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CONDENSATION OF VAPORS
OF
IMMISCIBLE LIQUIDS

by

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SUMMARY

Heat transfer coefficients for condensing vapors of the immiscible systems benzene-water, heptane-water, carbon tetrachloride-water, and methanol-heptane have been determined. The condensing surface used for the studies was a $2\frac{1}{2}$ inch diameter 3 inch long vertical brass cylinder. Correlations for these coefficients have been made by modifications of Nusselt's theory²¹, applied to separate condensation mechanisms.

Three types of condensation were noted:

1. film-drop
2. film-lens
3. channeling

The first two mechanisms may be described as film condensation for the wetting component, while the second component forms drops or lenses. Channeling condensation consists of the formation of separate films by each component. A theory based on the concept of the spreading coefficient is proposed as an explanation for these condensation mechanisms.

INTRODUCTION

In a system of two immiscible liquids, each component will vaporize and exert its own vapor pressure independently of the other component. Assuming Dalton's law of additive pressures, the total equilibrium pressure is simply the sum of the vapor pressures of the individual components at the temperature of the system. Boiling must occur at a temperature lower than that of the normal boiling point of either component at the system pressure. This is, of course, the principle of steam distillation. A typical temperature-composition diagram for a system of two immiscible liquids is shown in Fig. 1.

In a three-phase two-component system (liquid A, Liquid B, and vapor) the pressure fixes the temperature T_E , called the eutectic temperature. This equilibrium temperature as well as equilibrium vapor composition may be computed from pure component vapor pressure data. Hence, as long as two components are present in separate liquid phases on the condenser surface and are in equilibrium with the bulk vapor, the interface temperature is the eutectic temperature. If both liquid phases are present on the condenser surface, the temperature drop across the liquid film can be taken as the difference in the eutectic temperature and the solid surface temperature. Thus the following equation

Fig. 1 - Temperature-Composition Diagram for an Immiscible Liquid System

gives the heat transfer coefficient:

$$h = \frac{q}{T_E - T_S} \quad (1)$$

Studies of immiscible condensation have been made by Kolb and Weeks¹⁶; Weeks²⁶; Cooper, Morrison and Henderson⁶; Kirkbride¹⁵; Patton and Feagan²³; Patterson, Weiland, Reeburgh, Huntington, and King²²; Baker and others^{2,3,4}; Edwards, Bonilla, and Cichelli⁸; and Tobias and Stoppel²⁵. Each chose water as one component, while second components have included benzene^{2,3,4,15,25,26}, toluene^{2,3,4,25,26}, trichloroethylene^{3,4,16,26}, chlorobenzene^{2,4}, heptane^{3,22,25}, carbon tetrachloride²⁵, cyclohexane²⁵, butyl acetate⁶, naphtha¹⁵, styrene⁸, butadiene⁸, and turpentine²³. Both vertical and horizontal tubes of a variety of sizes have been used. Kirkbride¹⁵ was the first to use the eutectic temperature difference. He suggested the following equation for heat transfer coefficients:

$$h_m = \frac{h_{NuA} q_A + h_{NuB} q_B}{q_A + q_B} \quad (2)$$

He stated that dropwise condensation might complicate the problem, since the film coefficients of both pure components would not be effective in determining the average coefficient. However, he made no observations of the condensation mechanism.

Baker and coworkers^{2,3,4} used horizontal and vertical tubes of different sizes on which the mechanism could be observed through glass windows. They reported various types of mechanisms to occur: filming, channeling, dropwise and combinations. Hazelton and Baker² proposed a Nusselt²¹-type equation, assuming adjacent films of the two components and negligible dropwise condensation.

$$h'_m = n_A h_A^* + n_B h_B^* \quad (3)$$

In the case where only one component wet the surface, $h_A=0$, and

$$h'_m = 0.943 \left[\frac{k_B^3 \rho_B^2 (a \lambda_A + b \lambda_B) g}{\mu_B L b (T_E - T_S)} \right]^{1/4} \quad (4)$$

This equation was not verified experimentally, but the investigators gave the following empirical equations, found to hold reasonably well for mixtures of benzene, toluene, and chlorobenzene with water at atmospheric pressure:

$$h_m = C \left[\frac{a \lambda_A + b \lambda_B}{b S} \right]^{1/4} \quad (5)$$

A more recent investigation by Edwards, Bonilla, and Cichelli⁸ revealed that equation (5) gave results fairly close for styrene-water and farther off (50%) with butadiene-water. The condensation mechanism was not observed in their

work.

In an attempt to include physical properties of the components, Tobias and Stoppel²⁵ formulated the following semi-empirical equation:

$$h_m = \frac{h'_m}{1 - \frac{1}{545} \left[\frac{(\Delta T^3 \Delta P)}{M_A^4 g} \left(\frac{a \rho_A k_A}{b \rho_B k_B} \right)^{1/2} \right]^{.21}} \quad (6)$$

This equation proved adequate for heptane, benzene, and toluene with water, but was unsatisfactory for carbon tetrachloride and cyclohexane with water. These workers, who took data at atmospheric pressure, mention only dropwise condensation of water on an organic film. The equation they offer is complicated and does not apply generally, but only for specific systems. In addition, the accuracy is no better than the simpler equations (2) and (5).

Preliminary efforts were made by Baker and Mueller³ to show the relationship between h and $T_E - T_S$ as given by Nusselt's pure component equation, i.e., h varies inversely as the one-fourth root of $T_E - T_S$. These and later investigators^{2,4} have shown that this relationship is not followed by immiscible liquids in general. In fact, for some systems, the trend is in the opposite direction. Mueller used this as a basis for repudiating Kirkbride's equation (2), which predicts a decrease in h with increasing $T_E - T_S$.

The studies of the condensation mechanism itself have

been meager. No more than limited observations were made by these workers^{2,3,4,25}, who hinted that mechanism may be a variable to consider.

EXPERIMENTAL APPARATUS AND PROCEDURE

The apparatus used consisted of a main condenser machined from a solid brass cylinder, $2\frac{1}{2}$ inches in diameter and 3 inches long. A Dewar flask, 7 inches inside diameter and 15 inches deep, enclosed the condenser. A brass plate covering Bakelite insulation which fit into the flask was placed on the top of the Dewar. Each piece of equipment within the flask was fastened directly or indirectly to the top plate. Rubber covered with a Teflon sleeve was used as a sealing gasket between the flask and the brass plate.

Liquids were introduced by means of a copper tube through the plate to the bottom of the flask, heated by an immersion heater, and vaporized. Most of the vapors were condensed on the brass condenser surface. Condensate flowed down through a funnel into a sample burette. A valve for directing condensate flow was controlled externally.

The system pressure was measured with a mercury manometer connected by a copper tube tapped into the brass plate. Condensate was measured volumetrically. Temperatures were measured by copper-constantan thermocouples with a precision potentiometer using an ice-point reference junction. Two thermocouples were inserted longitudinally into the condenser, $\frac{3}{16}$ inch from the surface, 180° apart and at different depths.

FIG. 2 -SCHEMATIC OF EXPERIMENTAL APPARATUS

Thermocouples were placed in the boiling liquids and in the vapor phase near the condenser surface. Also thermocouples were used to measure cooling water temperatures. Cooling water temperatures were controlled by means of a constant temperature bath. Flow rates for the cooling water were determined with a rotameter. Heater current was measured with an ammeter. Vapor from the system could be removed either continuously or at specific intervals by a water ejector system. This was necessary to eliminate air from the system under certain operating conditions.

Most of the previous researchers used apparatus in which vapors were generated separately, mixed in a chamber, and sent to a condenser to be partially condensed at atmospheric pressure. The eutectic temperature for a given system is solely a function of the pressure at the condenser surface. Hence, the apparatus used by the author offers a distinct advantage in controlling the vapor temperature by means of system pressure control. This is effected by the control of heater power input, surface temperature, and vapor take-off. However, the vapor composition could not be directly controlled for a given system. Vapors of approximately eutectic composition were usually generated in the apparatus. Since this is the most frequently encountered case, the lack of vapor composition control is not a serious detriment. Temperature of the vapor as determined by the thermocouple was compared with the calculated eutectic tem-

perature to show deviations from eutectic composition. Frequently this temperature difference amounted to 10-20°F.

Except in the case of a fogged flask, the entire condensing surface could be viewed. Condensation mechanisms were examined visibly for all experimental runs. Notes on the mechanism and other observations were recorded during runs. Several photographs of the condensing surface were made during different operating conditions and for each system.

Various procedures were followed in studying surface wetting and condensation mechanisms. Several runs for each system were conducted in which components were introduced simultaneously. This allowed components an equal chance to wet the newly polished brass surface. A second method was to introduce only one component at the start and to allow thorough wetting of the surface to take place. After condensing this component for a few hours, the second component was added, giving immiscible condensation. Comparisons of heat transfer rates and mechanisms were made for these different procedures.

The total heat transferred by the condenser was determined from the cooling water rate and temperature difference. The surface temperature was taken as the average of the two thermocouple readings, corrected for the drop across 3/16 inch brass at the known heat flux. From these

data, along with known surface area and the calculated vapor-liquid interface temperature, the heat transfer coefficient was determined.

All physical property data used in this investigation were taken from reliable sources^{11,13,17,24}, and checked wherever possible.

Overall accuracy of the heat transfer coefficients is probably within 10 per cent. Temperature measurements are accurate to 0.05 degrees. Accuracy of water flow rate determinations is 5 per cent, and pressure determinations are accurate to within 0.1 in. Hg. Total heat transferred as measured by the cooling water checked that obtained from electrical power input to within 10 per cent during closed system operation. Condensate compositions were reproducible to within about 1 weight per cent.

THEORY

Heat Transfer Coefficients for Condensing Vapors of Immiscible Liquids

Nusselt²¹ derived the following equivalent equations for predicting heat transfer coefficients for the case of a single pure component in laminar film flow on vertical tubes:

$$h_m = 0.925 \left[\frac{k^3 e^2 g}{\mu \Gamma} \right]^{1/3} \quad (7)$$

$$h_m = 0.943 \left[\frac{k^3 e^2 g \lambda}{\mu L \Delta T} \right]^{1/4} \quad (8)$$

No present theory or modification of Nusselt's equations has been generally successful in accounting for the important influence of condensation mechanism on heat transfer coefficients.

Nusselt's equations predict the following relations:

1. h varies inversely with $(\Delta T)^{1/4}$
2. h varies inversely with $(\Gamma)^{1/3}$
3. q varies directly with $(\Delta T)^{3/4}$
4. q varies directly with $(L)^{3/4}$

For given immiscible components with a stable condensation mechanism, relationships between these variables should exist, though not necessarily the exact proportionalities given. Deviations result from changing mechanisms, i.e., drop forming,

turbulence, and other film-disturbing factors.

Mechanism of Immiscible Liquid Condensation

A single component condenses either as a film which completely wets the surface, or by the formation of droplets, which grow until the influence of gravity causes them to roll from the surface. Frequently combinations of the two mechanisms occur. Nearly all condensation is of the film type, because of complete wettability of condensing surfaces by most liquids. Theories of drop-wise condensation have been developed by Eucken¹⁰ and Emmons⁹.

Emmons studied promoter effects on dropwise condensation, concluding that a monomolecular layer of the promoter is responsible for the phenomenon. From a free energy consideration of the interfaces between vapor, liquid, and solid, Emmons derives the following equations for the spreading tension:

$$Z = \gamma_{sg} - \gamma_{sf} - \gamma_{fg} \quad (9)$$

$$Z = \gamma_{fg} (\cos \theta - 1) \quad (10)$$

The necessary condition for film condensation of a pure component on a solid is $Z > 0$. For dropwise condensation, the necessary condition is $Z < 0$. This condition is not sufficient to insure dropwise mechanism. If a newly formed drop of liquid

grows and merges with another drop so slowly that other drops combine with them on all sides, film formation results. Therefore, conditions favoring dropwise condensation, in addition to $Z < 0$, are:

1. Low rate of condensation.
2. Low condensate viscosity.
3. Smoothness of surface.

From these ideas, Emmons recommends using substances to promote dropwise condensation by so altering the cooling surface properties to the extent that $Z < 0$. Since condenser tube metals will not effect this change, thin layers of substances which have a high affinity for the metal and a low affinity for the vapor must be used to cover the condenser with a monomolecular layer.

Emmons gives data on the effectiveness of several promoters for dropwise condensation of steam on several different surfaces. Nagle and Drew²⁰, Nagle, Bays, Blenderman and Drew¹⁹, Drew, Nagle, and Smith⁷ have made excellent reports of their work with promoter effects and surface effects on steam condensation.

In the case of two liquid phases on the condenser surface, several different mechanisms are possible. They may be broken down into the following and combinations of the following:

1. film-film
2. film-drop
3. drop-drop

The causes of these mechanisms may be explained in a fashion similar to that for pure components. The third type, drop-drop, would be expected to occur in the case of two immiscible liquids with negative spreading tensions and favorable conditions as previously stated. This mechanism has never been reported and is extremely unlikely because of the difficulty of obtaining liquids with negative spreading tensions.

Film-film and film-drop mechanisms may be understood by the introduction of the concept of a spreading coefficient. Harkins and Feldman¹² define the spreading coefficient of liquid A on liquid B as the difference between the work of adhesion and the work of cohesion. From thermodynamic and free energy considerations, this may be shown to be equivalent to the following relation:

$$S_{AB} = \gamma_B - \gamma_A - \gamma_{AB} \quad (11)$$

A positive coefficient corresponds to spreading, and a negative coefficient corresponds to non-spreading.

Now in the cases being considered, film condensation is assumed for one component, in which case the second component may form either drops or a film. The necessary condition for drop formation by liquid B is a negative spreading coefficient.

Conditions similar to those given by Emmons, along with $S > 0$, would favor film-drop condensation. On the other hand, a positive coefficient would indicate that film-film condensation should occur.

If the coefficient for liquid A to spread on liquid B is positive, then it is seen that the coefficient for B to spread on A is negative. Therefore, A cannot spread on B if B spreads on A.

The importance of mechanism influence on heat transfer should be strongly emphasized. It is well known that dropwise condensation of a single component gives very high rates of heat transfer in comparison with laminar film condensation. This is not generally true for immiscible liquids. Suppose component B wets the metal surface and forms a film. The effect of component A will depend on the mechanism. If drops of A are formed on B, then the film resistance of B remains essentially unchanged. However, if A forms a film, but does not wet the metal itself, the film will be on a monomolecular or thin layer of component B. In this case, the effect is that of adjacent films of A and B. Clearly if A (e.g., water) has a large thermal conductivity compared to B (e.g., organic), the overall heat transfer will be increased by the film-film or channeling mechanism.

Vapor-Liquid Interface Temperature

For the calculation of heat transfer coefficients, the vapor-liquid interface temperature must be known.

Consider a very small region on a condenser surface on which immiscible liquid phases are present. The liquid of only one component may occupy this area, in which case the vapor pressure of the second component may not be effective. It is possible for the vapor-liquid interface temperature to be very near the saturation temperature of the first component in this region. There is no assurance that the eutectic or three phase equilibrium temperature is the true interface temperature. However, in no case shall the interface temperature be lower than the eutectic temperature or higher than the pure component saturation temperature.

When saturated vapors of non-eutectic composition are encountered, the vapor temperature may be considerably higher than either the eutectic or true interface temperature. This results in a somewhat greater heat transfer driving force, corresponding to supersaturation. However, if two liquid phases are present at the interface, the total temperature drop across the liquid can be computed using the eutectic temperature without appreciable error.

RESULTS

Approximately 120 experimental runs were made on four immiscible systems: benzene-water; heptane-water; carbon tetrachloride-water; and methanol-heptane. The mechanism of condensation was observed and studied for all systems under different conditions. The channeling mechanism gives higher heat transfer coefficients than film-drop or film-lens mechanisms. No drop-drop mechanism was observed during the experiments. There were marked differences in the results for each system.

The benzene-water system condensed primarily by the film-drop mechanism, with coefficients ranging from 265 to 865 Btu/hr-ft²-°F. Heptane and water condensed by film-drop, film-lens, and channeling mechanisms, while the coefficients for this system were in the range 162 to 1800 Btu/hr-ft²-°F. Carbon tetrachloride condensed by film-drop and channeling mechanisms, and coefficients varied from 293 to 1810 Btu/hr-ft²-°F. The only non-water system studied, methanol-heptane, condensed by the film-lens mechanism. Coefficients for the system were from 440 to 860 Btu/hr-ft²-°F.

Differences between vapor and condensate compositions are estimated to be less than 5 per cent for most runs. Condensate compositions ranged as follows: benzene-water - 2.4 to 27.7 wt.% water; heptane-water - 0 to 25.8 wt.% water;

carbon tetrachloride-water - 2.6 to 28.6 wt.% water; methanol-heptane - 62.3 to 66.8 wt.% methanol. For about one-half the experimental runs, condensate compositions were within 2 weight per cent of the eutectic compositions.

Plots of some of the data are shown in the following figures. Coefficients for the heptane-water system generally increased with $T_E - T_S$, while the carbon tetrachloride-water, benzene-water, and methanol-heptane systems gave coefficients which decreased with $T_E - T_S$. Cooling surface temperatures were varied from about 80°F to 165°F. Absolute pressures ranged from 8 in. Hg to 35 in.Hg.

Fig. 3 - Benzene-Water System Data at Two
Surface Temperatures.
Surface Area - 0.16618 ft²

Fig. 4 - Heptane-Water System Data at Three Surface Temperatures

Surface Area - 0.16618 ft²

Fig. 5 - Carbon Tetrachloride-Water System
Data at Two Surface Temperatures

Surface Area - 0.16618 ft²

Fig. 6 - Methanol-Heptane System Data at
Two Surface Temperatures

Surface Area - 0.16618 ft²

DISCUSSION OF RESULTS

Observed Mechanisms and Effects

Heat transfer coefficients for immiscible liquid systems depend on, first, the components of the system; second, the particular conditions for operation; third, the physical apparatus; and fourth, the condensation mechanism. Frequently, the last factor has the most important influence.

Channeling mechanisms usually give higher coefficients than film-drop mechanisms. With the exception of runs made with very low heat fluxes, the film-film mechanism for organic-water systems did not consist of smooth well-defined films, but very irregular channels of liquid. Usually within these channels, tiny droplets of one component were carried down in the stream of the other. Occasionally wavy strips of liquid would "peel" off the condenser. The resistance to heat transfer for this type mechanism must depend on the physical properties of both condensing components.

At very low heat fluxes, a film-film mechanism of an entirely different nature was found to occur for certain systems. The non-wetting component spread on top of the film of the wetting component, usually forming a lens. These were carried down the condenser surface with the film. This lens formation results in a blanketing effect and very little disturbance of the main film. Coefficients for this mechanism,

obtained with all systems except benzene-water, closely follow the Nusselt relations, using the average physical properties of the two phases. In all cases these coefficients were found to be significantly lower than coefficients for channeling condensation.

The film-drop mechanism usually gives coefficients similar to those in the case of film condensation of the wetting component. Frequently, however, disturbances of the film from formation and falling of drops are such to appreciably alter coefficients.

Figure 7 illustrates condensation mechanisms of each type. Comparisons may be made for the different systems.

Correlation of Data

As a result of the prevailing effects of mechanism over conventional physical properties, a single theoretical equation to accurately predict heat transfer coefficients for condensation of vapors of immiscible liquids is unavailable for the general case. However, by separating coefficients according to condensation mechanism, correlations may be made for each case.

For coefficients for film-drop and film-lens condensation, a correlation by modifications of equation (7) would be expected to result in reasonable accuracy.

Fig. 7 - Comparison of Condensation Mechanisms

CARBON TETRACHLORIDE - WATER

film-drop

channeling

HEPTANE - WATER

film-drop

film-lens

channeling

METHANOL - HEPTANE

film-lens

BENZENE - WATER

film-drop

In the case of film-drop condensation and low (less than 15-20%) drop-forming component compositions, physical properties of the film may be taken as those of the wetting component. The Reynolds number should be based on total condensate flow Γ to account for the slight increase in resistance to heat transfer caused by the drop-forming component.

$$\frac{h}{\left(\frac{k^3 \rho^2 g}{\mu^2}\right)_M}^{1/3} = \left(4 \Gamma / \mu\right)_M^{-1/3} \quad (12)$$

Similarly for the film-lens condensation, the Reynolds number should be based on the total mass flow. However, correlations are improved for this case by using an average of the physical properties of both components for those of the film. This average is based on weight per cent in the condensate.

Figure 8 shows data from this investigation correlated in the manner described. Data for the methanol-heptane system are seen to be very near the theoretical line. Scattering is somewhat increased for the other systems shown, but overall agreement is good.

Figure 9 is the same type plot for the heptane-water system for film-drop condensation. Water drops were observed to remain stagnant on the surface for runs with low Reynolds numbers. Condensate for these runs contained unusually low

water content. Apparently the water drops blanketed the surface to the extent of retarding the heat transfer rate. Runs with higher Reynolds numbers showed considerably more water in the condensate and coefficients significantly greater than for the case of pure heptane. Water drops were observed to fall freely over the surface in these instances. This disturbing effect on the film is the only explanation offered for the increasing coefficients with increasing Reynolds numbers. No valid reason for this effect being peculiar to the heptane-water system has been found.

Under certain conditions, the water-organic systems condensed by means of the channeling mechanism. This mechanism was found to be very irregular for these systems. In no case were smooth adjacent films of each component observed. However, this mechanism is best understood theoretically by assuming condensation of each component to occur independently of the other. From this assumption, the coefficients may be estimated by weighting the pure component Nusselt coefficients according to the amount of heat transferred by each. This relation is given by:

$$h = \frac{a\lambda_A h_{NuA} + b\lambda_B h_{NuB}}{a\lambda_A + b\lambda_B} \quad (13)$$

Figure 10 is a plot of coefficients for channeling condensation versus the coefficient calculated by equation (13). All predicted values exceed the experimental coefficients, except for Run No. 149.

Comparisons of data from other investigations have been attempted. Only Baker and Hazelton² have fully described the condensation mechanism observed in their work. However, their data is in the range of Reynolds numbers of 100-1000, as is the data of Tobias and Stoppel²⁵, who do not adequately describe observed mechanisms. Figure 11 shows some of their data, correlated by equation (12). These investigators used system compositions of much higher water weight per cent than the eutectic composition. Therefore, average values of the physical properties of both components were used for this plot. Agreement for these data with equation (12) is fair.

The basis for each of these correlations is theoretically justified. However, the author warns against their use in the case of very high water content and Reynolds numbers outside the range of experimental data. Predictions from equation (12) may be off considerably in either of these cases, but should always be on the conservative side.

FIG. 8 — CORRELATION OF HEAT TRANSFER COEFFICIENTS

Fig. 9 - Heat Transfer Coefficients for
Heptane-Water System Condensing
by Film-Drop Mechanism

Fig. 10 - Heat Transfer Coefficients for Systems Condensing by Channeling

Fig. 11 - Data for Benzene-Water System from Other Sources

Mechanism and Spreading Coefficients

In this research, as well as that of others, it was found that in organic-water systems, the organic component always wet the metal surface of the condenser. Pure steam will wet clean brass and form a film when condensing, but slight impurities cause drop formation. On the contrary, for all practical purposes, no organic liquids form drops on brass surfaces. The surface tension of water is about twice that of most organic liquids. Therefore, the organic liquid would normally be expected to wet the surface in water-organic systems. In general, in immiscible systems, the component having the lower surface tension will probably wet the surface after steady state has been attained.

Water condensate is formed in one of three ways in the water-organic systems:

1. drops
2. lenses
3. channels

No theory to explain and predict these different types of condensation has been proposed.

Data for spreading coefficients at 20°C have been given by Harkins and Feldman¹²:

Table I. Spreading Coefficients

Substance	S_{BA} (organic on water)	S_{AB} (water on organic)
Benzene	8.9	-79.1
Heptane	1.8	-90.2
Carbon tetrachloride	1.06	-104.9

From the theory of spreading, these spreading coefficients indicate that the organic liquids will spread on water at 20°C. Hence water cannot spread on the organic liquids. The magnitude of the negative spreading coefficients of water on organic liquids means that in no case does spreading to a monomolecular layer or even thin layers of water occur. Harkins and Feldman confirmed this on 18 organic liquids tested with water. Therefore, the spreading coefficient of water on organics, S_{AB} , cannot be used to explain the condensation mechanisms observed.

Harkins and Feldman further describe the form of water on immiscible organic liquids. They state that on organics which spread on water ($S_{BA} > 0$), a spherical drop of water forms, with the organic liquid rising as it approaches the sphere and spreading as a very thin film on the surface. On organic liquids which are non-spreading ($S_{BA} < 0$) on water, water forms lenses on the surface. The surface of the organic falls as it meets the water lens.

It is proposed to use these ideas as a basis for explaining the various condensation mechanisms. Spreading coefficients for organic liquids on water (S_{BA}) rather than coefficients for water on organic liquids (S_{AB}) may be used as a criterion for determining mechanisms. For $S_{BA} \gg 0$, dropwise condensation would be favored. For $S_{BA} \ll 0$, either film-lens or channeling condensation would be probable. In the case of spreading coefficients near zero, a combination of mechanisms may be expected. Channeling would be prevalent at very high rates of condensation, because of the combination of lenses or drops to form channels. Film-drop condensation would be favored by the same conditions given in the Theory for pure components.

Spreading coefficients given in Table I and experimental observations tend to support the spreading theory proposed. The benzene-water system condensed almost entirely by a film-drop mechanism. However, the carbon tetrachloride-water and heptane-water systems condensed by a variety of mechanisms, with channeling prevalent at high heat fluxes. No spreading coefficient data for the heptane-methanol system could be obtained.

Considerable research is needed to fully explain the effect of the spreading coefficient on condensation mechanism. Of special interest would be the influence of such variables as temperature and impurities on spreading coefficients.

Other Comments

Attempts were made to determine the time necessary for the apparatus to reach steady state conditions. Provided the condensation mechanism was stable, steady state operating conditions were attained within a very few minutes. However, mechanism changes occurred in some cases for several hours.

Continuous test runs were performed in the following manner. Beginning with a clean surface, pure water was condensed for about two hours. Benzene was introduced, the apparatus was set at constant heater input and cooling surface temperature, and coefficients were measured at frequent intervals. The two-phase coefficient at the beginning of the run was 1030 Btu/hr-ft²-°F. After 5 hours, the coefficient dropped to 585. After 36 hours, the coefficient had risen to 695. Following this run, the brass surface was repolished. Both components were introduced and data were taken at the same operating conditions as in the previous run. At the start, the coefficient was 322; after 5 hours, 605; after 12 hours, 700; after 30 hours, 640. Coefficients were not continuous in approaching a steady state, but oscillated widely on some occasions. Definite trends were present, however, and indications were that less than 24 hours was required to attain a steady mechanism.

A 90 hour continuous run was made with the heptane-water system, in which combinations of all mechanisms were

observed. Surface temperatures above 130°F resulted in channeling with heat inputs greater than 1200 Btu/hr, even after 24 hours of operation. Increasing the temperature to 160°F made channeling more predominant. Surface temperatures of 120°F and less resulted in film-drop condensation. Also scattered channeling occurred in some cases.

For steady state runs with the benzene water system, film-drop condensation was predominant. Heavy channeling was observed on three occasions with this system, however. Heat inputs were very high and the surface temperatures were about 140°F in these cases. The heat transfer coefficient of 865 Btu/hr-ft²-°F obtained for Run No. 84 was the highest observed for the system under steady state operation.

Considerable corrosion of the brass condenser surface occurred when water was present in the apparatus. Dark etched sections were formed after only two hours service with distilled water. In the presence of organic liquids, the action of the water was considerably slowed, and in some cases stopped completely. In no case did corrosion occur with a pure organic system. The condenser surface was sanded with rather coarse emery cloth to give a bright yellow but scratchy surface at the beginning of each series of runs. Then the surface was washed with hot water containing detergent and wiped dry with a soft clean cloth.

It was noticed in previous work that high coefficients were generally accompanied by rather large differences between the true vapor temperatures and the eutectic temperatures. This suggested that a basis other than the eutectic temperature be used to calculate heat transfer coefficients. The additional thermal potential present had been disregarded. The vapor temperatures and the effective temperatures were used in attempts to account for this added driving potential. No appreciable improvements in correlations emanated from this consideration. Thus, the idea was discarded, and coefficients were based on the eutectic temperature.

An effort was made to explain heat transfer rates in terms of diffusion. When a mass of saturated vapor of eutectic composition approaches the cooling surface, there should be no more resistance to mass transfer than in the case of the pure vapors. The vapor simply moves to the surface by a pressure gradient and condenses at the eutectic composition. However, with a saturated vapor of non-eutectic composition, the rich component supposedly must be condensed from the vapor before the second component may be condensed at the eutectic composition. This composition gradient could result in diffusion controlling the condensation rate, somewhat similar to condensation in the presence of a non-condensable gas. Experimental data did not confirm this. The expected decrease in heat transfer with increasingly non-eutectic vapor compositions was not

detected. This result lends evidence to the idea that condensation occurs with the vapor-liquid interface at non-eutectic temperatures and compositions. Vapors of each component may be in almost pure state very near the liquid phase of the component. This is in accord with re-evaporation theories derived from kinetic theory^{9,10}. However, it may be that diffusion is present and simply negligible as a rate controlling step.

DISCUSSION OF PREDICTIONS FOR OTHER SYSTEMS

Heat Transfer Coefficients

A limited number of immiscible liquid systems have been used in condensing heat transfer research. Experimental data of the author and of previous investigations discussed in the Introduction may be used for estimates of heat transfer coefficients for these particular systems. Need for coefficients for systems where no experimental data exist presents a difficult problem, however. Several generalities may be presented which may be used as guides in these cases.

This research indicates that heat transfer rates are determined to considerable extent by mechanisms of condensation. For the case of film-drop and film-lens condensation, the modified Nusselt equation (12) may be used for systems not studied experimentally. For organic-water systems which condense in this manner, heat transfer coefficients may be expected to range from about 300 to 600 Btu/hr-ft²-°F.

Coefficients for systems condensing by a channeling mechanism may be approximated by Equation (13). This equation gave results about 15 per cent high for the organic-water systems studied in this research. Channeling condensation for organic-water systems may be expected to give coefficients in the range 700-1800 Btu/hr-ft²-°F.

Condensation Mechanism

A prerequisite to predicting a heat transfer coefficient for a system is some knowledge of the condensing mechanism. The proposed method for predicting this mechanism depends on surface tensions and interfacial tensions of the liquid on the condenser. From these properties, the spreading coefficient of the organic component on water may be calculated:

$$S_{BA} = \gamma_A - \gamma_B - \gamma_{AB} \quad (14)$$

For S_{BA} negative, a film-lens or a channeling mechanism would be expected to predominate. For S_{BA} positive, a film-drop mechanism may be expected. For S_{BA} near zero, condensation by a combination of mechanisms may occur. Channeling mechanism would be favored by very high condensing rates.

Selected data have been used to prepare Table II in which spreading coefficients for certain immiscible systems are given. In addition, several general statements may be made on the basis of Harkins and Feldman's¹² research.

Normal paraffins have spreading coefficients near zero. Negative coefficients seem to accompany the presence of =S groups or =CS groups as substituents in paraffins and aromatics. Halogens, especially iodine and bromine, in organic compounds tend to give negative coefficients. At least two chlorine atoms in a molecule are necessary to give negative coefficients. Very polar molecules in compounds usually result in positive spreading coefficients.

TABLE II. Spreading Coefficients for
Substances on Water at 68°F

Substance	S_{BA} dynes/cm
Ether	45.5
2-Octanol	36.7
Enanthic Acid	37.1
i-Butyl Chloride	26.4
Ethyl Caproate	25.8
Ethyl Mercaptan	24.9
Trimethyl-ethylene	18.9
Ethyl Bromide	17.4
Benzaldehyde	17.3
Phenetole	10.7
Benzene	8.9
Toluene	6.8
Xylenes	6.7
Ethyl Benzene	5.6
Trichloroethylene	5.1
Nitrobenzene	3.8
Hexane	3.4
Chlorobenzene	2.3
Heptane	1.8
Octane	0.22
Carbon Tetrachloride	1.06
Bromobenzene	-3.3
Ethylenedibromide	-3.2
Perchloroethylene	-6.4
Carbon Disulfide	-6.9
Bromonaphthalene	-13.9
Cyclohexane	-(?)

CONCLUSIONS

1. By grouping heat transfer coefficients according to the condensing mechanism of the immiscible components, correlations may be made by modifying Nusselt's theory²¹. However, no single equation has been found to give accurate predictions for coefficients of immiscible systems in general.

2. Three distinct condensation mechanisms have been observed. Assuming component B wets the condenser surface, the second component A may condense by the formation of drops on the film of component B. This is called film-drop condensation. Under certain conditions, component A may condense as liquid lenses on the film of the wetting component. This mechanism is called film-lens condensation. Occasionally condensation by a channeling mechanism has been noted. In this case, each component condenses on its own film. These films appear as channels, flowing down the condenser in an erratic path. Heat transfer rates for the latter mechanism considerably exceed those for film-drop and film-lens mechanisms.

3. Channeling condensation mechanisms are probable in the case of large negative spreading coefficients. Systems with large spreading coefficients may be expected to condense by a film-drop mechanism.

NOMENCLATURE

- A - Refers to a component, usually water.
- a - Wt. % of component A in condensate.
- B - Refers to a component, usually organic.
- b - Wt. % of component B in condensate.
- C - Constant for Equation (5).
For vertical tubes, $C = 79$.
For horizontal tubes, $C = 61$.
- D - From Equation (5), for
Vertical tubes, $D =$ tube length, ft.
Horizontal tubes, $D =$ tube diameter, ft.
- g - Acceleration of gravity, 4.17×10^8 ft/hr².
- h - Heat transfer coefficient, Btu/hr-ft²-°F.
- h_m - Mean heat transfer coefficient, Btu/hr-ft²-°F.
- h'_m - Heat transfer coefficient defined by Equations (3) and (4).
- h_{Nu} - Heat transfer coefficient defined by Equation (10).
- h^* - Heat transfer coefficient used in Equation (3) defined by
- $$h_A^* = 0.943 \left[\frac{k_A^3 e_A^2 g}{\mu_A L (T_E - T_s)} \left(\frac{q_A}{q_A + q_B} \right) \left(\frac{a \lambda_A + b \lambda_B}{a} \right) \right]^{1/4}$$
- k - Thermal conductivity, Btu/hr-ft-°F.
- L - Length of condenser, ft.
- n_A, n_B - Fraction of surface wet by components A and B, respectively.
- P - Absolute pressure, in. Hg.

Q	-	Heat transfer rate, Btu/hr.
q	-	Heat flux, Btu/hr-ft ² .
Re	-	Reynolds number, $4\Gamma/\mu$, dimensionless.
S_{AB}	-	Spreading coefficient for liquid A on liquid B, dynes/cm.
T	-	Temperature, °F.
T_1, T_2	-	Wall temperatures given by thermocouples at two locations in condenser wall, °F.
T_E	-	Eutectic temperature, at which the sum of the pure component vapor pressures equals the total system pressure, °F.
T_L	-	Liquid temperature, °F.
T_S	-	Surface temperature, °F.
T_V	-	Vapor temperature, °F.
T_{CW}	-	Cooling water temperature in, °F.
ΔT	-	Temperature drop acting as potential for heat transfer, °F.
ΔT_{corr}	-	Temperature correction for drop across brass wall, °F.
ΔT_{CW}	-	Cooling water temperature rise, °F.
V	-	Vapor.
x_E	-	Eutectic weight per cent.
Z	-	Spreading tension of liquid on solid, dynes/cm.
γ	-	Surface tension, dynes/cm.
γ_{AB}	-	Interfacial tension, dynes/cm.
$\Delta \gamma$	-	Difference in surface tensions of components, dynes/cm.
Γ	-	Mass flow rate of condensate, #/hr-ft.

- θ - Contact angle.
- ρ - Liquid density, $\#/ft^3$.
- $\Delta\rho$ - Difference in densities of components, $\#/ft^3$.

Subscripts

- A - Component A.
- B - Component B.
- E - Eutectic.
- M - Modified for condensation mechanism.
- S - Solid.
- g - Vapor.
- f - Liquid.

Mechanism

- 1 - film-drop
- 2 - film-lens
- 3 - channeling

APPENDIX A

APPENDIX A - BIBLIOGRAPHY

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APPENDIX B

APPENDIX B - APPARATUS DETAILS

1. Condenser

Length - 3 1/8 in.
Diameter - 2 7/16 in.
Area - 0.16618 ft².
Wall Thickness - 3/8 in.
Material - brass

2. Thermocouples

Material - copper-constantan, 30 gage,
 silvered-soldered junctions.

Reference Junction - ice point

Locations

- 1,2 - within 1/8 in. copper tube in condenser wall, 1/2 in. and 2 1/2 in from top, 180° apart.
- 3 - within 1/8 in. copper tube in vapor phase 1 in. from condenser surface.
- 4 - within 1/8 in. copper tube in liquid 1 - 2 in. deep.
- 5,6 - within cooling water exit tubes, 1/2 in. from top of condenser.
- 7 - within cooling water entrance tube, 1/2 in. from top of condenser.

3. Dewar Flask

Type - unsilvered Pyrex glass
Maker - Scientific Glass Blowing Company
Size - 7 in. I.D.
 9 3/4 in. O.D.
 15 in. depth

4. Immersion Heater

Type - Copper immersion coil
Rating - 1000 watts, 12.6 ohms

5. Miscellaneous Equipment

- 1. Potentiometer, Minneapolis-Honeywell, Model No. Y156X15(VH)-X-V
- 2. Ammeter, Triplet, 10 amp., AC.
- 3. Powerstat, Superior, 2KVA.

FIG. 12 - CONDENSER AND FUNNEL APPARATUS
COOLING WATER

4. Rotameter, Fischer-Porter, 84A-25.
5. Constant temperature bath, Precision Scientific, Inc., with heater, refrigerator, pump, and thermal regulator.
6. Water Ejector.
7. Vacuum Pump, with trap.
8. Mercury Manometer, with trap.
9. Graduated Cylinders and Receivers.
10. Lab-jack, Cenco-Lerner.
11. Rotary Switch, electrical connections, etc.
12. Copper Tubing, brass fittings.
13. Brass needle valves.
14. Three-way metal stopcock.
15. Brass Funnel.
16. Bakelite Insulation.
17. Teflon Gaskets and Deflector.

COMMENTS

In building the apparatus, certain difficulties were encountered which should be mentioned. Benzene vigorously attacked all gasket materials used, with the exception of Teflon. The Bakelite insulation material was completely unharmed throughout the tests, however. Leaks presented considerable difficulty before installing the ejector system. Pure steam coefficients were of the order of 400-500, instead of 1500-2000, with only seemingly small leaks. (The system vacuum would drop less than one inch of mercury in 24 hours.) The presence of air had less effect on pure organic coefficients. Nevertheless, air was removed with the ejector system before immiscible liquid data were taken.

Trouble with thermocouple readings was encountered during early calibrations. This difficulty was remedied by

using a special switching arrangement in which both ends of a thermocouple were disconnected from the circuit. Since the junctions were grounded and thus connected, keeping one lead connected in common with the other thermocouples and switching out the other lead would not remove the potential from other thermocouple circuits. After changing the switching arrangement, calibrations showed that each circuit functioned properly.

APPENDIX C

APPENDIX C - SAMPLE CALCULATIONS

Run No. 118, Heptane-water

Data:

T_1	T_2	T_V	T_L	T_{CW}	ΔT_{CW}	P	CW	Heater	Condensate
°F	°F	°F	°F	°F	°F	in. Hg.	#/hr	Btu/hr	Wt.% H ₂ O
151.5	154.0	175.0	192.5	141.1	2.7	27.4	390	1350	9.9

Calculation of h:

$$Q = 390 \text{ \#/hr} \times 2.7 \text{ }^\circ\text{F} \times 1.0 \text{ Btu/\#-}^\circ\text{F} = 1050 \text{ Btu/hr}$$

$$q = 1050 \text{ Btu/hr} \div 0.16618 \text{ ft}^2 = 6310 \text{ Btu/hr-ft}^2$$

$$T_S = \frac{T_1 + T_2}{2} + \Delta T_{\text{corr}}$$

$$\Delta T_{\text{corr}} = \frac{q}{k_{\text{brass}} / 1} = \frac{6310}{58 \times 12 / \frac{5}{16}} = 1.7 \text{ }^\circ\text{F}$$

$$T_S = \frac{151.5 + 154.0}{2} + 1.7 = 154.5 \text{ }^\circ\text{F}$$

From vapor pressure data, at P = 27.4 in. Hg,

$$T_E = 168.0 \text{ }^\circ\text{F}$$

$$T_E - T_S = 13.5 \text{ }^\circ\text{F}$$

$$h = \frac{q}{T_E - T_S} = 6310 / 13.5 = 467 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Calculation of λ :

$$\lambda_{\text{heptane}} = 146 \text{ Btu/\#}$$

$$\lambda_{\text{water}} = 1006 \text{ Btu/\#}$$

$$\lambda' = a\lambda_w + b\lambda_h = 0.099(1006) + 0.901(146)$$

$$\lambda' = 231 \text{ Btu/\#}$$

$$\Gamma = \frac{Q}{\lambda' \pi D} = \frac{1050 \text{ Btu/hr}}{231 \text{ Btu/\#} \times \pi \times 0.203 \text{ ft}}$$

$$\Gamma = 7.14 \text{ \#/hr-ft}$$

APPENDIX D

APPENDIX D - SUMMARY OF DATA

Run No.	T _S °F	T _E °F	T _V °F	T _L °F	Benzene and Water			wt. %H ₂ O	q $\frac{\text{Btu}}{\text{hr-ft}^2}$	Γ #/hr-ft	h $\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	Mechanism
					T _E -T _S °F	P in.Hg						
43	87.4	96.5	106.0	113.0	9.1	7.8		6.3	3930	4.3	432	1
44	86.2	93.0	101.0	109.0	6.8	7.1		6.2	2650	2.9	390	1
45	90.9	110.5	116.5	124.5	19.6	11.0		6.8	6960	7.4	354	1
46	86.6	88.0	91.5	100.0	1.4	6.3		6.1	371	0.4	265	1
47	102.8	111.0	116.5	123.0	8.2	11.1		6.8	3130	3.4	382	1
48	105.6	123.0	127.5	136.0	17.4	14.5		7.3	7850	8.4	450	1
49	124.7	141.5	145.0	158.0	16.8	21.9		8.0	7240	7.6	430	1
50	118.4	129.5	134.0	144.0	11.1	16.9		7.5	4310	4.7	398	1
51	89.7	106.5	109.5	118.5	16.8	10.0		6.6	6270	6.8	373	1
52	87.6	104.0	107.5	115.0	16.4	9.4		6.5	5870	6.4	357	1
53	85.5	91.0	97.0	102.5	5.5	6.8		6.1	2690	3.0	490	1
54	127.5	138.5	140.5	151.5	11.0	20.4		7.8	3720	4.0	338	1
55	125.5	127.0	129.0	137.0	1.5	15.9		7.4	911	1.0	608	1
56	139.5	160.0	162.0	180.0	20.5	31.8		8.8	9320	9.7	455	1
57	140.5	161.0	163.0	182.0	20.5	32.5		8.9	9250	9.6	452	1
58	145.9	156.5	159.5	175.0	10.6	29.7		8.7	5110	5.3	483	1
59	148.2	157.5	159.5	173.0	9.3	30.4		8.7	3470	3.7	373	1
60	138.1	146.0	148.5	159.0	7.9	23.8		8.2	3120	3.3	395	1
61	137.7	150.0	151.5	167.0	12.3	25.9		8.4	6200	6.6	503	1
62	138.5	154.5	155.5	172.5	16.0	28.5		8.6	8380	8.9	523	1
64	142.5	146.0	152.0	172.0	3.5	23.9		8.2	2010	2.1	574	1
65	146.0	149.5	159.5	176.0	3.5	25.7		8.4	2510	3.4	720	1
66	145.7	149.5	154.5	165.0	3.8	25.6		4.7	2450	3.0	650	1
67	145.3	149.5	155.5	165.5	4.2	25.7		8.4	2110	2.2	500	1
68	145.1	149.0	153.0	164.0	3.9	25.5		5.7	2380	3.2	585	1
69	146.5	150.0	154.5	166.0	3.5	26.1		8.4	2550	4.6	730	1
71	146.7	150.0	154.5	165.5	3.3	25.9		3.5	2650	3.5	805	1
73	146.9	150.0	155.5	167.0	3.1	25.9		2.4	2430	3.2	785	1
75	146.6	150.0	155.0	163.0	4.9	26.0		2.4	2360	3.2	480	1
76	144.3	149.0	154.5	162.0	4.7	25.6		8.4	1950	2.4	415	1
77	145.2	149.5	157.5	161.5	4.3	25.7		8.4	2440	2.6	570	1

Benzene and Water - Continued

Run No.	T _S °F	T _E °F	T _V °F	T _L °F	T _{E-TS} °F	P in.Hg	wt.%H ₂ O	q Btu hr-ft ²	Γ #/hr-ft ²	h Btu hr-ft ² -°F	Mechanism
78	145.9	149.0	158.0	162.0	3.1	25.6	2.4	2640	3.5	850	1
79	145.6	149.0	157.5	161.5	3.4	25.4	3.5	2390	3.0	700	1
80	146.0	149.0	151.5	160.0	3.0	25.5	4.6	2470	2.1	820	1
81	145.8	149.5	150.5	168.0	3.7	25.8	11.4	2740	2.6	740	1
82	145.0	149.0	151.0	171.0	4.0	25.6	11.4	2020	1.9	505	1
83	145.9	150.0	153.0	174.0	4.1	26.0	11.4	2630	2.5	640	1
84	137.0	159.5	161.5	208.0	22.5	31.7	16.0	19450	16.4	865	3
85	134.9	158.7	160.0	207.0	23.8	31.2	23.5	20150	14.0	845	3

Heptane and Water

93	113.8	150.5	160.5	164.0	36.7	17.7	12.3	8620	7.1	235	1
94	112.8	142.0	152.0	154.0	29.2	14.5	11.9	5600	10.0	192	1
95	109.5	124.0	134.0	135.0	14.5	9.6	11.9	2720	2.8	188	1
96	120.4	164.0	176.0	180.0	43.6	24.6	12.5	11680	11.7	268	2
97	127.4	172.5	189.5	194.0	45.1	31.0	16.1	13450	12.0	298	2
98	146.9	167.5	183.0	204.5	20.6	27.0	12.4	13200	13.5	640	1
99	135.3	169.0	180.5	207.0	33.7	28.0	12.4	15100	15.3	450	1
100	111.3	144.0	155.5	169.0	32.7	15.1	5.5	6800	8.9	208	1
101	113.9	149.0	162.0	180.5	35.1	17.1	7.1	7820	9.5	223	1
102	111.6	144.0	158.0	176.0	32.4	15.2	7.1	6800	8.2	210	1
103	139.3	156.0	169.5	191.5	16.7	20.2	5.3	6640	15.7	386	1
104	136.6	148.5	161.5	182.0	11.9	16.7	0	2820	4.9	237	1
105	129.9	137.5	149.5	167.0	7.6	13.0	0	1505	2.6	198	1
106	145.4	161.5	167.0	200.0	16.1	22.9	13.5	8800	8.7	546	2,3
107	156.0	170.0	191.0	212.5	14.0	29.1	15.9	11800	10.9	840	3
108	155.2	167.5	177.0	206.5	12.3	27.0	12.4	6900	7.1	560	2,3
109	159.3	167.5	176.0	207.5	8.2	27.0	8.2	4920	6.3	600	2,3
110	157.4	166.0	173.0	204.0	8.6	25.8	9.6	4200	4.8	488	2,3
111	162.2	170.5	178.5	213.0	8.3	29.6	15.8	8260	7.6	996	3
112	142.8	151.5	161.0	176.0	8.7	18.1	0	2060	3.6	237	1
113	140.3	146.5	146.5	169.0	6.2	16.1	0	1195	2.1	193	1

Heptane and Water - continued

Run No.	T _S °F	T _E °F	T _V °F	T _L °F	T _E -T _S °F	P in.Hg	wt.%H ₂ O	q $\frac{\text{Btu}}{\text{hr-ft}^2}$	Γ $\frac{\#/\text{hr-ft Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	h $\frac{\text{hr-ft Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	Mechanism
114	141.2	148.5	152.0	172.0	7.3	16.7	0	1470	4.2	201	1
115	140.8	146.5	150.0	169.0	5.7	16.2	0	1200	2.1	210	1
116	144.8	153.0	159.5	180.0	8.2	18.7	1.0	1770	2.9	216	1
117	147.5	160.5	174.0	224.0	13.0	22.4	9.6	3900	4.4	300	1
118	154.5	168.0	175.0	192.5	13.5	27.4	9.9	6310	7.1	467	1
140	100.5	123.0	134.5	141.5	22.5	1.4	10.2	3650	3.9	162	1
141	105.8	138.5	152.5	158.5	32.7	13.3	10.2	6730	7.2	206	1
142	106.6	142.5	154.5	176.0	35.9	14.6	8.2	7620	8.8	212	1
143	105.8	138.5	145.0	175.0	32.7	13.3	10.2	6750	7.2	206	1
145	130.4	160.0	170.0	197.0	39.6	22.0	10.2	16220	11.8	572	2,3
146	123.7	140.7	151.0	175.0	17.0	14.0	7.4	7200	8.7	423	2,3
147	125.7	163.0	168.0	202.0	37.3	24.1	23.3	14250	10.5	382	2,3
148	150.6	167.5	169.5	206.0	16.9	26.8	17.1	14200	12.6	840	3
149	160.9	170.0	187.0	211.0	9.1	28.9	16.6	16500	14.9	1800	3
150	163.9	170.8	185.5	211.0	6.9	29.4	19.6	9520	7.9	1380	3
151	159.4	167.3	170.0	202.0	7.9	26.7	18.8	8880	7.5	1120	3
152	105.9	125.5	135.0	149.5	19.6	10.2	6.7	5867	7.2	300	1
153	104.4	125.5	135.0	149.0	21.1	10.2	9.1	5892	6.6	279	1
154	141.1	160.0	173.0	186.0	18.9	22.1	8.7	10223	11.9	541	2,3
155	125.3	160.0	167.0	192.0	34.7	22.1	15.6	17970	16.3	518	1
156	154.0	160.0	174.5	185.5	6.0	22.1	4.3	2506	3.6	418	1,3
158	104.9	128.0	141.0	152.0	23.1	10.6	9.6	5758	6.3	249	1
159	150.1	171.0	186.5	198.0	20.9	29.8	8.2	13343	16.0	638	1
160	139.6	157.0	166.0	192.5	17.4	20.7	11.0	7950	8.5	456	1
161	158.1	176.5	189.5	219.0	18.4	34.7	11.3	13210	14.2	718	1
162	153.5	165.0	169.5	201.0	11.5	25.0	21.2	5464	4.5	475	1

Carbon Tetrachloride and Water

Run No.	T _S °F	T _E °F	T _V °F	T _L °F	T _{E-TS} °F	P in.Hg	wt.%H ₂ O	q $\frac{\text{Btu}}{\text{hr-ft}^2}$	Γ #/hr-ft	h $\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	Mechanism
121	100.0	124.5	133.5	136.0	24.5	17.1	5.0	8210	15.7	335	1
122	110.0	132.0	143.0	144.5	22.0	20.0	5.6	7430	13.7	338	1
123	108.9	145.0	159.0	160.0	36.1	26.3	2.6	10580	24.3	293	1
124	119.4	140.5	151.0	152.5	21.1	23.9	9.8	9630	13.9	455	1,3
125	137.2	141.0	150.5	152.5	3.8	24.1	12.2	6880	8.9	1810	3
131	145.1	151.0	160.0	162.0	5.9	29.4	12.9	7620	9.7	1290	3
132	143.9	149.0	157.5	157.5	5.1	28.3	28.6	6920	5.1	1360	3
133	150.4	154.0	161.5	163.5	3.6	31.1	8.5	5640	8.7	1560	3
134	110.8	121.0	123.0	130.0	10.2	15.7	3.6	4760	10.1	465	1
135	108.7	117.5	118.5	124.5	8.8	14.5	2.7	3450	8.0	392	1
136	112.7	125.5	128.0	134.0	12.8	17.3	25.4	5460	4.3	426	1
137	125.8	138.5	145.0	148.5	12.7	23.0	21.3	7470	6.8	588	1,3
138	131.1	156.0	164.0	167.0	24.9	32.6	16.0	13250	14.5	532	1,3

Heptane and Methanol

Run No.	T _S °F	T _E °F	T _V °F	T _L °F	T _{E-TS} °F	P in.Hg	wt.%CH ₃ OH	q $\frac{\text{Btu}}{\text{hr-ft}^2}$	Γ #/hr-ft	h $\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	Mechanism
168	110.2	139.5	144.0	144.5	29.3	32.9	66.8	12850	8.9	440	2
169	110.4	133.5	137.5	137.5	23.1	28.7	64.6	10720	7.6	464	2
170	111.6	126.5	130.0	131.0	14.9	24.2	63.9	8420	6.0	565	2
171	111.3	119.6	123.0	124.0	8.3	20.5	62.3	5510	4.0	665	2
172	111.8	115.5	119.0	120.0	3.7	18.5	63.6	3180	2.3	860	2
173	111.7	113.5	116.5	117.5	1.8	17.5	64.6	2470	1.7	1370	2
174	119.7	135.0	138.5	139.0	15.3	29.6	64.3	8280	5.9	540	2
175	118.8	130.2	133.0	134.0	11.4	26.4	65.5	6840	4.8	600	2
176	118.7	125.0	128.0	129.5	6.3	23.4	64.0	4420	3.2	703	2
177	119.4	145.5	151.0	151.0	26.1	38.1	64.2	12450	8.9	478	2
178	118.7	139.8	144.0	144.5	21.1	33.0	65.2	10600	7.5	505	2