A STUDY OF HEAT TRANSFER THROUGH CONDENSING
HYDROCARBON FILMS

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Bachelor of Science

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Stillwater, Oklahoma

1938

Submitted to the Department of Chemical Engineering

Oklahoma Agricultural and Mechanical College

In Partial Fulfillment of the Requirements

For the degree of

MASTER OF SCIENCE

1940

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ACKNOWLEDGEMENT

The writer wishes to acknowledge and express his deep appreciation for the help of Dr. Charles L. Nickolls, Professor of Chemical Engineering, under whose direction this work was done. He also wishes to thank other members of the faculties of chemistry and chemical engineering for their suggestions and advice.

The mixture of hexanes was prepared in the Special Products Laboratory of the Phillips Petroleum Company of Bartlesville, Oklahoma.

PREFACE

The problem of heat transfer through a condensing film is one of major importance in modern industry. Wherever there is a transition from the gaseous to the liquid phase some aspect of this problem will be encountered.

Heat transfer to vertical tubes has not been given its proper share of attention. This may account for the erroneous belief, long held by some engineers, that heat transfer coefficients to vertical tubes are lower than those to horizontal tubes. It is also believed that vertical tubes are harder to clean and recondition. This may explain why horizontal condensers are more often used in industry.

OUTLINE AND TABLE OF CONTENTS

I. REVIEW OF SELECTED LITERATURE

A. On Condensing Film Coefficients.

In 1916 Nusselt (26) derived the theoretical relations that are most commonly used to correlate the data on heat transfer through a condensing film. In his derivations he assumed that the condensing vapor was pure, that the condensate was in streamline motion and formed an unbroken film over the condensing surface, that the force of gravity alone caused the motion of the condensate, that variations in physical properties of the condensate caused by the temperature gradient through the film could be neglected, and that this temperature gradient was constant. His derivations are presented in English by Monrad and Badger (22) and Colburn and Hougen (7) and a simplified and slightly modified version is given by Walker, Lewis, McAdams and Gilliland (33). Nusselt's theory is discussed by Ten Bosch (32), Stander (31), Schack (29), Merkel (21), and Grober (10).

A theory somewhat similar to Nusselt's was published in 1921 by Parr (28). Whereas Nusselt assumed constant temperature differential between the vapor and the wall Parr assumed uniform rate of condensation around the perimeter of the pipe. Monrad and Badger (22) and Jacob (12) have discussed and compared the two theories. According to McAdams (17) Parr's relation may be put in the same form as Nusselt's and gives values of $\underline{h}$ 1.035 times as great.

Chilton, Colburn, Genereaux and Vernon (5) have an alignment chart based on Nusselt's theory from which $\underline{h}$ may be read directly without the necessity of evaluating the physical constants of the film. This chart has been published and its use explained by McAdams (18).

In making his derivations Nusselt assumed continuous film condensation, therefore they may not be applied to dropwise condensation. A critical discussion and mathematical analysis of the problem of dropwise condensation and promoter action is given by Emmons (8). Fitzpatrick, Baum and McAdams (9) describe a number of experiments in which they caused steam to condense dropwise and on vertical tubes by using various promoters. Schmidt, Schurig and Sellschopp (30) present pictures of the two types of condensation with a discussion of the causes of each. Badger and McCabe (1) believe that dropwise condensation "apparently occurs very often in practise", but Wulfinghoff (34) and Kirkbride (15) believe that this is not true. They claim that too low a condensation rate and too smooth a surface are required. The experience of several investigators in the field has shown that dropwise condensation gives coefficients from 50% to 800% higher than film condensation.

McAdams and Frost (20) give data on the condensation of benzene on horizontal pipes. They also present equations for predicting critical conditions at which viscous flow in the condensate layer breaks down into turbulence. Data on the condensation of benzene on horizontal pipes are reported by Bray and Sayler (4).

Data on condensation of steam on a vertical tube one meter long are given by Jordan (14). In general, his heat transfer coefficients are lower than those predicted by Nusselt's relation. Jacob and Erk (13) used a vertical tube 18.35 inches tall and condensed steam on its outer wall. Their data agree rather poorly with the Nusselt theory, being lower, sometimes by as much as 100%. Morris and Whitman (25) have published data on the condensation of steam on horizontal tubes which also give heat transfer coefficients that are lower than those predicted by Nusselt's theory. The data of Othmer (27), McAdams and Frost (19), and Clement and Garland (6) on the condensation of steam on horizontal tubes give heat transfer coeffieients that are too high according to Nusselt's theory.

Ophuls (26), Horne (11), Zumbro (35), and Kratz, Macintire, and Gould (16) have published data on the condensation of ammonia on the outside of vertical tubes.

Badger, Monrad, and Diamond (2) condensed diphenyl on the outside of vertical tubes, and Montillon, Rohrbach, and Badger (23) condensed diphenyl on the outside of horizontal tubes. Their data are not very consistent. It has been found that diphenyl is more likely to give dropwise condensation than most of the other substances that have been used in these studies. This may be attributed to its oily nature.

The condensation of light and heavy naphtha on the inside of cast iron pipe has been studied by Badger, Rogers, and Diamond (3).

McAdams and Frost (19) used carbon tetrachloride and horizontal tubes in their studies on condensing film coefficients.

Bray and Sayler (4) in their paper mentioned above include data on the condensation of 95% ethyl alcohol on horizontal pipes. They report coefficients higher than those predicted by Nusselt's theory.

The majority of the data on condensing vapors in the literature is higher than that predicted by Nusselt's theory, but there is a considerable portion that is lower. These variations are attributed to a number of factors, most important among them being turbulence in the condensate layer, dropwise condensation, the presence of non-condensable gas, and the effect of vapor velocity.

B. On Thermocouple Installation.

Smith (6) recommends #22 B&S gauge wire for general thermocouple applications. He recommends iron-constantan couples for their reliability, for maintaining their calibration and for their economy and tensile strength. To determine the effect of heat transfer along the leads of thermocouples he immersed wires varying from 0.013 to 0.031 inches in diameter 1/2 inch deep in mercury and alternatively heated the emergent leads red hot or surrounded them with ice. The indicated temperature did not vary appreciably. He listed ten factors that determine the accuracy of temperature measurement by means of thermocouples.

Kreisinger and Barkley (3) describe a method of installing thermocouples in which a hole only slightly larger than the wires to be used is drilled or punched into the wall whose temperature is to be measured. One hole is made for each lead and the leads are peened into place with a special tool. This method was used on boiler tubes and the leads brought out through the water. This method demonstrated the following facts:

1. Embedding wires separately does not affect the hot junction.
2. The hot junction is formed at the surface of the embedding metal.
3. Since the leads were brought out through a region of different temperature from the wall it was supposed that the

substitution of a larger wire for a smaller wire (or vice versa) would cause a change in indicated temperature because of heat transfer along the leads. This was found to be a false supposition.

They used the same system, i. e., two junctions and only three leads, that is described later under description of apparatus, and stated that it was successful.

Hebbard and Badger (2) believe that thermocouples are the most practical devices for measurement of wall temperatures. The method of installation they recommend involves embedding the junctions and leads in the tube wall. The leads are brought away from the junction in opposite directions in slots cut in the wall and are taken away from the tube at a point diametrically opposite the junction. The wires are insulated and the slots filled with Bakelite cement and the surface sanded smooth.

Othmer and Coats (5) electroplated their junctions to the tube wall. This method of installation requires special apparatus and is not approved by Hebbard and Badger. Othmer (4) used this method to install two junction copper-constantan couples and believes it to be satisfactory. Othmer measured the potential developed by his couples with a Leeds and Northrup type K potentiometer which he was able to read to one microvolt.

In 1930 Colburn and Hougen (1) published a review of the literature on measurement of surface temperatures.

II. EXPERIMENTAL APPARATUS

A. Condenser Assembly.

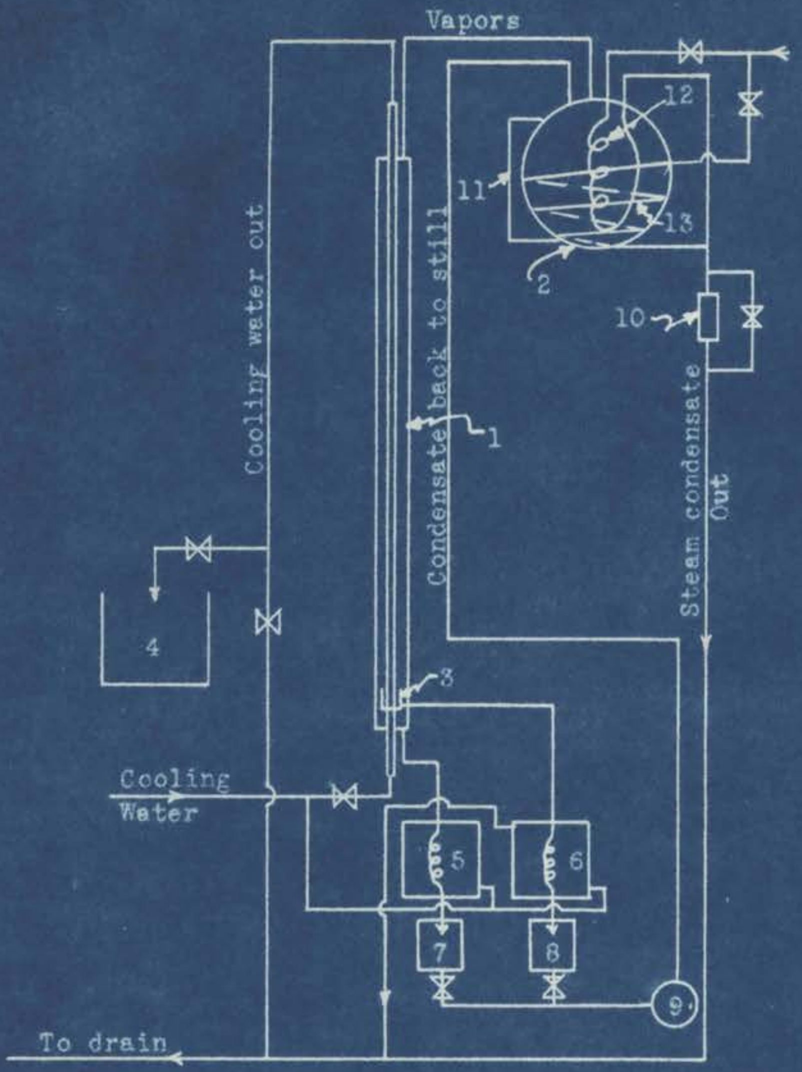
The condenser assembly consisted of a vertical copper pipe 1" i. d., 1 3/16" o. d., and 10' long supported concentrically in a Pyrex glass pipe 2" i. d. and 6' long. The copper tube was provided with fittings on each end so that cooling water could be brought in at the bottom and taken away at the top. By means of a suitable piping arrangement the cooling water could be run into a tank for weighing. The vapor was brought into the top of the annular space between the glass and copper pipes and the excess vapor and the condensate were taken out at the bottom.

A cup was installed as shown in the accompanying sketch to catch the condensate formed above the section under investigation and another to catch that formed on this section.

A condenser made of a coil of 1/2" copper tubing surrounded by circulating water was provided to condense and cool the excess vapor. This will be referred to as the auxiliary condenser. A similar coil made of 1/4" copper tubing cooled the liquid from the cup.

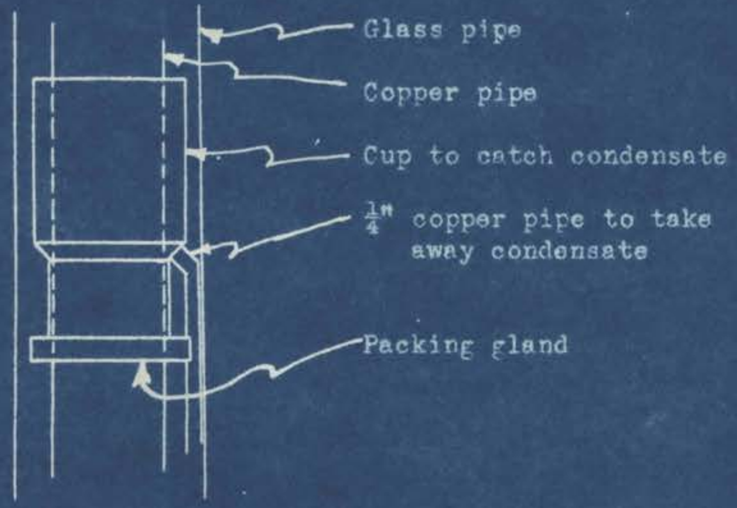
B. Equipment For Generating Vapors.

The vapors to be used were obtained from an almost spherical copper still of a little more than five gallons capacity, heated by external and internal steam coils. The external coil was made of standard 3/8" wrought iron pipe bent to form a "nest" for the still. The internal coil consisted of a 10' length of standard 1/8" pipe bent to form a coil 5" o. d. and 10" high. Steam was admitted to



1. Condenser Assembly
2. Still
3. Cup to catch condensate formed on pipe.
4. Weigh tank for cooling water.
5. Auxiliary condenser.
6. Condensate cooler.
7. Receiver for liquid from auxiliary condenser.
8. Receiver for condensate formed on pipe.
9. Small centrifugal pump.
10. Steam trap.
11. Level glass on still.
12. Internal steam coil.
13. External steam coil.

SCHEMATIC DIAGRAM
OF APPARATUS USED



DETAIL OF CUP INSTALLATION

the coils through needle valves from a line carrying 120 lbs. per square inch pressure. The coils exhausted through an ordinary steam trap. In order to maintain smooth operation it was found necessary to bypass this trap so that some live steam could be exhausted constantly.

Vapors were taken from the top of the still by a 1 1/2" line and delivered to the top of the vapor space in the condenser. This line was 2 1/2' long and 2' of its length was insulated with a layer of asbestos fibre 3/4" thick. Condensate was elevated back into the still by means of a small centrifugal pump.

C. Apparatus for Temperature Measurements.

Thermometers were provided to measure the temperatures of the incoming and outgoing cooling water.

The temperatures of the cooling water at various points along the length of the tube were measured by means of a three-junction iron-constantan thermocouple. The thermocouple leads were encased in 1/4" copper tubing which was held in the center of the pipe by means of 3 legs of thin brass wire soldered to its lower end. The thermocouple junctions were separated and tied to these legs. The copper tubing could be moved up and down through a packing gland so that the temperature of the water at any position along the length of the pipe could be measured. The junctions and leads were insulated with waterproof insulating cement.

Iron-constantan thermocouples were provided to measure the temperature of the vapor and the external surface of the copper pipe at one foot intervals over a seven foot section. They were installed as follows: A hole just large enough to accomodate the 22 gauge wire was punched into the wall of the pipe. An end of one of the wires was inserted in this hole and soldered in place. The excess solder was then removed from the wire and pipe so that the surface would be as free as possible from projections and roughness. One iron and one constantan wire were attached in this manner. The constantan lead of the junction used to measure vapor temperatures was cut off at a length of 3/16" and its end attached to the pipe as described above. This held the junction at a distance slightly less than 3/16" from the wall of the pipe. The leads were gathered into a bundle and brought up parallel to and about 1/4" from the pipe and were taken out through a suitable seal at the top of the vapor space. They were connected to a panel in an arrangement such that it was easy to select the leads desired for a particular temperature measurement.

The cold junctions were inserted in a thermocouple well surrounded by an ice bath.

A Leeds and Northrup "Type K" potentiometer equipped with a Weston standard cell, a Leeds and Northrup #2420 galvanometer, and a one cell Willard lead storage battery was used to measure the potential developed by the thermocouples.

All the thermocouples and leads to the potentiometer were made of standard thermocouple grade Leeds and Northrup 22 gauge wire. This set-up permitted the measurement of temperatures to within 0.4° F. with the single junction couples and to within 0.2° F. with the three junction couples.

The original plan for the apparatus called for copper-constantan rather than iron-constantan couples but it was decided that the latter was better because of the greater tensile strength and lower thermal conductivity of the iron. The difference in sensitivity of the two was not appreciable and it was not expected that corrosion would be a problem since the apparatus was to be in use only a short time.

III. EXPERIMENTAL PROCEDURE

During the course of the investigation the thermocouples were calibrated several times. Each time the calibration was made at room temperature (around 100° F.) and at steam temperature (around 212° F.). It was found that the room temperature did not change more than 1° F. from 4:00 P. M. to 6:00 P. M. if the doors of the building housing the apparatus were kept closed. Accordingly, the room temperature calibrations were made at 6:00 P. M. The steam temperature calibrations were made immediately afterwards.

Only one couple was found to be in error. This was #5 vapor couple and the results it gave are not reported for the runs coming after 11B. Before this run it gave correct results.

In starting a run steam was admitted to the heating coils and the contents of the still brought to boiling. When vapor began coming over cooling water was admitted to the condenser pipe and to the auxiliary condenser and coolers. While the apparatus was coming to equilibrium this water was run directly to the drain. As fast as condensate was formed it was pumped back into the still. The steam rate necessary to give the desired amount of vapor and the cooling water rate were adjusted by means of valves. The apparatus was said to be in equilibrium when the temperature of the leaving cooling water, the rate of formation of condensate on the pipe, and the rate at which liquid drained from the auxiliary condenser became constant. The liquid condensed on the inside of the glass pipe and the condensate formed from the vapor coming through the vapor space made up the effluent from the auxiliary condenser. It was found that when the above three factors were constant the tube wall and vapor temperatures were also constant.

The time required for the apparatus to reach equilibrium varied from thirty minutes to three hours, depending on the vapor and water rates desired and the temperature of the apparatus at starting.

When a run was begun the time was noted and the cooling water turned into the measuring tank. The vapor and wall temperatures were measured in the following order: #1 vapor, #1 wall, #2 vapor, #2 wall, etc. The temperature of the cooling water at the various points was then measured by means of the traveling thermocouple assembly, one set of data being taken as the junctions were moved down, another as they were moved up. The condensate rate was measured two or three times during each run by diverting the liquid from the cup catching the condensate formed on the pipe and the liquid formed in the auxiliary condenser into graduated cylinders and noting the time taken for the collection of a given volume. The temperature and density of the condensate was measured along with its volume. This volume of liquid was always small enough that the equilibrium was not upset by taking it out of the system.

IV. PRESENTATION OF DATA

A. Experimental Data.

The liquids used to produce the vapors were ordinary commercial benzene and a mixture of hexanes obtained by fractional distillation of a cut from natural gasoline from the Burbank, Oklahoma field. No analysis of this mixture of hexanes was available but it probably contained n-hexane, 2,3-dimethyl butane, 2-methyl pentane, 3-methyl pentane, benzene and cyclohexane. The A. P. I. gravity was 79.8 and the vapor pressure 6.35 pounds per square inch at 100° F. With a 732 mm. barometer an Engler distillation gave the following data:

% Distilled	Temperature, ° F.
First drop	140
5	141
10	142
20	142
30	142
40	143
50	143
60	143
70	144
80	144
90	145
95	146
Dry	148

In the calculations it was assumed that the mixture had the same physical properties as n-hexane. It is believed that the error introduced by this assumption is comparatively small.

Position number 1 was at the bottom of the section under investigation and number 7 at the top.

Tables I and II present the experimental data for all the runs in which a complete set of data was taken. The letter B indicates a benzene run and H a hexane run. The temperatures were read from a curve of temperature vs. millivolts developed by iron-constantan thermocouples. The temperatures shown are in many cases averages of two or more readings. It was found to be rather difficult to assemble the apparatus without breaking some of the wires or detaching them from the wall of the pipe. This explains the blank spaces in the temperature tables.

The amount of condensate collected is given in pounds per hour. This value is the product of the volume and density of the condensate.

The amount of water was obtained by direct weighing.

The indicated inlet and outlet temperatures of the cooling water were taken with mercury thermometers.

B. Treatment and Discussion of Data.

In Tables III and IV are tabulated the calculated data. The product $L\Delta t$ was obtained by graphical integration. It represents the area between the curves of temperature of vapor vs. position and temperature of wall vs. position. The B.T.U. transferred were calculated by multiplying the weight of water per hour by its temperature rise over the desired section. <u>h</u> for any given section was obtained by dividing the heat transferred in that section by the product of the outside area of a one foot length of the pipe and $L\Delta t$ for that section. The average Δt for any section was obtained by dividing its $L\Delta t$ product by L.

The figure (Nu) represents the group $\frac{k^3\rho^2 gr}{N\mu\Delta t}$ for which the symbols are defined at the end of this section. The physical constants

EXPERIMENTAL DATA

TABLE I

	Run Number									
	8B	10B	11B	13B	14B	16B	17B	18B	20B	21B
Cooling water inlet temp., ° F.	89.9	85.3	85.5	85.7	86.0	80.3	81.0	84.3	85.5	84.3
Cooling water outlet temp., ° F.	133.2	97.7	117.0	123.4	119.0	117.4	133.0	111.4	116.4	124.0
Cooling water rate, pounds/hour	335.0	852.5	351.5	358.0	455.3	295.3	278.0	377.0	366.5	538.0
Average vapor temperature (° F.)										
at position number -----------1			163.5	156.0	156.0	153.2	163.0	161.2	156.9	156.8
2	151.0	150.0	173.5	159.9	164.8	159.7	170.3	169.0	157.9	159.9
3	159.5	161.2	166.7	164.0	161.9	158.0	169.8	166.8	158.0	159.0
4	158.5	159.0	168.5	166.1	163.0	159.0	167.5	168.8	156.5	157.7
5	159.5	158.5								
6	158.4	158.5	173.0	165.5	164.0	160.4	167.5	168.0	159.2	160.1
7			171.0	164.3	162.3	158.9	169.0	168.0	157.1	158.0
Average wall temperature (° F.)										
at position number------------1	147.3	144.0	127.0	127.0	134.8	126.1	149.3	119.9	129.5	131.0
2			131.3	129.0	138.3	129.2	152.5	125.2	130.8	136.7
3	139.5	132.1	140.0	136.3	143.5	135.2	153.0	127.3	139.5	138.5
4			147.8	138.0	148.7	136.8	156.5	131.7	134.5	143.0
5	142.5	126.1								
6	143.8	127.0	145.0	142.7	151.8	134.1	160.5	131.7	141.1	147.3
7				146.2	153.0	142.9	162.7	137.5	141.9	147.9
Average cooling water temperature (Junctions moving up) Pos. No. 1	99.0	88.0	101.0	101.0	103.9	96.0	96.5	99.0	98.4	96.0
2	103.0	89.3	105.5	107.0	107.5	102.7	107.1	100.3	103.2	102.3

EXPERIMENTAL DATA

TABLE I
Continued

		Run Number									
		8B	10B	11B	13B	14B	16B	17B	18B	20B	21B
Ave. cooling water temperature (Junctions moving up)	Pos. No. 3	108.5	90.3	107.0	111.3	108.0	107.7	114.7	101.1	106.8	107.3
	4	111.5	90.3	109.1	114.1	109.9	109.8	121.3	102.0	109.0	111.8
	5	113.0	92.0	110.2	117.3	113.3	112.2	126.0	104.0	110.7	114.9
	6	116.7	94.0	110.9	119.7	114.3	114.0	129.5	105.9	112.0	117.5
	7	129.0	96.1	115.0	121.4	115.8	116.0	131.3	108.2	114.0	120.8
Average cooling water temperature (° F.) (Junctions moving down)	Pos. No. 1	102.3	90.5	105.0	103.3	106.0	98.0	104.0	100.5	103.8	103.3
	2	104.3	92.0	107.0	109.1	110.7	106.5	113.5	103.0	106.7	107.2
	3	110.0	93.0	108.2	115.2	113.7	109.1	119.3	106.1	108.7	111.4
	4	124.2	93.5	109.2	116.0	116.3	112.9	123.7	107.7	110.2	114.3
	5	126.3	94.0	110.7	117.9	115.4	116.0	127.2	108.0	111.3	117.0
	6	127.5	95.0	111.8	119.7	116.0	116.0	129.5	107.7	112.0	117.6
	7	129.3	96.0	115.0	121.4	115.8	116.0	131.3	108.2	114.0	120.8

EXPERIMENTAL DATA

TABLE II

		Run Number						
		2H	3H	5H	6H	7H	9H	10H
Cooling water inlet temperature, °F.		85.3	85.3	88.3	85.1	86.3	80.7	81.7
Cooling water outlet temperature, °F.		103.1	103.2	122.0	114.2	115.1	103.0	115.2
Cooling water rate, pounds/hour		456.5	364.2	143.25	268.0	146.3	294.0	249.0
Average vapor temperature (°F.) at position	1	135.0	129.0	139.0	141.2	146.0	137.3	144.0
	2	138.0	129.8	144.0	144.9	144.3	140.5	146.0
	3	135.5	129.2	141.0	143.1	148.5	142.0	147.7
	4	140.0	129.2	142.7	144.0	145.0	141.0	144.0
	5							
	6	141.5	131.0	145.3	144.8	143.5	143.0	145.0
	7	140.0	127.5	145.0	144.0	145.0	141.0	145.0
Average wall temperature (°F.) at position	1	117.0	109.0	125.5	126.5	122.6	110.3	120.8
	2	117.5	108.1	126.0	126.3	123.5	112.3	121.7
	3	115.0	112.0	123.5	128.0	126.5	112.0	121.0
	4	120.1	114.0	130.0	128.9	127.5	115.5	125.3
	5	122.0	109.9					
	6	125.1	114.0	135.3	132.8	131.8	120.0	129.0
	7				135.9	131.5	125.3	133.0
Average cooling water temperature, Pos. No. (°F.) Junctions moving up	1	97.0	92.0	100.0	96.3	97.0	92.5	96.0
	2	98.5	93.7	108.0	101.3	101.2	94.0	98.3
	3	95.0	95.0	110.0	104.6	105.2	95.2	100.3
	4	96.2	96.0	114.5	106.9	108.3	96.2	102.8
	5	96.9	98.0	118.0	110.0	111.0	97.5	105.0

EXPERIMENTAL DATA

TABLE II Cont'd

		Run Number						
		2H	3H	5H	6H	7H	9H	10H
Average cooling water temperature, (°F.), Junctions moving up.	Pos. No. 6	98.0	99.7	118.5	111.0	112.0	98.3	107.0
	7	102.0	101.0	120.0	112.3	113.7	101.0	111.7
Average cooling water temperature, (°F.), Junctions moving down	Pos. No. 1	91.0	93.5	100.0	103.0	97.0	95.0	100.7
	2	93.0	93.7	108.0	105.5	104.5	97.2	102.3
	3	93.5	95.0	111.0	107.3	109.0	99.2	103.5
	4	95.0	96.1	114.7	109.2	111.0	100.0	104.0
	5	98.0	99.0	118.0	110.0	111.8	100.5	104.9
	6	99.5	100.1	118.5	111.0	112.0	100.5	107.0
	7	102.0	101.0	120.0	112.3	113.7	101.0	111.7

of the film were evaluated at a temperature equal to the sum of the average wall temperatures and 1/2 Δt. The values of the physical constants were read from charts in the appendix of McAdams' "Heat Transmission".

In the "Rising h sect." column the first two numbers define the borders of the section at the bottom of the pipe in which h is increasing and the third the length of that section. Thus 1-4.5:3.5 means that from position 4.5 to position 1, a distance of 3.5 feet, h is increasing.

When Reynolds' criterion was evaluated for the cooling water it was discovered that conditions of flow were in the doubtful range between definitely streamline and definitely turbulent. Therefore, it is not surprising that agreement between actual heat transfer coefficients and those predicted by the accepted relations is poor.

Figure I shows a typical set of curves from the experimental data. It is believed that #1 vapor thermocouple did not indicate the true temperature of the vapor at that point. It probably was covered by the layer of condensate. However it makes very little difference in the calculated results whether the vapor temperature line is made linear to position #1 or is curved as shown.

It will be noted that the indicated vapor temperatures is not the boiling point of the liquid. This is true for all the benzene runs. Since the thermocouples were calibrated a number of times during the investigation and found to give satisfactory readings it is believed that the indicated temperatures are correct. The fact that the hydrocarbons were saturated with water may be the key to an explanation for this apparent anomaly. This inconsistency was ignored in making the calculations.

Figures II and III show the variation of h with position on the condenser pipe. In the majority of the runs h was relatively high at the top of the condensing section and decreased toward the bottom. After a minimum located between positions 3.5 and 5.5 the coefficients increased toward the bottom.

There are two logical explanations for this first decreasing h section below position 7. It was observed that the vapor condensed in droplets at the top of the pipe and these droplets gradually merged into a continuous film as they ran down. The length of pipe on which droplets formed fluctuated erratically during any one run from a few inches to around three feet, but most of the time was less than eighteen inches. Since dropwise condensation gives heat transfer coefficients higher than film condensation, sometimes by as much as 800%, this transition from dropwise to film condensation would explain the decrease in h. A second explanation may be that in practically all the runs t increased toward the bottom of the pipe. Nusselt's theory predicts that h will decrease with an increase in Δt.

The increase in h toward the bottom after the minimum point can most easily be explained by the development of turbulence and ripples in the condensate layer. It was observed that on the lower half of the condenser pipe, especially during the runs using a high condensation rate the condensate seemed to be very turbulent and formed ripples. Sometimes the film would split leaving the pipe bare until the formation of drops on the bare spot was sufficient to reestablish a continuous film. These observations agree with those of Kirkbride who found that for values of $W/\mu d$ from 5 to 1800 ripples and turbulence developed that caused the data to disagree seriously with the Nusselt theory. $W/\mu d$ for all the runs described was well within this doubtful range.

The copper condenser pipe was removed and cleaned a number of times during the course of the investigation but this had no apparent effect on the behavior of the condensate.

In Figure IV the curve of h vs. (Nu) for the entire condensing section is plotted on log log coordinates. Figure V shows this same curve for the rising h section at the bottom of the pipe. $N = 6$ was used for the determination of all these points. This seems logical since condensate formed above the section in question ran down onto it increasing the film thickness and having approximately the same effect that the increased length would have. A straight line is drawn through each set of points. Both the lines are represented by the equation

$$h = 5.53 \times 10^{-14} (Nu)^{1.69}$$

On each sheet the line defined by Nusselt's relation is drawn for comparison.

An attempt to correlate h for the falling h section at the top of the pipe gave points so badly scattered that they are not included.

NOMENCLATURE

Symbol	Meaning of term	Consistent English Units
d	Diameter of tube	Ft.
g	Gravitational constant	Ft./hr^2
h	Film coefficient of heat transfer	$\text{BTU/ft}^2/^\circ\text{F/hr}$
k	Thermal conductivity	BTU/ft/°F/hr
L	Length of section under investigation	Ft.
N	Distance from bottom of section under investigation to top of condenser	Ft.
(Nu)	The group $\frac{k^3\rho^2 gr}{N\mu\,\Delta t}$	
r	Latent heat of condensation	BTU/lb
W	Weight rate of condensation	Lb/hr/tube
Δt	Temperature difference between vapor and wall	° F.
ρ	Density	Lb/ft^3
μ	Viscosity	Lb/ft/hr

CALCULATED DATA FOR BENZENE RUNS

TABLE III

		Run Number									
		8B	10B	11B	13B	14B	16B	17B	18B	20B	21B
LΔt for the intervals---	1-2	10.00	4.25	37.20	33.00	23.30	28.20	15.50	43.20	27.50	26.00
	2-3	15.75	20.50	32.30	32.20	21.80	26.10	16.20	41.80	25.50	21.50
	3-4	18.50	28.20	27.90	28.75	16.00	23.40	14.00	38.00	23.50	17.80
	4-5	17.00	32.80	25.50	25.20	14.80	21.20	11.80	35.00	21.50	14.80
	5-6	15.50	32.30	24.00	22.00	7.98	19.50	9.62	32.30	19.50	12.50
	6-7	14.00	30.30	23.00	20.00	4.62	17.60	7.40	31.00	17.50	11.60
Total LΔt------------------------		90.75	148.35	169.90	161.15	90.50	136.00	74.52	221.20	135.00	104.20
B.T.U. transferred for intervals	1-2	1105	1295	989	2147	1698	2125	2725	830	1247	2910
	2-3	1675	947.8	638	1470	1196	1300	1809	716	1100	2425
	3-4	1874	170.5	427	1110	830	856	1530	528	844	1993
	4-5	1573	692.0	321	860	555	591	1085	339	440	1453
	5-6	1273	1203.0	603	752	415	413	779	264	403	1078
	6-7	1940	1800.0	1200	609	370	295	528	528	697	1615
Total B.T.U. transferred-----------		9440	6108.3	4178	6949	5064	5580	8456	3205	4731	11474
Total B.T.U. transferred, based on condensate----------------		6050	12200.0	8770	7035	4860	9870	8040	4160	5670	10900
Actual h for the intervals------	1-2	355.0	980.0	85.5	209.3	234.2	242.0	566.0	61.9	145.9	360.0
	2-3	342.0	148.5	63.5	146.7	176.2	160.2	359.0	55.0	138.7	362.5
	3-4	326.0	19.45	49.20	124.1	148.2	117.5	351.5	44.7	115.5	360.0
	4-5	297.5	67.8	40.4	109.7	120.5	89.7	295.5	31.15	15.8	315.5
	5-6	264.0	119.9	80.8	109.8	167.3	68.2	260.5	26.35	66.5	277.0
	6-7	446.0	191.0	167.7	97.9	258.0	53.9	229.5	54.8	128.0	448.0
h for entire length of condenser---		334.5	132.3	79.2	138.7	180.0	132.0	365.0	46.6	112.8	354.0

CALCULATED DATA FOR BENZENE RUNS

TABLE III Cont'd

	Run Number									
	8B	10B	11B	13B	14B	16B	17B	18B	20B	21B
Average t for entire condenser--	15.12	24.72	28.30	26.86	15.10	22.70	12.42	36.90	22.50	17.37
Average film temperature for ontire condenser (°F.)------	148.9	144.3	154.0	149.5	153.0	147.2	160.8	143.8	147.0	150.0
(Nu) for entire condenser (x 10^{-8})	17.88	10.95	9.70	10.09	18.20	11.82	23.00	7.32	14.30	30.90
Rising h section at bottom------- of condenser	1-7:6	1-3.25: 2.25	1-4.5 :3.5	1-7:6	1-4.5: 3.5	1-7:6	1-7:6	1-5.5: 4.51	1-5:4	1-5.5: 4.5
Average t for this section------	15.12	14.12	31.50	26.86	20.10	22.70	12.42	38.70	24.50	19.20
Ave. film temp. for this section-	148.9	144.3	151.0	149.5	150.1	147.2	160.8	147.9	145.0	150.0
Total B.T.U. transferred in this section--------------------	9440	2285.4	2215	6949	4002	5580	8456	2545	3631	9320
1Δt for this section-------------	90.75	31.80	110.2	161.15	70.5	136.0	74.52	174.1	98.0	86.4
h for this section---------------	334.5	231.0	64.5	138.7	182.5	132.0	365.0	47.0	119.1	347.0
(Nu) x 10^{-8} for this section-----	17.88	19.17	9.70	10.09	15.20	11.82	23.00	6.90	11.10	15.90

CALCULATED DATA FOR HEXANE RUNS

TABLE IV

		Run Number					
	2H	3H	5H	6H	7H	9H	10H
$L\Delta t$ for the intervals--------1-2	17.00	18.41	15.40	17.20	21.40	28.50	23.80
2-3	17.77	17.75	17.00	16.20	20.00	29.60	22.80
3-4	20.50	15.75	15.50	15.80	18.40	28.40	21.40
4-5	19.00	15.25	13.50	14.50	16.80	26.40	19.90
5-6	16.38	15.00	11.00	12.50	15.00	23.50	17.40
6-7	11.00	15.25	8.00	9.62	13.50	19.20	14.00
Total ΔL t----------	103.65	97.41	80.40	85.82	105.10	155.60	119.30
B.T.U. transferred for intervals--------1-2	593	510	1144	804	864	510	747
2-3	456	328	660	697	571	412	448
3-4	548	364	430	616	381	353	398
4-5	730	838	301	483	264	206	299
5-6	913	619	230	268	161	147	548
6-7	1278	364	143	348	146	500	1120
Total B.T.U. transferred----------	4518	3023	2908	3216	2387	2128	3560
Total B.T.U. transferred based on condensate	5830	7310	10150	4800	5030	3310	5160
Actual *h* for the intervals--------1-2	112.1	89.0	239.0	150.3	129.9	57.6	101.0
2-3	82.5	59.4	124.9	138.3	91.75	44.75	63.2
3-4	86.0	74.4	89.2	125.2	66.6	39.9	59.8
4-5	123.6	176.7	71.6	62.7	50.5	25.1	48.3
5-6	179.2	132.6	67.3	69.0	34.5	20.1	101.3
6-7	376.5	76.8	57.5	116.3	34.8	83.8	257.3
h for entire length of condenser----------	140.0	99.9	116.2	120.6	73.1	44.0	95.9

CALCULATED DATA FOR HEXANE RUNS

TABLE IV Cont'd

	Run Number						
	2H	3H	5H	6H	7H	9H	10H
Average t for entire condenser	17.28	16.23	13.40	14.31	17.50	25.90	19.90
Average film temperature for entire condenser	130.2	120.7	137.5	136.1	135.6	125.6	133.2
(Nu) for entire condenser $(\times 10^{-8})$	9.73	10.22	12.53	11.73	9.77	6.44	8.51
Rising <u>h</u> section at bottom of condenser	1-3:2		1-7:6	1-5:4	1-7:6	1-5.5 :4.5	1-4.5 :3.5
Average Δt for this section	17.40		13.40	15.92	17.50	27.70	22.27
Average film temperature for this section	126.0		137.5	136.0	135.6	127.0	134.0
B.T.U. transferred in this section	1049		2808	2600	2387	1555	1743
$L\Delta t$ for this section	34.77		80.40	63.70	105.1	124.7	77.95
<u>h</u> for this section	97.0		116.2	131.2	73.1	40.1	71.9
(Nu) $\times 10^{-8}$ for this section	9.59		12.53	10.73	9.77	6.03	7.60

FIGURE I

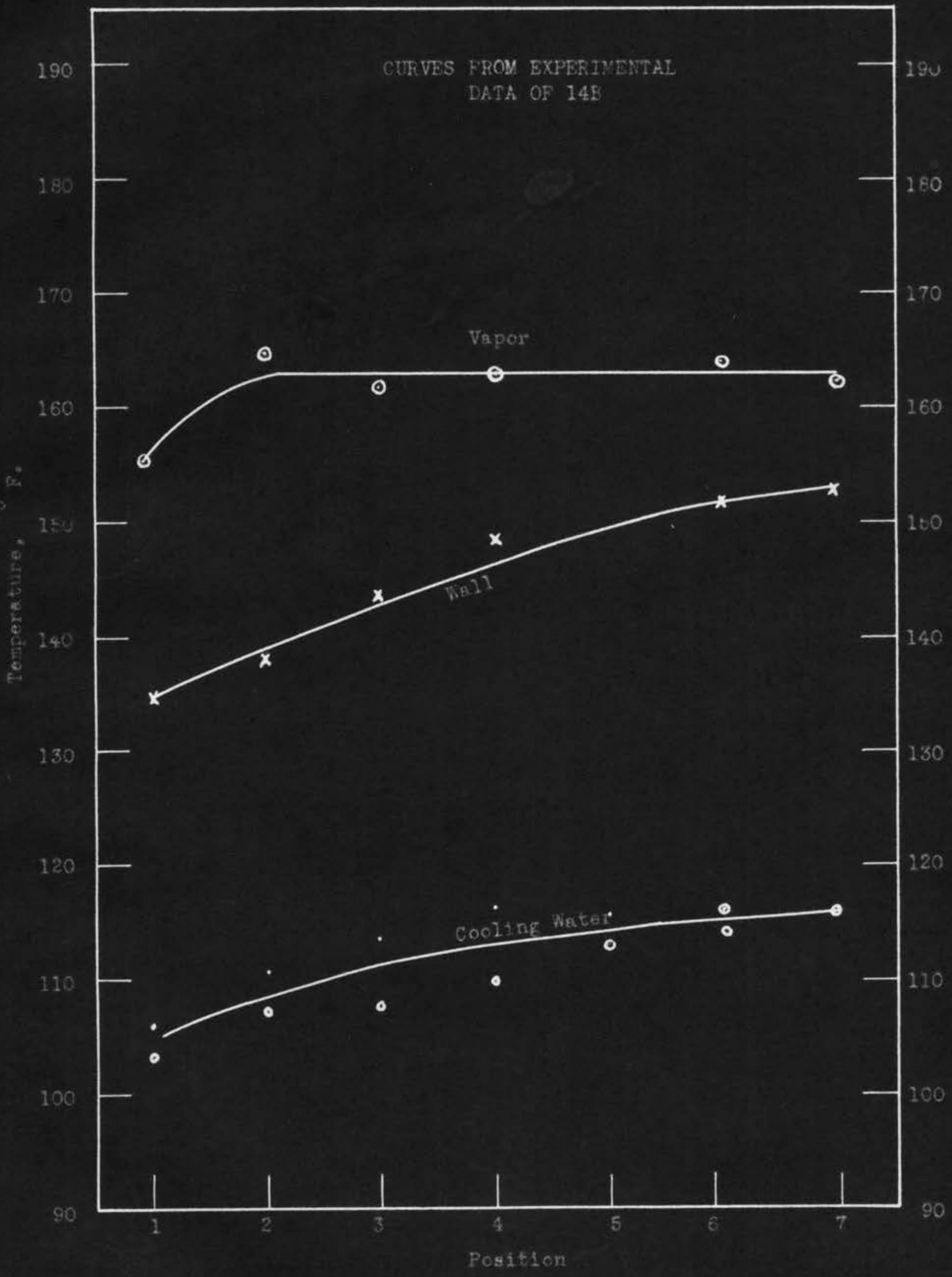

CURVES FROM EXPERIMENTAL
DATA OF 14B
Vapor
Wall
Cooling Water
Temperature, ° F.
Position
190
180
170
160
150
140
130
120
110
100
90
1
2
3
4
5
6
7

FIGURE II

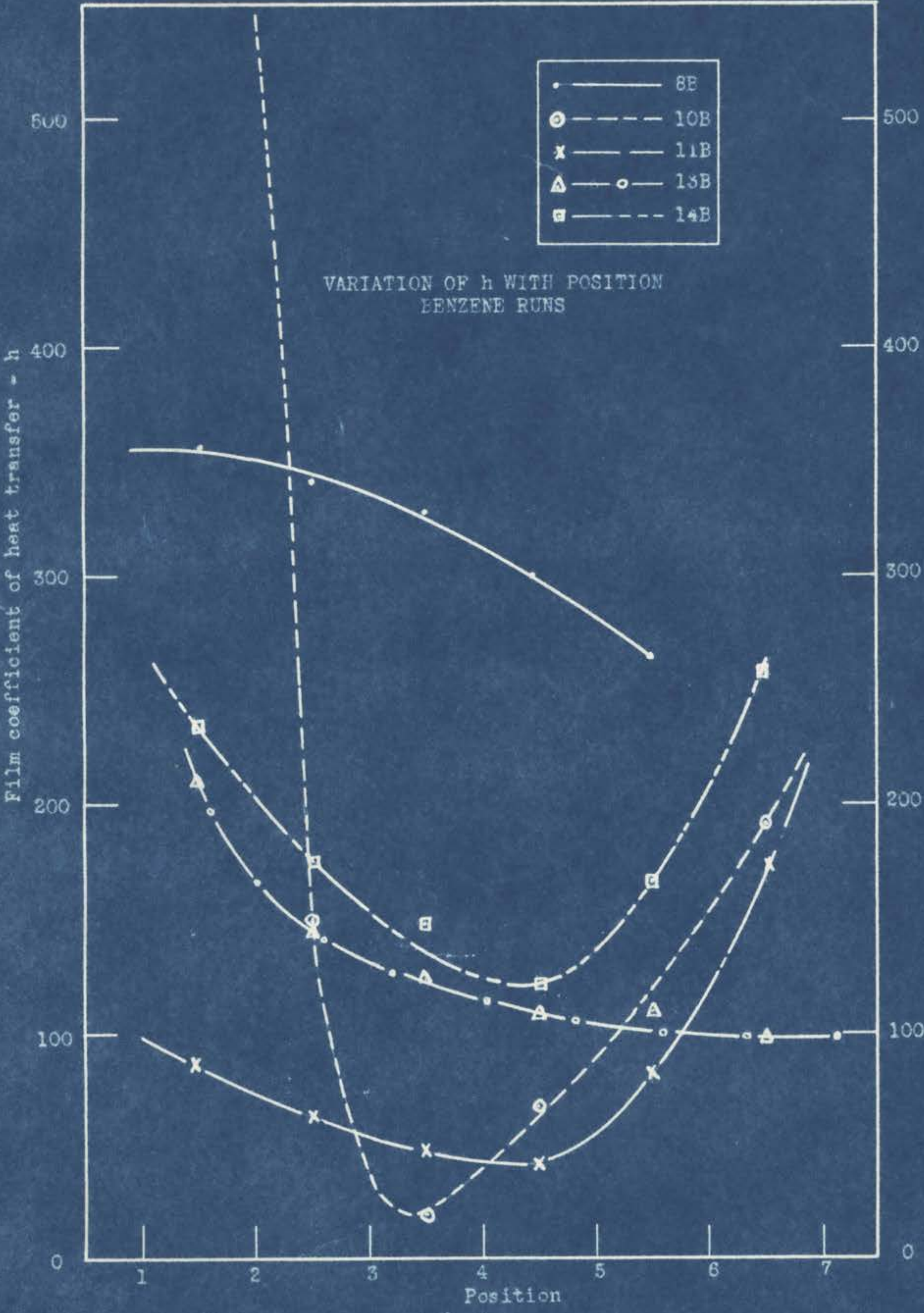

8B
10B
11B
13B
14B
VARIATION OF h WITH POSITION
BENZENE RUNS
Film coefficient of heat transfer - h
0
100
200
300
400
500
Position
1
2
3
4
5
6
7

FIGURE II (Cont'd)

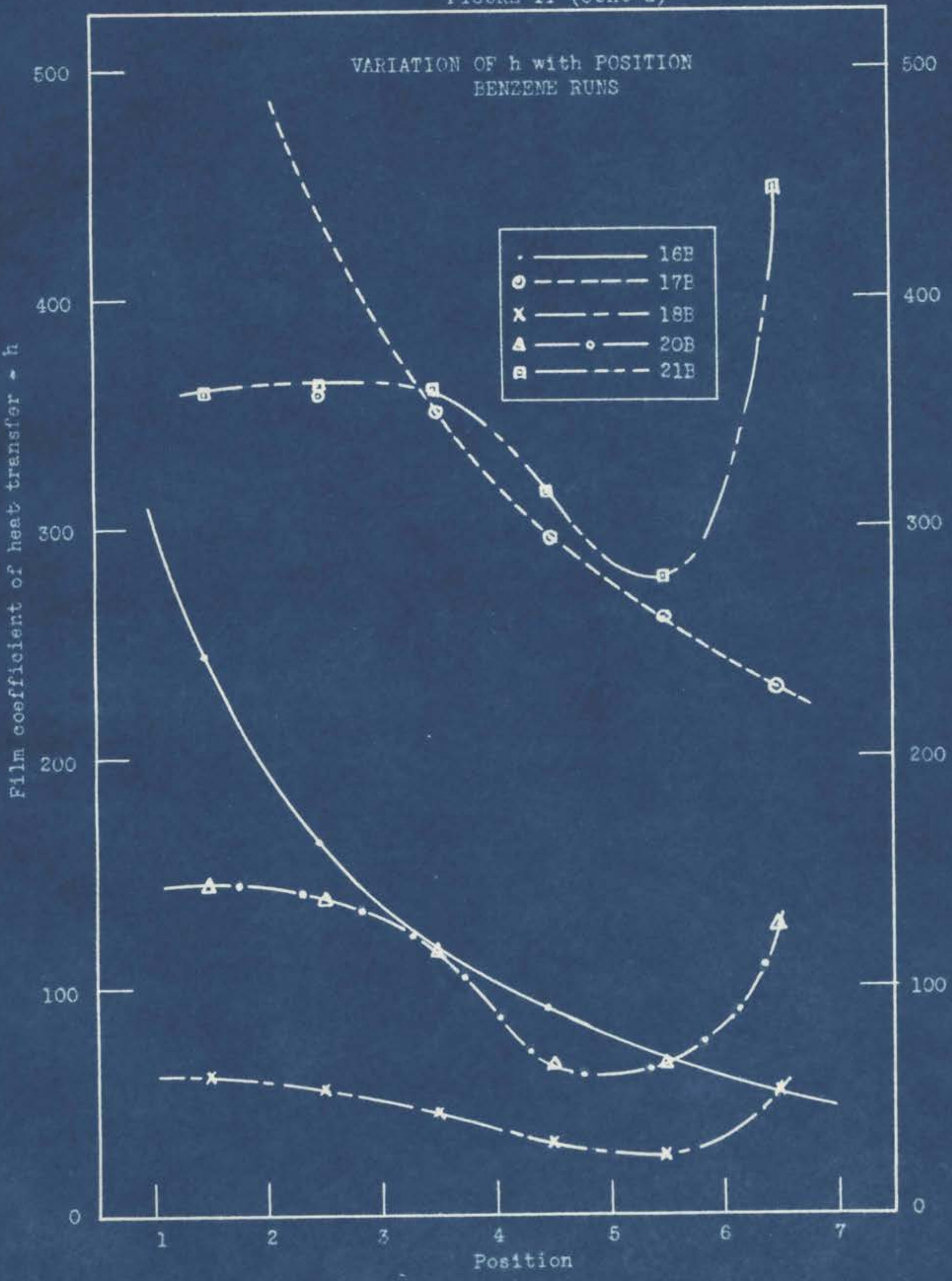


FIGURE III

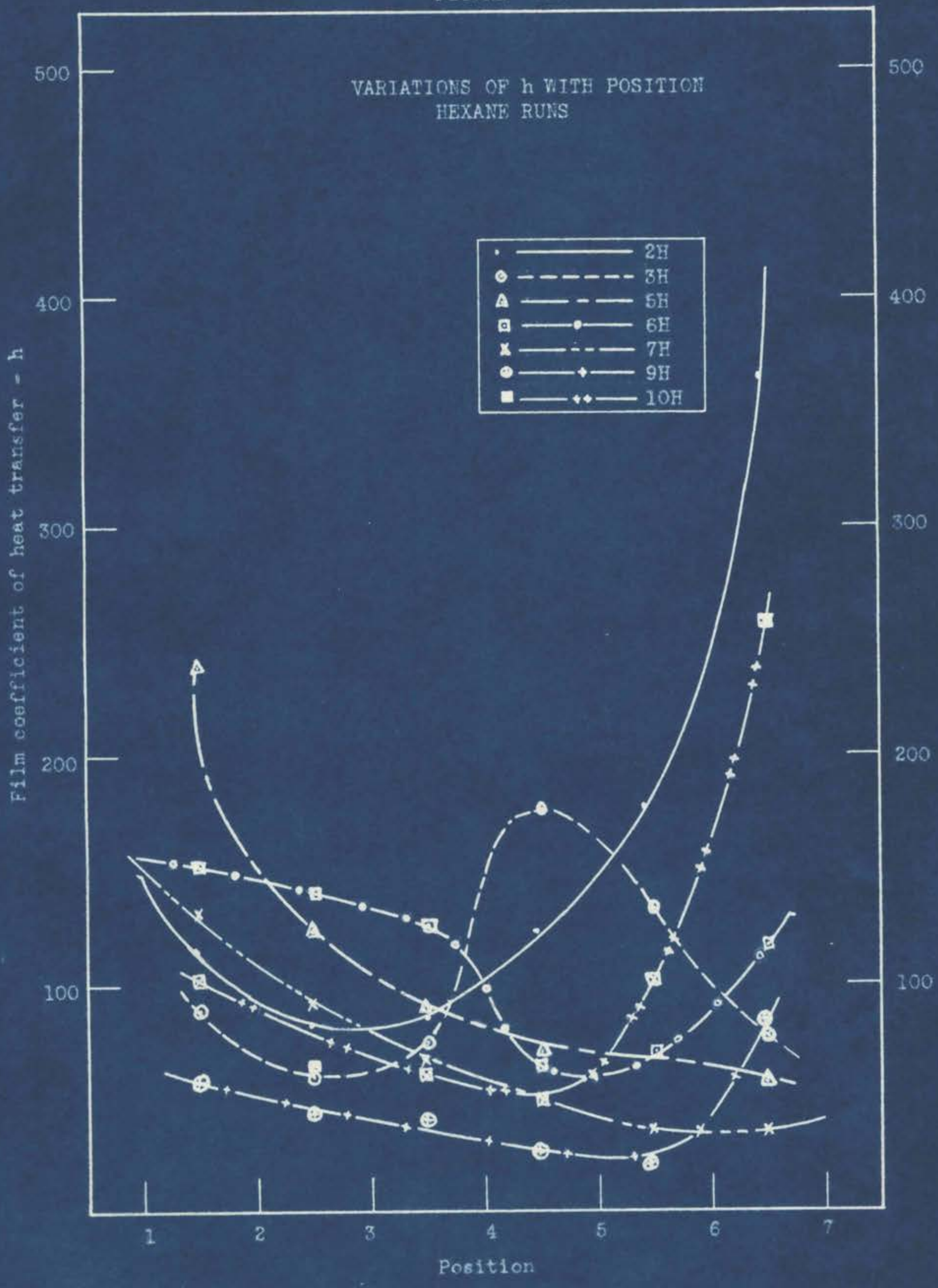
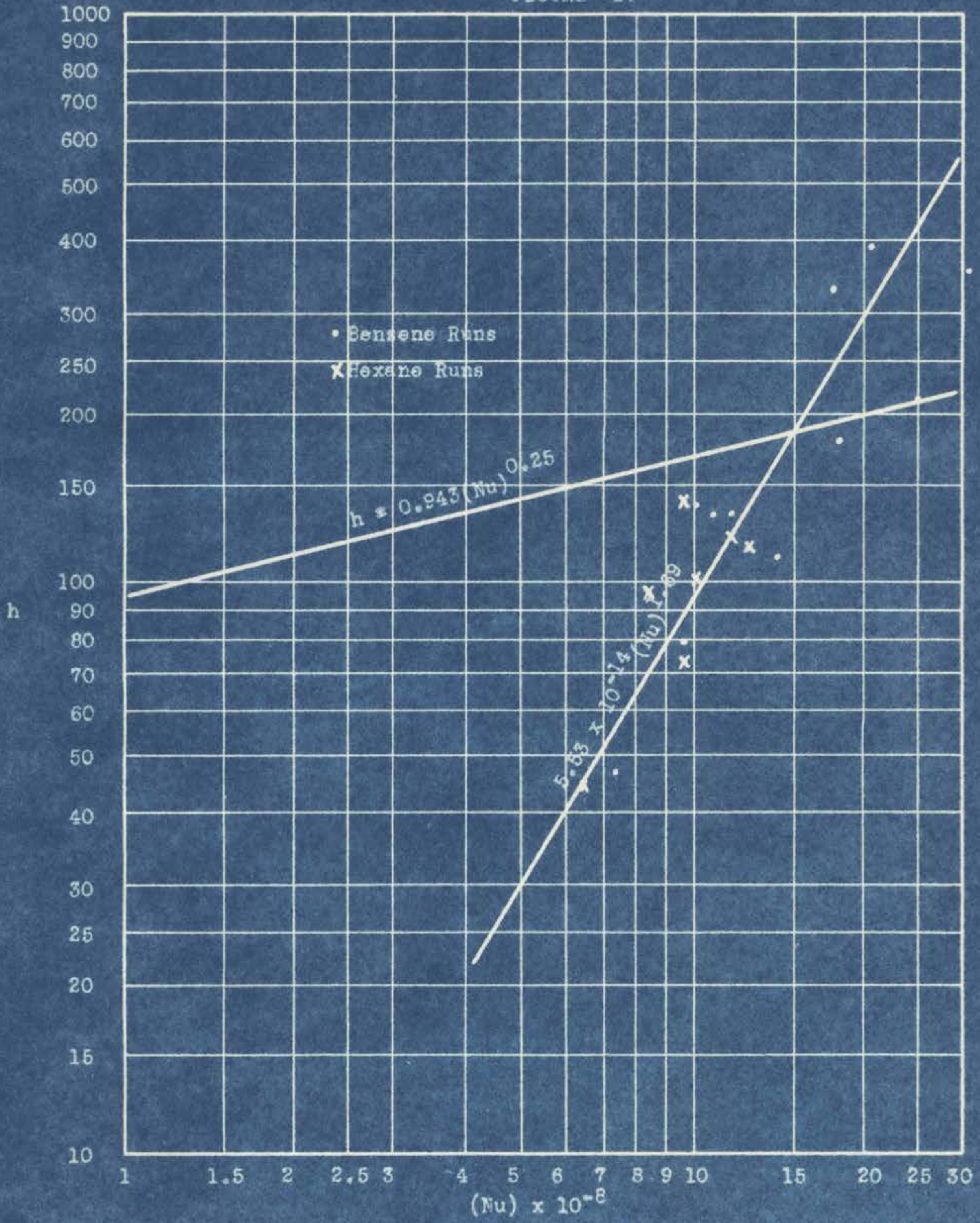
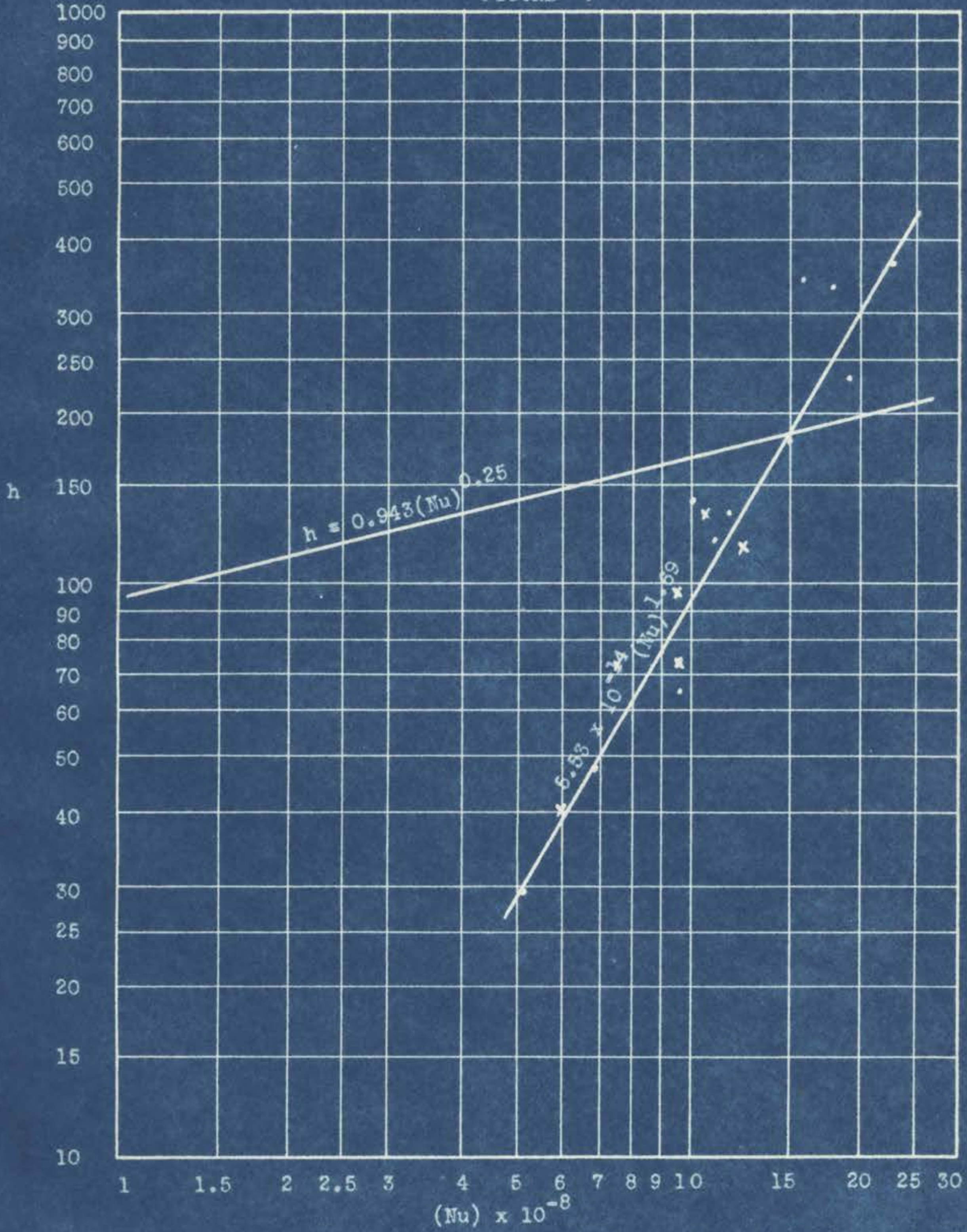

VARIATIONS OF h WITH POSITION
HEXANE RUNS
2H
3H
5H
6H
7H
9H
10H
Film coefficient of heat transfer - h
500
400
300
200
100
500
400
300
200
100
1
2
3
4
5
6
7
Position

FIGURE IV



h vs. (Nu) for Entire condensing sections

FIGURE V



h vs. (Nu) for Rising h section at bottom of condenser

V. CONCLUSIONS

The following conclusions may be drawn from observations of the behavior of the experimental apparatus and from the data and discussion presented here.

1. Heat transfer data on condensing films of benzene and a mixture of hexanes obtained as described in this paper may be correlated by plotting h vs. $\frac{k^3\rho^2 gr}{N\mu\Delta t}$
2. The slope of the line established by this plot is 1.69 and its intercept 5.53×10^{-14}.
3. For a short distance at the top of a vertical condenser tube the condensation is very likely dropwise.
4. It is very difficult to establish and maintain a continuous condensing film on a vertical condenser tube.

VI. SUMMARY

A review of selected literature reveals that condensing film heat transfer data quite often are in poor agreement with the predictions of Nusselt's theory. This may be attributed in part to failure to comply with his fundamental assumptions.

Vapors of benzene and a mixture of hexanes were condensed on the outside of a vertical copper pipe 1 3/16 inches o.d. and six feet long. The vapors moved down in the annular space between the pipe and a 2.0 inch i.d. glass tube and cooling water moved up inside the pipe. The vapor temperature, external pipe wall temperature, and cooling water temperature were measured at intervals of one foot along the length of the condenser by means of thermocouples.

Data obtained with this assembly are correlated by plotting h vs. $\frac{k^3\rho^2 gr}{N\mu\Delta t}$. They establish a line represented by the equation

$$h = 5.53 \times 10^{-14} \left(\frac{k^3\rho^2 gr}{N\mu\Delta t}\right)^{1.69}$$

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