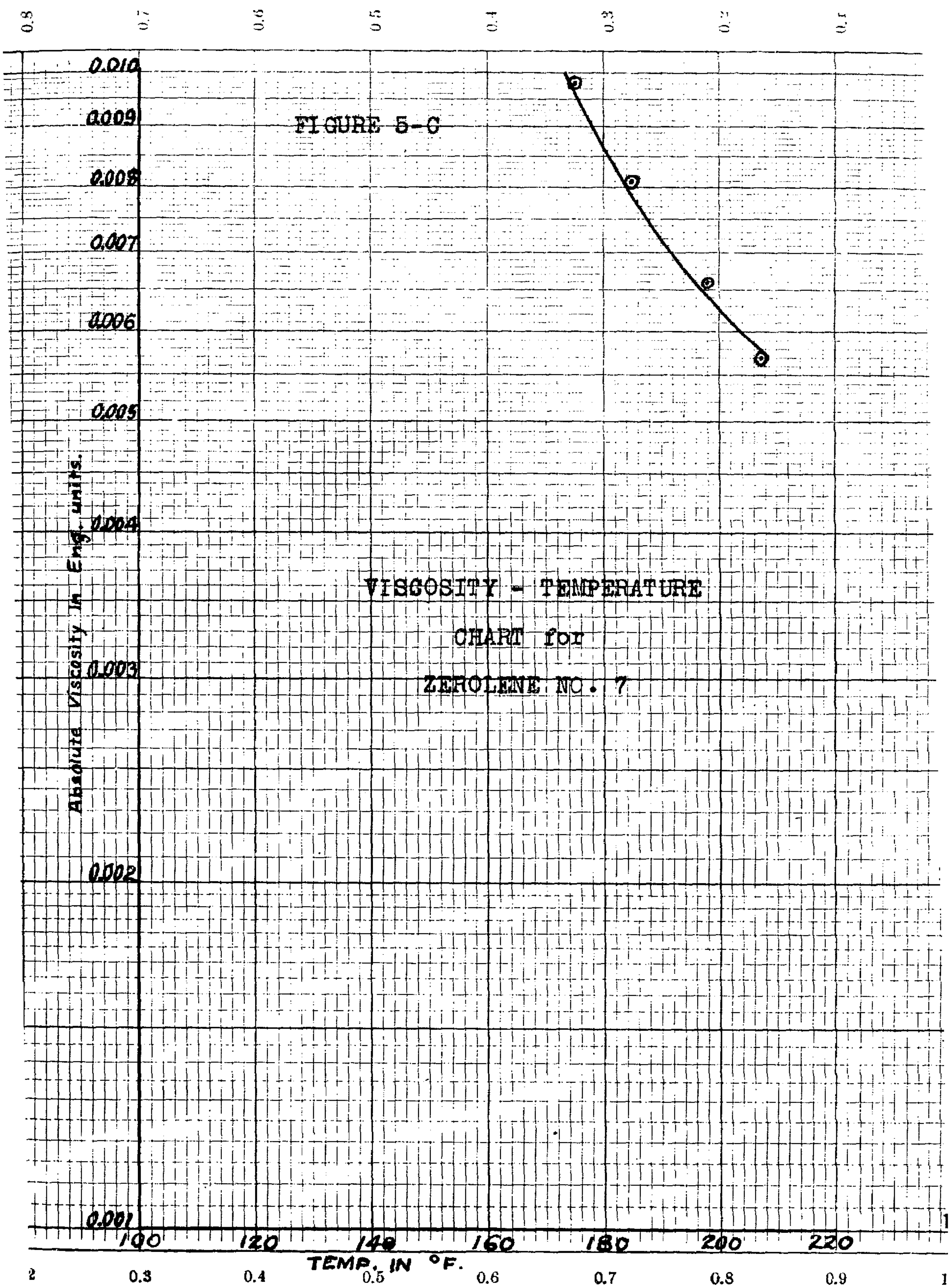
Semi-Logarithmic Paper.

FORM M 5



Semi-Logarithmic Paper.

FORM 3



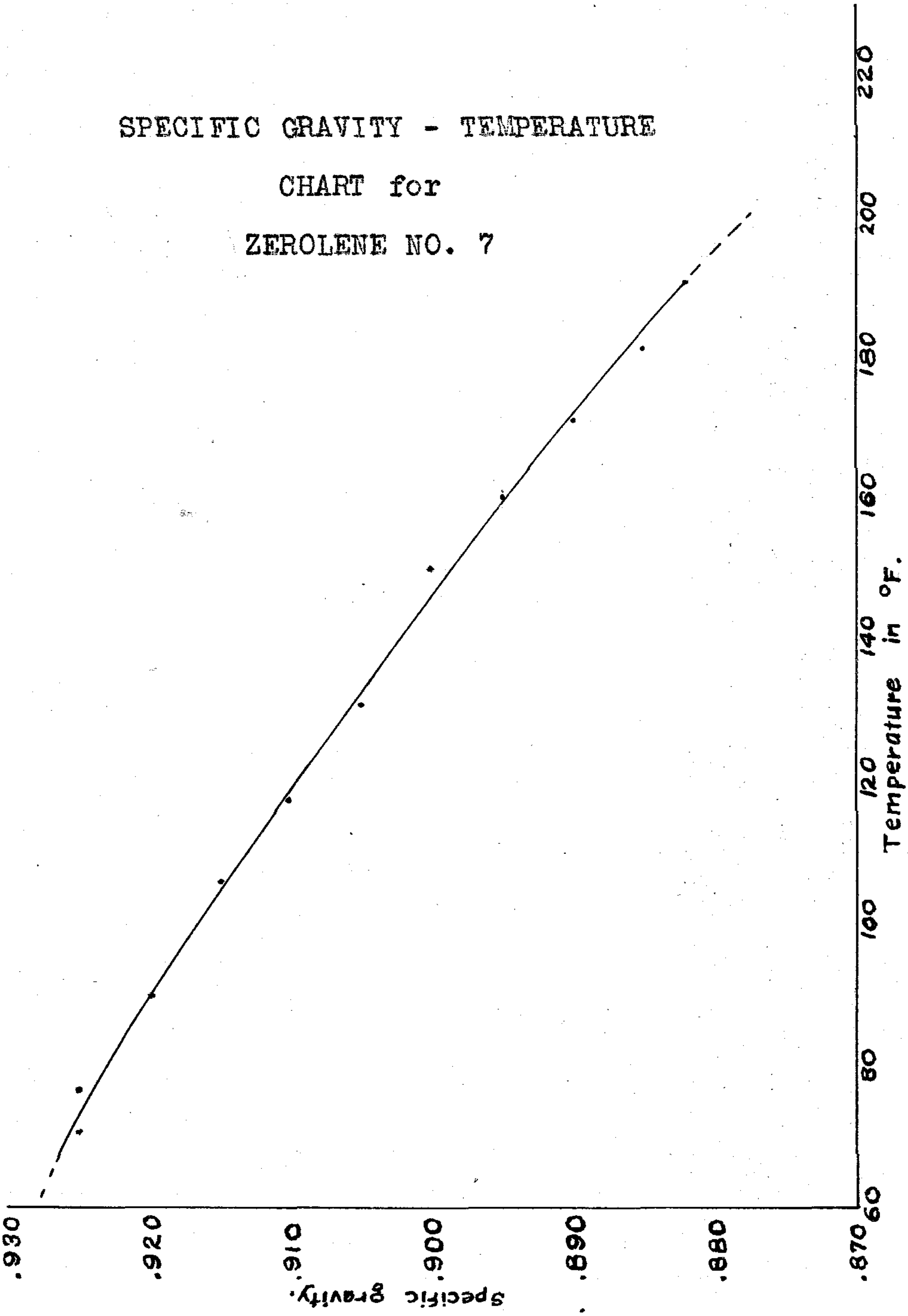
Semi-Logarithmic Paper.

FIGURE 6

SPECIFIC GRAVITY - TEMPERATURE

CHART for

ZEROLENE NO. 7



Zerolene No. 7 its critical velocity at different temperatures through a 3/8 inch pipe were calculated according to the formula:

$$u_c = \frac{942\,\mu}{\rho\,d} = \frac{23050\,\mu}{\rho}$$

Where: u_c = Critical velocity in ft. per sec.

μ = Absolute viscosity in Eng. units.

ρ = Density in lbs. per cu. ft.

d = Diameter of the pipe in ft. 0.0408 ft.

The calculations give:

Temp. in °F.	Critical vel. in ft./sec.
60	199
80	84
100	31
120	17
140	9.0
160	5.8
180	3.7
200	2.7