

THE EFFECT OF VAPOR VELOCITY OF THE
COEFFICIENTS OF HEAT TRANSFER OF VAPORS CONDENSING
INSIDE A HORIZONTAL TUBE

by

HAROLD MARTIN BREWSTER

B. Ch. E., The City College of New York, 1950

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1951

ments
LD
2668
T4
1951
B74
C.2

TABLE OF CONTENTS

INTRODUCTION	1
METHOD	4
Construction of Apparatus	4
Operation of Equipment	10
Experimental Data and Basic Calculated Results	12
Development of an Equation Correlating the Data	16
DISCUSSION	24
SUMMARY	29
ACKNOWLEDGMENTS	30
LITERATURE CITED	31
APPENDIX	32
Nomenclature	33
Source of Physical Data	35

INTRODUCTION

This paper presents the work done in obtaining a generalized correlation for the coefficients of heat transfer of condensing vapors on the inside of a horizontal tube. The correlation relates the coefficient of heat transfer to the velocity of the vapor, the heat transfer rate, and the temperature difference. The vapors of heptane, methanol, acetone, sec-butyl alcohol, and carbon di-sulfide were used in this investigation.

Coefficients of heat transfer for a condensing vapor have been investigated for condensation on the outside of horizontal and vertical tubes (5, 9, 10, 11), and on the inside on vertical and inclined tubes (8), but little work has been done on the condensation of vapors on the inside of horizontal tubes (1, 6).

The transfer of heat from a hot fluid through a solid to a cold fluid depends upon conduction and convection through the fluids and conduction through the solid. Most of the resistance to heat flow is exhibited by the relatively stagnant films of the fluids on the surface of the solid. The overall resistance to the flow of heat is the sum of the resistances of the fluid films and the solid. Because of the impracticability of defining film thicknesses, an overall resistance to heat transfer, $1/U$, is defined as (7, p. 33)

$$(1) \quad \frac{1}{U} = \frac{1}{h_0} + \left(\frac{1}{k}\right)_{\text{solid}} + \frac{1}{h_1}$$

where $1/h_0$ and $1/h_1$ are the resistances to heat transfer offered by the fluid films, and $(1/k)_{\text{solid}}$ is the resistance offered to heat transfer by the solid.

Over a differential length the transfer of heat between the fluids can be expressed as (3, p. 464)

$$(2) \quad dq = U \, dA \, \Delta t$$

where dq is the differential rate of heat transferred from one fluid to the other over an area dA , and Δt is the temperature difference between the main bodies of fluids. For a finite transfer area, considering U constant (7, p. 18)

$$(3) \quad q = UA \, \Delta t_m$$

where Δt_m is the logarithmic mean temperature difference over the entire area.

In 1916, Nusselt, according to McAdams (2, p. 259), by a mathematical treatment, developed an equation for the coefficient of heat transfer of a condensing vapor,

$$(4) \quad h_c = 0.493 \left(\frac{k_f^3 \rho_f^2 g \lambda}{\mu_f L \Delta t_c} \right)^{0.25} \quad \text{for all vertical surfaces, and}$$

$$(5) \quad h_c = 0.725 \left(\frac{k_f^3 \rho_f^2 g \lambda}{\mu_f D \Delta t_c} \right)^{0.25} \quad \text{for the outside surface of horizontal tubes}$$

Nusselt assumed that:

a. The heat is all carried to the metal surface by

conduction in a direction perpendicular to the surface.

b. The physical properties of the condensate may be taken at the mean film temperature.

c. The film of condensate always moves in a viscous motion.

d. The interface between film and vapor is at the saturation temperature.

e. The condensation is of the film type.

f. The vapor velocity is taken as zero.

Nusselt did no work on condensation inside horizontal tubes.

A dimensional analysis of the factors involved in determining the coefficient of heat transfer of a condensing vapor, neglecting vapor velocity, as presented by McAdams (2, p. 94), is

$$(6) \quad \frac{h_c D}{k_f} = F \left[\left(\frac{D^3 e_f^2 g}{\mu_f^2} \right), \left(\frac{\mu_f \lambda}{k_f \Delta t_c} \right) \right]$$

where $\left(\frac{\mu_f \lambda}{k_f \Delta t_c} \right)$ is a variable and $\left(\frac{D^3 e_f^2 g}{\mu_f^2} \right)$ remains substantially constant for a given fluid. Equation 6 will reduce to Nusselt's equation. Since the purpose of this investigation was to determine the coefficient of heat transfer as a function of the vapor velocity, the Reynolds number $\left(\frac{DG}{\mu_v} \right)$ was included as one of the variables and equation 6 becomes

$$(6a) \quad \frac{h_c D}{k_f} = F \left[\left(\frac{D^3 e_f^2 g}{\mu_f^2} \right), \left(\frac{\mu_f \lambda}{k_f \Delta t_c} \right), \left(\frac{DG}{\mu_v} \right) \right]$$

Jakob (1, p. 682) in 1936 and Spencer (6) in 1950 investigated the steam coefficient of heat transfer in a horizontal tube. Both came to the conclusion that this coefficient varies with the length and periphery of the condensing tube; i.e., the film thickness is greater at the bottom of the tube, and the thickness increases from the inlet to the outlet of the tube. Spencer found that the following equation held for a mean value of the steam coefficient over a range of G_{av} from 12,000 to 25,000 (lb.)/(hr.)(sq.ft.)

$$(7) \frac{h_c}{\mu_f} = \left[0.0887 + 3.154 \times 10^{-6} G_{av} \right] \left(\frac{4r}{\mu_f} \right)^{0.1412}$$

Spencer also concluded that the rise in coefficient with rise in heat transfer rate is due to the turbulence in the film caused by the steam velocity. McAdams (2, p. 267) states that Kirkbride also attributed the rise in the coefficient of condensing vapors with rise in the heat transfer rate on the outside of tubes to the turbulence induced in the condensate layer on the lower portion of the tube.

METHOD

Construction of Apparatus

The test condenser shown in Plate I consisted of a conventional double-pipe heat exchanger having a 1-foot effective

cooling length. It consisted of a 1/8-inch (I.P.S.), smooth, cold-drawn stainless steel pipe jacketed by a 1/2-inch, extra strong, red brass pipe. Plugs were placed on both ends of the brass jacket, and drilled to carry the stainless steel pipe in the exact center.

In order to insure that only vapor passed into the inside pipe of the test condenser, a condensate collector, Plate II, was inserted at the inlet of the test condenser. This removed any entrained liquid as well as any vapor condensed because of heat loss from the insulated pipe leading from the vapor generator. Another condensate collector was placed at the outlet of the test condenser to remove the condensate from the uncondensed vapor. The uncondensed vapor was sent to an aftercondenser.

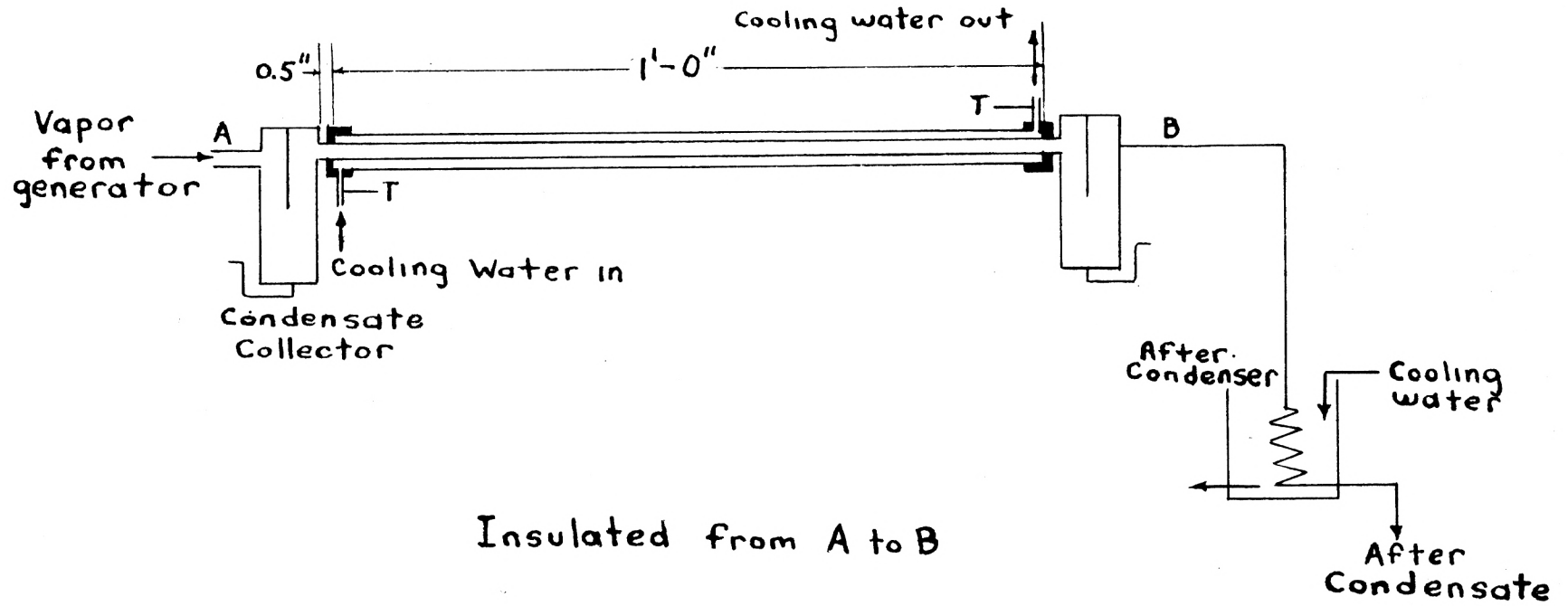
The 1/8-inch copper water inlet tube was arranged so that it could be heated for a length of three feet by means of an electric resistance heating element.

Temperatures of the cooling water which flowed through the annular space were measured by thermocouples placed in the center of the inlet and outlet streams. The iron-constantan (No. 30) thermocouples were constructed by filing the tips of the respective leads, and joining them by means of a spot welder. This method preserved the original insulation. The thermocouples were connected to a selector switch and a thermometer calibrated in 0.5° C. units was placed next to the switch to determine the temperature of the reference

EXPLANATION OF PLATE I

Diagram of equipment

PLATE I

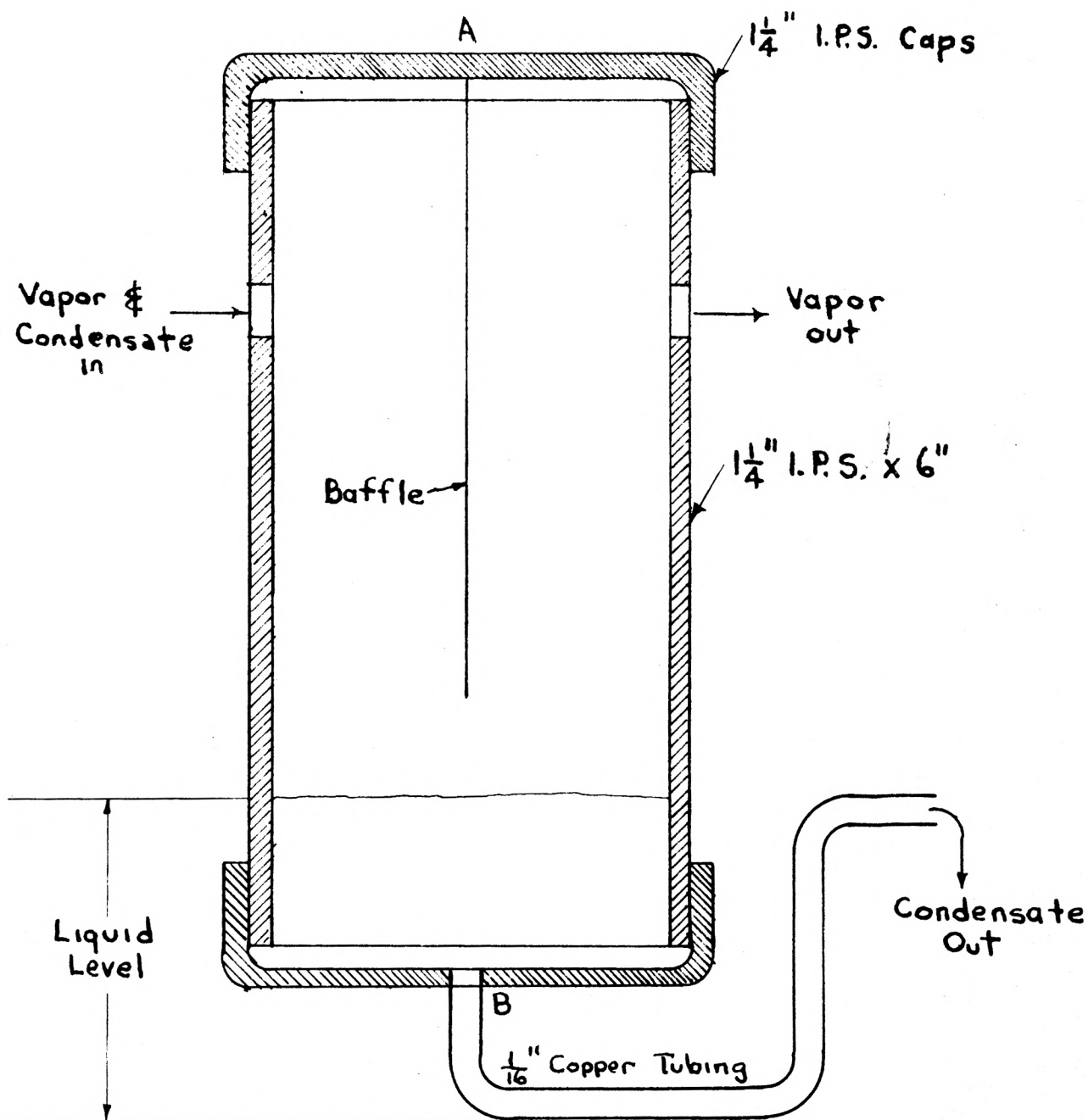


8

EXPLANATION OF PLATE II

Diagram of condensate collector

PLATE II



Insulated from A to B

junction. A Leeds and Northrup portable precision potentiometer was used for measuring the potentials.

The connecting water lines to the jacket were insulated for a distance of 3-inches from the jacket, and the jacket was also insulated.

The vapor was supplied by a 5-liter 3-necked flask covered by a Glas-col electric heating mantle. The energy input into the mantle was controlled by a Variac. By changing the Variac setting, the heat input was changed. This made variation of the vapor velocity entering the test condenser possible. A thermometer calibrated in 0.5° C. units was placed in the flask to measure the vapor temperature. A well insulated $\frac{1}{2}$ -inch copper tube connected the flask to the inlet condensate separator.

Operation of Equipment

Before assembly of the apparatus, the inner surface of the stainless steel pipe was carefully cleaned with detergent to insure film-type condensation.

During an entire series of runs, the water rate through the annular space was adjusted and held constant. The inlet water stream was heated to an average temperature of 85° F. during all runs. In this manner, the temperature driving force was reduced, and in turn the chance of total condensation

occurring in the test condenser was decreased.

The heat input into the vaporizer was fixed and for the first run with each new fluid the vapor was allowed to pass through the system for 3/4-hour to insure a purge of noncondensibles. When steady state conditions were reached, as ascertained by constant thermocouple readings for a five minute period, three runs were taken consecutively, each lasting approximately 8 minutes. The condensate, and aftercondensate were collected and weighed for each run. Two sets of thermocouple readings were taken during each run. The cooling water rate was obtained by weighing the water collected during the run. After the first series of runs, the vaporizer was refilled, the heat input to the flask was adjusted to a new value and another series of runs were made.

At the completion of a set of runs for a given fluid, the apparatus was purged to remove the condensed vapor trapped in the condensate collectors and aftercondenser. The collecting flasks and vapor generator were cleaned thoroughly before a new fluid was introduced. The above procedure was then repeated to obtain data on the new fluid.

The range of vapor velocities investigated were limited in this apparatus by the capacity of the heater. As the outlet pressure was atmospheric and the inlet pressure very slightly above atmospheric pressure, the vapor temperature was taken to be that corresponding to the saturation temperature at atmospheric pressure.

Experimental Data and Basic Calculated Results

A total of 72 runs were made. The average value for each series of runs is reported in Table 1, as three runs were used to obtain each average value. The last two columns of the table were determined from the observed data.

The heat transfer rate for the apparatus in (Btu)/(hr.) can be evaluated for the respective runs:

1. By using the quantity of condensate formed in the test condenser, or
2. By using the cooling water rate and its rise in temperature.

The value used in the following calculations was that obtained from the measurement of the amount of condensate formed in the test collector for the following reasons:

1. The condensate collected was below its saturation temperature (because of the method of construction of the condensate collector, Plate II), and therefore, loss by evaporation was negligible.
2. It is a directly determined value.

Table 2 presents the basic calculated results and the following is a discussion of the methods by which these results were obtained.

Table 1. Experimental data.

Material	Run	°F.		(lb.)/(hr.)				(Btu)/(hr.)	
		t ₁	t ₂	w	W ₁	W ₂	W	q	Q
Heptane	1	80	94	83	8.59	0	8.59	1160	1180
	2	89.5	106	45.5	5.35	0	5.35	750	735
	3	95	114.5	47.4	6.64	0	6.64	924	911
	4	96	120	47.4	7.23	1.68	9.95	1137	1140
	5	96	119	47.4	7.79	0	7.79	1090	1060
	6	96	115	47.4	6.29	0	6.29	900	860
Methanol	1	90	100	72.1	1.66	0.608	2.268	721	785
	2	88	99	73.0	1.85	1.01	2.86	802	874
	3	85.5	97	73.1	1.86	1.32	3.18	841	879
	4	82	94	73.4	1.87	1.08	2.95	880	883
	5	81	92	74.8	1.88	0.985	2.865	821	887
Acetone	1	83.5	91.5	73.4	2.98	1.30	4.28	578	660
	2	83	91	73.6	3.11	1.51	4.62	589	689
	3	83.5	92.5	76.1	3.33	2.24	5.57	684	738
	4	82	91	77.0	3.33	2.19	5.52	693	738
	5	81	90.5	76.8	3.34	3.10	6.44	729	740
	6	78.5	88	77.0	3.32	1.05	4.37	731	734
	7	79.5	89	72.5	3.09	1.09	4.18	688	685
S-Butyl-Alcohol	2	83	101	73	6.45	0.629	7.079	1313	1560
	3	79	98	73	5.96	1.27	7.23	1388	1441
	4	80	98	73	5.42	0.414	5.834	1314	1311
	5	76	96	73	5.36	0.076	5.436	1460	1298
Carbon Di-Sulfide	1	82.5	88	74.5	3.21	4.2	7.41	410	486
	2	83	90	72.0	3.09	5.44	8.63	690	469

Equation 3 was used to calculate $\frac{1}{UA}$, and equation 1 was divided by A to yield the following (3, p. 465):

$$(7) \quad \frac{1}{UA} = \frac{1}{h_w A_o} + \left(\frac{1}{k A_m} \right)_p + \frac{1}{h_c A_i}$$

An additional resistance, known as a "fouling factor", which might be present due to foreign material in the vapor or water stream was negligible because of:

1. High purity liquids used to produce the vapors
2. The condenser being thoroughly clean
3. Softened water being used for cooling

The water film coefficient was determined by use of the equation (9, p. 26):

$$(8) \quad h_w = 2.53 \left(k/D_o \right) \left(\frac{wc}{kL} \right)^{0.33}$$

This equation was recommended for water if the Graetz number, $\left(\frac{wc}{kL} \right)$, lies between 8 and 3500. Calculation (Table 2) shows that the Graetz number for the cooling water in this investigation was between 125 and 231..

The mean Δt_c was calculated according to the following derivation:

$$(9a) \quad q = h_w A_o \Delta t_w = h_c A_i \Delta t_c$$

neglecting the temperature drop across the pipe

$$(9b) \quad \Delta t_m = \Delta t_w + \Delta t_c$$

Solving for Δt_c

$$(9c) \quad \Delta t_c = \frac{\Delta t_m}{\frac{h_c A_i}{h_w A_o} + 1}$$

Table 2. Basic calculated results.

Material	Run	$^{\circ}\text{F.}$ Δt_m	UA	$\frac{\text{wc}}{\text{kL}}$	h_w	$\frac{1}{\text{UA}}$	$\frac{1}{h_w A_o}$	$\frac{1}{K}$	h_c	$^{\circ}\text{F.}$ Δt_c	$^{\circ}\text{F.}$ t_r
$\text{(Btu)/(hr.)(sq.ft.)(}^{\circ}\text{F.)}$											
Heptane	1	123	9.6	231	204	0.1042	0.0463	0.0063	275	65	160
	2	114	6.45	125	169.5	0.155	0.0556		152	71.4	155.5
	3	103	8.85	130	171	0.113	0.0559		280	49.5	172
	4	101	11.3	128	172.5	0.0885	0.0565		553	32.2	185
	5	101	10.5	128	172.5	0.0954	0.0565		435	37.9	181
	6	103	8.36	130	171	0.1198	0.0559		246	52.8	169
Methanol	1	52.4	16.5	198	197	0.0606	0.0479		2220	6.2	143
	2	54.5	16.1	200	198	0.0621	0.0476		1730	8.0	142
	3	54.8	16.0	200	198	0.0625	0.0476		1650	8.3	141.8
	4	57.7	15.3	202	196	0.0664	0.0481		1185	11.5	139.4
	5	58.8	15.1	208	197	0.0671	0.0479		1100	12.5	138.6
Acetone	1	40.4	16.35	202	196.5	0.0635	0.0480		1540	6.5	128.8
	2	46.3	14.90	207	197	0.0672	0.0479		1090	9.9	126.3
	3	45.6	16.15	211	198	0.0620	0.0476		1750	6.7	128.7
	4	47.1	16.00	214	200	0.0625	0.0471		1560	7.6	128.0
	5	45.6	16.23	213	199.5	0.0616	0.0474		1800	6.5	128.8
	6	50.5	14.6	214	200	0.0685	0.0471		940	12.3	124.5
	7	55.8	12.3	202	196.5	0.0814	0.0470		505	20.6	118.3
S-butyl- alcohol	2	118.5	13.2	203	196	0.0757	0.0481		666	36.4	184
	3	122	11.55	203	196	0.0866	0.0481		440	49	174
	4	122	10.74	203	196	0.0931	0.0481		366	54.5	170
	5	125	10.39	203	196	0.0965	0.0481		337	58.5	167
Carbon Di- sulfide	1	40.4	12.05	207	197	0.0831	0.0479		510	11.2	110
	2	39.0	12.00	200	195	0.0835	0.0474		476	11.4	110

Physical properties of the films were evaluated at the mean film temperature, t_f , which was found by the following equation, recommended by Drew (2, p. 260):

$$(10) \quad t_f = t_s - \left(\frac{3}{4}\right) \Delta t_c$$

Development of an Equation Correlating the Data

The correlation of the data was based on equation 6a,

$$\frac{h_c D}{k_f} = F \left[\left(\frac{D^3 e_f^2 g}{\mu_f^2} \right) \left(\frac{\mu_f^2 \lambda}{k_f \Delta t_c} \right) \left(\frac{DG}{\mu_w} \right) \right]$$

and the calculations are presented in Table 3. For simplification the following symbols stand for the respective dimensionless quantities.

$$\begin{aligned} \text{Nu} &= \left(\frac{h_c D}{k_f} \right) \\ \text{Py} &= \left(\frac{D^3 e_f^2 g}{\mu_f^2} \right) \\ \text{Cd} &= \left(\frac{\mu_f \lambda}{k_f \Delta t_c} \right) \\ \text{Re} &= \left(\frac{DG}{\mu_w} \right) \end{aligned}$$

All the following plots were on 2 by 2-cycle log paper:

Holding Re and Py as constant as possible from the calculated results, Nu was plotted against Cd, Fig. 1, and appeared to be a function of $(\text{Cd})^{0.8}$.

$\text{Nu}(\text{Cd})^{-0.8}$ was then plotted against Re, Fig. 2, holding Py constant. Since Py for heptane and acetone are very close, it was difficult to distinguish the individual plots and a

single line was drawn representing both fluids. The line drawn through the points representing sec-butyl alcohol was under the assumption that it would have the same slope as the lines representing the other fluids. $Nu(Cd)^{-0.8}$ was found to be a function of $(Re)^{0.8}$.

$Nu(Cd Re)^{-0.8}$ was plotted against Py to determine the final correlation. As both terms are fairly constant, the results for the individual fluids tended to cluster in groups, Fig. 3. As in Fig. 2, the calculated points for heptane and acetone overlapped due to similarity in Py . $Nu(Cd Re)^{-0.8}$ was found to be a function of $(Py)^{0.4}$ and the equation representing the correlation is:

$$(11) \quad \frac{h_c D}{k_f} \left(\frac{\mu_f^2}{D^3 \rho_f^2 g} \right)^{0.4} = 7.6 \times 10^{-4} \left(\frac{DG \lambda \mu_f}{k_f \Delta t_c \mu_r} \right)^{0.8}$$

To check the results obtained $Nu(1/Py)^{0.4}$ was plotted against $(Cd Re)$, Fig. 4, and was found to be a function of $(Cd Re)^{0.8}$. This confirmed the slopes of the lines drawn in Figs. 1 and 2. The equation for the correlation obtained from Fig. 4 was

$$(12) \quad \frac{h_c D}{k_f} \left(\frac{\mu_f^2}{D^3 \rho_f^2 g} \right)^{0.4} = 7.91 \times 10^{-4} \left(\frac{DG \lambda \mu_f}{k_f \Delta t_c \mu_r} \right)^{0.8}$$

The coefficients of equations 11 and 12 check to within 4 per cent. Equation 12 is recommended as the scattering of

points in Fig. 4 was much less than in Fig. 3, and thus a more accurate line could be drawn to represent the data.

Since only two points were determined for carbon di-sulfide, they were not included in the preliminary plots (Figs. 1, 2, and 3); they are included in Fig. 4 from which the correlation was obtained.

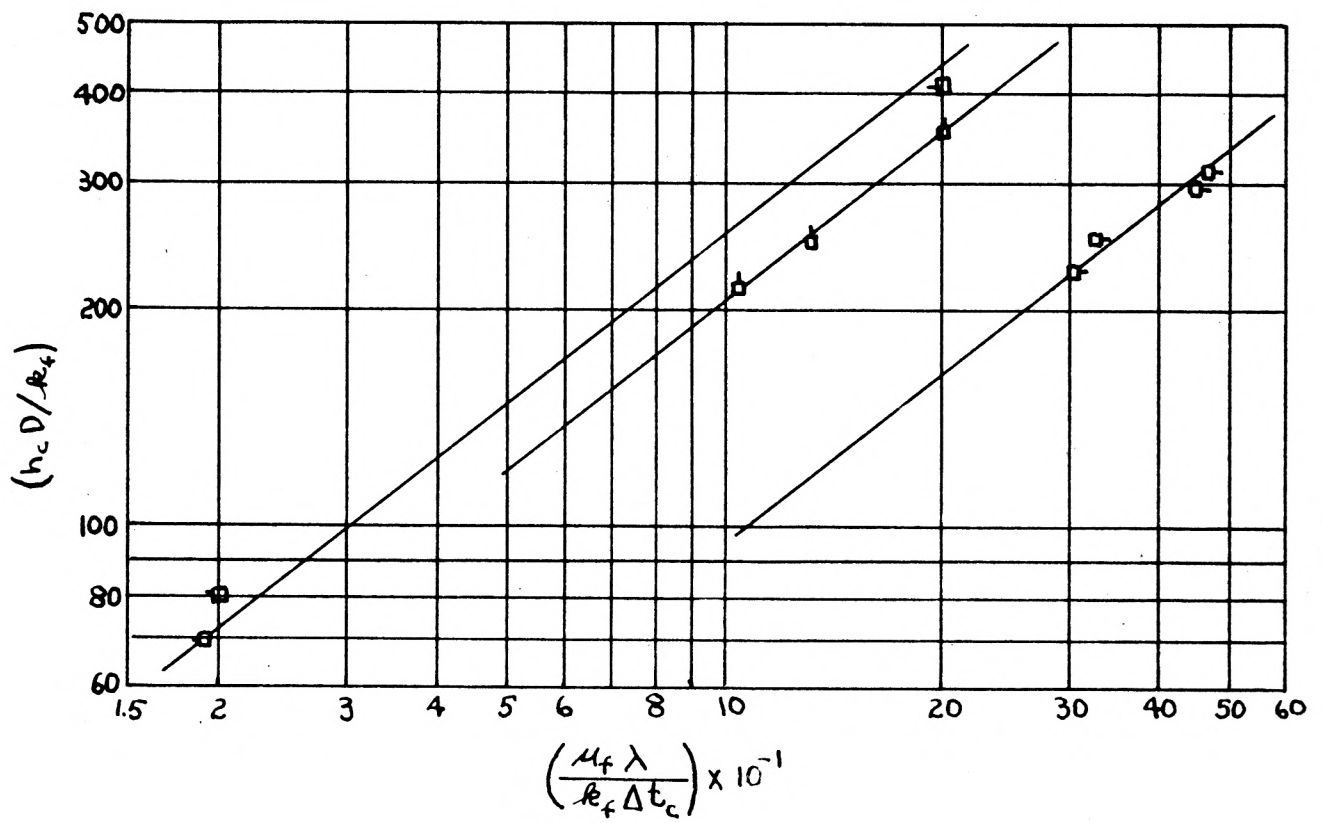


Fig. 1 - $\left(\frac{h_c D}{k_f}\right)$ vs $\left(\frac{\mu_f \lambda}{k_f \Delta t_c}\right)$ at constant $\left(\frac{DG}{\mu_f}\right)$ and $\left(\frac{D^3 \rho_f^2 g}{\mu_f}\right)$

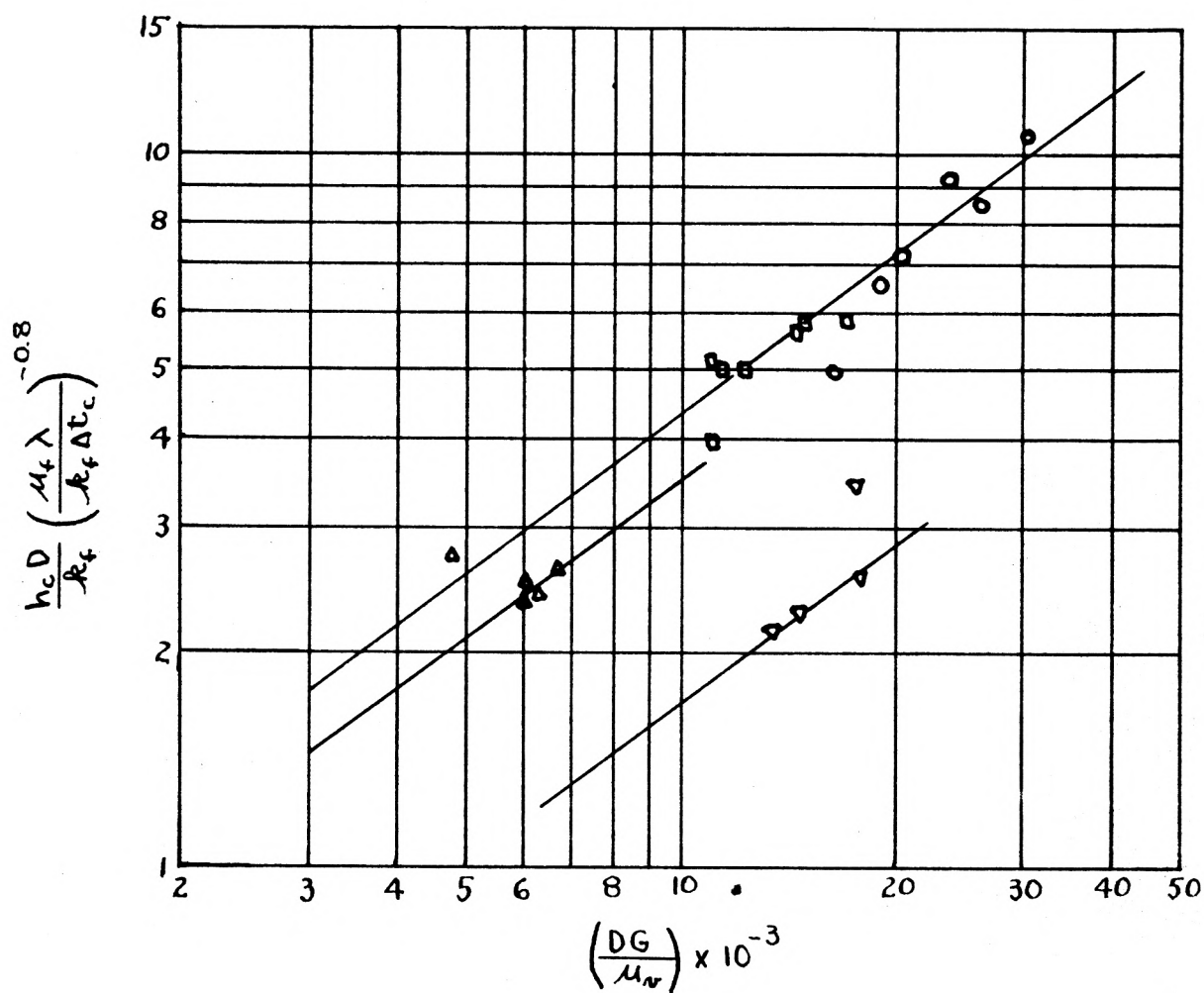


Fig. 2- $\frac{h_c D}{k_f} \left(\frac{\mu_f \lambda}{k_f \Delta t_c}\right)^{-0.8}$ vs. $\left(\frac{DG}{\mu_r}\right)$ at constant $\left(\frac{D^3 \rho_f^2 g}{\mu_f}\right)$

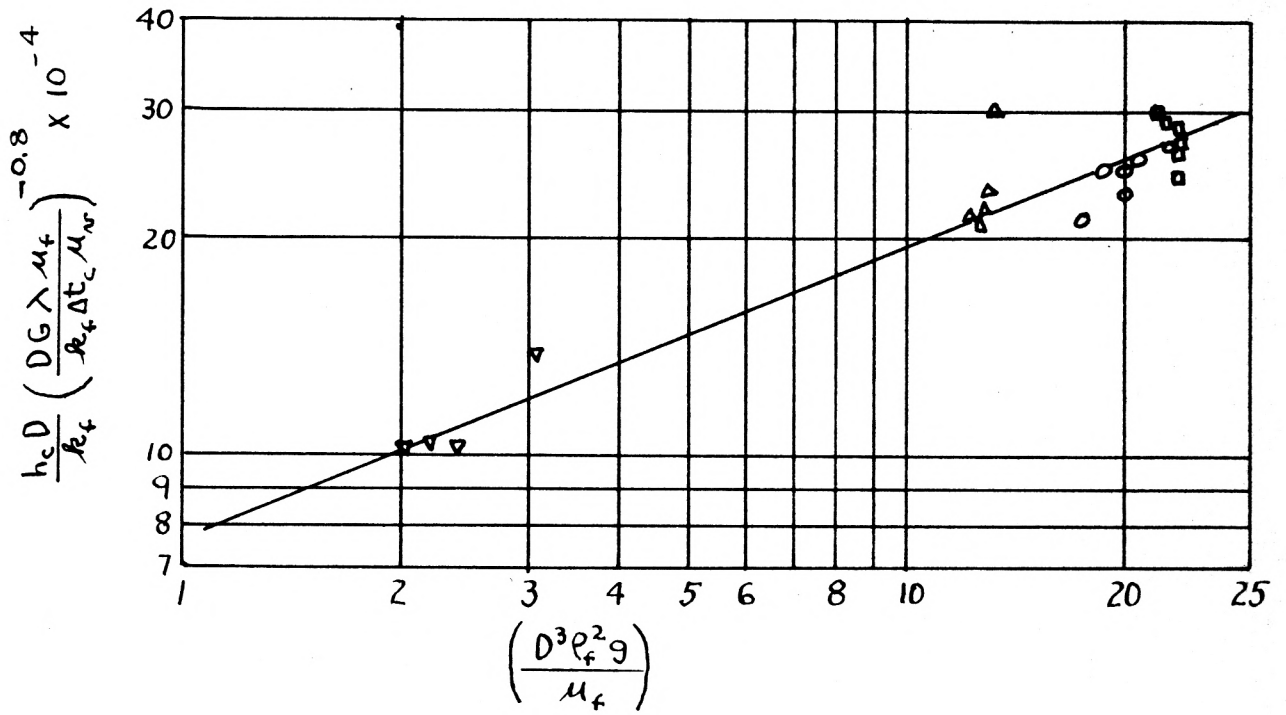


Fig. 3 - $\frac{h_c D}{k_f} \left(\frac{DG \lambda \mu_f}{k_f \Delta t_c \mu_w} \right)^{-0.8}$ vs. $\left(\frac{D^3 \rho_f^2 g}{\mu_f} \right)$

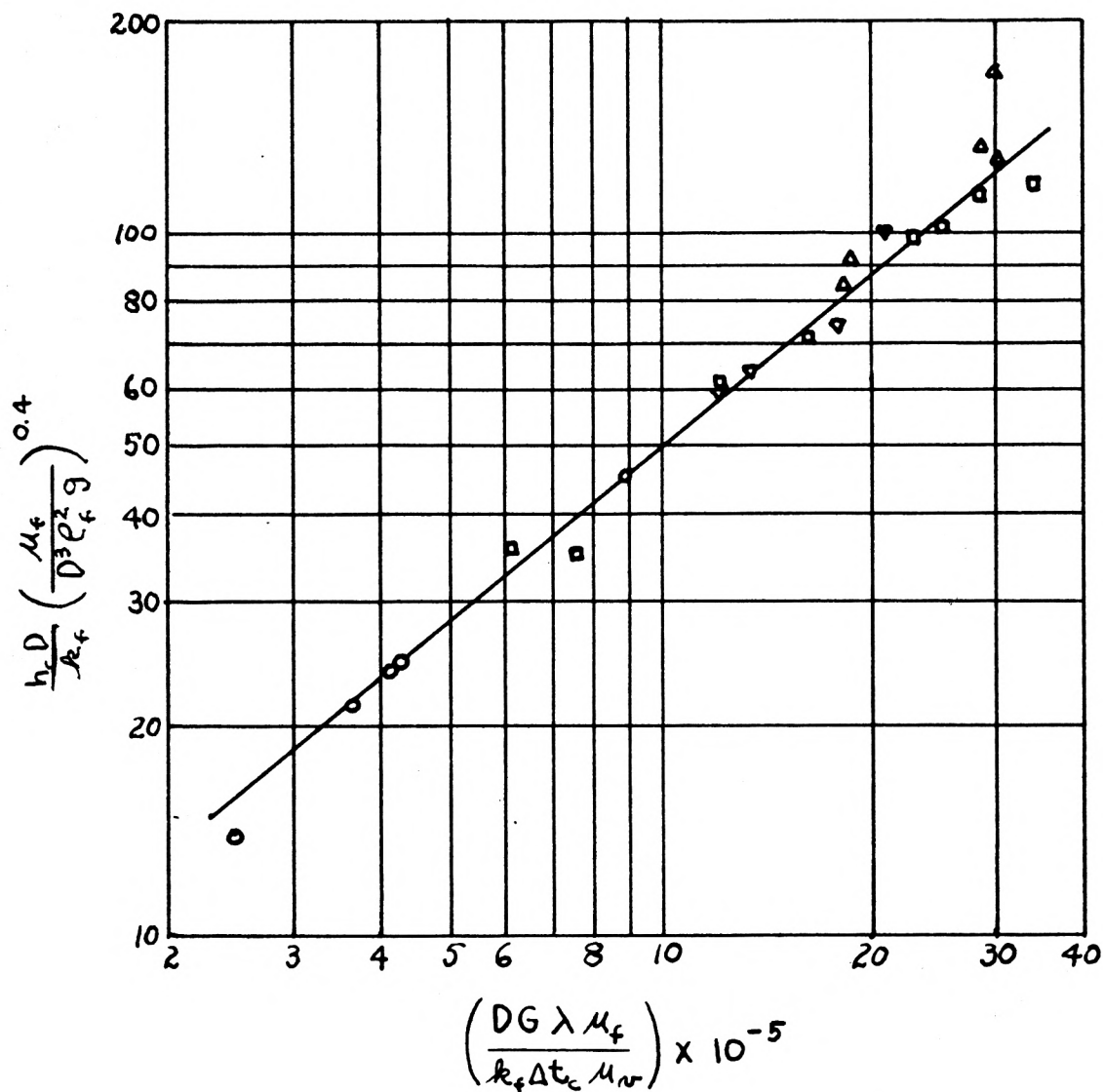


Fig. 4 - $\frac{h_c D}{k_f} \left(\frac{\mu_f}{D^3 \rho_f^2 g} \right)^{0.4}$ vs. $\left(\frac{DG \lambda \mu_f}{k_f \Delta t_c \mu_r} \right)$

DISCUSSION

The correlation determined in this investigation holds for a 1/8-inch pipe, 1-ft. long, and for Reynolds numbers in the range from 4790 to 30,100. Considering the conclusion reached by Spencer (6); i.e., that there is turbulence produced in the condensate film by the vapor velocity, then this correlation can be safely extended to higher Reynolds numbers. The forementioned conclusion can be substantiated in this paper by the fact that a large increase in vapor velocity had little effect on the amount of condensate formed, Table 1. Thus, the increase in film coefficient with increase in vapor velocity can be attributed to increased turbulence in the condensate film.

The correlation should hold for all organic vapors regardless of molecular structure. In this investigation the following organic structures were used.

Heptane - straight chain hydrocarbon

Acetone - ketone

Methanol - straight chain alcohol

Sec-butyl alcohol - branched chain alcohol

Carbon di-sulfide - an organic sulfide

Othmer and Berman (4) determined the condensing film coefficient of organic vapors on the outside of horizontal tubes as a function of Δt_c . Figure 5 is a comparison of the

condensing film coefficients on the inside and outside of horizontal pipes as a function of Δt_c . Figure 5 shows that h_c varies proportionally with Δt_c^{-1} for condensation on the inside of a horizontal tube, while h_c varies as a function of $(\Delta t_c)^{-m}$, where $m < 1$, for condensation on the outside of a horizontal tube. The former is due to the fact that inside the horizontal pipe, the condensate continues to build up down the length of the pipe, increasing, the film thickness, and increasing Δt_c and decreasing h_c at the same rate. However, if this relationship holds for a longer pipe, it is yet to be determined. Spencer (6) showed that this relationship did hold in the case of condensing steam for the first $1\frac{1}{2}$ -ft. length of a $\frac{1}{2}$ "-6 ft. long tube.

It is interesting to note that the Nusselt group, $\frac{h_c D}{k_f}$ is a function of the 0.8 power of the Reynolds number. This also holds true for the film coefficients of liquids and gases in turbulent flow being heated or cooled inside tubes with no phase change (2, chapt. VII).

A comparison of h_c calculated from experimental data and of h_c calculated from the generalized correlation equation, 12, is presented in Table 4. The deviation from the experimentally determined value was calculated as follows:

$$\text{per cent deviation} = \frac{h_{cc} - h_{ce}}{h_{ce}} \times 100$$

where h_{cc} is the film coefficient determined from the correlation

equation and h_{ce} is the film coefficient determined from experimental data. The average deviation of h_{cc} from h_{ce} was +1.04 per cent.

Only 5 of the 24 points deviated more than +10 per cent, the maximum deviations being +18.0 per cent and -29 per cent.

$$(12) \quad \frac{h_c D}{k_f} \left(\frac{\mu_f^2}{D^3 \rho_f^2 g} \right)^{0.4} = 7.91 \times 10^{-4} \left(\frac{D G \lambda \mu_f}{k_f \Delta t_c \mu_r} \right)^{0.8}$$

can be simplified to the following dimensional equation for h_c :

$$(13) \quad h_c = 7.91 \times 10^{-4} \left(\frac{D^{3.3} G \rho_f \lambda g^{0.5}}{k_f \Delta t_c \mu_r} \right)^{0.8}$$

Recommendations for further work in this field of investigation are:

1. The range of vapor velocities investigated should be increased.
2. Different lengths of the same pipe diameter should be used.
3. Pipes of different diameters should be used.
4. Other organic vapors should be used.

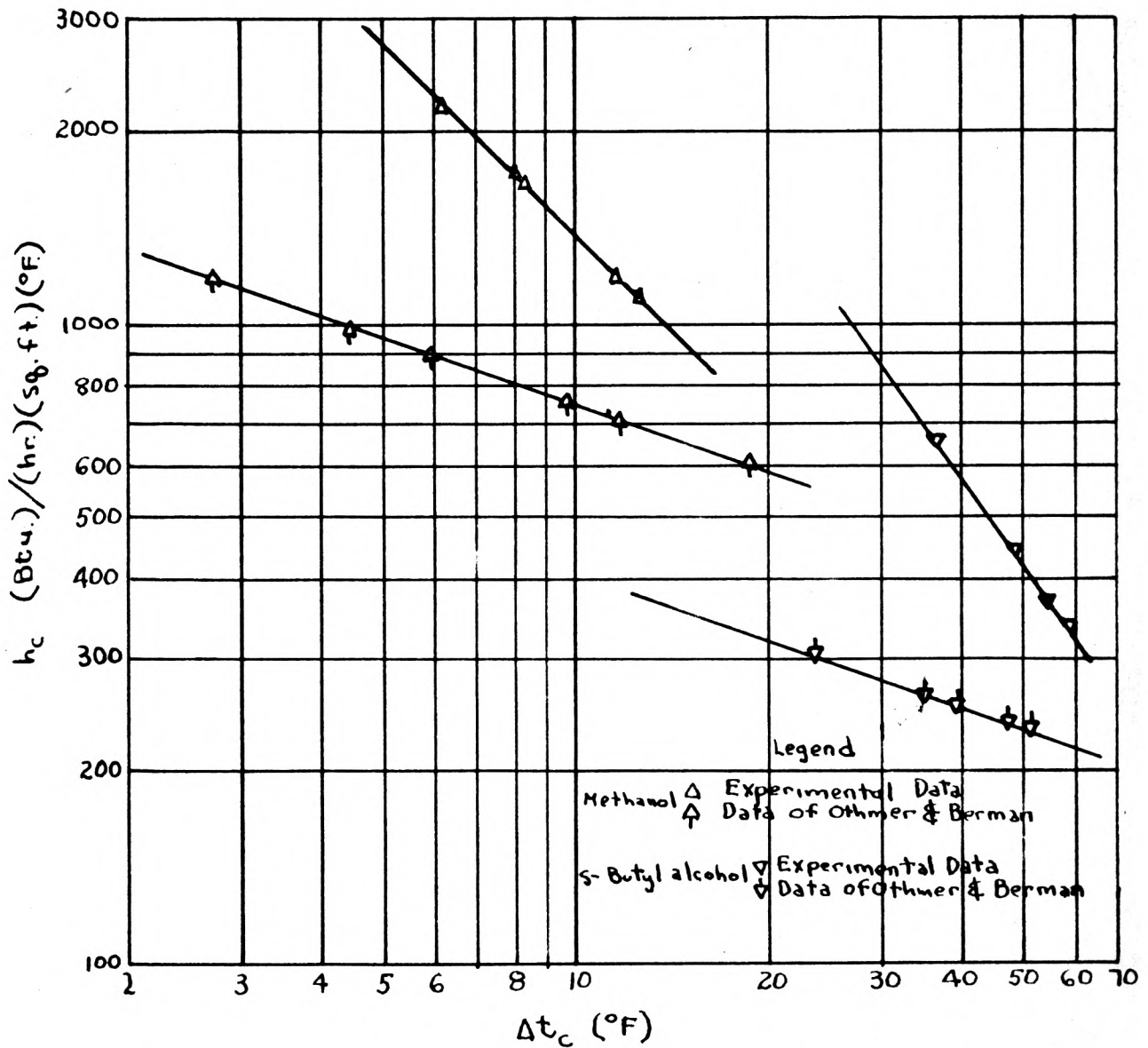


Fig. 5- Comparison of the heat transfer coefficients vs. Δt_c of condensing vapors on the outside and inside of horizontal tubes.

Table 4. Comparison of experimentally determined and calculated values of h_c .

Material	: Run	: h_{ce}	: h_{ce}	: Per cent deviation
Heptane	1	275	284	+ 3.28
	2	152	180	+18.05
	3	280	291	+ 3.93
	4	553	556	+ 0.54
	5	435	400	- 8.05
	6	246	257	+ 4.48
Methanol	1	2220	1570	-29.2
	2	1730	1610	- 6.95
	3	1650	1605	- 3.03
	4	1185	1170	- 1.27
	5	1100	1060	+ 3.63
Acetone	1	1540	1510	- 1.95
	2	1090	1140	+ 4.59
	3	1750	1790	+ 2.28
	4	1560	1630	+ 4.48
	5	1800	2070	+15.00
	6	940	910	- 3.20
	7	505	585	+15.90
S-Butyl	2	666	600	- 9.90
	3	440	493	+12.00
	4	366	372	+ 1.64
	5	337	326	- 3.28
Average				+ 1.045

SUMMARY

The effect of vapor velocity on the coefficients of heat transfer of vapors condensing in a horizontal tube was investigated. The vapors of heptane, methanol, acetone, sec-butyl alcohol, and carbon di-sulfide were used. Experiments covered a range of vapor Reynolds numbers, $\left(\frac{DG}{\mu_v}\right)$, from 4790 to 30,100, and a range of heat transfer coefficients, h_c , from 152 to 2220 (Btu)/(hr.)(sq.ft.)(°F.). The following equation was developed to fit the experimental data:

$$\frac{h_c D}{k} \left(\frac{\mu_f^2}{D^3 \rho_f^2 g} \right)^{0.4} = 7.91 \times 10^{-4} \left(\frac{DG \lambda \mu_f}{k_f \Delta t_c \mu_v} \right)^{0.8}$$

The equation can also be written in the following form:

$$h_c = 7.91 \times 10^{-4} \left(\frac{D^{3.3} G \rho_f \lambda g^{0.5}}{k_f^{1.8} \Delta t_c \mu_v} \right)^{0.8}$$

The following conclusions may be drawn for the range of variables investigated:

1. The coefficient of heat transfer is almost proportional to the reciprocal of the temperature drop across the film.
2. An increase in the vapor velocity will increase the coefficient of heat transfer, apparently through an increase in the turbulence of the film.
3. The correlation obtained can be used to predict coefficients of heat transfer for organic vapors.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Professor W. H. Honstead, Dr. G. D. Shilling, Dr. R. G. Taecker, and Dr. H. T. Ward for their encouragement, advice, and counsel, and to Mr. B. A. Rittis of the Physics Department shop for the use of his equipment.

LITERATURE CITED

- (1) Jakob, Max.
Heat transfer, Volume I. New York: John Wiley.
785 p. 1949.
- (2) McAdams, W. H.
Heat transmission, 2nd ed. New York and London:
McGraw-Hill. 459 p. 1942.
- (3) Perry, J. H., Editor.
Chemical engineers handbook, 3rd ed. New York and
London: McGraw-Hill. 1950.
- (4) Othmer, D. and S. Berman.
Condensation of vapors. Indus. and Engg. Chem.
35: 1068-1077. 1943.
- (5) Kirkbride, C. G.
Heat transfer by condensing vapors on vertical
tubes. Indus. and Engg. Chem. 26: 425-428. 1934.
- (6) Spencer, Harvey G.
Film coefficients of vapors condensing inside hori-
zontal tubes. M. S. Thesis. Kansas State College.
1950.
- (7) Holdgraf, Earl W.
The study of heat transfer. New York City: The
City College Press. 1950.
- (8) Tepe, J. B. and A. C. Mueller.
Condensation and subcooling inside an inclined tube.
Chem. Engg. Prog. 43: 267-278. 1947.
- (9) Fitzpatrick, J. P., S. Baum and W. H. McAdams.
Dropwise condensation of steam on vertical tubes.
Amer. Inst. Chem. Engg. Trans., 35: 97-107. 1939.
- (10) Baker, E. M., E. W. Kazmark and G. W. Stroebe.
Steam film heat transfer coefficients for vertical
tubes. Amer. Inst. Chem. Engg. Trans., 35: 127-
135. 1939.
- (11) Baker, E. M. and U. Tsao.
Heat transfer coefficients for condensation on hor-
izontal tubes. Amer. Inst. Chem. Engg. Trans.,
36: 517-554. 1940.

APPENDIX

Nomenclature

- A area of heat transfer, (sq.ft.)
- A_i area of heat transfer on the inside of the pipe, (sq.ft.)
- A_o area of heat transfer on the outside of the pipe, (sq.ft.)
- A_m log mean average $\left(A_o - A_i / \log \frac{A_o}{A_i} \right)$ heat transfer area, (sq.ft.)
- c specific heat, (Btu)/(lb.)(°F.)
- Cd dimensionless term
- D inside diameter of pipe, (ft.)
- D_e equivalent diameter for heat transfer (annulus), (ft.)
- g constant of gravity, 32.2 (ft.)/(sec.)(sec.)
- G entering mass velocity of the vapor, (lb.)/(hr.)(sq.ft.)
- G_{av} average mass velocity of the vapor, (lb.)/(hr.)(sq.ft.)
- h_o film coefficient of heat transfer on the outside of the pipe, (Btu)/(hr.)(sq.ft.)(°F.)
- h_i film coefficient of heat transfer on the inside of a pipe, (Btu)/(hr.)(sq.ft.)(°F.)
- h_w film coefficient of heat transfer for water, (Btu)/(hr.)(sq.ft.)(°F.)
- h_c film coefficient of condensing vapor, (Btu)/(hr.)(sq.ft.)(°F.)
- k thermal conductivity, (Btu)/(hr.)(sq.ft.)(°F.)/(ft.)
- l thickness of solid or pipe wall, (ft.)
- L length of pipe, (ft.)
- Nu dimensionless term
- Py dimensionless term
- q rate of heat transfer (water), (Btu)/(hr.)
- Q rate of heat transfer (condensate), (Btu)/(hr.)
- Re dimensionless term

- t_1 entering cooling water temperature, ($^{\circ}\text{F.}$)
 t_2 exiting cooling water temperature, ($^{\circ}\text{F.}$)
 t_s saturation temperature of the vapor, ($^{\circ}\text{F.}$)
 t_f mean temperature of the film, ($^{\circ}\text{F.}$)
 Δt temperature difference between main bodies of fluids, ($^{\circ}\text{F.}$)
 Δt_c mean temperature drop through condensing film, ($^{\circ}\text{F.}$)
 Δt_w mean temperature drop through the water film, ($^{\circ}\text{F.}$)
 Δt_m log mean temperature driving force, ($^{\circ}\text{F.}$)
 U overall heat transfer coefficient, $(\text{Btu})/(\text{hr.})(\text{sq.ft.})(^{\circ}\text{F.})$
 W_1 weight of condensate collected, $(\text{lb.})/(\text{hr.})$
 W_2 weight of aftercondensate collected, $(\text{lb.})/(\text{hr.})$
 W total amount of vapor entering the condenser, $W_1 + W_2$, $(\text{lb.}/\text{hr.})$
 ρ density, $(\text{lb.})/(\text{cu.ft.})$
 λ heat of vaporization, $(\text{Btu})/(\text{lb.})$
 μ viscosity, $(\text{lb.})/(\text{hr.})(\text{ft.})$
 Γ mass rate of condensate per unit length of circumference,
 $(\text{lb.})/(\text{hr.})(\text{ft.})$
 $\phi \left(k_f^3 \rho_f^2 g / \mu_f^2 \right)$
 Subscripts
 f evaluated at mean film temperature
 v vapor
 p pipe

Source of Physical Data

viscosity of vapor - I.C.T. 5: 1-4, 1928.

Chem. Engg. Handbook, p. 371. 1950.

viscosity of liquid - I.C.T. 7: 211-221. 1928.

density of liquid - I.C.T. 3:23-29. 1928.

latent heat of vaporization - Chem. Engg. Handbook, p. 215-216. 1950.

thermal conductivity of liquid - Chem. Engg. Handbook, p. 459. 1950.

THE EFFECT OF VAPOR VELOCITY ON THE COEFFICIENT
OF HEAT TRANSFER OF CONDENSING VAPORS ON
THE INSIDE OF A HORIZONTAL TUBE

by

HAROLD MARTIN BREWSTER

B. Ch. E., The City College of New York, 1950

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1951

The effect of vapor velocity on the heat transfer coefficient of condensing vapors in a horizontal tube were investigated. The vapors of heptane, methanol, acetone, sec-butyl alcohol, and carbon di-sulfide were used. A dimensional analysis of the factors involved led to the development of the following equation.

$$\frac{h_c D}{k_f} = F \left[\left(\frac{D^3 \rho_f^2 g}{\mu_f^2} \right) \left(\frac{\mu_f \lambda}{k_f \Delta t_c} \right) \left(\frac{DG}{\mu_r} \right) \right]$$

A conventional double-pipe heat exchanger, consisting of a 1/8" stainless steel pipe jacketed by a 1/2" copper tube, was used. Condensate collectors were placed at the inlet and outlet of the condenser; the former to insure that only vapor entered the condenser, and the latter to collect the condensate formed in the condenser. The uncondensed vapor was sent to an after condenser. Water was used as the cooling medium and the inlet and outlet water temperatures were measured by means of thermocouples inserted in the inlet and outlet streams. The vaporizer consisted of a 3-necked 5-liter flask heated by means of an electrical Glas-col heating mantle. The entering vapor velocity was varied by varying the heat input into the vaporizer by means of a Variac.

A total of 72 runs were taken; a series of 3 runs for each set heat input into the vaporizer were averaged and reported. The heat transfer rate was obtained from the amount of condensate formed in the condenser. The coefficient of heat transfer

was obtained by use of the equation expressing the total resistance to heat transfer offered by the condenser.

$$\frac{1}{UA} = \frac{1}{h_w A_o} + \left(\frac{\ell}{k A_m} \right)_p + \frac{1}{h_c A_i}$$

In this investigation the Reynolds number was varied from $(DG/\mu_v) = 4790$ to $30,100$ and the coefficient of heat transfer varied from 152 to 2220 (Btu)/(hr.)(sq.ft.)(°F.). The following correlation was obtained to fit the data:

$$\frac{h_c D}{k_f} \left(\frac{\mu_f^2}{D^3 \rho_f^2 g} \right)^{0.4} = 7.91 \times 10^{-4} \left(\frac{DG \lambda \mu_f}{k_f \Delta t_c \mu_v} \right)^{0.8}$$

This equation may also be written as:

$$h_c = 7.91 \times 10^{-4} \left(\frac{D^{3.3} G \rho_f \lambda g^{0.5}}{k_f \Delta t_c \mu_v} \right)^{0.8}$$

The conclusions are:

1. The heat transfer coefficient increases with increased vapor velocity, due to an apparent increase in the turbulence of the condensing film.
2. The heat transfer coefficient varies proportionally with the reciprocal of the temperature drop through the condensing film.
3. The correlation can be used to determine the heat transfer coefficients of organic vapors.