

THE EFFECT OF TEFLON ON THE CONDENSATION
OF BENZENE ON A HORIZONTAL COPPER TUBE

by
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I. INTRODUCTION

Improved methods of heat transfer are continually being sought, since a more efficient and more rapid exchange of heat increases the economy of many commercial operations.

When condensation takes place in a heat exchanger, either film or dropwise condensation may occur. Dropwise condensation offers less resistance to heat transfer than film condensation and is, therefore, more desirable. Since the predominant type of condensation is film condensation, some method must be found to promote dropwise condensation.

The promotion of dropwise condensation has been accomplished, but most of the chemical promoters were soon washed away by condensate. Too much promoter added more resistance to heat transfer than dropwise condensation could compensate for. A thin coating of durable Teflon was considered as a possibly ideal promoter with none of the limitations of injected promoters.

The purpose of this investigation was to determine the effect of a thin Teflon coating upon the heat transfer coefficients of a horizontal copper tube during the condensation of benzene vapor at atmospheric pressure.

II. LITERATURE REVIEW

A review of the literature on heat transfer, condensation, and the application of promoters to the heat transfer process is presented in this section.

Heat Transfer

There are three modes of heat transfer, according to Perry⁽⁷⁾ and McAdams.⁽¹³⁾ They are conduction, convection, and radiation.

This investigation deals with the rates of heat transfer in an exchanger during the condensation of vapors, which is primarily heat transfer by conduction.

Heat must flow through three "resistances": (1) from the vapor to the outside surface of the tube; (2) through the tube wall; and (3) from the inside surface of the tube wall to the water through the layer of slow-moving water against the tube wall. If the tube is coated, the heat must also flow through the coating, adding another resistance. The magnitude of these resistances determines the rate of heat transfer.

Condensation

There are two types of condensation:⁽⁷⁾ film and dropwise. A "mixed" condensation is a combination of these two.

Film Condensation. In this type of condensation, the vapor condenses in a film on the heat exchanger tube, completely covering the tube surface. This extra layer of material reduces the rate of heat transfer. Theoretical equations for the rate of heat transfer with the assumption that the film flows in streamline motion down the cooling surface were derived in 1916 by Nusselt.⁽¹⁸⁾

Some investigators, however, have obtained values much lower than the Nusselt equation values. Henderson,^(9,10) Buckles,⁽²⁾ and Morrison⁽¹⁵⁾ determined vapor-side heat transfer coefficients for a three-foot long vertical copper tube and, in each case, their calculated coefficients were only 20 to 30 per cent of the Nusselt value. Henderson and Morrison, plotting the vapor-side coefficient against the temperature drop between the vapor and the tube wall, obtained a curve the same shape as, but lower than, the Nusselt curve; Buckles obtained a convex curve for the calculated results and the usual concave curve for the Nusselt values.

On the other hand, most investigators^(22,12,19,11,18,6,3,20,21) have obtained values equal to, or higher than, Nusselt values.

Dropwise Condensation. When some investigators^(4,17,18) began to obtain coefficients from condensing steam to vertical tubes considerably higher than those calculated from theory, three possibilities⁽¹⁸⁾ to explain the discrepancies were considered. The first was that the condensate was in turbulent, rather than

streamline, motion; this was disproved by Reynolds number calculations. Second, thermocouples were suspected of inaccuracy; this was also disproved. Finally, the possibility of dropwise or mixed condensation was considered. Investigation of the data led Nagle⁽¹⁸⁾ to conclude that dropwise condensation was the cause of the larger discrepancies from theory.

Dropwise condensation occurs when individual drops form on the cooling surface.⁽¹⁷⁾ These drops enlarge, then roll down the tube, sweeping the surface clean until more drops form. This, in effect, decreases the resistance to heat transfer on the area of the surface that is free of condensate and, in turn, increases the vapor-side heat transfer coefficient up to 18 times the Nusselt value.⁽⁷⁾

Noncondensable Gases. The presence of noncondensable gases in a condenser lowers the rate of heat transfer. The gas forms a layer above the condensate on the tube. This layer forms a barrier through which the condensable gas must diffuse to reach the condensing tube, resulting in observed and overall heat transfer coefficients much lower than those for pure condensable gases.

Promoters

Since dropwise condensation is characterized by larger heat transfer coefficients, and, therefore, greater heat transfer, it is desirable to attempt to produce dropwise condensation in condensers. Substances which do this are called promoters.⁽⁴⁾

Characteristics. Dropwise condensation of steam, according to McAdams⁽¹⁴⁾, is obtained only when the condensing surface is contaminated with a suitable promoter. There is evidence that this is not strictly true, since Selin⁽²⁰⁾ has produced both film and dropwise condensation on a copper tube by varying only ΔT . This investigation, however, is more concerned with chemical promoters.

A promoter, therefore, must (1) adhere to the surface of the condenser and (2) prevent the condensate from wetting the surface.

Examples. Many promoters have been tried,^(4,6,8,11,14,17,18) but few of them stick to the condenser surface. Examples⁽⁴⁾ include petroleum oils and greases, fats, waxes, soaps, mercaptans, and a silicone oil. They were applied by wiping the surface of the condenser with a promoter-soaked cloth or by injecting the promoter into the vapor line above the condenser. These promoters were soon carried away by the steam.

Two promoters, silicone resins⁽¹¹⁾ and Teflon,^(3,5) are coated onto the condensing surface. They do not wash off, can withstand high temperatures (500°F for some Teflon coatings), and have a long life.

Teflon. Teflon has been found effective for condensing steam, ethylene glycol, nitrobenzene, and aniline by Topper and Baer,⁽²¹⁾ but no heat transfer data was reported by the authors.

Depew and Reisbig⁽³⁾ reported heat transfer coefficients for the condensation of steam on a Teflon coated aluminum tube. Vapor-side heat transfer coefficients were significantly higher when a 0.00025-inch thick Teflon coating was used. Thin Teflon coatings adhered well to stainless steel and copper, as well as aluminum.

III. EXPERIMENTAL

This section includes information relating to actual laboratory material, apparatus, procedure, data obtained and results calculated.

Plan of Experimentation

The vapor-side heat transfer coefficients were to be determined--by experimentation--for a clean copper tube before and after applying a Teflon coating to the outside tube surface. These coefficients would then be compared with literature data and with the vapor-side heat transfer coefficients calculated from the Nusselt equation. The effect of the Teflon coating, was well as data reliability, could then be determined.

Materials

The source and description of the materials used in this investigation are presented below.

Benzene. Purified, cat. no. B-243, lot no. 753566. Boiling range, 80-82°C. Obtained from Fischer Scientific Co., 1 Reagent Lane, Fair Lawn, N. J. Used as a condensing organic vapor for heat transfer coefficient determination.

Teflon (Polytetrafluoroethylene). Trade name: Enralon 323 (air dry). Resin-bonded colloidal PTFE lubricant containing Freon 12, propyl acetate, toluol, and MEK. Obtained from Acheson

Colloids Co., Port Huron, Michigan. Used to coat copper tube with layer of Teflon.

Apparatus

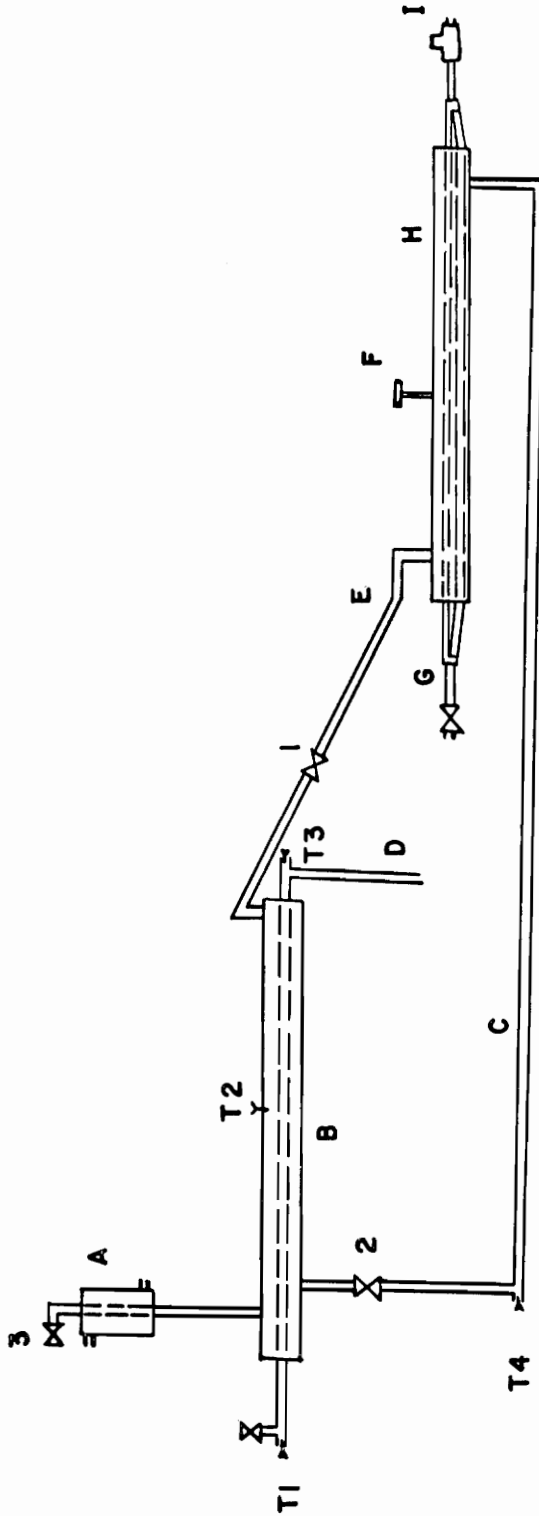
A detailed description of each piece of equipment is given below. Arrangement of the apparatus is shown in Figure 1, page 9. Detailed drawings of the still and condenser are presented in Figures 2 and 3, pages 10 and 11, respectively. The apparatus was supported on ring stands: two rings for the condenser and two for the still. The still and condenser were insulated with glass wool.

Steam Trap. Impulse, 0.5 inch, no. 60. Max pressure, 400 lb; max temperature, 450°F. Obtained from Yarnall-Waring Co., Philadelphia, Pa. Used to remove steam condensate from the still.

Gauge. Compound pressure-vacuum. From 30 inches Hg vacuum to 15 pounds per square inch, gauge. Obtained from Jas. P. Marsh Corp., Chicago, Ill. Used to determine pressure of the system.

Tubing. Type M hard drawn copper. Half-inch nominal diameter. Used to transport cooling water, steam, and benzene vapor.

Fittings and Valves. Standard fittings and valves were used.



LEGEND

- | | |
|---------------------------|------------------------------------|
| A. SECONDARY CONDENSER | 1. STEAM TRAP |
| B. MAIN CONDENSER | T1. INLET WATER THERMOCOUPLE |
| C. CONDENSATE RETURN LINE | T2. VAPOR THERMOCOUPLE |
| D. COOLING WATER LINE | T3. OUTLET WATER THERMOCOUPLE |
| E. VAPOR LINE | T4. CONDENSATE THERMOCOUPLE |
| F. PRESSURE-VACUUM GAUGE | 1. VAPOR FLOW CONTROL VALVE |
| G. INLET STEAM LINE | 2. CONDENSATE RETURN CONTROL VALVE |
| H. STILL | 3. VENT VALVE |

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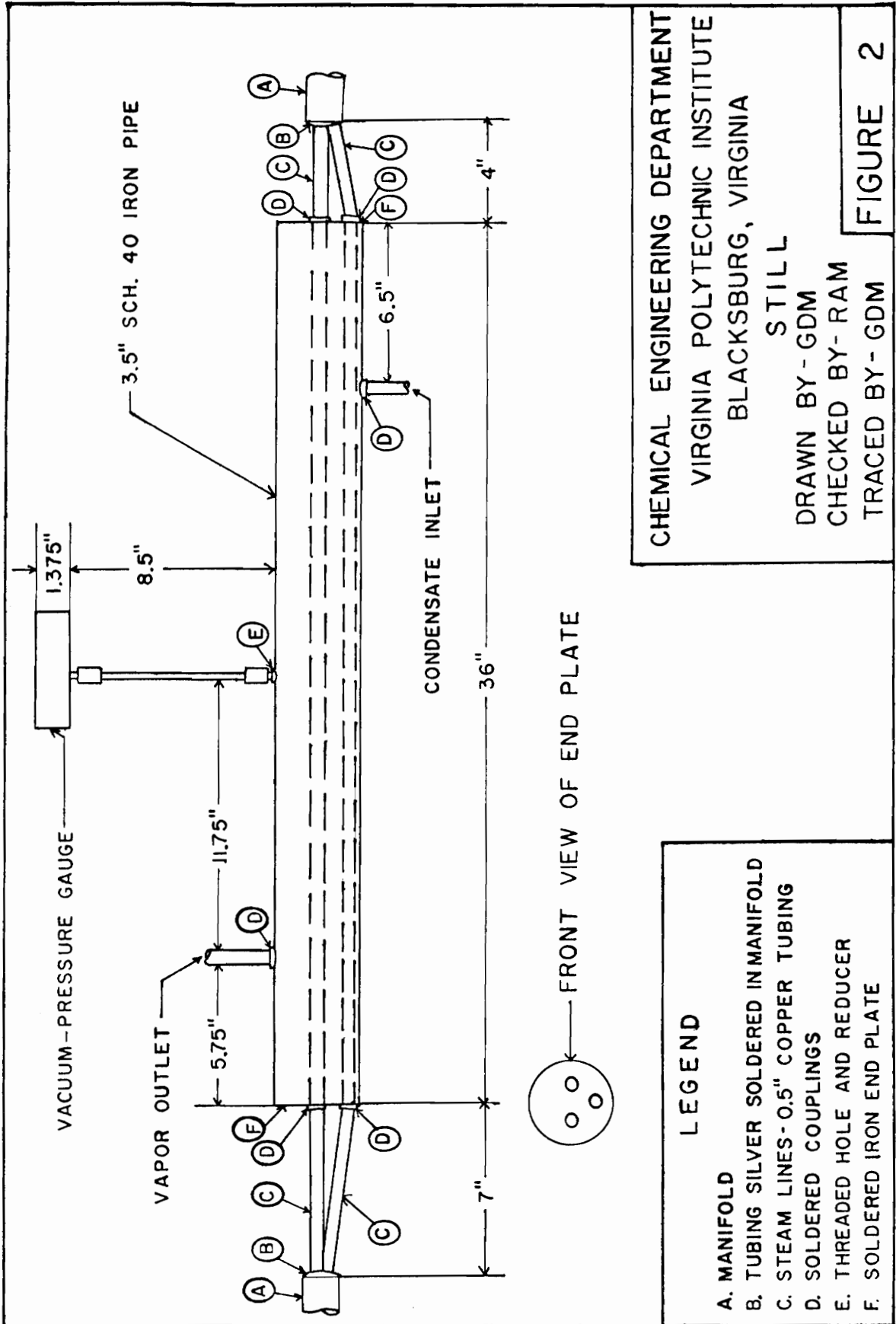
HEAT TRANSFER APPARATUS

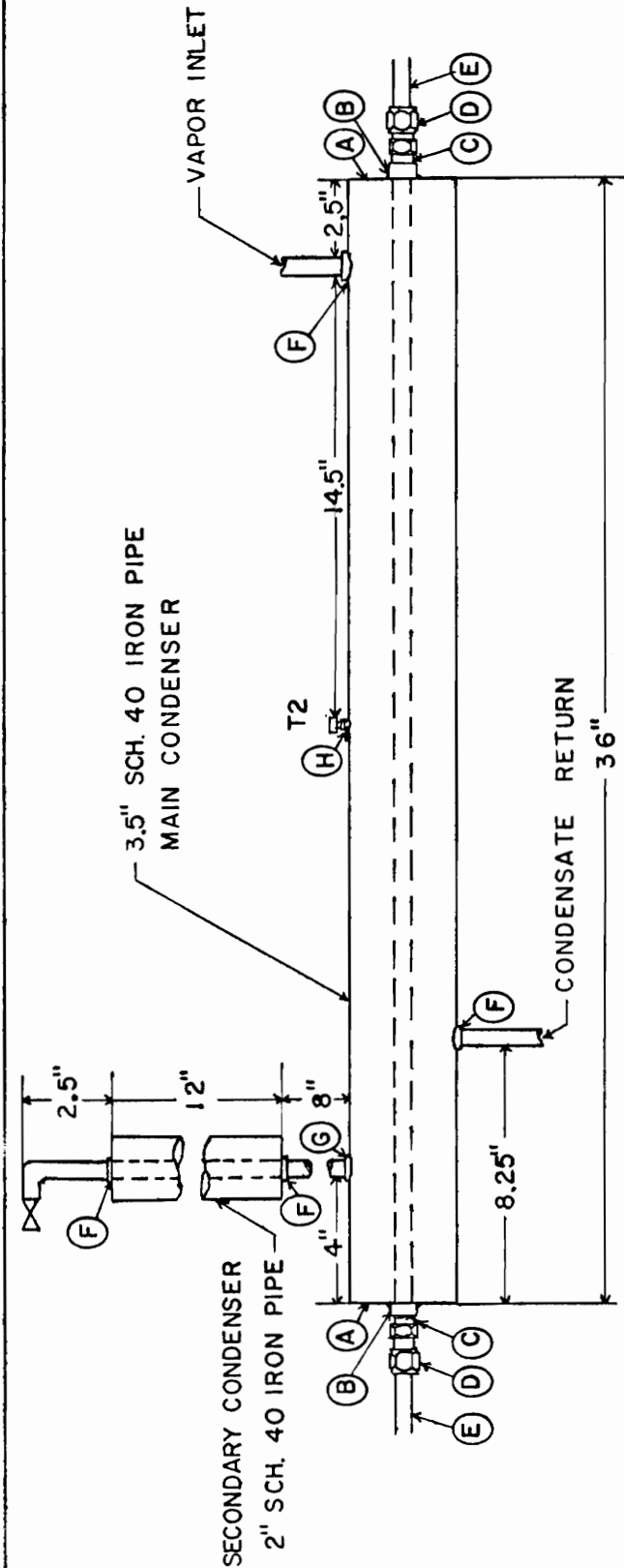
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FIGURE 1





LEGEND

- A. SOLDERED IRON END PLATE
- B. SOLDERED COUPLING ON END PLATE
- C. HALF-INCH TUBING FERRULE
- D. STANDARD COPPER TUBING FITTINGS
- E. REMOVABLE COPPER TUBING
- F. SOLDERED COUPLINGS ON PIPES
- G. THREADED HOLE WITH REDUCER & FITTINGS
- H. T2 THERMOCOUPLE THREADED HOLE & FITTINGS

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CONDENSER

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FIGURE 3

Potentiometer. Type S. Range zero to 1.70 volts and zero to 17 millivolts. Obtained from Fisher Scientific Co., Pittsburgh, Pa. Used in the determination of thermocouple emf.

Galvanometer. Catalog no. 570-202. Manufactured by G.M. Laboratories, Inc., Chicago, Ill. Obtained from Fisher Scientific Co., Pittsburgh, Pa. Used in the determination of thermocouple emf.

Thermocouples. 30 gauge iron and constantan wire. Obtained from Fisher Scientific Co., Pittsburgh, Pa. Used to obtain temperatures in the apparatus.

Still. (Figure 2, page 10). Three-foot length of schedule 40 iron pipe. Nominal diameter, 3-1/2 inches. Ends soldered shut with iron plates. Three lengths of 1/2-inch copper tubing pass into the still through couplings soldered onto the iron plates. The copper tubes lead into manifolds on each side of the still, where the tubing is silver-soldered into place for air-tightness. Reducers connect the manifolds to ordinary 1/2-inch copper tubing and fittings. Steam flows through the copper tubing inside the still. Holes for outgoing vapor and incoming condensate fitted with soldered couplings. Constructed at VPI Chemical Engineering shop, Blacksburg, Va. Used to produce benzene vapor.

Condenser. (Figure 3, page 11). Three-foot length of schedule 40 iron pipe. Nominal diameter, 3-1/2 inches. Ends soldered shut with iron plates. Removable copper tubing through center of condenser passed through couplings soldered onto iron end plates. Half-inch

tubing ferrules used to hold first part of ordinary tubing fitting permanently to couplings on each end. Remainder of fitting comes loose to allow removal of copper tube for cleaning and/or coating. Holes for incoming vapor and outgoing condensate fitted with soldered couplings. Threaded hole used for tubing leading to secondary condenser. Constructed at VPI Chemical Engineering shop, Blacksburg, Va. Used to obtain heat transfer data.

Scale. Model no. 31-0851FB, serial no. 1788, factory no. 2080-0-102. Limit 15 pounds. One ounce graduations. Obtained from Toledo Scale Co., Toledo, Ohio. Used to weigh tared buckets of water.

Method of Procedure

The procedure used to clean and coat the copper tube and to evacuate and operate the apparatus are described in this section.

The copper tube was immersed 15 minutes in a phosphoric acid bath, buffed on a wire wheel, and installed in the main condenser. Benzene was funneled into the still through the hole created by removing the pressure gauge. The pressure gauge was replaced and cooling water to both the main and secondary condensers was turned on. Refer to Figure 1, page 9, for the positions of the valves mentioned in the evacuation and operation procedures.

Evacuation of the System. Refer to Figure 1 for valve locations. After closing valves 1 and 2, which connect the main condenser to the still, a neoprene hose was attached from the nozzle of valve 3 to an aspirator. A vacuum of approximately 20 inches of mercury was produced in the condenser. Valve 1 was then opened ten or 20 seconds to remove air from the still.

Atmospheric pressure was restored to the still--after re-closing valve 1--by opening the steam valve and vaporizing benzene. Keeping still pressure slightly greater than atmospheric, valve 3 was closed and valve 1 slowly opened until the entire system reached atmospheric pressure.

Valve 1 was again closed and the evacuation procedure was repeated. Care was taken to open valve 3 slowly to allow the secondary condenser to condense the benzene vapor before it was sucked out of the system.

Operation. Refer to Figure 1 for valve locations. Following the evacuations, the system pressure was maintained at 0.5 to 1.5 pounds per square inch above atmospheric pressure by steam flow adjustment. The hose used during the evacuation was removed from the aspirator and placed into a beaker of benzene. Valve 3 was opened slightly, allowing noncondensable gases to escape. Opening valve 3 too widely permitted benzene vapor to escape from the system.

An ice-water cold junction was provided in an insulated

bucket. System equilibrium was assumed when thermocouple emf potentiometer readings for the entering and exiting cooling water and for the vapor entering the condenser remained constant for 15 minutes. Water flow was collected and weighed in a tared bucket for a timed period during each test.

Coating the Tube. The copper tube was removed from the main condenser and 50 random measurements of the outside diameter of the tube were taken with a micrometer to the nearest 0.0001 inch. The average of these 50 readings was 0.49986 inch. The tube was then immersed in a phosphoric acid bath for 15 minutes, washed, wiped dry with a clean rag, and buffed on a wire wheel.

Suspended from an overhead pipe by wound-up rubber bands, the clean copper tube was released, the rubber bands causing it to spin rapidly. While spinning, the tube was sprayed with Teflon and allowed to air-dry overnight. Another 50 random micrometer measurements were made the following day; the average outside tube diameter was 0.49982 inch.

The Teflon coating had been tested on a copper plate for temperature limits and solubility. It was insoluble in benzene and could withstand 200°F.

Evacuation and operation during the test was the same for both coated and uncoated tubes.

Data and Results

Four tests--three with the tube clean but uncoated and one

with the tube Teflon-coated--were made at different water flow rates. The data from these tests appears in Table I, page 17; results calculated from the data appear in Table II, page 18. Information needed to calculate the results, such as the properties of water and benzene, appear in Table III, page 19.

Table IV, page 20, lists vapor-side heat transfer coefficients obtained by other observers for benzene vapor condensation. Various tubes, temperature drops, and cooling water flow rates account for the wide range of values.

Observed, Nusselt, and literature vapor-side heat transfer coefficients were plotted versus the temperature drop across the benzene film in Figure 4, page 21, and versus the cooling water flow rate in Figure 5, page 22.

TABLE I

DATA FOR THE CONDENSATION OF BENZENE
VAPOR ON A HORIZONTAL COPPER TUBE

Thermocouple Readings Converted to Temperature					Water
Test	Water In	Water Out	Vapor in Condenser	Condensed Vapor ^a	Flow Rate
	°F	°F	°F	°F	lb/min
1 ^b	57	74	174	154	4.78
2 ^b	61	73	175	152	7.01
3 ^b	57	51	173	146	20.63
4 ^c	59	63	174	147	21.04

^a Thermocouple located 14.5 inches below condenser in condensate return tube (T4 in Figure 1).

^b Uncoated tube

^c Teflon-coated tube

TABLE II

RESULTS FOR THE CONDENSATION OF BENZENE
VAPOR ON A HORIZONTAL COPPER TUBE

Test	Reynolds Number Re	Heat Transferred Q	Overall Heat Transfer Coefficient U ₂	Water-side Heat Transfer Coefficient h ₁	Overall Temperature Difference ΔT	Vapor-side Temperature Difference Δt _v	Observed Vapor-side Heat Transfer Coefficient h ₂	Nusselt Vapor-side Heat Transfer Coefficient h _N
		$\frac{\text{Btu}}{\text{hr}}$	$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	$^\circ\text{F}$	$^\circ\text{F}$	$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$
1 ^a	3840 ^c	4870	131	318	106.5	63.5	220	395
2 ^a	5610 ^c	5050	136	427	107	76.5	190	362
3 ^a	16500	4950	113	1170	113	102	139	318
4 ^b	16800	5050	128	1180	113	97	149	320

^a Uncoated tube

^b Teflon-coated tube

^c Water flow not fully turbulent

TABLE III

INFORMATION REQUIRED IN THE CALCULATION OF RESULTS FROM
THE DATA OBTAINED DURING THE INVESTIGATION

Information	Symbol	Values	Location in Perry's ^a
Thermal conductivity of water @ 63°F	k_w	0.352 Btu/hr-ft-°F	3-204
Viscosity of water @ 63°F	μ_w	2.66 lb/hr-ft	3-199
Specific heat of water @ 63°F	C_w	1.0 Btu/lb-°F	3-123
Density of water @ 63°F	ρ_w	62.4 lb/ft ³	3-70
Inside diameter of tubing	D_1	0.0369 ft.	6-55
Outside area of copper tube ^b	A_2	0.391 ft ²	--
Inside area of copper tube ^b	A_1	0.348 ft ²	--
Average area of copper tube ^b	A_m	0.364 ft ²	--
Thickness of copper tube wall	L_m	0.0023 ft	6-55
Thermal conductivity of copper	k_c	223 Btu/hr-ft (°F/ft)	3-203
Thickness of Teflon coating	L_t	(determined by measurement)	
Thermal conductivity of Teflon ^c	k_t	0.14 Btu/hr-ft ² (°F/in)	--
Thermal conductivity of liquid benzene @ 97.5°F	k_b	0.091 Btu/hr-ft-°F	3-204
Density of condensed benzene @ 97.5°F	ρ_b	54.8 lb/ft ³	3-24
Viscosity of liquid benzene @ 97.5°F	μ_b	1.26 lb/hr-ft	3-199
Outside diameter of copper tube	D_2	0.0417 ft	6-55
Latent heat of vaporization of benzene	λ_b	180 Btu/lb	3-114

^a Perry's Chemical Engineer's Handbook, 4th Edition
^b Calculated from $A_1 = 2\pi r_1 l$
^c Obtained from Depew and Reissburg (3):

TABLE IV
LITERATURE VALUES OF THE VAPOR-SIDE HEAT TRANSFER
COEFFICIENT FOR THE CONDENSATION OF BENZENE
VAPOR ON METAL TUBES

Investigators	Reference Number	Range of		Tube Characteristics		
		Heat Transfer Coefficient h_2	Vapor-side Temperature Difference Δt_v	Vertical (V) or Horizontal (H)	Diameter	Length Metal
		$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	$^\circ\text{F}$		in.	ft.
Wallace & Davidson	22					
Observed		264-289				
Wilson Plot		276	88-110	H	0.84	2.5
Nusselt		270				brass
Rhodes & Younger	19					
Wilson Plot		412	none	H		
Nusselt		303	given		0.373	--
						copper
Betton and Rhodes	22	353				
McAdams & Frost	12	310-370	23-28	H	0.675	4.0
						brass
Kirkbride	14	242-381	42-67	H	1.31	8.2
						--
Baker & Mueller	14	235-262	31-62	H	1.31	3.67
						--
Baker & Mueller	14	307-315	114	H	0.625	3.67
						--

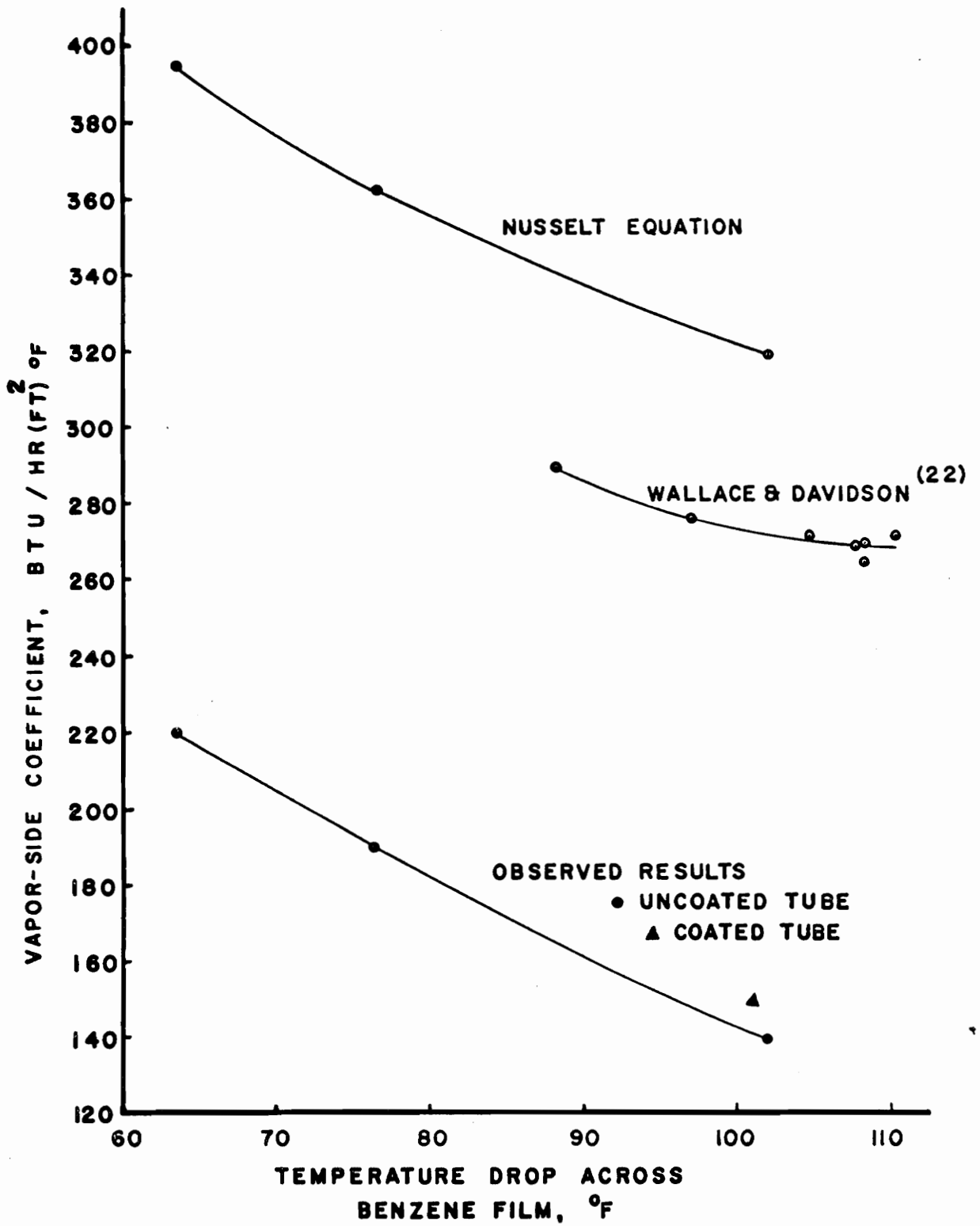


FIGURE 4. VAPOR-SIDE COEFFICIENT VERSUS
TEMPERATURE DROP ACROSS BENZENE FILM IN
THE CONDENSATION OF BENZENE VAPOR

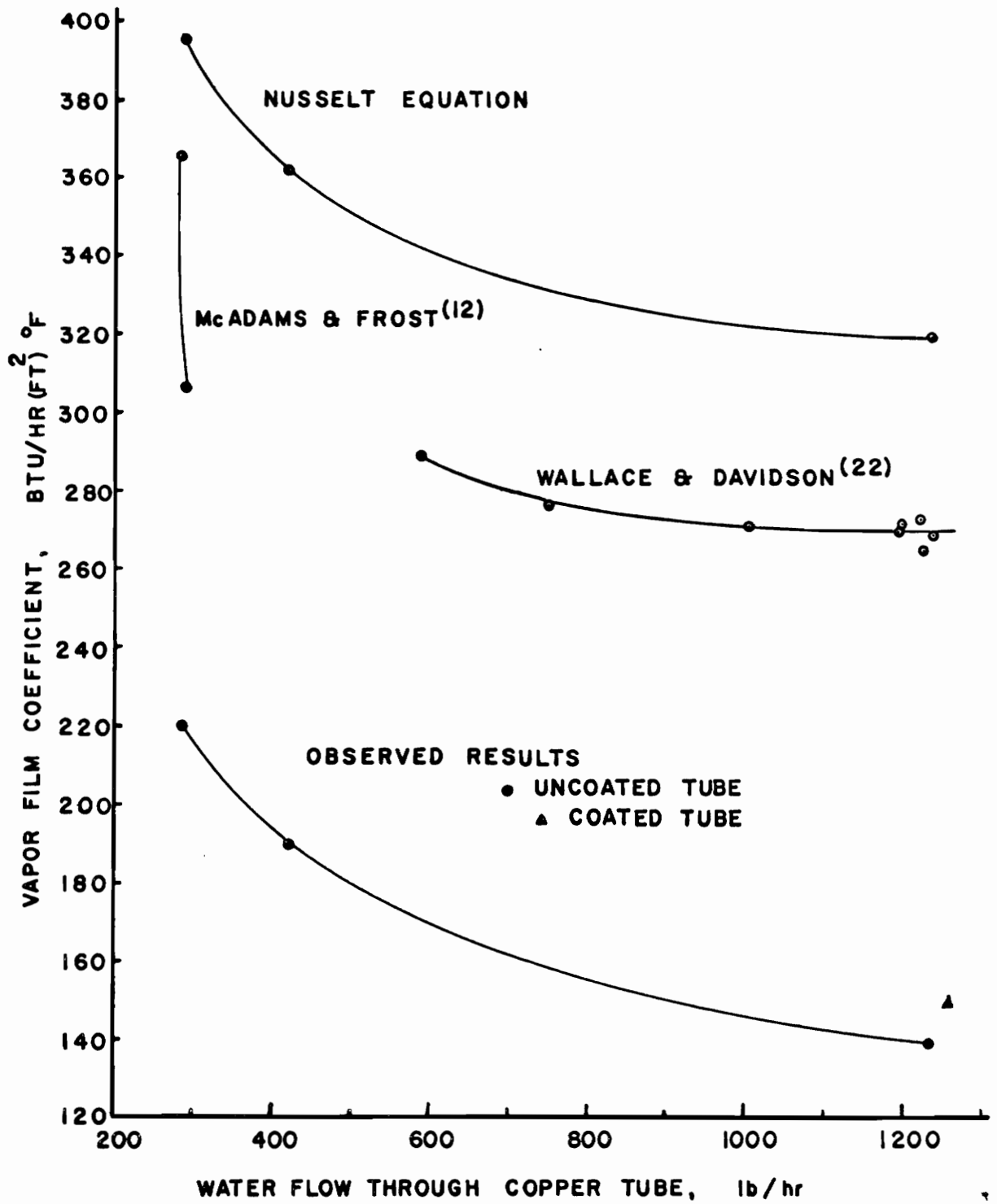


FIGURE 5. VAPOR-SIDE COEFFICIENT VERSUS
WATER FLOW RATE THROUGH THE TUBE

Sample Calculations

Values for the properties of water, benzene, and copper were obtained from Perry's Handbook of Chemical Engineering. An average temperature of 63°F was used to determine all water properties. The equations come from Badger and Banchero.⁽¹⁾

Determination of the Water-Side Coefficient. The water-side heat transfer coefficient was determined, when the Reynolds number was greater than 10,000, by the following equation:

$$h_1 = 0.023 \frac{k_w}{D_1} (Re)^{0.8} \left(\frac{C_w \mu_w}{k_w} \right)^{0.4}$$

where:

h_1 = water-side heat transfer coefficient, Btu/hr(ft²)°F

k_w = thermal conductivity of water, Btu/hr-ft-°F

D_1 = inside diameter of tubing, ft

Re = Reynolds number, dimensionless

C_w = specific heat of water, Btu/lb-°F

μ_w = viscosity of water, lb/hr-ft

Substituting data from Table I, test 3, page 17 and Table III, page 19:

$$h_1 = 0.023 \left[\frac{0.352}{0.0369} \right] [16500]^{0.8} \left[\frac{1(2.66)}{0.352} \right]^{0.4}$$

$$h_1 = 1170 \text{ Btu/hr-ft}^2\text{-°F}$$

If the Reynolds number was between 2100 and 10,000, a graph was needed to find $f(Re)$. The graph used was from Badger and Banchero,⁽¹⁾ page 133. When film resistance is not the controlling

factor, the water to inside tube surface temperature drop is small and the ratio μ_w/μ_{sw} approaches one in the following equation:

$$h_1 = \left(\frac{k_w}{D_1} \right) \left[\frac{\mu_w}{\mu_{sw}} \right]^{0.14} \left[\frac{C_w \mu_w}{k_w} \right]^{0.33} f(Re)$$

where:

μ_{sw} = water viscosity at temperature of inner tube, lb/hr-ft

$f(Re)$ = dimensionless variable obtained from a graph and dependent upon Re .

Substituting data from Table I, test 2, page 17, and assuming that the ratio μ_w/μ_{sw} equals one:

$$h_1 = \left(\frac{0.352}{0.0369} \right) (1)^{0.14} \left[\frac{1(2.66)}{0.352} \right]^{0.33} \quad (23)$$

$$h_1 = 427 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Determination of the Overall Heat Transfer Coefficient. The overall coefficient was based on the outside area of the tube and the determined from the following equation:

$$U_2 = \frac{Q}{A_2 \Delta T}$$

where:

U_2 = overall heat transfer coefficient based on the outside area of the copper tube, Btu/hr-ft²-°F

Q = heat carried from condenser by cooling water, Btu/hr

A_2 = outside surface area of the copper tube, ft².

ΔT = overall temperature difference between vapor & water °F
Substituting data from Table I, test 3, page 17, and Table III, page 19:

$$U_2 = \frac{4950}{(0.391)(113)}$$

$$U_2 = 113 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$$

Determination of Observed Vapor-Side Heat Transfer Coefficient.

Since the overall heat transfer coefficient is the sum of the reciprocals of the individual coefficients, the observed vapor-side coefficient is the reciprocal of the overall coefficient minus the water-side, wall, and--if coated--Teflon coefficients:

$$\frac{1}{h_2} = \frac{1}{U_2} - \frac{A_2}{A_1 h_1} - \frac{L}{k_c} \frac{A_2}{A_m} - \frac{L_T}{k_T}$$

where:

h_2 = observed vapor-side heat transfer coefficient, Btu/hr-ft²-°F

A_1 = inside surface area of copper tube, ft²

L = thickness of copper tube wall, ft

k_c = thermal conductivity of copper, Btu/hr-ft²(°F/ft)

A_m = logarithmic mean surface area of copper tube, ft²

L_T = thickness of Teflon coating, in.

k_T = thermal conductivity of Teflon, Btu/hr-ft²(°F/in)

Substituting data from Table I, test 3, page 17, and Table III, page 19:

$$\frac{1}{h_2} = \frac{1}{113} - \frac{0.391}{(0.348)(1170)} - \frac{0.0023}{223} \frac{0.391}{0.364} - \frac{0}{(0.14)}$$

$$h_2 = 139 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$$

Determination of Vapor to Outside Tube Surface Temperature

Difference. The temperature difference between the benzene vapor in the condenser and the surface of the tube (or Teflon surface) was determined from the ratio of the vapor-side resistance to the total

resistance:

$$\Delta t_v = \Delta T \frac{\frac{1}{h_2}}{\frac{1}{U_2}}$$

where:

Δt_v = temperature difference between the vapor and the tube (or coating) surface, °F.

Substituting data from Table I, test 3, page 17:

$$\Delta t_v = 113 (1/134)/(1/113)$$

$$\Delta t_v = 102^\circ\text{F}$$

Determination of Condensate Film Temperature. The temperature of the film of condensed vapor on the outside of the copper tube was the temperature at which the properties of liquid benzene were calculated for the Nusselt equation. Film temperature was determined by:

$$t_f = t_{sv} - 0.75 (\Delta t_v)$$

where:

t_f = condensate film temperature, °F

t_{sv} = saturated vapor temperature, i.e., temperature of the vapor in the condenser, °F.

Substituting data from Table I, test 3, page 17:

$$t_f = 173 - 0.75 (102)$$

$$t_f = 97.5^\circ\text{F}$$

Determination of the Vapor-Side Heat Transfer Coefficient from the Nusselt Equation. The vapor-side coefficient was also calculated

from the experimentally-derived Nusselt equation for film condensation on a horizontal tube:

$$h_N = 0.725 \left[\frac{k_b^3 \rho_b^2 g \lambda_b}{D_2 \mu_b \Delta t_v} \right]^{0.25}$$

where:

h_N = Nusselt equation value of the vapor-side heat transfer coefficient, Btu/hr-ft²-°F

k_b = thermal conductivity of condensed vapor at t_f ; Btu/hr-ft² (°F/ft)

ρ_b = density of condensate at t_f , lb/ft³

g = 4.18×10^8 ft/hr²

λ_b = latent heat of vaporization of benzene, Btu/lb

μ_b = viscosity of liquid benzene at t_f , lb/hr-ft.

Substituting data from Table III, page 19, and Table I, test 3, page 17:

$$h_N = 0.725 \left[\frac{(9.1 \times 10^{-2})^3 (54.8)^2 (4.18 \times 10^8) (180)}{(0.0417) (1.26) (97.5)} \right]^{0.25}$$

$$h_N = 318 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$$

IV. DISCUSSION

Previous work, procedure, results, and limitations are discussed and analyzed and suggestions for further study are made in this section.

Discussion of Literature

Henderson,^(9,10) Morrison,⁽¹⁵⁾ and Buckles⁽²⁾ determined vapor-side heat transfer coefficients for steam and several organic compounds. All three investigators used the same condenser with a three-foot long vertical copper tube, vapor flow downward, and water flow upward. All three obtained observed coefficients only 20 to 30 per cent of the Nusselt value.

At first, Henderson suggested changing the constant in the Nusselt equation to bring Nusselt values down to his results,⁽⁴⁾ but he later suggested that vapor velocity was the cause of his low observed coefficients.⁽¹⁰⁾ Badger and Banchemo⁽¹⁾ and McAdams,⁽¹⁴⁾ however, state that a downward flow of vapor would decrease condensate film thickness and therefore raise the observed coefficients above the Nusselt values by 30 or 40 per cent, rather than reducing the observed values.

Morrison⁽¹⁵⁾ and Buckles⁽²⁾ advanced the possibility of air in the system, since a noncondensable gas would form a film around

the condensate and lower the rate of heat transfer.⁽¹⁾ Low vapor flow rates were blamed for allowing air to contact the tube.

Since Henderson, Morrison, and Buckles made runs of only 15 minutes duration with no vent to release noncondensable gases, the presence of air in the condenser seems probable. Furthermore, Wallace and Davison,⁽²²⁾ as well as many other investigators, obtained nearly identical observed and Nusselt values with a vented reflux system that allowed longer runs and assured complete flushing of the system.

Musgrave,⁽¹⁶⁾ while working with a horizontal glass heat exchanger at Virginia Polytechnic Institute, noted air bubbles in the cooling water. Low water flow rates enabled a layer of air to form at the top of the tube, reducing heat transfer.

Air, either in the condenser or in the cooling water tube, appears from previous work to be the cause of inconsistent vapor-side heat transfer coefficients.

Discussion of Procedures

The inability of the present secondary condenser to totally condense the vapor made it necessary to keep the vent valve nearly closed, a limitation that made proper flushing of the system with benzene vapor impossible.

A larger secondary condenser, capable of total condensation of excess benzene vapor flowing from the main condenser, should be

installed horizontally with just enough slope to permit the condensed benzene to flow down into a funnel draining into a vertical length of tubing connected to the reflux line returning condensate from the main condenser to the still. Both the secondary condenser and the vertical pipe should be open to the atmosphere to maintain atmospheric pressure in the system and to vent the noncondensable gas.

The above changes should eliminate the evacuation procedure and result in more reasonable heat transfer coefficients. Investigation of Teflon coating effects could then proceed.

Measurements of the tube diameter with a micrometer should be made at 50 or more marked points on the tube before and after coating the tube. Random readings, as was shown, introduced unintentional bias and resulted in a smaller average tube diameter after coating than before coating.

Discussion of Results

Graphs of the Nusselt and observed vapor-side coefficients versus the vapor-side temperature difference and the cooling water flow rate yielded curves for the observed values similar in shape to, but lower than, the Nusselt values. The curves compare favorably with literature values, and the literature values fall close to the Nusselt curve despite the number of variables.

The observed vapor-side coefficients obtained in this invest-

gation were only 44 to 56 per cent of the Nusselt value. Morrison,⁽¹⁵⁾ Henderson,^(9,10) and Buckles⁽²⁾ encountered the same problem when they should have obtained observed values 30 to 40 per cent higher, not lower, than the Nusselt values. The presence of noncondensable gases in the condenser was the most probable cause of the low observed values obtained during this research.

Only one test was made with the tube Teflon-coated, so the objective of this investigation--the study of the effects of Teflon coatings on condensers--was not accomplished. The single coated tube test showed a larger observed vapor-side coefficient than the uncoated tube, but the increase was less than the margin of error.

A difference of one °F in the water temperature rise would mean a change in the observed heat transfer coefficients of nearly 20 per cent.

Recommendations

A total condenser, open to the air and connected to the main condenser at the opposite end from the vapor inlet, should be installed to provide proper venting of the system. This would permit flushing the system with benzene vapor and should remove noncondensable gases from the condenser.

Preheating, to remove air from the cooling water, should be employed if the more effective venting fails to increase the observed heat transfer coefficients.

The study of Teflon-coated tubes should be continued with another type of Teflon. Enralon 323 has a temperature limit, according to the literature, of 150°F (although it withstood 200°F when tested) and is soluble in alcohols, esters, and ketones. The advantages of spray coating with Enralon 323 were reduced by the limitations on usable organic compounds and operating temperatures.

Determination of the thickness of the Teflon coating should be effected by using a punch to mark 50 or more points on the tube and then measuring the diameter of the tube at these points before and after coating the tube. Subtracting the average of these two sets of readings and dividing by two would give the Teflon film thickness.

Limitations

Several of the quantitative variable boundaries were critical enough to affect results, but temperature was the most sensitive.

Temperature. Accuracy to one degree was possible with the potentiometer and interpolation of the emf-temperature tables.

Water Flow. The water was measured in tared pails on scales accurate to the nearest ounce. Timing of the water flow into the bucket was accurate to the nearest 0.02 minute.

Calculations. All calculations were performed on a slide rule, accurate to three significant figures.

V. CONCLUSIONS

The condensation of benzene vapor at atmospheric pressure with a horizontal three-foot length of 0.499 inch outside diameter copper tubing led to the following conclusions:

1. Air, either in the condenser or in the cooling water, decreased the observed vapor-side heat transfer coefficients to values from 44 to 56 per cent of the Nusselt values.
2. Observed vapor-side heat transfer coefficients increased from 44 per cent up to 56 per cent of the Nusselt value as cooling water flow was decreased from 20.63 to 4.78 pounds per minute.
3. Insufficient and incorrect data made it impossible to determine the effect of a Teflon coating on the heat transfer characteristics of the copper tube.

VI. SUMMARY

The condensation of benzene vapor at atmospheric pressure was used to determine the effect of a thin coating of Teflon on the vapor-side heat transfer characteristics of a horizontal copper tube.

The condenser consisted of a three-foot length of 3.5 inch diameter iron pipe containing 0.4999 inch outside diameter copper tubing with 0.028 inch thick walls.

Experiments with the uncoated tube resulted in vapor-side coefficients about half as large as the Nusselt values. Teflon-coated tube coefficients were slightly higher than the uncoated tube results, but were still less than half of the Nusselt values.

From the results and equipment of other investigators, air in the condenser was considered the most probable cause of the low observed vapor-side coefficients. Equipment and procedure modifications were recommended to assure removal of air from the system. A different type of Teflon was recommended to remove temperature and organic vapor limitations.

VII. BIBLIOGRAPHY

1. Badger, W. L. and J. T. Banchero: "Introduction to Chemical Engineering," pp. 117-142. McGraw-Hill Book Company, Inc., New York, N.Y., 1955.
2. Buckles, B. D.: Coefficients of Heat Transfer Between Condensing Alcohol Vapors and a Vertical Copper Tube, pp. 40-46. Unpublished B. Sc. Theses, Library, Va. Poly. Inst., Blacksburg, Va., 1940.
3. Depew, C. A. and R. L. Reisburg: Vapor Condensation of a Horizontal Tube Using Teflon to Promote Dropwise Condensation, Ind. Eng. Chem., Proc. Design Develop., 3, No. 4, 365-9 (1964).
4. Drew, T. B., W. M. Nagle, and W. Q. Smith: The conditions for dropwise condensation of steam, Trans. A.I.Ch.E., 31, 605-621 (1935).
5. Edwards, J. A. and J. S. Doolittle: Tetrafluoroethylene Promoted Dropwise Condensation, Intern. J. Heat Mass Transfer, 8, No. 4, 663-6 (1965).
6. Fitzpatrick, J. P., S. Baum, and W. H. McAdams: Dropwise Condensation of Steam on Vertical Tubes, Trans. A.I.Ch.E., 35, 97-107 (1939)
7. Gilmour, C. H.: Heat Transmission, "Chemical Engineers' Handbook" (J. H. Perry, Editor), pp. 2-33, McGraw-Hill Book Co., Inc., New York, N.Y., 1963. 4 ed.
8. Hampson, H.: Modes of condensation and their effect on heat transfer, Brit. Chem. Eng., 2, 532-5 (1957); C.A., 52, 3425b (1958).
9. Henderson, H. E.: Coefficients of Heat Transfer Between Condensing Alcohol Vapors and a Vertical Copper Tube, pp. 22-29. Unpublished B.Sc. Thesis, Library, Va. Poly. Inst., Blacksburg, Va., (1939).
10. _____: Coefficients of Heat Transfer Between Condensing Organic Vapors and a Vertical Copper Tube, pp. 82-87. Unpublished M.Sc. Thesis, Library, Va. Poly. Inst., Blacksburg, Va., (1940).

11. Kullbert, G. K. and H. B. Kendall: Improve heat transfer coefficients with silicone resin coatings, Chem. Eng. Progress, 56, No. 1. 82-4 (1960).
12. McAdams, W. H. and T. H. Frost: Heat Transfer, Ind. Eng. Chem., 14, 13 (1922).
13. McAdams, W. H.: "Heat Transmission," p.1. McGraw-Hill Book Co., Inc., New York, N. Y., 1942 2nd Edition.
14. *ibid*, pp. 254-293.
15. Morrison, R. H.: Heat Transfer Coefficients Between Condensing Organic Vapors and a Vertical Copper Tube, pp. 38-75. Unpublished M.Sc. Thesis, Library, Va. Poly. Inst., Blacksburg, Va., (1939).
16. Musgrave, J. S.: Heat Transfer Studies on Silicone Coated Tubes, pp. 33-36. Unpublished B.Sc. Thesis, Library, Va. Poly. Inst., Blacksburg, Va., (1956).
17. Nagle, W. M., and T. B. Drew: The Drop-Wise Condensation of Steam, Trans. A.I.Ch.E., 30, 217-55 (1933-34).
18. Nagle, W. M., G. S. Bays, L. M. Blenderman, and T. B. Drew: Heat Transfer Coefficients During Dropwise Condensation of Steam, Trans. A.I.Ch.E., 31, 593-603 (1935).
19. Rhodes, F. H. and K. R. Younder: Rate of Heat Transfer Between Condensing Organic Vapors and a Metal Tube, Ind. Eng. Chem., 27, 957-61 (1935).
20. Selin, G.: Condensation of water vapor in droplets, Dechema Monograph, 40. Nos. 616-41. 149-54 (1962); C. A., 58, 10965e (1962).
21. Topper and Baer: Dropwise Condensation of Vapors and Heat-Transfer Rates, J. Colloid Science, 10, 225-6 (1955).
22. Wallace, J. L. and A. W. Davison: Condensation of Mixed Vapors, Ind. Eng. Chem., 30, 948 (1938).

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IX. VITA

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