A METHOD OF DETERMINATION OF COEFFICIENTS OF THERMAL CONDUCTIVITY OF GASEOUS MIXTURES

A THESIS

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by

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A METHOD OF DETERMINATION OF COEFFICIENTS OF THERMAL CONDUCTIVITY OF GASEOUS MIXTURES

Approved:

Date Approved by Chairman 12/30/42

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SYMBOLS USED (unless otherwise specified)

T - Absolute Temperature (°R)

t - Temperature (°F)

P - Absolute Pressure (p.s.i.)

u - Absolute Viscosity (centipoises)

RH - Relative Humidity (per cent)

M - Gravimetric Mass Rate of Flow (pounds per sec.)

C_d - Coefficient of Discharge (dimensionless)

C_p - Specific Heat at Constant Pressure (B.T.U./lb.-°F)

A - Area (square feet)

D - Diameter (feet)

d - Clearance between Thermocouple and Tube (feet)

L - Length of Test Section (feet)

l - Thickness of Gas Layer (feet)

p - Density (pounds per cubic foot)

U - Velocity (feet per second)

N - Reynolds' Number (dimensionless)

R - Gas Constant (foot lb. per lb. per degree Rankine)

T_m - Logarithmic Mean Temperature Difference (°F)

Q - Heat Transferred (B.T.U./hr.)

h - Transmissivity Coefficient (B.T.U.-ft./hr.-sq. ft.-°F)

k - Thermal Conductivity Coefficient (B.T.U.-ft./hr.-sq.ft.-°F)

- Number Sign or pounds

SUBSCRIPTS USED (unless otherwise specified)

av - Average

c - Center

g - Gas

i - Pipe

o - Orifice

s - Steam

1 - Entering Section of Orifice
or First Thermocouple Station

2 - Leaving Section of Orifice
or Second Thermocouple Station

3 - Third Thermocouple Station

I. ANALYSIS AND BACKGROUND OF THE PROBLEM

The determination of the Coefficient of Thermal Conductivity of any material; whether it be solid, liquid, or gaseous; is a problem dealing with heat transmission. Moreover, any problem involving heat transfer must take cognizance of the many aspects involved in the several methods of heat transmission.

From the literature of thermodynamics it is found that this heat transmission may be accomplished in two or three different ways. If heat transmission is considered as merely the transfer of energy due to a temperature differential, there are but two distinct methods of heat transmission - they being known as conduction and radiation. If, on the other hand, heat transmission is considered as including heat that has been stored in a substance, remains so stored, and is thus capable of being transferred from one location to another by the physical flow of the substance from the one location to the other; then allowance must be made for this method of heat transfer, known as Convection, as well as the first two - Conduction and Radiation - and each of the three must be considered as a means of heat transfer. As the problem under consideration involves steady flow of the medium through the equipment, the investigator is forced to consider all three means as vehicles for heat transmission.

Since the transmission of heat may occur by any one or all of the three methods mentioned, one of the main problems of this investigation is the isolation of the heat transferred by conduction from that transmitted through the other two mediums. This isolation will be accomplished by a process involving steady flow of the fluid medium, this being a more popular method of attack than the non-flow type of process which involves the delicate problem of maintaining equilibrium conditions without any movement of the medium.

Previous work on this and allied problems has been carried out with processes involving steady flow also. However, the work of the other investigators was based upon principles quite different from those governing this investigation.

The work of Mason and Doe[1] and that of Palmer and Weaver[2] are both based upon the same principle. That being: the equilibrium temperature of a wire of known resistance, carrying a known current, and surrounded by a known gas under known conditions, flowing through

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(1) C. M. Mason and R. M. Doe - "Determination of Thermal Conductivities of Gases." J. Chem. Education, 14: 182 (1937)

(2) E. R. Weaver and P. E. Palmer - "Application of Thermal Conductivity Method to the Automatic Analysis of Complex Mixtures of Gases". Ind. & Eng. Chem. J. 12: 359-66 (1920); ibid 12: 894-9 (1920).

a cell of known dimensions, will be a function of the conductivity of the gas flowing. Conversely, the conductivity of the gas under consideration will be a direct function of the temperature of the wire.

With these investigations, the heat transfer is from the wire in the center of the cell to the surrounding gas inside the cell and to the atmosphere surrounding the cell itself. On the other hand, in the case of the study being made here, the heat is transferred from a jacket surrounding the test section to the medium inside the test section. The heat flow measured is only that flowing from the gas near the inside surface of the test section to the gas moving along the center line of the test section. As only this heat is of interest to the investigator, no other preliminary deductions must be made from the measured heat transfer.

II. METHOD OF ATTACK

A. General:

As has been stated previously, the main problem in the performance of this investigation is the isolation of the conducted heat from the heat transferred by radiation and convection. This investigation, being based upon a steady flow process, proposes to minimize the convected heat transfer by means of forced convection, in varying rates, of such a magnitude so as to preclude the existence of natural convection currents.

This line of reasoning is based upon the assumption that the rate of heat transmission and the coefficient of heat transmission (Transmissivity Coefficient as it will henceforth be called) will increase with increased flow at constant temperature.

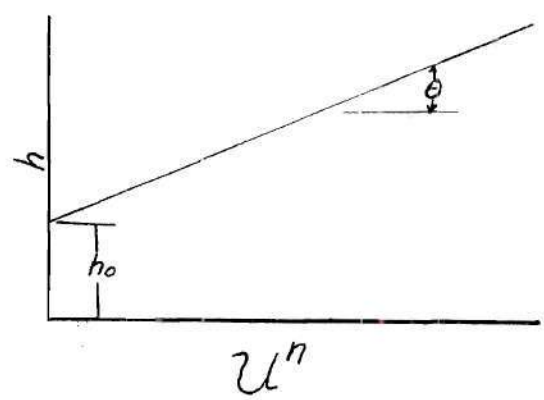

Fig. 1 - h vs U^n

The variation in transmissivity coefficient with a variation in rate of flow (U) will be assumed to occur in a manner similar to the curve as shown in figure 1, where the curve will be the form $h = h_o + (U)^n \tan\theta$ in which h_o will be the intercept of the curve or the value of the transmissivity coefficient (h) at zero velocity.

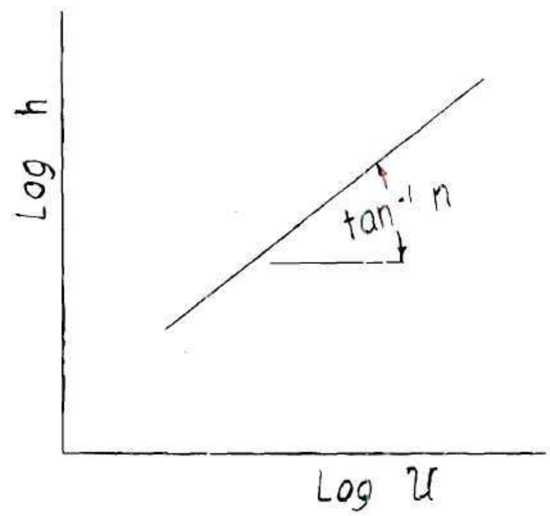

Fig. 2 - log (h) vs log (U)

The value of the exponent (n) may be determined easily as n will be the slope of the curve resulting from the plot of log (h) vs log (U) similar to the curve shown in figure 2.

The fact that this work was done in a section of polished aluminum tubing with an approximate emissivity of 0.040[3] will reduce the radiant heat transfer to an estimated minimum and at the same time will give a basis for predicting, quantitatively, the extent of the radiant heat transmission. Thus, with the convected heat transfer eliminated, the radiant heat transfer minimized and calculable, it would seem evident that the remaining portion of the total heat transferred would be that transferred by virtue of conduction.

B. Velocity Variation:

The variation of the velocity necessary for the elimination of the heat transfer by convection presents no difficult problem. It merely necessitates the variation of rate of gas flow from a maximum flow which is small enough to assure viscous flow, down to the minimum flow determined by the accurate range of the flow meter.

For these tests the flow ranges from approximately 3½ pounds of gas per hour (based upon a Reynold's Number 2000) down to a rate of 0.625 pounds of gas per hour, the minimum flow which can be measured accurately by the orifice type meter which was used.

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[3] W. H. McAdams, "Heat Transmission" (McGraw-Hill Book Company, 1933) page 45.

C. Temperature Variation:

In the design of the apparatus, provision has been made for the variation of the average temperature of the gas entering the test section as well as the temperature of the heat source. This has been done in order to keep a uniform temperature difference between the source of heat and the gas regardless of the initial gas temperature. The value of this arrangement is that it allows the observance of the variation of the conductivity coefficient over a slight temperature range.

D. Calculations:

In order to convert the values of the data observed and recorded in the laboratory to results which would have more significance, a number of relationships were used and a definite procedure was followed to eliminate confusion.

After the thermocouple data from the data sheet had been correlated, averaged, and converted to temperature by Table I, the temperature drop from the inside surface of the tube to its center line was obtained at each station and averaged for the three stations.

Then the steam temperature was read from the steam tables[4] as the saturation temperature corresponding to the absolute steam pressure as taken from the data.

From the preceding temperatures the Logarithmic Mean temperature Difference (T_m) between the steam and gas flowing at the center of the pipe was calculated from the relationship

$$T_m = \frac{(t_s - t_{c_1}) - (t_s - t_{c_3})}{\log_e \frac{t_s - t_{c_1}}{t_s - t_{c_3}}}$$

Next, to determine the Mass Rate of Flow (M), use was made of the relationship[5]

$$M = A_o \cdot C_d \cdot 8.02 \sqrt{\frac{P_1(P_1 - P_2)(144)^2}{RT_1}}$$

which may be used when $P_1 - P_2$ does not exceed .01 P_1 as was the case with these calculations.

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[4] J. H. Keenan and F. G. Keyes, "Thermodynamic Properties of Steam," John Wiley & Sons, 1936.

[5] P. J. Kiefer and M. C. Stuart, "Principles of Engineering Thermodynamics," John Wiley & Sons, (1930) page 234.

From there Reynold's Number was calculated for assurance that laminar flow was occurring. This is true if Reynold's Number does not exceed about 2100.[6] Reynold's Number (N) was computed from the relationship[6]

$$N = \frac{U \cdot D \cdot p}{.000672 \cdot u}$$

where

$$p = \frac{P_1 \cdot 144}{R \cdot T_1} \qquad (7)$$

and

$$U = \frac{M}{p \cdot A_i} \qquad (7)$$

Having determined the necessary temperatures, and flow values, and having been assured that the conditions of flow were consistent with those planned; this information was then used to calculate the heat transferred (Q) using the relationship

$$Q = 3600 \cdot M \cdot C_p \cdot \Delta t_{av}$$

whence the transmissivity coefficient (h) was evaluated by

$$h = \frac{Q \cdot 1}{A_{av} \cdot T_m} \qquad (8)$$

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(6) J. K. Vennard, "Elementary Fluid Mechanics," John Wiley & Sons (1940), page 108.

(7) Kiefer & Stuart

(8) W. A. McAdams

where: $l = 1/2(D_i - d)$

and: $A_{av} = 1/2(A_c + A_i)$

Then the radiation effects were calculated and found to be negligible. These computations were based upon results of investigation of the Infra-Red spectra by Coblentz[9] and were adapted to fit the needs of the investigation according to the method outlined by Hottel.[10] The calculations made indicate that the radiation effects were of the order of one tenth of a per cent of the heat transfer and therefore may be disregarded.

Finally, with the information based upon the foregoing material at hand, the value of the thermal conductivity was ascertained. According to the method previously outlined, the transmissivity coefficients were plotted against the velocities, at which they were calculated, on log-log coordinates. The slope of the resulting straight line between the plotted points was then taken as the exponent (n) in the relationship $h = f(U^n)$. Then a plot of transmissivity coefficient (h)

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[9] W. W. Coblentz, "Investigation of Infra-Red Spectra," page 12 and 22, Carnegie Institute Publication No. 35 (1905).

[10] H. C. Hottel, "Heat Transmission by Radiation of Non-Luminous Gases," Trans. AIChE, vol. 19, 173.

was made for each series of tests. This is the velocity raised to some power (U^n).

The resulting straight line between the points plotted, which from the theory form a rectilinear relationship between h and U^n, was extrapolated to a zero velocity where the transmissivity coefficient becomes the thermal conductivity coefficient as the heat transfer by convection is eliminated. The value of this coefficient was then read from the intercept of the curve.

III. ARRANGEMENT AND CONSTRUCTION OF APPARATUS

In general it may be said that the equipment was constructed from standard pipe and fittings (see Fig. 3). However, with regard to the jackets (Fig. 7) and the orifice installations (Fig. 4), special provision had to be made for the particular needs of the investigation.

The main air and methane sections were constructed of standard one-inch pipe and fittings as well as the aluminum test section which was selected so that it would have the same dimensions as the standard one-inch pipe to which it was to be attached, as shown in Figure 3.

The selection of a drawn seamless aluminum tube was governed by two factors. First, aluminum when well polished retains an emissivity of approximately 0.04 which is as low as that of any material practically and economically obtainable. Second, the fact that the tube was drawn made the fine finish possible with a minimum of effort on the part of the experimenter. The finish, as is shown in Figure 6, was what would be classified as a polished finish. While the rings in the photograph seem to indicate that the sides of the tube were not exactly parallel, the deviation was of a magnitude so as to have a negligible effect upon the flow.

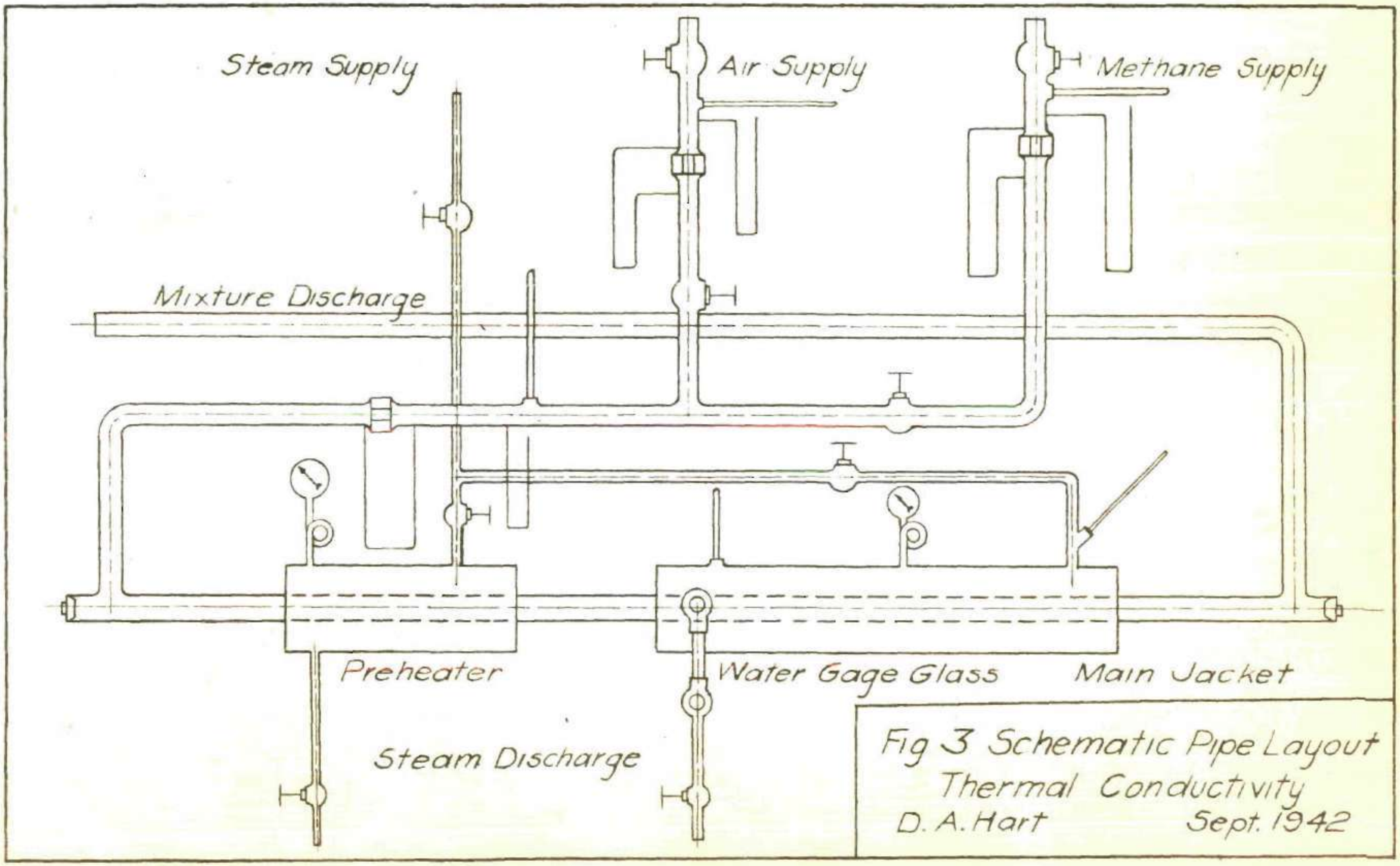

Fig 3 Schematic Pipe Layout
Thermal Conductivity
D. A. Hart Sept. 1942

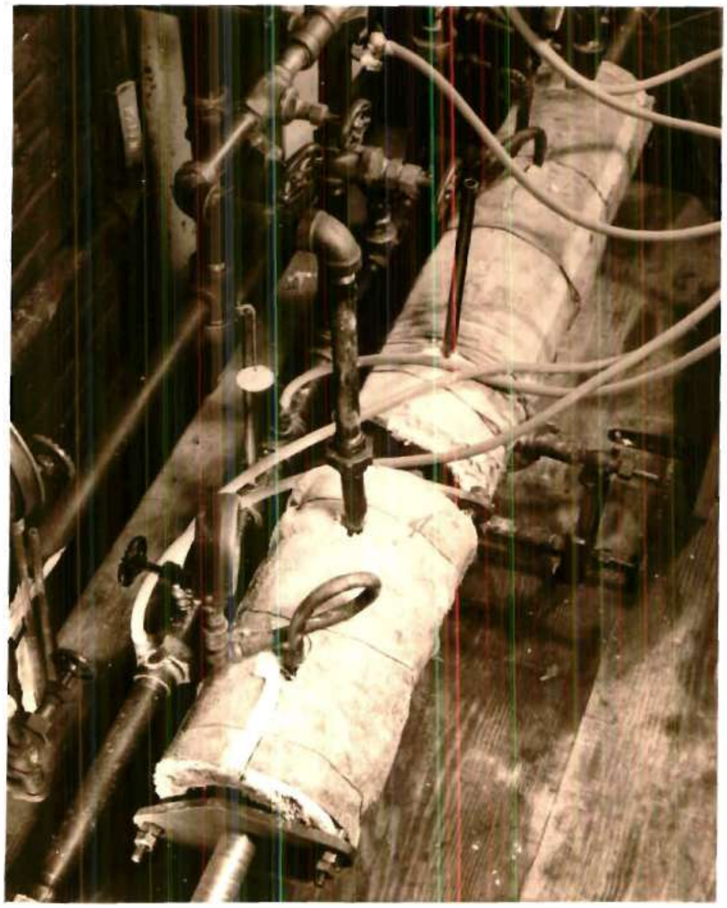

Fig. 4 - Top View of Test Section
and Orifice Section

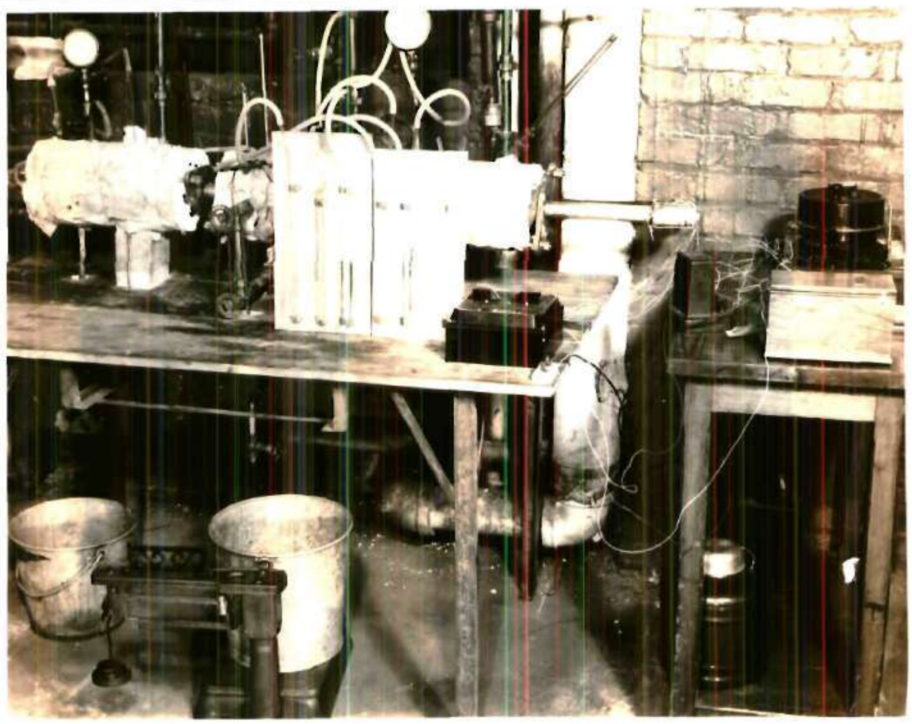

Fig. 5 - Front View of Apparatus with

Potentiometer Set Up

The layout of the piping, as shown in figure 3, was designed so that there were no fittings within 10 pipe diameters of any of the orifices (see Fig. 4) or within 30 pipe diameters of the main test section which extends over a distance of 24 pipe diameters (see Fig. 5). This was done to insure uniformity of flow conditions.

The steam piping from the main to the preheater and main jacket was made of standard 1/2-inch pipe and fittings which was more than adequate to handle the steam flow required. The condensate piping was constructed of standard 1/2 and 1/4-inch pipe and fittings, which again, was more than sufficient to handle the required flow.

The preheater and main jackets were built up using standard 4-inch pipe for the shell with 1/4-inch steel plate welded on the ends and drilled to fit over the test pipe. These jackets were slipped over the test section and sealed with specially designed packing joints, designed and installed as is shown in figures 4 and 7. These packing joints were not of the more common design but were suited to the particular needs of the equipment and were adequate to withstand the relatively low pressure

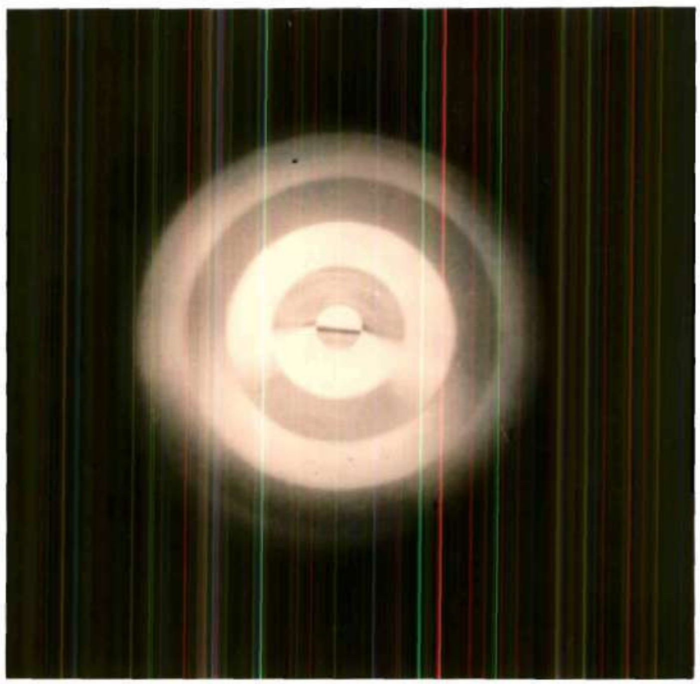

Fig. 6 - View of Inside of Test Section

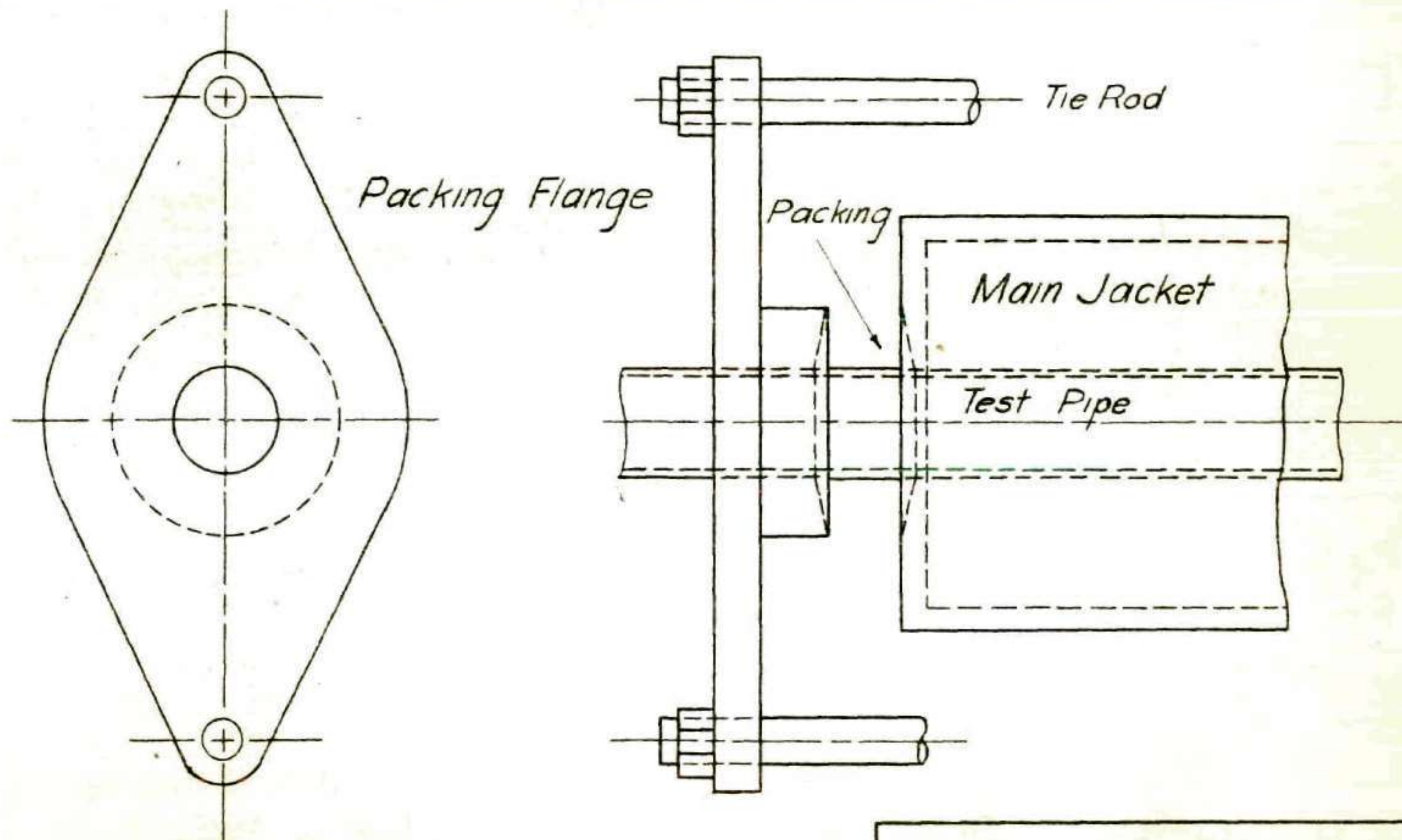

FIG 7 Packing Detail
Thermal Conductivity
D. A. Hart Sept. 1942

used in the tests. The piping and packing were tested at seventy-five pounds per square inch gage momentarily and forty pounds per square inch gage for a period of a half hour and found to be more than satisfactory. These pressures were in excess of the pressure used in the tests which ran to a maximum value of fourteen pounds per square inch gage.

The orifices were designed and installed so as to conform to accepted standards of orifice meter installation.[11] Three orifices were used, as is shown in figure 3, - one to meter the air alone, one to meter the methane alone, and one to meter the mixture as sent through the test section. All three orifices were similar as to design and installation as shown in figure 8. They were .02345 inch diameter orifices drilled in 1/32 inch orifice plate. The orifice plates were then set in standard one-inch pipe unions which had been built up on the inside on both sides of the orifice so that the inside surfaces were flush with the inside of the pipe. The pressure taps on the upstream and downstream sides of the

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[11] "Fluid Meters - Their Theory and Application," A.S.M.E. Research Publication, pg. 16.

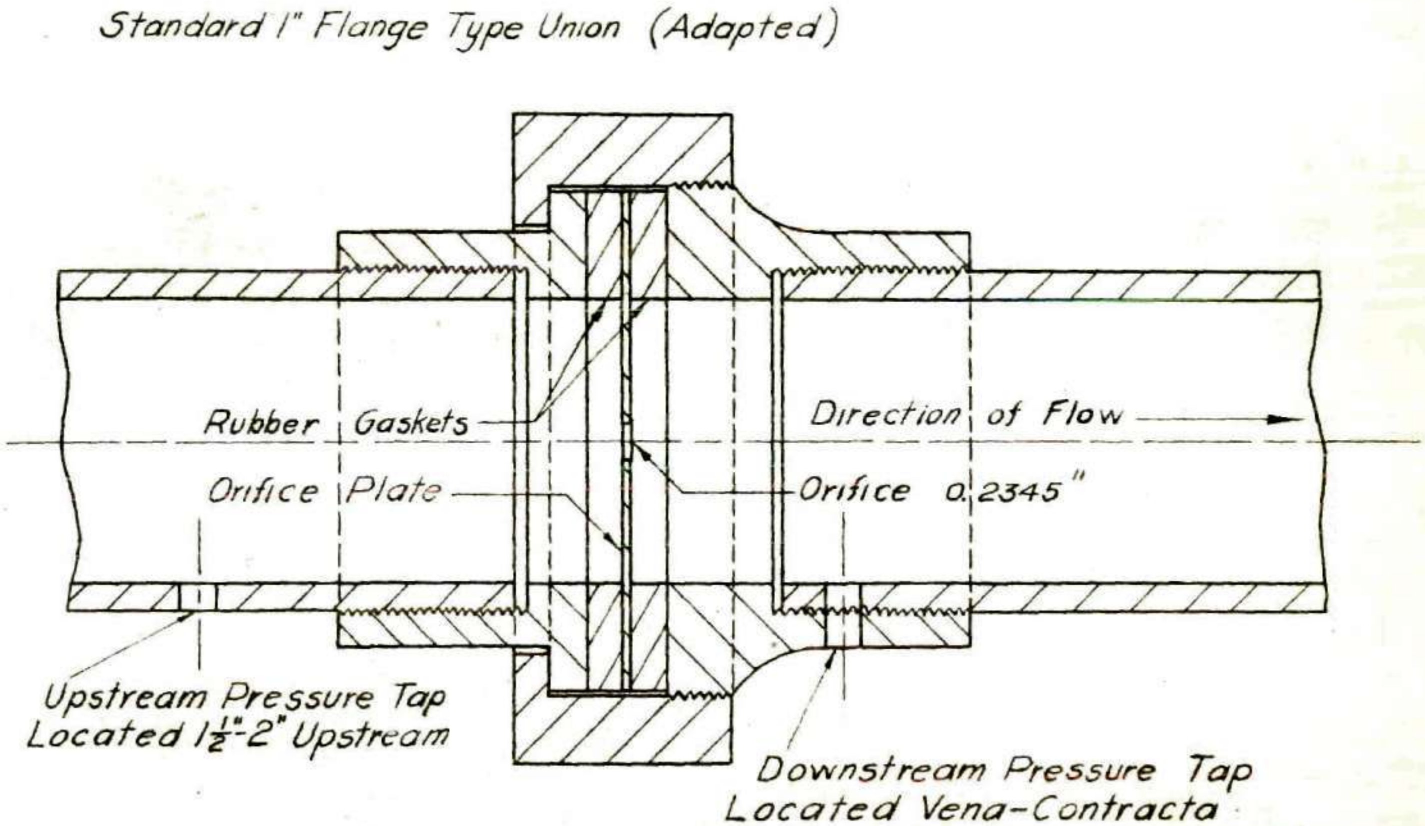

Fig 8 Orifice Installation Section
Thermal Conductivity
D. A. Hart Sept. 1942

orifice plate were located two inches away and at the vena contracta respectively. This set-up was in accordance with standard specifications and therefore a coefficient of discharge 0.605 may be assumed from the literature[12] as the standard coefficient of discharge. In support of this reasoning, the orifices were checked against a positive displacement meter. The results showed that using $C_d = .605$ the discrepancy was less than two per cent.

The installation which proved to be an invaluable part of the equipment was a sight glass in the steam exhaust line from the main jacket. This was made of boiler gage glass and standard 1/2-inch fittings and was placed so that the center of the sight glass was at approximately the same elevation as the inside of the bottom of the jacket. This is shown in figure 9. The sight glass provided a method of assuring the condition that the test section was entirely surrounded by steam at a constant pressure. The installation of the gage glass may be followed as shown in figure 10.

The arrangement of the thermocouples in the three stations of the test section was accomplished by

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[12] Cit. Loc., page 36.

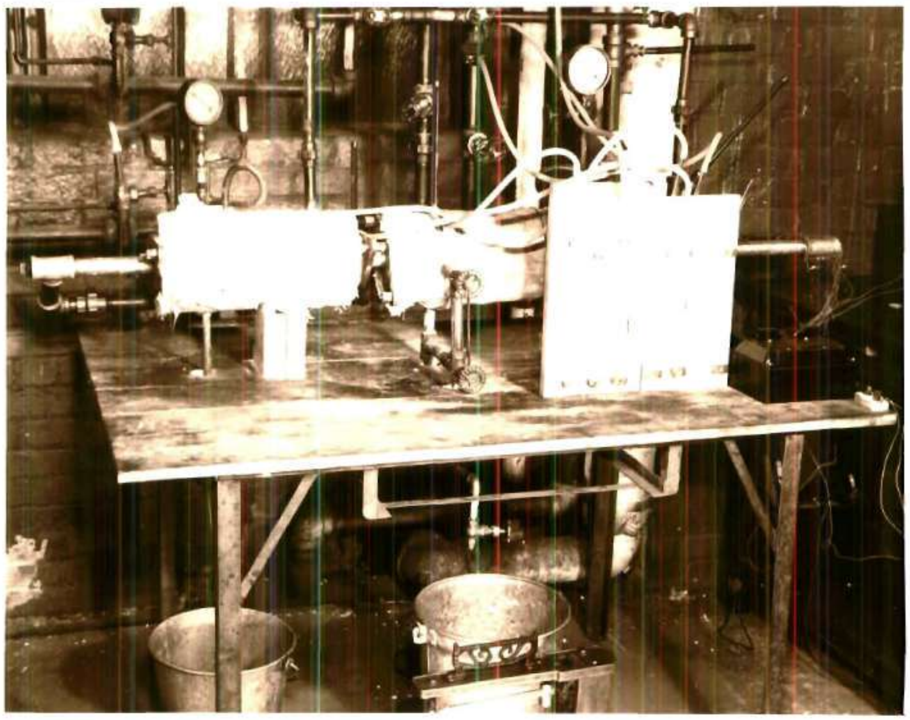

Fig. 9 - Front View of Apparatus

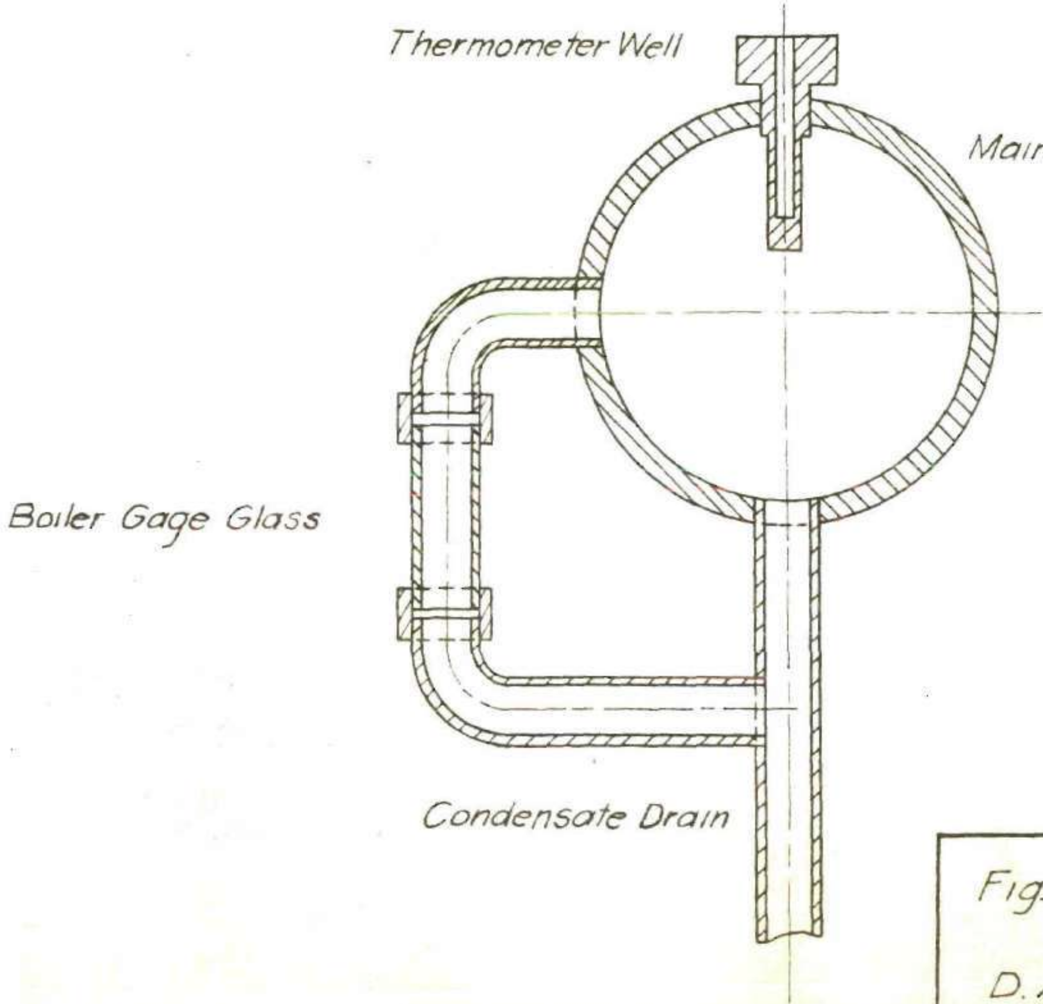

Fig. 10 Gage Glass Section
Thermal Conductivity
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the use of fibre board spacers. At each of the three stations, three thermocouples were fixed to the spacers - two near the inside surface of the tube and one at the center of the tube. The "near surface" temperatures were not, strictly speaking, surface temperatures because those thermocouples were located at a position 3/32 inch from the inside tube surface. This was done to assure the elimination of film effects, which would have complicated computations unnecessarily. The thermocouples were located at each of the three stations in a similar manner and were numbered according to figure 11. From the stations the thermocouple wires (B&S No. 24 iron-constantan) were run along the test section to the discharge end and out of the pipe through holes drilled in a rubber stopper which was forced into a one inch "tee" and sealed with rubber cement. From there the leads from all nine thermocouples were run to a multiple point switch box as is shown in figures 5 and 12. Then from the switch box a common pair of leads were run to the potentiometer with a common cold junction thermocouple having been inserted in series with the potentiometer. This equipment is also pictured in figures 5 and 12. The wiring of the potentiometer (Leeds and Northrup Type K-2) and accessories has been diagrammed in figure 13.

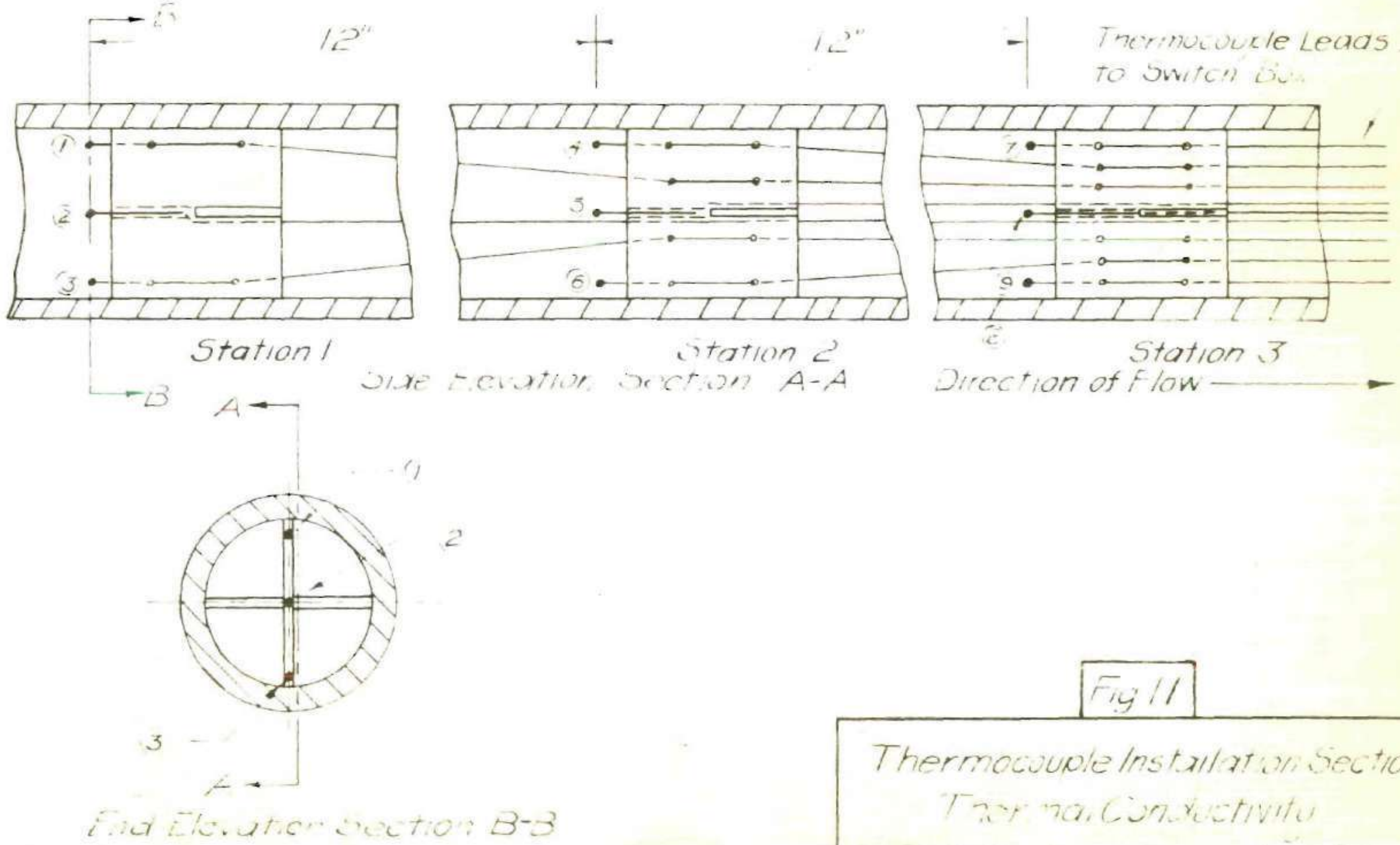

Fig 11

Thermocouple Installation Sections
Thermal Conductivity
D. A. Hart Sept. 1942

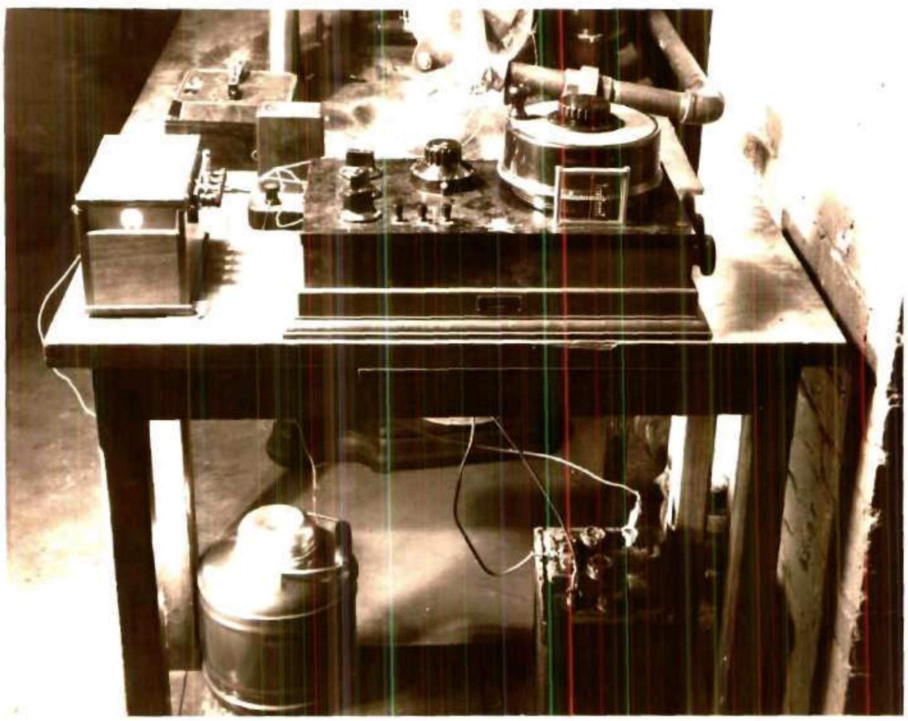

Fig. 12 - View of Potentiometer and Accessories

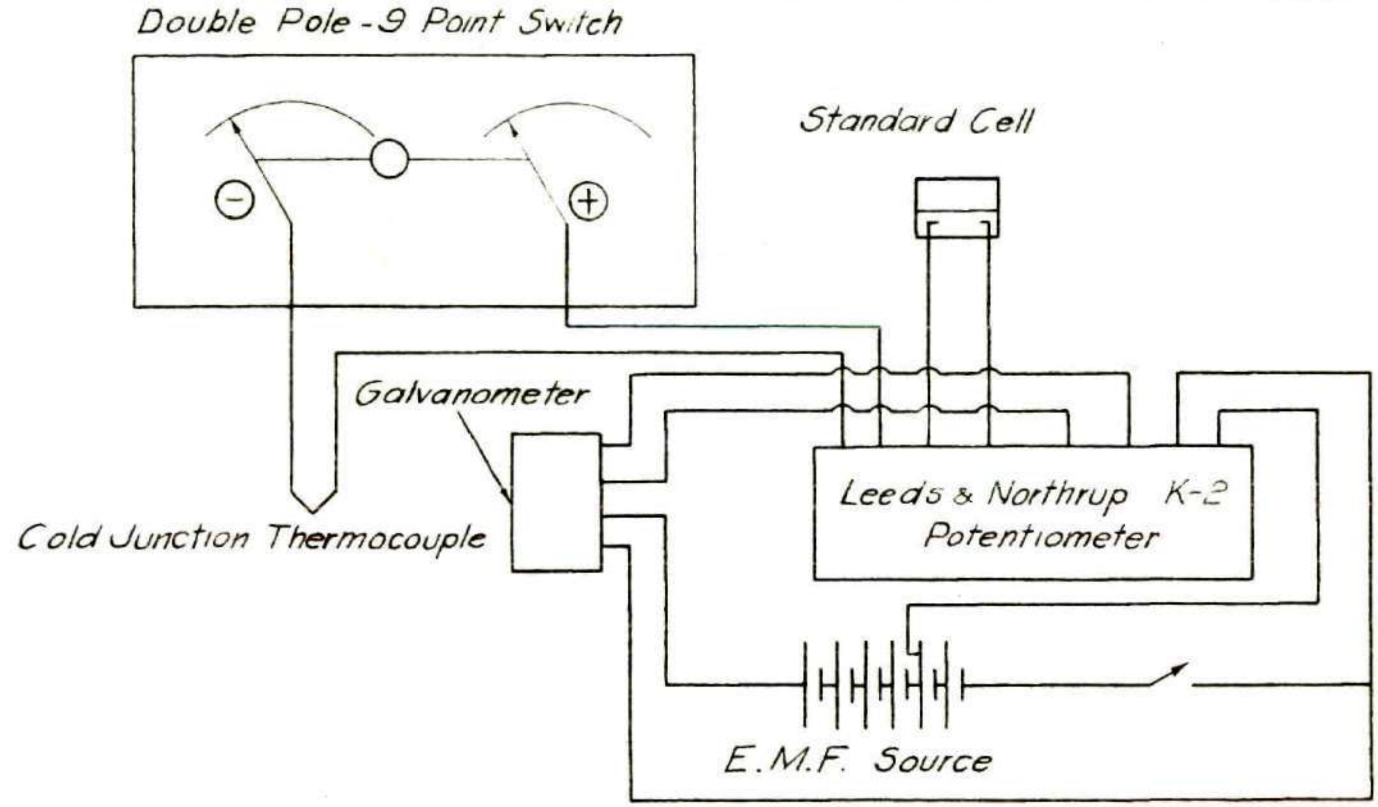

Fig. 13 Potentiometer Hookup
Thermal Conductivity
D. A. Hart Sept. 1942

IV. METHOD OF OPERATION

In performing a typical test, the first step was the regulation of the gas flow to conform to a previously determined rate. This regulation was accomplished with the use of a micromanometer, graduated in thousandths of an inch of alcohol, which was placed to measure the pressure drop across the orifice.

When the flow had been adjusted to the previously determined rate, the steam was allowed to enter the jacket (or jackets depending upon whether or not preheating was required). The heat transfer from the steam caused condensation which was removed at the bottom of the jacket at such a rate that the water level in the previously mentioned gage glass remained at the same elevation as the bottom of the jacket. This assured uniform heating of the test section of pipe on all sides and also afforded an exact knowledge of the condition of the steam leaving the jacket.

The major operational difficulty encountered was the fluctuation in jacket pressure as a result of variations in the line pressure from the steam generation unit. This pressure regulation, which was done manually, therefore required considerable attention of the operator.

However, by careful operation the regulation was maintained within limits of one-tenth of a pound per square inch in all cases. Aside from the pressure variation, the difficulties encountered in maintaining steady flow conditions were relatively minor.

After the flow of the gas and steam had been regulated, the potentiometer was standardized. Then representative readings were taken at each of the three stations to give an indication of the temperature of the gas before and after heat transfer. On the basis of these trial readings, the steam pressure was raised or lowered to raise or lower the mean temperature difference and rate of heat transfer as required.

When these conditions were adjusted so as to be consistent with the requirements of the series under consideration, these conditions were maintained for ten or fifteen minutes to assure constancy.

At the beginning of a test, the condensate container (previously weighed and the weight recorded) was placed under the hose from the jacket condensate line and a complete set of data was taken. The taking of a complete set of data was repeated at ten minute intervals for a period of a half hour - the duration of the test. At this point the condensate container was removed, weighed, and the weight recorded.

The decisions as to the length of runs and the time interval between readings were based upon the rate of steam condensation and the speed of potentiometer operation respectively. It was found that the steam condensed at a minimum rate of 0.40 pounds per half hour making the maximum error in weighing 2-1/2 per cent, which is acceptable. It was also found that the reading of all nine thermocouples could be accomplished, with the potentiometer being used, in approximately six minutes. Thus, by reading at ten minute intervals, time was allowed for careful use of the instrument with a reasonable time allowance for periodic standardization.

As to the general organization of the tests, the results of the investigation were divided into those of five series of tests. The first series of tests were made on methane at varying velocities and at an average temperature of 145.89°F. These tests were run without the benefit of the preheater jacket. For the second series of tests the preheater was used to raise the average temperature of the methane to 183.61°F.

In running the third series of tests, air was substituted for the methane as the absorption medium and was run through without any preheating at an average temperature of 143.04°F. For the fourth series of tests the average temperature of the air was raised to 188.50°F by means of the preheater.

The fifth series of tests was made with a mixture of methane and air in the approximate gravimetric ratio of 4:3 or approximately 4.35% of the air-fuel ratio required for the chemically correct combustion of methane. This series was made with the average temperature of the mixture at 135.70°F without the use of the preheating jacket.

For each of the five series at least four tests were made at velocities which varied in approximately equal increments within the range of laminar flow.

Run # 21 Date 8-6-42

THERMAL CONDUCTIVITY OF GASEOUS MIXTURES

Barometer 29.03 "Hg

Observer: D.A.Hart and H.H.

Reading Number	Time Hr.-Mi.	Temperature °F: Air in	Gas in	Mix D.B.	Mix W.B.	Steam 1 (in)	Steam 2 (out)	Thermocouple Readings in μV: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Pressure: Steam Preh.	Steam Jack.	Air Stat.	Air P.D.	Gas Stat.	Gas P.D.	Mix. Stat.	Mix. P.D.	Weight of Condensate
0	12:32	93	90	93	83	208	209	3.55	2.70	3.40	4.60	4.45	4.70	5.10	4.75	5.05								1.0	.136	.023	.128	.070	.219	.114	5.37
1	12:42	94	90	94	84	210	210	3.50	2.70	3.35	4.60	4.45	4.70	5.05	4.70	5.00								1.0	.136	.023	.128	.068	.219	.114	
2	12:52	94	91	94	84	208	208	3.45	2.70	3.30	4.60	4.45	4.70	5.05	4.65	5.00							None	1.0	.136	.023	.128	.068	.219	.114	
3	1:02	95	92	95	85	208	207	3.45	2.70	3.30	4.60	4.45	4.70	5.05	4.75	5.00								1.0	.136	.023	.128	.068	.219	.114	6.69
4																															
5																															
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10																															
11																															
12																															
Avg.																															

- Sample Data Sheet -

V. TABULATED DATA

Table I

Temperature-Voltage Conversion For Iron-Constantan Thermocouples[13]

(Reference Junction 32°F)

Deg. F	0	50	100	150	200	250
0	---	.518	1.96	3.44	4.92	
5	---	.658	2.11	3.59	5.07	
10	---	.808	2.26	3.74	5.22	
15	---	.948	2.40	3.88	5.37	
20	---	1.100	2.55	4.03	5.53	
25	---	1.240	2.70	4.18	5.68	Millivolts
30	---	1.380	2.85	4.33	5.83	
35	.088	1.530	3.00	4.48	5.98	
40	.228	1.670	3.14	4.62	6.13	
45	.378	1.820	3.29	4.77	6.28	
50	.518	1.960	3.44	4.92	6.44	

[13] Standard Conversion Tables - Wheelco Inst. Company.

Table II

Temperature Data

Series No.	Run No.	Average (Station 1)	Center (Station 1)	Drop (Station 1)	Average (Station 2)	Center (Station 2)	Drop (Station 2)	Average (Station 3)	Center (Station 3)	Drop (Station 3)	Average Drop
I	1	146.16	137.33	8.83	173.75	164.72	9.03	183.72	174.2	9.52	9.13
	2	146.98	140.11	6.87	179.87	168.07	11.80	192.97	177.83	15.14	11.27
	3	127.10	106.68	20.42	170.19	137.47	32.72	197.44	163.12	34.32	29.32
	4	122.97	103.13	19.84	171.71	124.13	47.58	194.02	161.21	32.81	33.4
	5	149.05	128.74	10.31	179.88	158.20	21.68	204.22	173.57	30.65	20.88
	6	133.94	111.04	22.90	173.43	131.90	41.53	194.53	164.57	29.96	31.46
II	7	190.86	186.93	3.93	205.47	198.13	7.34	209.23	203.57	5.66	5.64
	8	184.26	178.27	5.99	207.66	195.90	11.76	215.48	204.27	11.21	9.65
	9	185.20	181.77	3.43	203.76	194.20	9.56	211.00	202.67	8.33	7.11
	10	168.59	162.00	6.59	194.40	192.33	22.07	206.14	185.63	21.51	16.72
	11	164.84	150.00	14.84	199.67	158.67	41.00	201.17	179.83	21.34	29.06
III	12	169.75	148.30	21.45	199.64	194.50	5.14	204.30	201.67	2.63	9.74
	13	133.86	112.00	21.86	172.00	168.20	3.80	190.64	173.30	17.34	14.33
	14	120.80	92.67	27.33	150.00	130.00	20.00	177.67	151.30	26.37	24.50
	15	120.59	96.70	23.89	154.50	133.00	21.50	180.33	152.00	28.33	24.57
	16	126.76	104.67	22.09	163.00	129.33	33.67	182.83	158.10	24.73	26.84
IV	17	206.00	200.67	5.33	219.00	214.00	5.00	219.00	217.67	1.33	3.89
	18	184.73	180.30	4.45	205.39	196.00	9.39	214.67	204.67	10.00	7.95
	19	173.50	168.00	5.50	196.50	182.67	13.83	207.30	191.33	16.17	11.83
	20	169.50	154.00	15.50	193.16	167.33	25.83	201.00	185.33	15.67	19.00
V	21	149.21	125.00	24.21	191.00	184.00	7.00	203.83	193.00	10.83	14.01
	22	123.30	99.67	23.53	158.67	137.50	21.17	183.33	156.30	27.03	23.91
	23	116.08	98.67	17.41	158.30	116.30	42.00	171.80	150.30	21.50	26.97
	24	115.83	100.00	15.83	153.90	117.00	36.90	171.80	150.67	21.13	24.62

Table IIIa

Flow Data - Methane

Series No.	Run No.	P_1	Pressure Drop	t_1	u	C_p	T_1 °C	Steam Temp.
I	1	14.293	.00253	91.75	.01140	.537	33.2	219.26
	2.	14.300	.0139	93.50	.01142	.537	34.15	226.06
	3	14.320	.0276	95.75	.01149	.538	34.45	242.01
	4	14.330	.0448	98.75	.01154	.539	37.10	246.99
	5	14.250	.0348	85.70	.01125	.534	29.83	228.38
	6	14.268	.0565	88.70	.01132	.535	31.50	233.81
II	7	14.290	.00675	106.75	.01164	.543	41.50	217.23
	8	14.298	.0090	108.00	.01172	.545	42.20	288.83
	9	14.227	.0110	90.00	.01134	.536	32.20	215.93
	10	14.250	.0341	91.00	.01139	.536	32.80	221.40
	11	14.272	.0567	91.00	.01139	.536	32.80	224.42

Table IIIb - Flow Data - Air

Series No.	Run No.	t_1 °F	Pressure Drop	P_1 Total	P_1 Dry Air	P_1 Vapor	R.H. %	M_V #/#da.	t_1 °C	u	C_p	Steam Temp.
	12	89.50	.00307	14.305	13.880	.427	62	.01758	31.97	.01866	.241	214.12
	13	92.00	.0226	14.320	13.852	.468	63	.01785	33.35	.01872	.241	217.26
III	14	94.00	.0517	14.350	13.954	.396	50	.01695	34.10	.01876	.241	220.12
	15	97.25	.0675	14.360	13.923	.437	50	.01695	36.55	.01887	.241	223.50
	16	91.67	.0973	14.360	13.890	.5005	68	.01920	33.10	.01871	.241	223.23
	17	93.75	.00324	14.295	13.784	.5100	65	.01900	34.30	.01877	.241	220.75
IV	18	96.75	.02366	14.312	13.830	.486	57	.01685	35.95	.01885	.241	223.41
	19	100.50	.0515	14.340	13.820	.520	54	.01665	38.05	.01895	.241	225.98
	20	103.75	.0968	14.385	13.864	.521	49	.01550	38.85	.01903	.241	229.03

Table IIIc

Flow Data - 43% Air and 57% Methane

Run No.	t_1 °F For Air	t_1 Gas	t_1 Mix.	P_1 Air	P_1 Vapor	P_1 DA	Pressure Drop Air	P_1 Gas	Pressure Drop Gas	P_1 Mix	Steam Temp.
21	94.00	90.75	94.00	13.790	.396	13.394	.000665	14.265	.00197	14.270	213.89
22	95.00	92.00	95.00	13.756	.436	13.320	.00457	14.278	.01410	14.300	217.07
23	96.25	94.50	96.00	13.820	.476	13.344	.0119	14.375	.03590	14.340	220.15
24	99.00	97.00	99.00	13.924	.482	13.542	.0195	14.480	.06230	14.420	223.23

VI. TABULATED RESULTS

Table IV

Important Apparatus Dimensions

Area of Orifices	=	.000302	$ft.^2$
Inside Area of Pipe	=	.006	$ft.^2$
Length of Test Section	=	2.0	ft.
Thickness of Gas Layer	=	.0359	ft.
Average Area of Transfer Surface	=	.02285	$ft.^2$

Table Va - Flow Results - Methane

Series No.	Run No.	M	P	U	N
	1	.0001735	.03860	.749	329
	2	.000407	.03855	1.760	771
	3	.000573	.03840	2.490	1081
I	4	.000729	.03825	3.180	1370
	5	.000647	.03890	2.770	1246
	6	.000823	.03870	3.540	1571
	7	.000280	.03760	1.24	520
	8	.000359	.03750	1.595	662
II	9	.000363	.03860	1.57	694
	10	.000639	.03855	2.76	1212
	11	.000824	.03858	3.56	1565

Table Vb - Flow Results - Air

Series No.	Run No.	M D. Air	M Vapor	M Mix	R Mix	p Mix	U Mix	N Mix
III	12	.000251	.000004	.000255	53.9	.0695	.960	469
	13	.000689	.000011	.000700	53.9	.0694	1.681	815
	14	.001043	.000017	.001060	53.9	.0692	2.55	1391
	15	.001188	.000019	.001207	53.9	.0688	2.92	1492
	16	.001432	.000028	.001460	53.9	.0696	3.5	2004
IV	17	.000260	.000005	.000265	53.9	.0689	.641	359
	18	.000701	.000011	.000712	53.9	.0686	1.73	888
	19	.001031	.000018	.001049	53.9	.0683	2.555	1244
	20	.001408	.000022	.001430	53.9	.0681	3.50	1630

Table Vc - Flow Results
43% Air - 57% Methane

Run No.	M Air	M Gas	M Mix	R Mix	p Mix	U Mix	N Mix
21	.000118	.000153	.000271	77.8	.0476	.535	227
22	.000308	.000410	.000718	78.1	.0475	1.44	610
23	.000496	.000656	.001152	78.0	.0476	4.04	1709
24	.000636	.000864	.001500	79.3	.0469	5.33	2210

Table VI

Heat Transfer Results

Series No.	Run No.	Steam Temp.	T_m Center	Q	h	U^n	
I	1	219.26	61.9	3.062	.0778	0.644	n = 1.52
	2	226.06	65.5	8.87	.213	2.36	
	3	242.01	101.8	32.60	.5025	4.00	
	4	246.99	112.6	47.20	.672	5.88	
	5	228.38	74.9	25.95	.544	4.70	
	6	233.81	93.0	49.90	.840	6.58	
II	7	217.23	20.9	3.09	.232	1.412	n = 1.6
	8	218.83	36.0	6.80	.2965	2.110	
	9	215.93	22.1	4.98	.3535	2.06	
	10	221.40	46.6	20.7	.696	5.065	
	11	224.42	58.5	46.1	1.238	7.625	
III	12	214.12	32.1	2.19	.107	.947	n = 1.33
	13	217.26	70.0	8.86	.198	1.996	
	14	220.12	95.0	22.85	.378	3.47	
	15	223.50	96.9	27.05	.423	4.15	
	16	223.23	89.5	34.58	.607	5.30	
IV	17	220.75	9.18	.910	.1591	.674	n = 0.889
	18	223.41	29.3	4.99	.267	1.63	
	19	225.98	45.5	10.93	.377	2.31	
	20	229.03	57.75	23.85	.649	3.05	
V	21	213.89	47.0	5.56	.186	.647	n = 0.696
	22	217.07	85.8	25.30	.464	1.289	
	23	220.15	97.4	45.90	.741	2.64	
	24	223.23	95.5	54.00	.889	3.205	

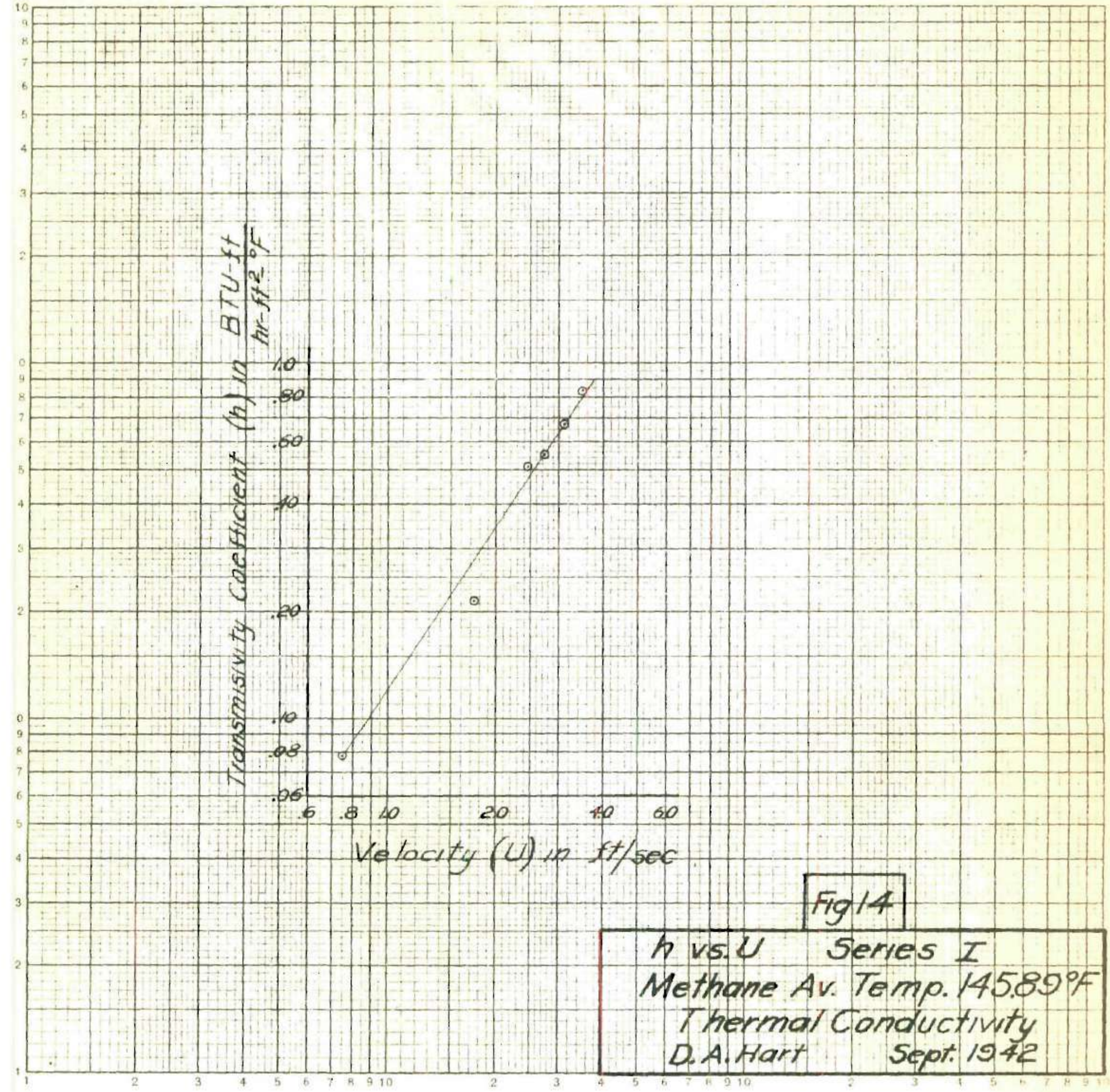


Fig 14

h vs. U Series I
Methane Av. Temp. 145.89°F
Thermal Conductivity
D. A. Hart Sept. 1942

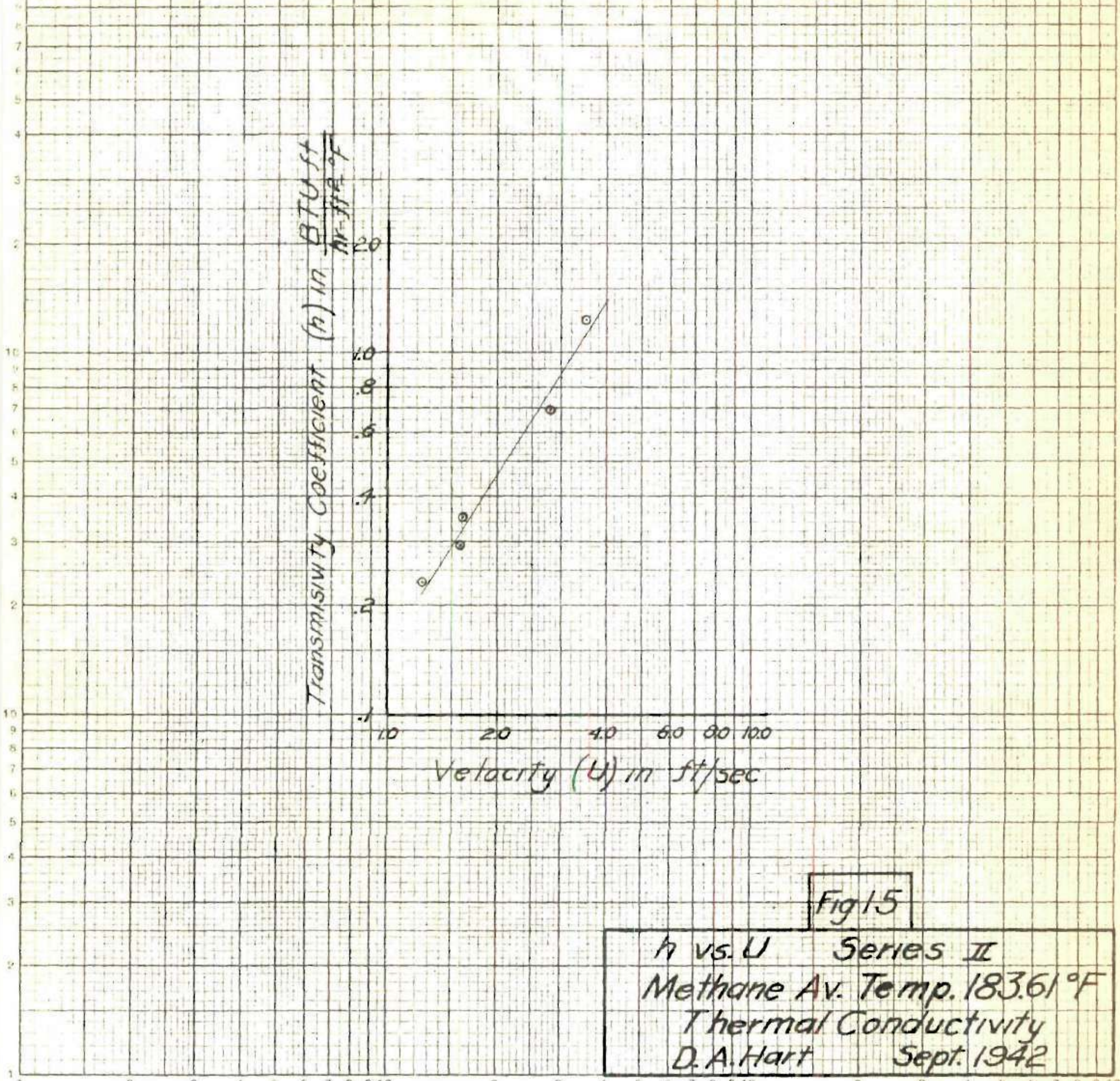


Fig 15

h vs. U Series II
Methane Av. Temp. 183.61 °F
Thermal Conductivity
D. A. Hart Sept. 1942

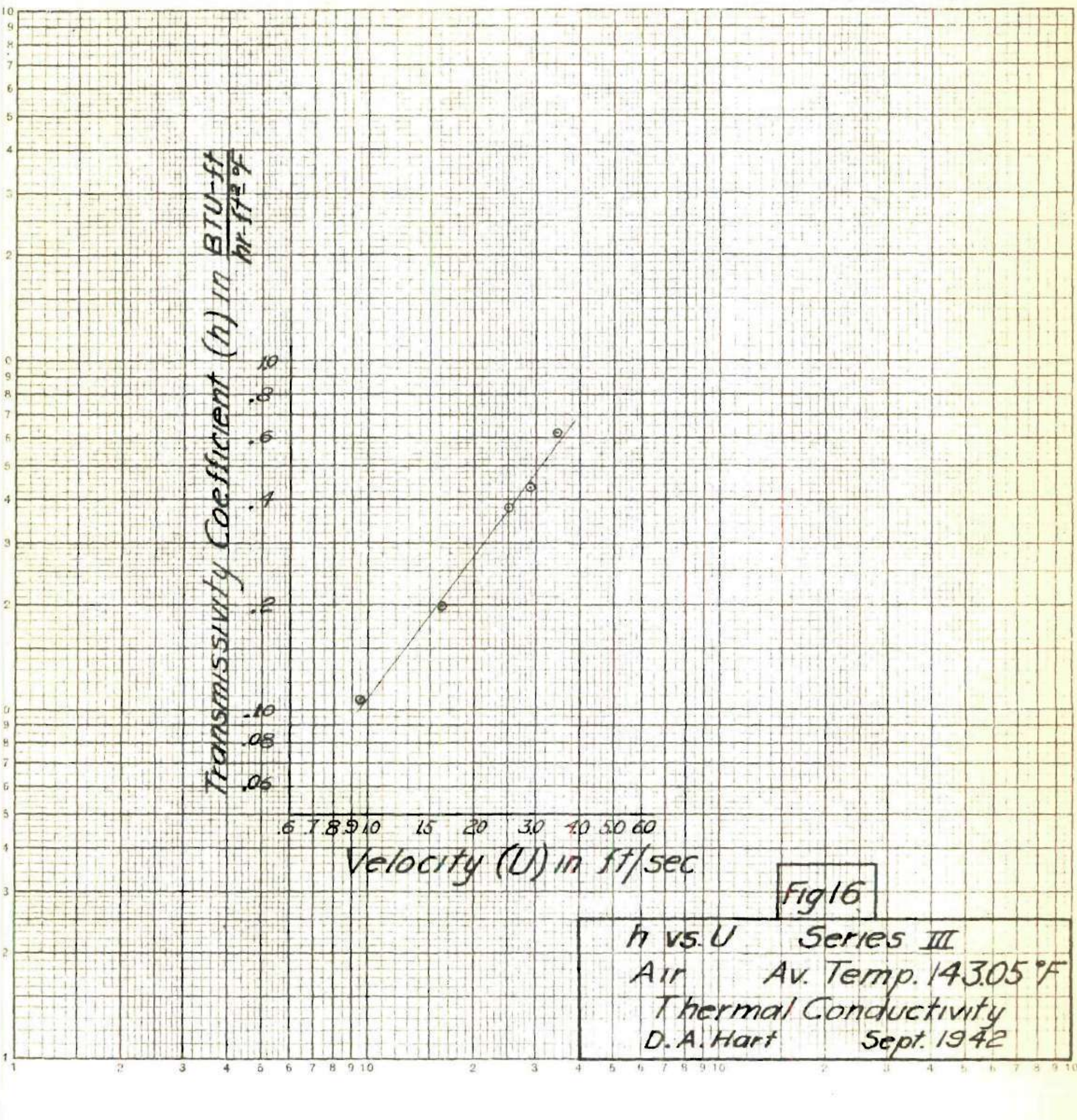


Fig 16

h vs. U Series III
Air Av. Temp. 143.05 °F
Thermal Conductivity
D. A. Hart Sept. 1942

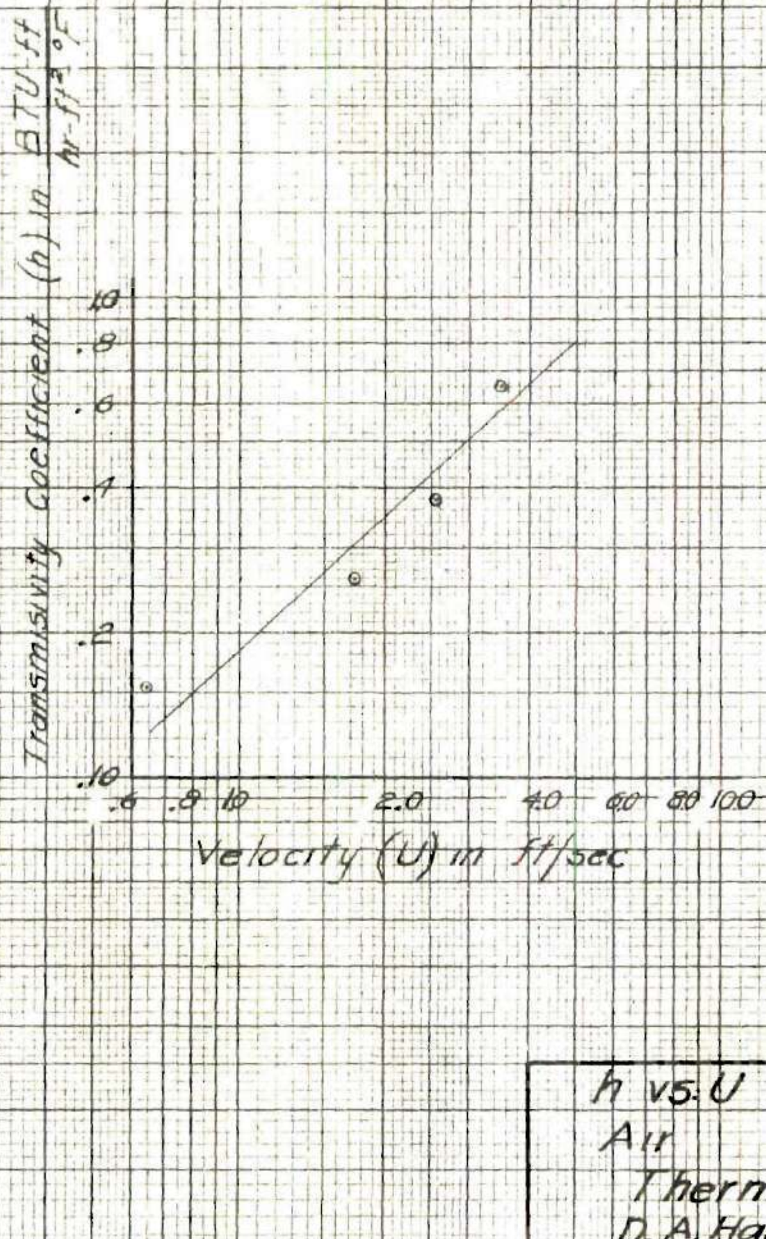


Fig 17

h vs. U Series IV
Air Av. Temp. 188.50°F
Thermal Conductivity
D. A. Hart Sept. 1942

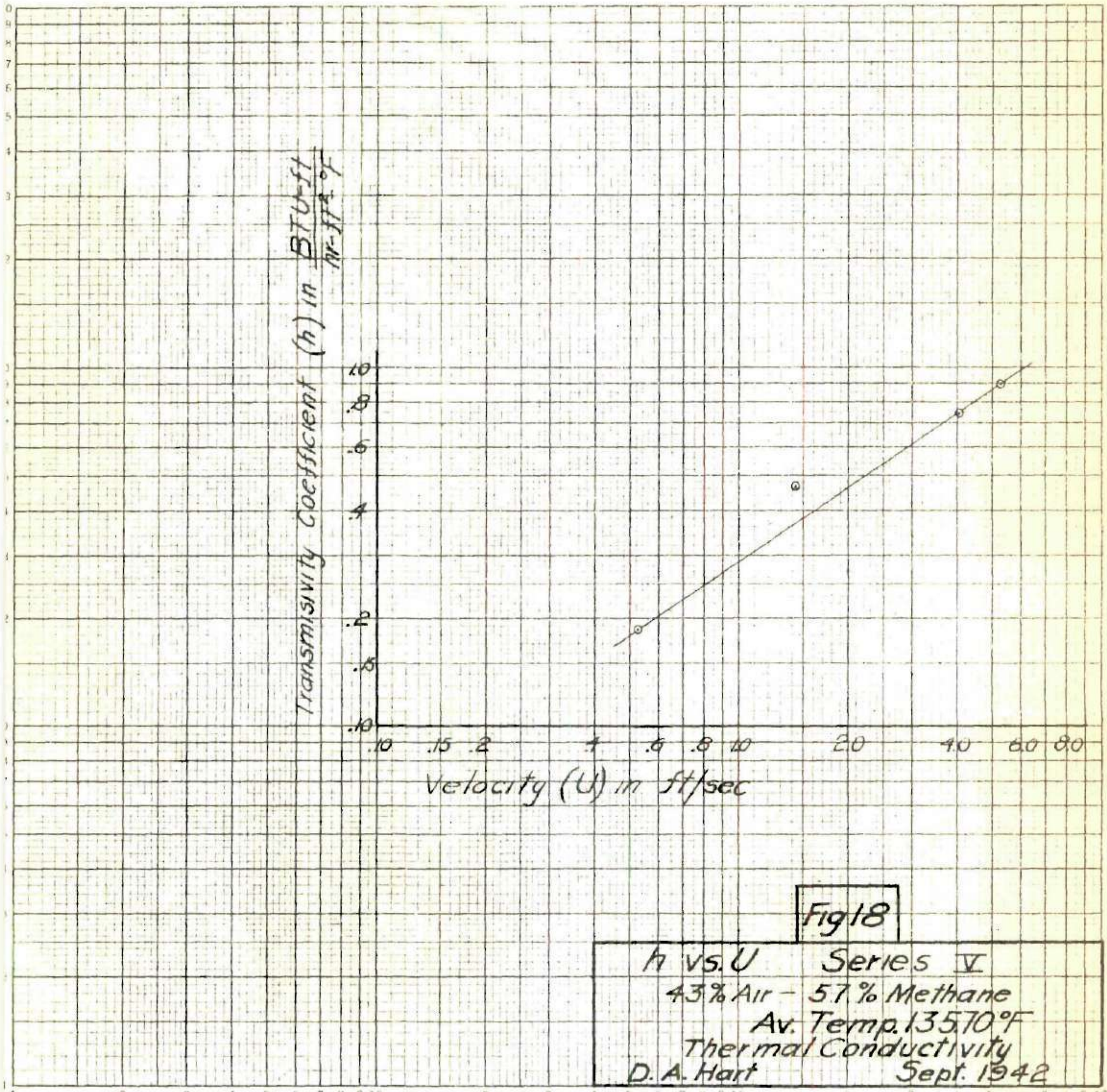
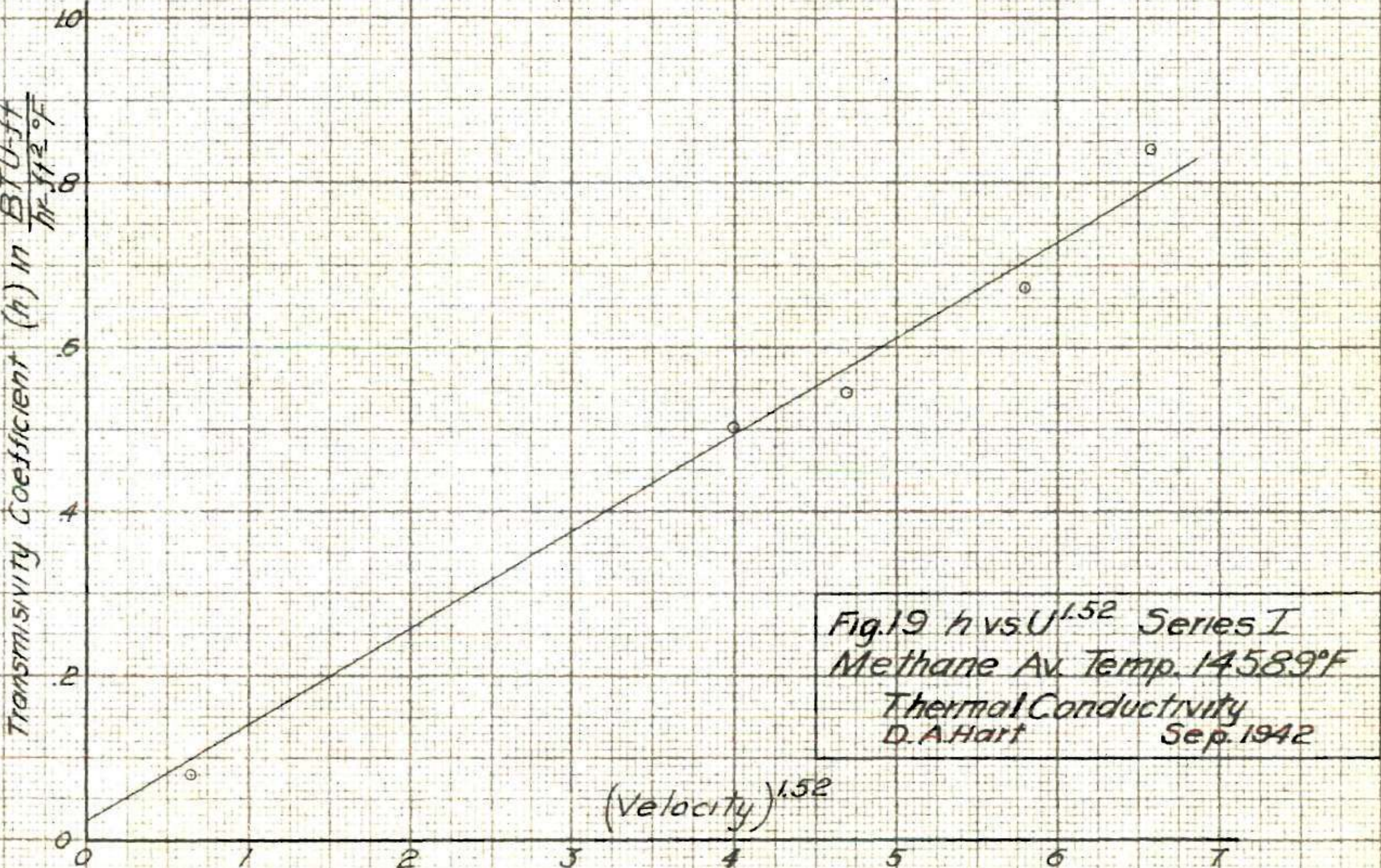


Fig 18

h vs. U Series V
43% Air – 57% Methane
Av. Temp. 135.70°F
Thermal Conductivity
D. A. Hart Sept. 1942



Transmisivity Coefficient (h) in $\frac{BTU\text{-}ft}{hr\text{-}ft^2\,°F}$
10
8
6
4
2
0
0
1
2
3
4
5
6
7
$(Velocity)^{1.52}$
Fig.19 h vs. $U^{1.52}$ Series I
Methane Av. Temp. 145.89°F
Thermal Conductivity
D.A.Hart Sep.1942

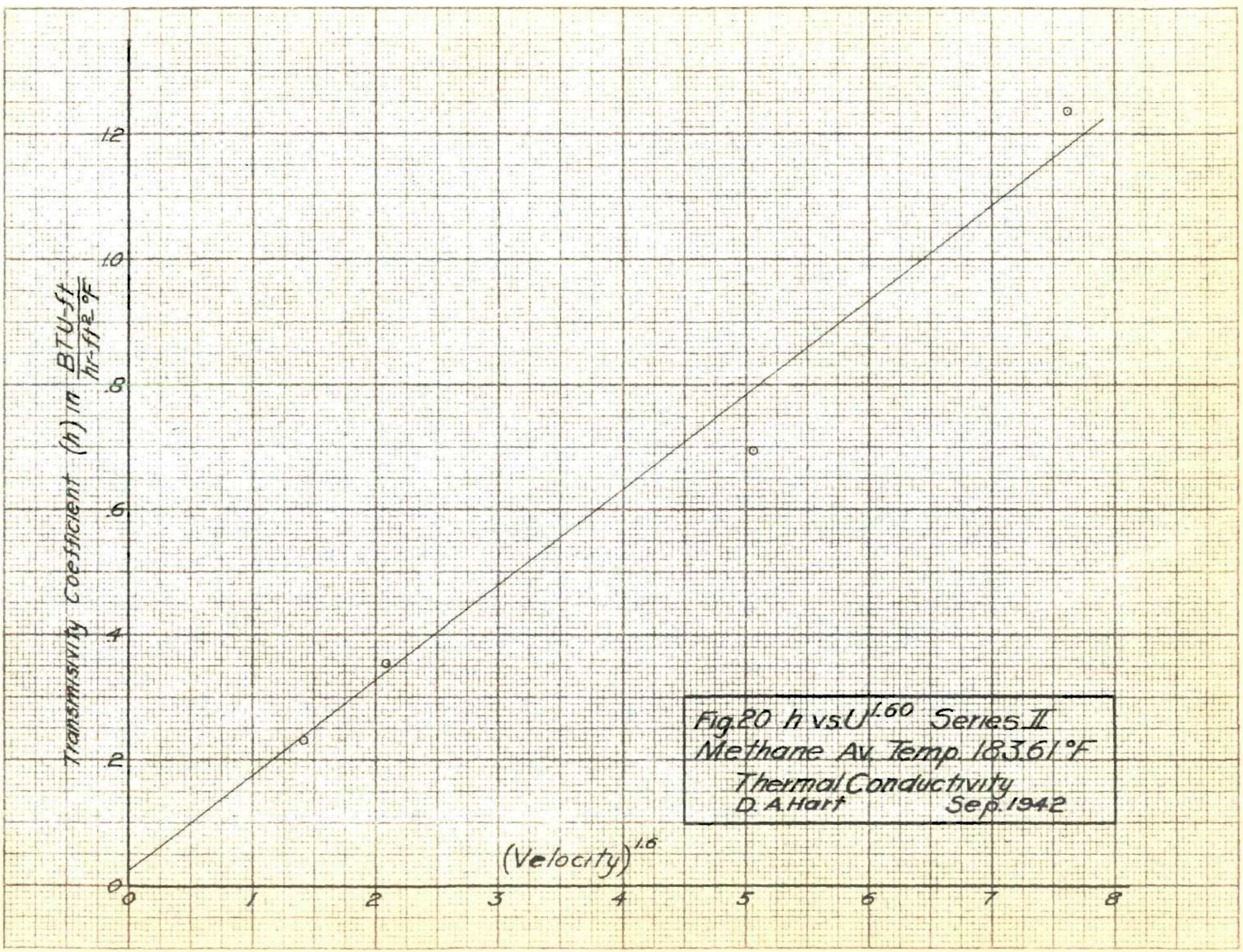
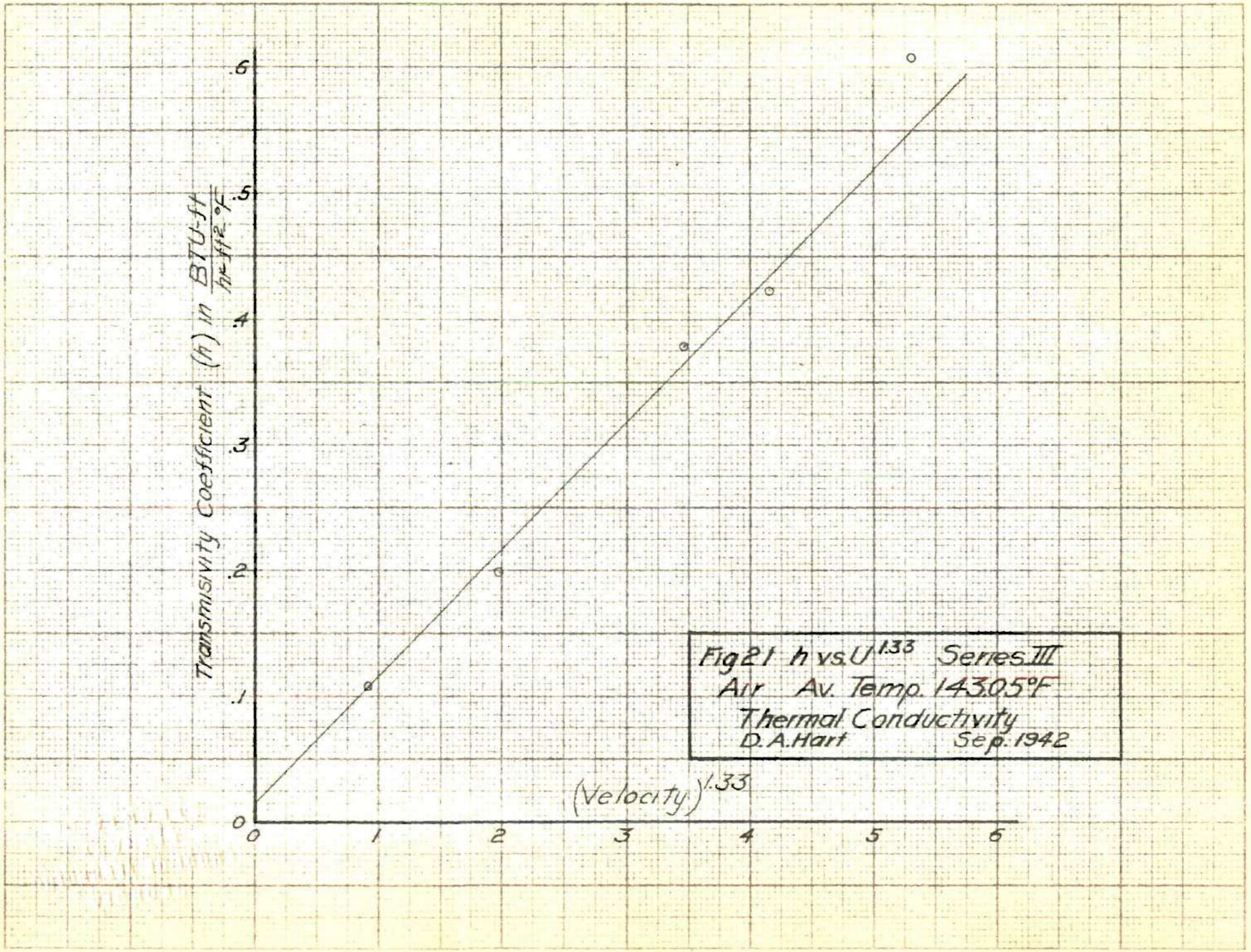
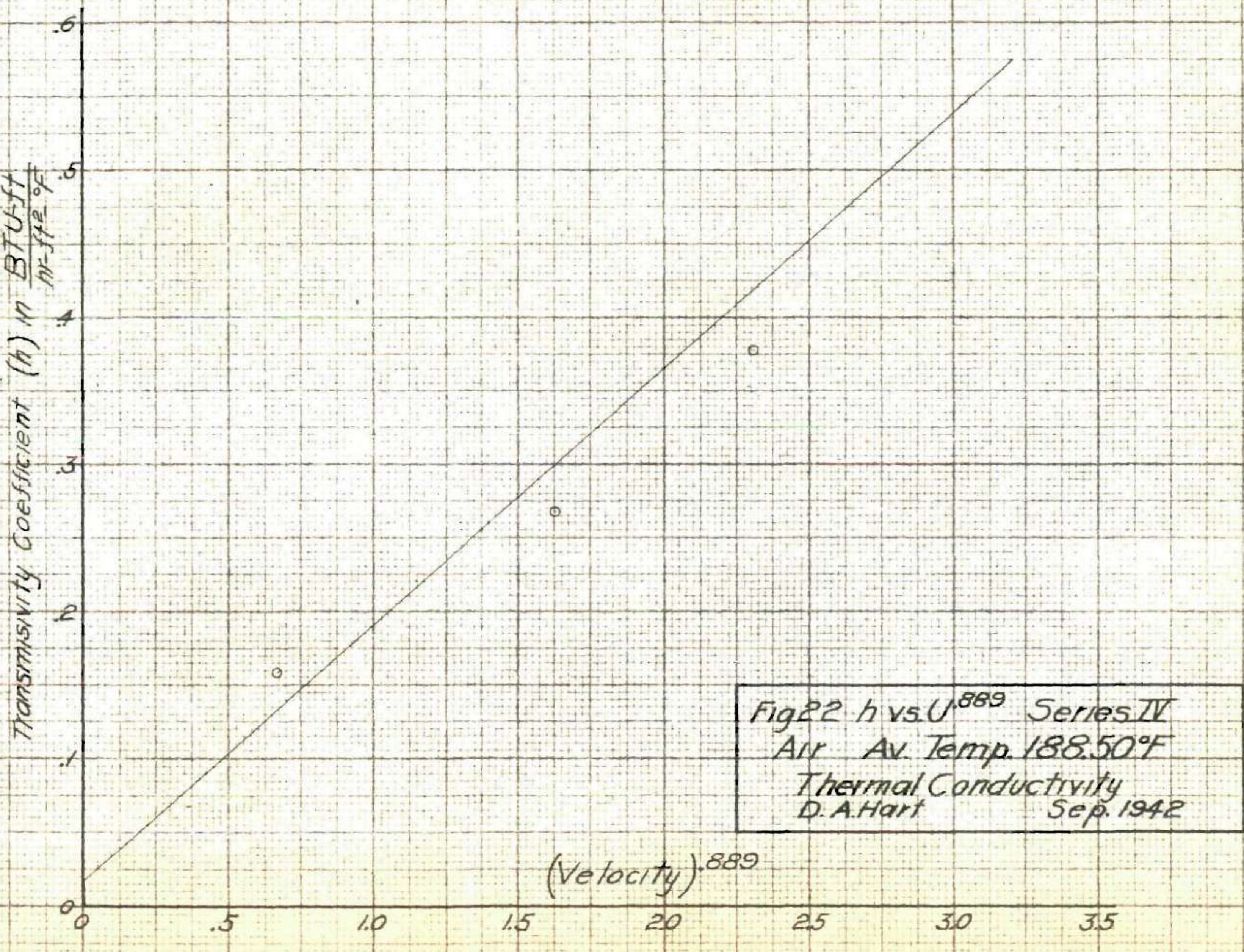


Fig. 20 h vs. $U^{1.60}$ Series II
Methane Av. Temp. 183.61 °F
Thermal Conductivity
D. A. Hart Sep. 1942


Transmisivity Coefficient (h) in BTU-ft / hr-ft² °F
(Velocity)^1.33
0
.1
.2
.3
.4
.5
.6
0
1
2
3
4
5
6
Fig 21 h vs. U^1.33 Series III
Air Av. Temp. 143.05°F
Thermal Conductivity
D. A. Hart Sep. 1942


Transmisivity Coefficient (h) in BTU-ft / hr-ft2 °F
.6
.5
.4
.3
.2
.1
0
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
(Velocity).889
Fig22 h vs. U.889 Series IV
Air Av. Temp. 188.50°F
Thermal Conductivity
D. A. Hart Sep. 1942

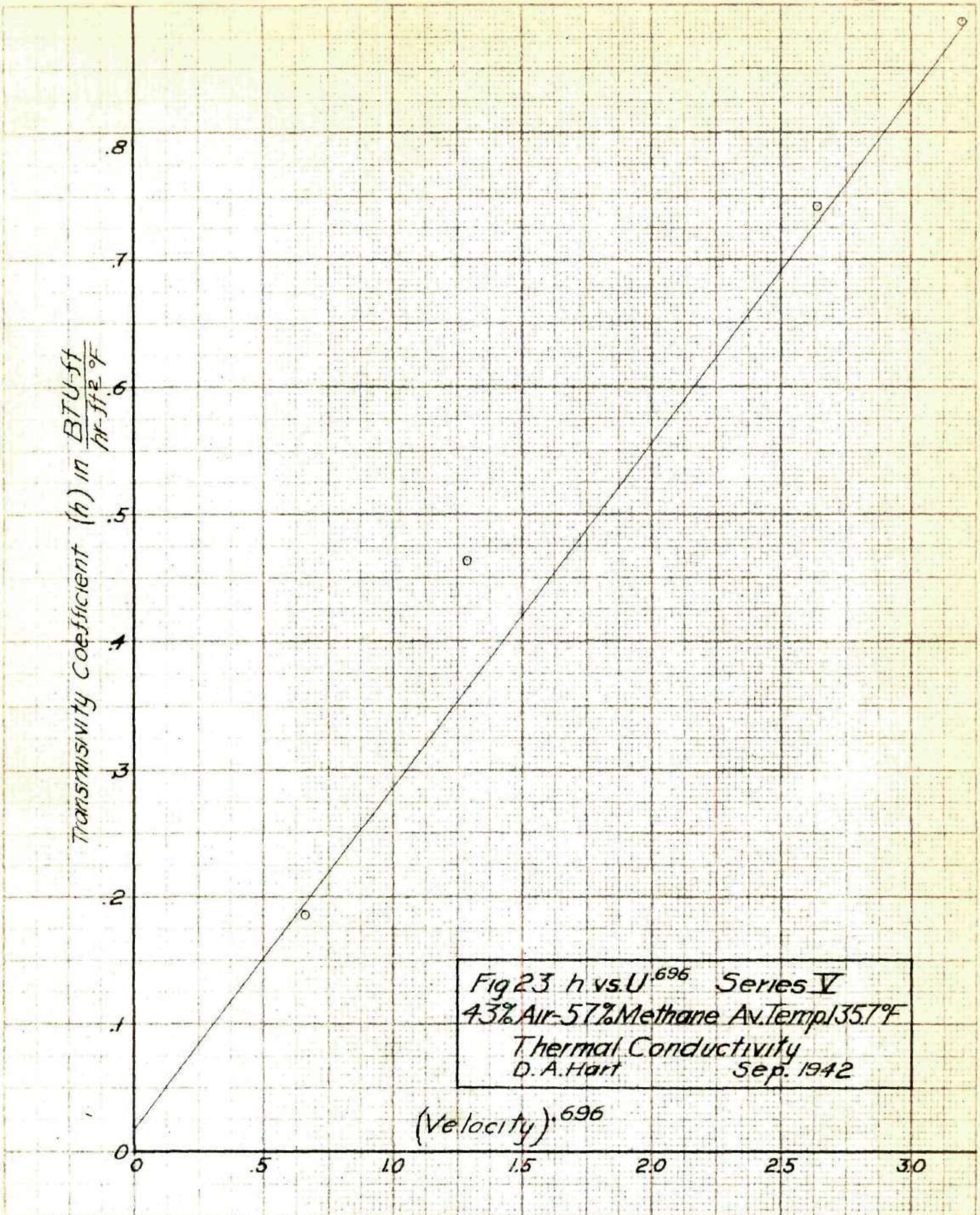


Fig 23 h vs. $U^{.696}$ Series V
43% Air-57% Methane Av. Temp 135.7°F
Thermal Conductivity
D. A. Hart Sep. 1942

Table VII

Thermal Conductivity Results

Series No.	Fluid Used	Avg. Temp. Centerline	k From Tests	k From Literature (14)
I	Methane	145.89	.023	.0215
II	Methane	183.61	.024	.0230
III	Air	143.05	.0155	.0152
IV	Air	188.50	.0175	.0161
V	43% Air & 57% Methane	135.70	.0185	.0185

(14) International Critical Tables, Vol. V: page 214.

VII. DISCUSSION OF RESULTS

The tabulation of the items calculated was divided into four groups: (1) Those items which were characteristic of the equipment and therefore had constant values throughout the complete set of tests, (2) Those items which gave indication of the magnitude and conditions of the fluid flowing, (3) Those items, in the individual runs of each series, which dealt with the magnitude and rate of heat transfer, and (4) A general tabulation of the results of the extrapolation of the plots of each series. This tabulation contains the final results of the investigation.

All of the calculations upon which the first three groups of results are based were made from relationships commonly encountered in heat transfer and fluid flow work. They are relatively straightforward as has been shown on the preceding pages.

The method used in obtaining the results in Table VII is, to the author's knowledge, unique in this field and, in general, quite satisfactory. However, it must be stated that, reasonable caution must be exercised in plotting all curves for upon the accuracy of the curves as well as the accuracy of the data depends the accuracy of the results.

At first the investigator was a bit doubtful of the advisability of employing an orifice type meter to measure the flow. However, these orifices were checked against a positive displacement type meter. This check was made in the small flow range where, according to the literature[15] the maximum error is likely to occur. The results of this check showed an error of less than two per cent using the previously assumed coefficient of discharge.

The consistency of the results obtained was very gratifying. The variation of the average temperatures was enough to be of value in differentiating the results of the different series and the variation of the Logarithmic Mean Temperature Difference over each series of tests was very consistent with what was expected.

The relationship between velocity and Reynold's Number was nearly linear in all five series. This was due largely to the constancy of the temperature, in each of the series, which held the variation of viscosity and density to a minimum. Therefore, the variation of the Reynold's Number gave an excellent indication of velocity variation in each of the individual series.

In connection with this reasoning, the variation of Reynold's Number was creditably uniform in each series. Furthermore, the number itself was well below the upper limit of the laminar region in all but the last run of series V, where it reached a value of 2210. While this

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[15] "Fluid Meters - Their Theory and Application," ASME Research Publication.

value lies in the uncertain region between laminar and turbulent flow, the fact that the plot of h vs U^n for this test lies so well in line with the other tests of series V leads to the conclusion that laminar flow conditions still prevailed.

The variation of the transmissivity coefficient with velocity in each of the five series was, without exception, in the correct direction. Furthermore, with but few exceptions, the magnitude of the variation was quite consistent so that the points on the plots of each series were reasonably close to a straight line as was expected.

The values of the thermal conductivity obtained for each of the five series were gratifying, to say the least. Universally, there was good agreement with the accepted values of conductivity as found in the literature.[16] In addition the variation of thermal conductivity with temperature was consistent with the predictions of the previously developed theory.

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[16] International Critical Tables, Vol. V; Page 214.

VIII. CONCLUSIONS

After quite extensive investigation into factors governing heat transmission to a fluid flowing in a pipe and allied subjects with which the investigation has been either intimately or remotely concerned, it is the author's firm conviction that the subject of heat transfer contains almost limitless possibilities for further work. Throughout the literature consulted in preparation for this work, the number of discrepancies in the results obtained by various investigators is striking. In general, the investigations agree qualitatively in their results and the empirical relationships developed follow the same general form. However, with regard to a quantitative comparison of the same relationships, the agreement often is rather disappointing. It, therefore, seems as though the surface merely has been scratched in the study of heat transmission and there is room for much more work on many phases of so intriguing a field.

With particular reference to the investigation, it must be said that the results leave room for improvement. However, the general trends of the results obtained by actual experimentation are so consistent with the reasoning, upon which the investigation is based, that the investigator has the honestly firm conviction that, with several modifications of the apparatus and improvements in operating technique, the method shows much promise.

Among the suggested improvements in apparatus are the following. The substitution of a vertical test section for the horizontal one used would do much to insure uniform temperature distribution at any given displacement from the center line of the test section. The use of stations at five or nine positions in the same length of test section, while introducing an added problem in apparatus design, would add to the possible accuracy of results. Accurate control of fluid flow would be facilitated if automatic pressure regulation were available. However, the error due to irregularity in flow was minimized by the extreme care used by the operators to assure pressure constancy.

The suggested improvements in technique might include the use of more observers as this would aid in getting simultaneous data. This, however, would have a minor effect upon improvement of results as steady flow conditions were maintained insofar as possible. Mainly improved technique would accompany refinements in apparatus which would be the main factor governing any possible improvement in results.

The main value of this investigation would appear to lie in the fact that it shows such conclusive consistency with the reasoning upon which it is based. In addition the close agreement with the literature which was obtained in every case clearly indicates that, with the recommended modifications, determination of Thermal Conductivity of gases and gaseous mixtures by the method followed in this investigation shows great promise.

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