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A STUDY OF DROPWISE CONDENSATION

USING VAPORS OTHER THAN WATER VAPOR

A THESIS

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A STUDY OF DROPWISE CONDENSATION

USING VAPORS OTHER THAN WATER VAPOR

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SUMMARY

Dropwise condensation is a phenomenon which is observed quite frequently in the condensation of steam and has been studied rather extensively since it was discovered (in 1930) that the coefficient of heat transfer is tremendously improved when the condensation changes from film-type to dropwise. The existence of the phenomenon in the case of vapors other than water vapor, however, has been rarely mentioned in the literature and an investigation was conducted to determine the conditions for the promotion of dropwise condensation of these vapors.

The heat transfer problem in dropwise condensation is complicated because the phenomenon is entirely dependent on the application of a contaminant to the condensing surface. The conventional equations for heat transfer in condensation can not be used. In order that the solution of this heat transfer problem may attain the state of development presently attained in film-type condensation, it seems necessary to gain a more precise knowledge of the nature and behavior of contaminants used to promote the dropwise condensation. This investigation has attempted to add to the knowledge of the nature and behavior of contaminants in dropwise condensation through the consideration of the conditions pertaining to nonaqueous vapors.

The theory is proposed that substances classified as nonpolar may not be condensed in the dropwise mode and experimental results and an analysis is presented to support the theory. Aniline, a

substance classified as polar, was condensed in the dropwise mode in the presence of large quantities of air and with low condensation rates. Those characteristics which render a contaminant suitable for use as a promoter of dropwise condensation for aniline are outlined and compared with the characteristics of contaminants successfully used for the dropwise condensation of water vapor. The observation is made that every known instance of dropwise condensation has involved contaminants with similar characteristics and it is concluded that the requirements for a good promoter of dropwise condensation are the same for all cases where the phenomenon can exist.

An attempt was made to obtain data to show the effect of dropwise condensation on the heat transfer coefficient for aniline, but the condition was unstable and no quantitative conclusions could be reached. Further research into the behavior of dropwise condensation of aniline under low pressures is needed.

CHAPTER I

INTRODUCTION

The problem.--Dropwise condensation of water vapor has been studied by
numerous investigators (5,6,7,8,13,18,24) and the conditions necessary
to maintain the phenomenon are fairly well established. The dropwise
condensation of vapors other than water vapor, however, has been rarely
mentioned in the literature and it was considered worthwhile to investi-
gate this phase of the problem. The object of this investigation is
three-fold: 1) to ascertain the conditions necessary to maintain drop-
wise condensation of vapors other than water vapor and, if possible,
compare these conditions with those established for water vapor; 2) to
study the mechanism of the phenomenon so as to gain an understanding of
the probable molecular processes involved; and, 3) to study the heat
transfer in the condensation of these vapors. It is hoped that these
efforts will add to the understanding of the general problem of drop-
wise condensation.

The general problem of heat transfer in dropwise condensation is
complicated by the fact that drops occur only when the condensing sur-
face is contaminated by a substance for which the condensed liquid has
only a small affinity. In order that the solution of this problem may
attain the state of development presently attained in film-type conden-
sation, it seems necessary to gain a more precise knowledge of the
nature and behavior of contaminants in the condensation mechanism, for

the occurrence of dropwise condensation seems to depend entirely on the contaminant. In this work it has been assumed from the beginning that the fundamental nature of drop formation is the same for all substances. That is, if a substance such as aniline is condensed in the dropwise mode, it is assumed that the basic forces causing the formation of drops are the same as those which cause the dropwise condensation of water vapor, although the conditions necessary to produce these forces may be different in each case. Hence, a review of the literature pertaining to dropwise condensation of water vapor is in order.

Review of the literature on dropwise condensation of water vapor.--According to Nagle and Drew(19) the first systematic investigations of dropwise condensation were the researches of Schmidt, Schurig and Sellschap in Germany in 1930. These investigations were instigated by the observation that a condenser increased its capacity by sixty per cent without change in operating conditions. This pioneer work revealed for the first time the differences in the heat transfer coefficients for the two modes of condensation. First to study the phenomenon in this country were Nagle and Drew (19) who began a rather extensive series of projects at Massachusetts Institute of Technology in 1933.

As stated by Nagle and Drew, the problem divides into two parts: 1) the measurement of the heat transfer coefficients, and 2) the study of wettability under non-isothermal conditions. In the measurement of the heat transfer coefficients the researchers at Massachusetts Institute of Technology found that the dropwise heat transfer coefficients were about ten times those found for film-type condensation. These high

values encouraged the workers to intensively pursue the problem of promoting the dropwise condensation of steam. Ultimately, W. M. Nagle was granted patent numbers 1,195,361 and 2,399,611 covering certain promoters of dropwise condensation. The commercial exploitation of these findings met with little success, however, because the maintaining of dropwise condensation required too much expense and effort from the operators of condensing equipment.

The problem of finding suitable contaminants for the dropwise condensation of steam was not an easy one and at first the investigators used all substances at hand which were not wettable by water. The following is a list of substances tried by the early investigators (19).

Contaminant	Value
Russian mineral oil	Poor
Fuel oil	Fair
Kerosene	Poor
Mutton tallow	Unsuited
Beeswax	Good
Stearic acid	Good
Oleic acid	Excellent

These contaminants were tried on various metals as follows:

Metal	Value
Copper	Good
Brass	Good
Nickel	Good

Monel metal	Good
Steel	Poor
Aluminum	Unsuited
Chrome plate	Excellent
18-8 Stainless steel	Good

Though somewhat haphazard, the experiments served to establish the following points: 1) Substances which do not stick to the surface, such as kerosene, and substances which do not withstand higher temperatures, such as mutton tallow are not suited as promoters. 2) Metals such as steel and aluminum which have matt oxides are unsuited for dropwise condensation.

The results of the early experiments were somewhat erratic and were not always reproducible. This condition was later (5) traced to unsuspected impurities in the steam and in rubber stoppers and gaskets used in the early experiments. All such impurities were eliminated by the use of an apparatus similiar to that shown in figure 1. Distilled water was used and great care was exercised to isolate the pure vapor from all contaminants save the one chosen for experiment. These experiments are especially significant because it was definitely established that perfectly clean metal and pure vapor will give film-type condensation in all cases. Dropwise condensation was thus shown to be a result of contamination. It is interesting to note that chromium plate was found to give dropwise condensation by simply exposing it to the air for a short time after cleaning, no other promoter was necessary.

As is the case with most scientific progress, voices were raised

from some quarters to dispute the validity of the reasoning. One of the most persistent questions occuring in the literature is that pertaining to the resistance offered to the flow of heat by the extra layer of contaminant. The experience of many had been that the deposit of contaminants on condensing surfaces constituted a barrier to the flow of heat with a resulting decrease in performance and an ultimate cleaning job. It is certainly not inconceivable that a thick layer of contaminant could increase the resistance of the heat path enough to nulify any advantage gained by drop formation. Indeed, Nagle (18) early remarked that a thin adsorbed film seemed to give the best results and on at least one occasion, too much promoter was accidently added and the results were worse than those with the clean surface. It remained for Emmons (6) in 1935 in an almost classic work to show that a mono-molecular layer of contaminant is sufficient to produce the desired results and any in addition is unnecessary and may be detrimental. Emmons deposited the layers of contaminant on the tube surface by the method developed by Blodgett which takes advantage of the fact that oils will spread on the surface of water in a mono-molecular layer if the water surface is large enough.

Other experiments (7,8,13,24) extended the store of information concerning the dropwise mode, until presently the research worker can promote the dropwise condensation of water vapor with great efficiency by the proper choice of metal and promoter.

A summary of important facts pertaining to the dropwise mode as given in the literature may be listed as follows:

1) A promoter must adhere to the metal surface tightly enough to prevent its being easily washed off.

2) A polished surface is best for the dropwise mode and metals which will not stay shiny are unsuited.

3) A clean metal surface will give film condensation and dropwise condensation is the result of contaminants.

4) A mono-molecular film of contaminant is best for the promotion of the dropwise mode.

5) Certain promoters are more effective with certain metals than with others; i. e., benzl mercaptan is very effective on copper and its alloys; oleic acid is very effective on chromium, and zirconium will absord the fatty acids most readily.

6) At excessive condensation rates, drops may run together and form a thick film over even a well contaminated surface.

7) A high surface tension of the condensate is to be desired.

Review of the literature pertaining to the dropwise condensation of vapors other than water vapor.—There have been numerous publications (2, 3,4,9,15,16,21,22,28) which deal with the condensation of vapors other than water vapor but none mention the dropwise mode in pure vapors.

Both Nagle (5) and Emmons (6) mention that liquids with high surface tension such as glycerine and aniline may be condensed in the dropwise mode but no data is given.

In the condensation of mixtures of vapors where one of the vapors is water vapor, reference is sometimes made (2,9,16,22) to a peculiar

type of "dropwise condensation" in which the water forms in flat drops and appears to be covered by a film of the second substance. For example, in the condensation of a mixture of benzene and water vapors on clean tubes, it is found that the water forms in drops and a film of benzene forms between the drops and even appears to cover the drops of water. This occurrence is of little interest here except that it indicates the difficulty to be expected in trying to promote the dropwise condensation of the vapors of liquids which have low surface tensions.

CHAPTER II

THEORIES PERTAINING TO THE MECHANISM

<u>Theory of drop formation</u>.--Comparatively recent work (8) in which micro-photographs of condensing water vapor were used, indicate that in drop condensation a thin film of about 0.001 mm thickness forms on the condensing surface initially and this film then breaks into many small droplets which grow in size until the force of gravity causes them to roll from the surface. The process is then repeated in the cleared area. No explanation for this series of events is offered in the reference given and, although the matter is probably of little importance, the following remarks seem appropriate to support a theory to be mentioned later.

A film of liquid on a condensing surface is composed of layers of molecules which can be represented thus:

Film surface — Molecule "B"
Molecule "A"
Condensing surface
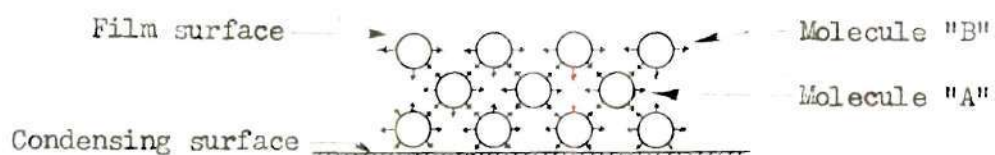
Molecules "A" in the body of the liquid attract and are attracted by the surrounding molecules and can be said to be in a state of equilibrium, that is, the forces are the same on all sides. To be sure, there is molecular motion, but at any instant there is a balance of attractive forces within the body of the liquid. The molecules "B" on the surface cannot be said to be in a balanced state because the attraction from the

vapor side is not as strong as the attraction from within. Consequently there are unbalanced forces at the surface which draw the surface to the liquid and causes the surface to assume the smallest area possible. It is clear that the surface area of any given film is smaller than the surface area would be if the same volume were divided into many small drops and, hence, the surface forces are multiplied by drop formation. It follows that the surface energy, i. e. the potential energy in the surface forces, contained in a liquid system of a single film is smaller than the surface energy contained in a liquid system of drops. This additional energy must be supplied from an external source if a single film is to be converted into drops. Although the energy required is minute in the case of a thin film and tiny drops, it could well be that these tiny forces could have an effect on the mechanism because we are dealing with a phenomenon which begins with the molecules.

After the drop has formed on the surface, its stability and configuration depend upon the relative values of the forces present. Since three phases, i.e. solid, liquid and vapor, can meet only at a line, equilibrium is established by forces acting on that line. The forces acting on a drop of liquid on a flat solid surface may be represented by interfacial tensions γ_{sv}, γ_{sl} and γ_{lv} where s, l, v refer to solid, liquid and vapor respectively.
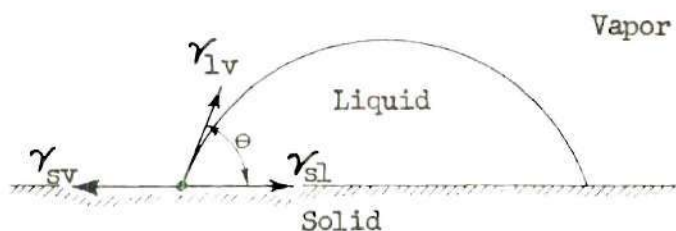
At equilibrium $\gamma_{sv} = \gamma_{sl} + \gamma_{lv} \cos \theta$. If $\gamma_{sv} > \gamma_{sl} + \gamma_{lv} \cos \theta$ the drop will spread and if $\gamma_{sv} < \gamma_{sl} + \gamma_{lv} \cos \theta$ the drop will get smaller. We readily see that if a liquid is to stand in drops, it must have a sufficiently large force of cohesion between the liquid molecules (large surface tension) and sufficiently small force of adhesion between the molecules and the surface (non-wettable surface). Hence, dropwise condensation is favored by high surface tension of the condensate, a non-wettable surface and large affinity of the vapor for the solid surface. It will be realized that little can be done to increase the surface tension of any given condensate and that we are limited in our efforts to promote dropwise condensation to treatment of the surface. The problem, of course, is to find a surface which is non-wettable by the condensate and which has a large affinity for the vapor.

It is of interest here to mention a curious occurrence reported by Nagle and Drew (19). It was noticed that drops sliding down the surface were attracted markedly if they passed close to a spot giving film condensation and that drops formed as much as one-fourth inch below such a film spot could even be drawn upward into that spot. Obviously, this occurrence was a demonstration of the relatively powerful surface forces in the water drop. The writer believes these strong attractive forces to be peculiar only to those compounds (such as water) which are sensitive to external electric fields, known as polar compounds.

Theory of molecular polarity applied to dropwise condensation.--Organic compounds such as those used in this work may be classed generally as

polar, nonpolar, and nonpolar-polar. Polar molecules are those which
have an internal unbalance of electrical charge and are therefore sensi-
tive to an external electric field. Water and acetic acid are examples
of strongly polar compounds. Nonpolar molecules are those which have
balanced internal charges and are thus indifferent to external electric
fields. Examples of this class of compounds are octane, benzene and
carbon tetrachloride. The nonpolar-polar molecules are strange com-
binations of groups of atoms in which a nonpolar group is linked to a
polar group by strong chemical bond so that one end of the molecule is
polar and the other end is nonpolar. These compounds occur with vari-
ous degrees of polar and nonpolar strengths. A polar group may be link-
ed to a small nonpolar group and the resulting compound would be strong-
ly polar. On the other hand, an extremely large nonpolar group may have
a polar group attached and the resulting compound would be nonpolar in
behavior. Those compounds which have the polar and nonpolar groups near-
ly balanced are the soaps and surface active agents. Examples of polar
groups are: hydroxyl, OH; carboxyl, $COOH$; aldehyde, CHO; amino, NH_2; and
sulfonic acid, SO_3H (25). Examples of nonpolar groups are: methyl, CH_3;
ethyl, C_2H_5; lauryl, $C_{11}H_{23}$; oleyl, $C_{17}H_{33}$; stearyl, $C_{17}H_{35}$; phenyl, C_6H_5
and naphthyl, $C_{10}H_7$ (25).

It is found that like attracts like and a polar compound has an
affinity for other polar compounds and an aversion for nonpolar com-
pounds. We may say that water will dissolve polar compounds and ben-
zene will dissolve nonpolar compounds. In the case of the nonpolar-
polar compounds which have nearly equal groups, known as surface active

agents, there is a tendency to migrate to the interface between two un-
like substances. For example, if there exists as interface between
water (polar) and octane (nonpolar) and there be added a surface active
agent, the molecules of the surface agent will orient themselves at the
interface in such a manner that the polar group will be turned toward
the water and the nonpolar group will be turned toward the octane, thus:

Polar ———→ ◯ ◯ ◯ ◯ ◯ ←——— Water

Interface ——↘ ⊕ ⊕ ⊕ ⊕ ⊕ ←——— Surface agent

Nonpolar ——↘ ▢ ▢ ▢ ▢ ▢ ←——— Octane
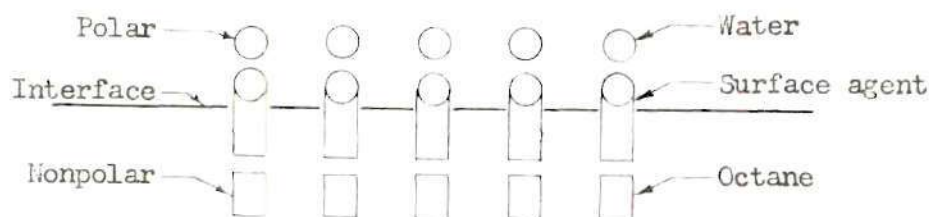
It happens that the best promoters, such as some of the fatty
acids, are nonpolar-polar in character and are slightly stronger on the
polar end. In the case of the fatty acids, one theory (8) is that the
polar carboxyl group referred to on page 11 is attached to a metal sur-
face by the substitution of a metal atom for the "H" atom in the car-
boxyl group. Hence, the best promoters arrange themselves on a condens-
ing surface in such a manner that the polar ends are turned toward the
surface and the nonpolar ends are exposed to the condensing vapor. It
is of interest to note that, apparently, metal has a polar nature and
it is true that metals have surface tensions (23). Manufacturing pro-
cesses cause metals to be non-uniform in structure and the surface prop-
erties vary from point to point.

It would seem, from the discussion so far, that the promotion of
dropwise condensation would consist merely of providing a nonpolar sur-
face for a polar vapor such as water and a polar surface for a nonpolar

vapor such as octane and therein lies the basis for much of the experimental work carried out in this investigation. Further analysis of this will be found in the discussion in Chapter V.

Two opposing theories of mass transport to the surface.--Emmons (6) and Eucken have proposed theories of mass transport to the surface and both will be discussed here because it is felt that a study of the behavior in condensation of vapors other than water vapor can add pertinent ideas to the subject.

Eucken, in a paper written in German and reported by Jakob (10), used the kinetic theory of gases to calculate a rate of arrival of molecules at a condensing surface. Assuming that all molecules which strike the surface are immediately condensed, he found that the corresponding heat transfer rate should be 72×10^6 Btu/(hr)(sq ft), which is 260 times more than has ever been observed in dropwise condensation. It follows that only about 0.4 per cent of the molecules remain in the liquid state on the surface and the rest are either re-evaporated or are reflected from the surface.

In experiments on the interchange of molecules between a liquid and its vapor which were performed on water and carbon tetrachloride by Alty and Nicoll (1), it was found that in the case of water at 12 degrees Centigrade, a reflection of 98.5 per cent of the molecules from the surface of water occurs; but, in the case of carbon tetrachloride, no reflection at all occurs. Jakob mentions that the reflection value obtained by Alty and Nicoll for water vapor is in agreement with Eucken's

calculations from the kinetic theory of gases and would thus indicate that a process called molecular diffusion is the driving force for the transport of mass to the surface, at least in the case of water vapor.

The theory of molecular diffusion assumes that in the close vicinity of the droplets, where condensation takes place, there is created a low density area and hence a concentration gradient which causes mass transportation toward the droplets.

The other theory, that of Emmons, assumes that vapor molecules which strike the surface are largely re-evaporated at the temperature of that surface and, since the temperature is low, must be in a state of supersaturation. The result would be that a layer of supersaturated vapor surrounds the droplets and covers the area between them. Emmons further assumes that, when condensation takes place, low pressure areas are created in the vicinity of the drops which cause violent eddy currents in the vapor. Hence, by the theory of Emmons, the transport of mass to the surface is a result of mechanical forces rather than a molecular diffusion.

The behavior of the liquids and vapors used in the present work seem to offer support to the theory of Emmons.

CHAPTER III

TEST MATERIAL AND APPARATUS

Test material.--In order to test the theory of polarity as presented in Chapter II, two series of simple tests were conducted: one of which involved surface wettability and the other required the use of the apparatus described below. Because of a limitation in time and because the nature of the problem is that seldom encountered in Mechanical Engineering, considerable difficulty was experienced in assembling the desired reagents and the list of materials tried is not as complete as might be desired. In spite of this, however, it is believed that sufficient information was obtained from the tests for the purpose outlined.

To represent the nonpolar compounds, the following liquids were chosen; 1) octane, 2) benzene and 3) carbon tetrachloride.

To represent the polar compounds, aniline and acetic acid were chosen.

The following is a list of contaminants which were tried as possible promoters of dropwise condensation during the course of the experiments.

1) Beeswax

2) Glycerine

3) Synthetic detergent (Tide)

4) Soap (Ivory)

5) Shellac

6) Castor oil

7) Linseed oil

8) Olive oil

9) Oleic acid

10) Acetic acid

11) Rosin

12) Petroleum jelly

The metals of copper, aluminum and steel were obtained both in tube and in sheet form to serve as a base for the contaminants.

Apparatus.--The design of the apparatus used in the present work has been used by at least two previous workers in this country, namely Nagle (18) and Emmons (6). This design, which is shown in Figure 1, was chosen for the following reasons.

1) It is simple to construct using standard copper tubing and fittings.

2) The test surface is easily observed.

3) A small quantity of liquid and vapor is required.

4) It is compact and easily disassembled for cleaning the surface.

5) Unwanted contaminants can be eliminated from the system easily.

Instrumentation.--It was considered desirable to check the heat transfer coefficients during the condensation and arrangements were made for measurements as follows.

1) Water temperature.--Copper-constantan thermocouples were sealed in short sections of glass tubing with a cement and these were installed in the inlet and outlet water lines by means of packing glands. The

thermocouple leads were connected through a transfer switch to a Leeds and Northrup type K-2 potentiometer. A circuit diagram is shown in Figure 2.

2) Water rate--A valve upstream from the inlet was installed to allow adjustment of water rate and a three-way valve was installed downstream from the outlet to allow diversion of the flow from the drain to the weighing buckets at any instant. The weighing buckets were one gallon pails and the scales were the platform type calibrated in 0.01 pound intervals.

3) Vapor temperature--A copper-constantan thermocouple was sealed in a glass tube and installed in the vapor space by means of a packing gland so that the junction was approximately half way down the condensing surface and approximately one inch away. The thermocouple leads were connected through the transfer switch as described before.

4) Surface temperature--At first it was proposed to use the resistance method previously used by White (20) which requires that a measured current be passed through the tube and the voltage drop between the ends of the tube measured. This method was found to be unsuited to the apparatus and was discarded. Thermocouples were installed in the tube wall as follows: A thin slice of metal was raised on the surface of the metal with a chisel; the constantan wire was pushed through from the water side and cleaned of insulation on the tip. The tip was pressed in the crevice and the copper slice was peened back in place and covered with solder. A copper wire was peened into a small hole in the copper surface near the top to serve as the other lead for the thermocouple. Two such

thermocouples were placed in the surface; one near the top (one inch down) and the other on the opposite side near the bottom. The leads were connected through the transfer switch as described before.

5) Miscellaneous instruments--A barometer with room temperature thermometer attached was available near the test area. A mercury glass thermometer previously calibrated by the U. S. Bureau of Standards was used in the calibration tests. A cold water source, variable between 45 degrees F and 110 degrees F, was available.

CHAPTER IV

PROCEDURE

Wettability tests.--Flat plates of copper, aluminum and steel were thor-
oughly cleaned and polished with steel wool and marked off into ten ap-
proximately equal areas with a scribe. The test liquids and contaminants
listed in Chapter III were assembled and a small magnifying glass was
procured to facilitate observation.

The test liquid "octane" was the first to be tested so the metal
plates were rinsed with octane to be sure that a good film was observed
on clean metal. Next, a "smear" of each of ten contaminants was placed
in a separate area on each metal and each "smear" was identified by a
number scratched on the metal. The contaminants were deposited by
pieces of clean cloth and rubbed to a thin and uniform film. A drop of
octane was placed in the first contaminated area with a medicine dropper
and the effect was noted before going to the next area. The process was
repeated until all areas had been tested.

The plates were then washed with a scouring pad, dried and rubbed
with steel wool. The procedure just described was repeated for each of
the test liquids.

When the plates were horizontal it was sometimes difficult to tell
whether the spreading (when spreading occured) was a result of a definite
affinity of the liquid for the contaminated surface or a result of the
low surface tension of the liquid. In such cases the plates were placed

in a vertical position and a drop of test liquid was touched to the surface. If there was any spreading of the drop upward, it was attributed to an affinity of the test liquid for the surface and, hence, wetting. If there was no upward spreading and the test liquid exhibited an indifference to the surface, it was assumed that spreading was a result of low surface tension only.

Condensation and heat transfer tests.—Results of the wettability tests, shown in Tables 1 through 5, were studied and used as the basis for the selection of liquids and contaminants to be used in the condensation and heat transfer tests. As an example, benzene with glycerine as contaminant was one of the combinations chosen and it was desired to discover what effect the contaminant glycerine has upon the heat transfer at various values of cooling water temperature. Consequently, it was necessary to make a test on a clean surface to serve as a basis for the comparison. The condensing surface was then coated with glycerine and the test was repeated under the same conditions. The method of applying the glycerine, as well as the other contaminants, was simply that of rubbing the surface with steel wool which had been dipped in glycerine. Between tests the condensing surface was cleaned with steel wool and carbon tetrachloride. The procedure used in making all the tests is as follows:

The test liquid was placed in the glass flask of the apparatus and cooling water was turned on and adjusted so as to allow a small rise in temperature as it passed the condensing surface. This adjustment was determined by trial and error and was not always constant throughout the

range of temperatures used. The cooling water line was connected to a source, the temperature of which could be varied between approximately 45 degrees F and 110 degrees F by the proper manipulation of valves.

The test liquid was then brought to the boiling point with an electric heater and the system was allowed to reach equilibrium. Equilibrium was assumed to exist when the inlet water temperature and the vapor temperature did not change appreciably with time. The following readings were taken: 1) water inlet temperature, 2) water outlet temperature, 3) vapor temperature, 4) surface temperature top, 5) surface temperature bottom, and 6) water flow rate in terms of time required for a known weight to pass. Similar readings were taken when equilibrium was established at five different levels of cooling water. Incidentally, the readings were taken three times at each temperature level to provide a means for obtaining average values and to be sure that no accidental error was made in reading the instruments.

CHAPTER V

DISCUSSION

The results of the wettability tests are given in Tables 1 through 5. The results of the condensation and heat transfer tests are given in Tables 6 through 14 and in Figures 4 through 8. For purposes of comparison, the experimental values of the surface coefficients are plotted along with corresponding theoretical values obtained from the equation of Nusselt as is shown in Figures 9 through 11.

The wettability tests, though somewhat elementary and lacking in scientific precision, were a necessary part of this investigation because they form the basis of the work. It will be remembered that the theory of polarity states that polar compounds are repelled by nonpolar compounds and vice versa. In view of this theory it is reasonable to assume that if we provide a polar surface on which to condense nonpolar vapors then one of the conditions for maintaining a dropwise mode of condensation should be satisfied.

Reviewing the case for water, we find that water vapor, a polar substance, is condensed most readily in the dropwise mode by the addition to the surface of nonpolar-polar molecules which will orient themselves so that the polar ends are turned toward the surface and the nonpolar ends are turned toward the water vapor. We are thus led to believe that metals exhibit a polar nature and we would expect, therefore, to find that water will wet a clean metal surface, which it does. We

would also expect that a nonpolar substance would not wet a clean metal surface. This, however, is open to question.

The wettability tests were designed with three nonpolar liquids and two polar liquids for the purpose of finding any similarities which might exist and which would allow conclusions to be drawn about the effect of polarity in dropwise condensation. The contaminants were selected as follows: 1) beeswax, because it is effective for promoting the dropwise condensation of water; 2) glycerine, because it is strongly polar; 3) soap (Ivory), because it has a nonpolar-polar nature; 4) detergent (Tide), because it represents the new nonpolar-polar synthetics; 5) olive, linseed and castor oils, because they are only slightly effective in promoting dropwise condensation of water vapor; 6) oleic acid, because it is effective on water; 7) acetic acid, because it is strongly polar; 8) petroleum jelly, because it represents the petroleum products for use with aniline.

It will be seen from Tables 1 through 5 that no drops were formed in the nonpolar liquids and an attempt was made to ascertain whether this occurrence was a result of the low surface tension of the liquid only or a result of an affinity of the liquid for the surface. In the latter case, of course, no dropwise condensation could be expected, but in the former case it could be possible that the low surface tension would merely affect the size of the drop and under special conditions a type of dropwise condensation might obtain. The condensation tests on some of the small affinity cases, listed as "S" in the tables, showed no evidence of such condensation although the condensing surface was

carefully observed under all the various conditions. We must conclude
that all the surfaces tested are wettable by the nonpolar liquids.

The two polar liquids, i.e., aniline and acetic acid, gave con-
flicting results. First, acetic acid, which is strongly polar and was
therefore expected to behave much the same as water, was found to wet
all surfaces (polar and nonpolar alike) with great readiness. This may
be partly explained by the fact that the surface tension of acetic acid
is low and it also could be possible that none of the contaminants used
were sufficiently inactive chemically to acetic acid.

Although acetic acid failed in the wettability tests to show any
tendency toward drop formation, a curious phenomenon was observed in
two instants when acetic acid was being used as a contaminant for the
nonpolar liquids. Acetic acid was being rubbed onto the surface of a
cleaned (with benzene) copper plate with a soft cotton cloth soaked in
the acid. Tiny droplets of acetic acid formed momentarily in the wake
of the cloth as it was pulled across the surface. It appeared that the
rubbing action itself was causing the formation of the drops, which
stood a moment and then disappeared. No explanation can be given for
this observed phenomenon since subsequent tests with purposely intro-
duced contaminants failed to reproduce the result.

The results with aniline were somewhat better, in that a non-
wettable surface was produced using petroleum jelly and "Ivory" soap.
Tests on the condenser surface with these two contaminants showed very
definite dropwise condensation when the liquid in the bottom of the
flask was below the boiling point. As the liquid began to boil and the

condensation rate increased, the dropwise condensation was progressively replaced by film-type condensation. The photographs in Figures 4 through 6 show the progress of the process with petroleum jelly as the contaminant. There was, without question, a large amount of air present and a very low condensation rate when the drops pictured were formed. When equilibrium was finally reached and the apparatus was ready for a run, the dropwise condensation had disappeared except for small patches near the top of the tube. These patches also disappeared after the third run in both cases. Further work with lower pressures and various amounts of air seems indicated. It is probable that a better promoter of dropwise condensation could be found which would adhere to the condensing surface better than those tried here.

It seems important to note that, in both cases above, the surface upon which dropwise condensation occurred was nonpolar and the vapor was polar. These are the same conditions which have existed in every known instance of dropwise condensation. We cannot, of course, say that all polar vapors can be condensed in the dropwise mode, but it seems that we might reasonably propose that it is impossible to cause the dropwise condensation of nonpolar vapors.

To support the proposal that it is impossible to cause the dropwise condensation of nonpolar vapors we recall the experiments of Alty and Nicoll (1) who found that there was little or no reflection of molecules from the surface of carbon tetrachloride. The molecules enter the surface easily and they easily leave the surface by evaporation. This indicates that there is very little force of attraction between

like molecules within the liquid. We recall also the condition which exists when water is condensed with a nonpolar substance; the water forms in drops and the nonpolar substance covers the drops of water. Nonpolar substances have small internal attractive forces and are neither repelled nor attracted by polar substances. All of which leads to the fact that drop formation is not so much a result of the repulsion of the liquid for any particular surface but is a result of the isolation of forces within the liquid so that these forces are left free to form a drop. In the case of nonpolar substances we may say that there is little force to isolate, hence a drop cannot form no matter what type of surface is exposed to the vapor.

Although no heat transfer data on the dropwise mode of condensation of vapors other than water vapor could be obtained, it was decided that data taken during film-type condensation when a contaminant was present might prove to be of value. Unfortunately, however, the design of the apparatus was not well suited for accurate heat transfer measurements, especially for the wide range of temperatures used, and the data obtained is suitable only for rough comparisons. For example, Figure 7 illustrates the effect of the contaminant (soap) on the vapor-side coefficient for octane and, as expected, the extra layer in the heat path causes a reduction in the coefficient. Figure 8 illustrates the effect of petroleum jelly on the vapor-side coefficient for aniline. Here, the points 1 and 2 were obtained while approximately on third of the surface showed patches of dropwise condensation. There is some evidence that the dropwise condensation improved the heat transfer enough to overcome

the extra resistance offered by the contaminant film but no quantitative estimates can be made. Figures 9, 10 and 11 show a comparison of observed data with the theoretical Nusselt equation.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--The following conclusions pertaining to the promotion of dropwise condensation of vapors other than water vapor were drawn from the studies and experiments herein described.

1) Vapors classified as "nonpolar" may not be condensed in the dropwise mode because the properties which define the classification are those which are adverse to drop formation.

2) Vapors classified as "polar" may be condensed in the dropwise mode only if the resulting condensate has a high surface tension and if a nonpolar condensing surface is provided.

3) A suitable contaminant for the promotion of dropwise condensation must; a) be chemically inert to the condensate, b) adhere to the surface in such a manner that a nonpolar film is exposed to the condensate, c) be capable of withstanding the temperatures involved in the condensation and d) have a low resistance to the flow of heat.

4) A low condensation rate is desirable, even necessary, when surface tension of the condensate is low.

5) A polished surface is best for the dropwise mode.

Comparison of these conditions with those found by others for water vapor shows that the conditions are very much the same, except that, in the case of nonpolar vapors, no comparison exists. Chemically, the conditions would be more difficult to satisfy for vapors other than

water vapor than they are for water vapor alone.

In the heat transfer aspect of the problem, no quantitative conclusions can be made. It is shown that a contaminant should not be introduced in the condensation of vapors of a nonpolar nature and that care should be taken in the selection of contaminants for polar vapors to be sure that no unwanted chemical reaction will take place.

Recommendations.--It is believed that the next step in continuing this study should be that of the design of an apparatus for the dropwise condensation of aniline at pressures below atmospheric. The apparatus should be capable of providing accurate heat transfer data, such as is not available at the present time.

APPENDIX A

NOMENCLATURE

NOMENCLATURE

t_{wi} Inlet water temperature, degrees Fahrenheit

t_{wo} Outlet water temperature, degrees Fahrenheit

W Water rate, pounds per hour

Q Rate of heat transfer, Btu per hour

t_{sv} Saturated vapor temperature, degrees Fahrenheit

t_v Observed vapor temperature, degrees Fahrenheit

t_s Condensing surface temperature, degrees Fahrenheit

A_o Outside area of heat transfer surface, square feet

Δt_s Temperature difference, $t_v - t_s$, degrees Fahrenheit

Δt_t Theoretical temperature difference, $t_{sv} - t_s$, degrees Fahrenheit

t_f Average film temperature, $t_{sv} - 3/4 \Delta t_t$, degrees Fahrenheit

k_f Thermal conductivity of condensate at t_f, Btu/(hr)(sq ft)(deg F/ft)

ρ_f Density of condensate film at t_f, pounds per cubic foot

μ_f Viscosity of condensate at t_f, lb/(hr)(ft)

h_m Mean observed vapor-side coefficient of heat transfer, Btu/(hr)(sq ft)(deg F)

h_{mt} Theoretical coefficient of heat transfer, Btu/(hr)(sq ft)(deg F)

λ Latent heat of condensation at t_{sv}, Btu per pound

g Acceleration due to gravity, ft/(hr)(hr)

L Length of tube, feet

D_o Outside diameter of tube, feet

c_p Specific heat at constant pressure, Btu/(lb)(deg F)

APPENDIX B

FIGURES
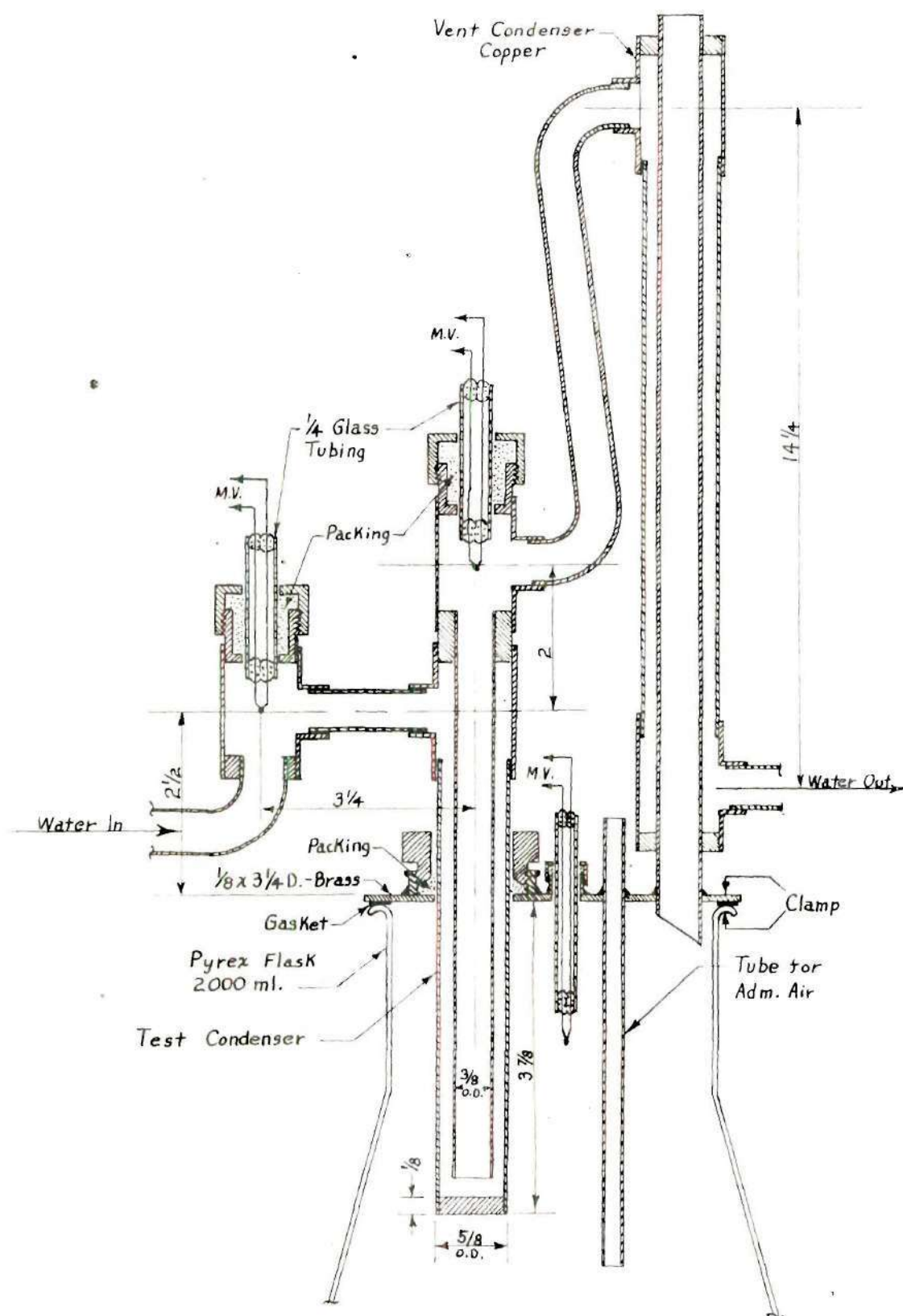
Figure 1. Diagram of Apparatus
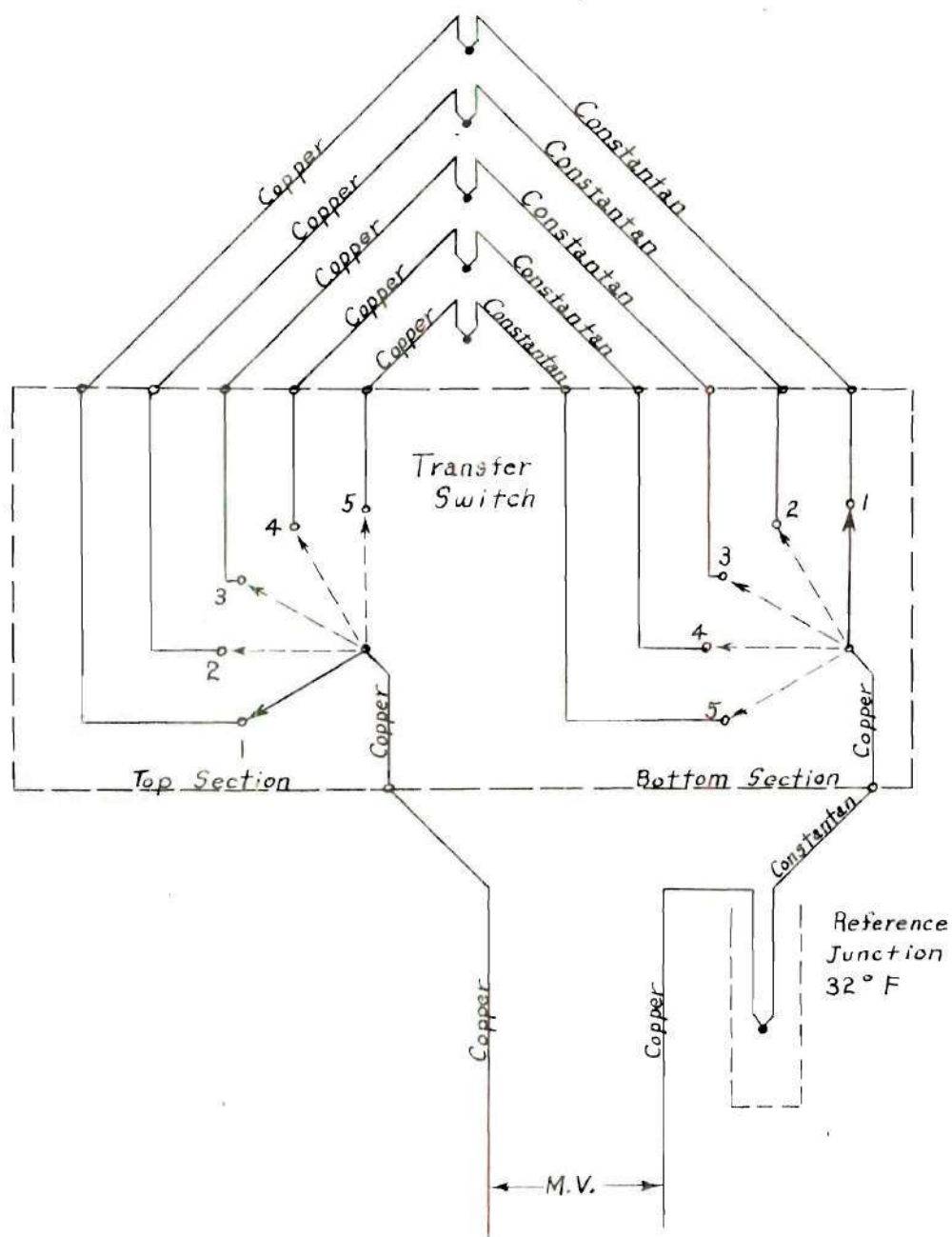
Figure 2. Thermocouple wiring Diagram

Figure 3
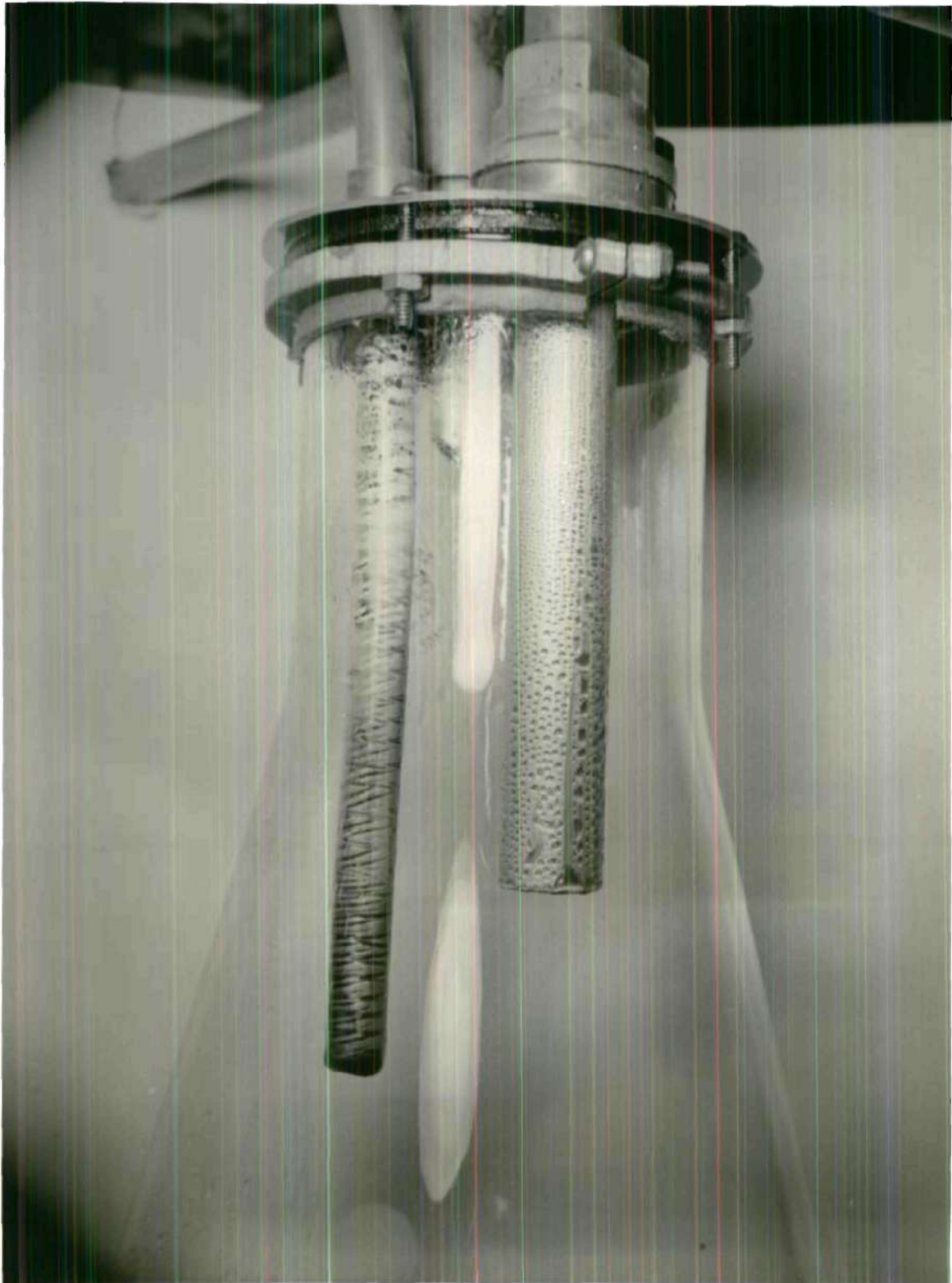
Figure 4. Dropwise Condensation - Aniline with Petroleum Jelly
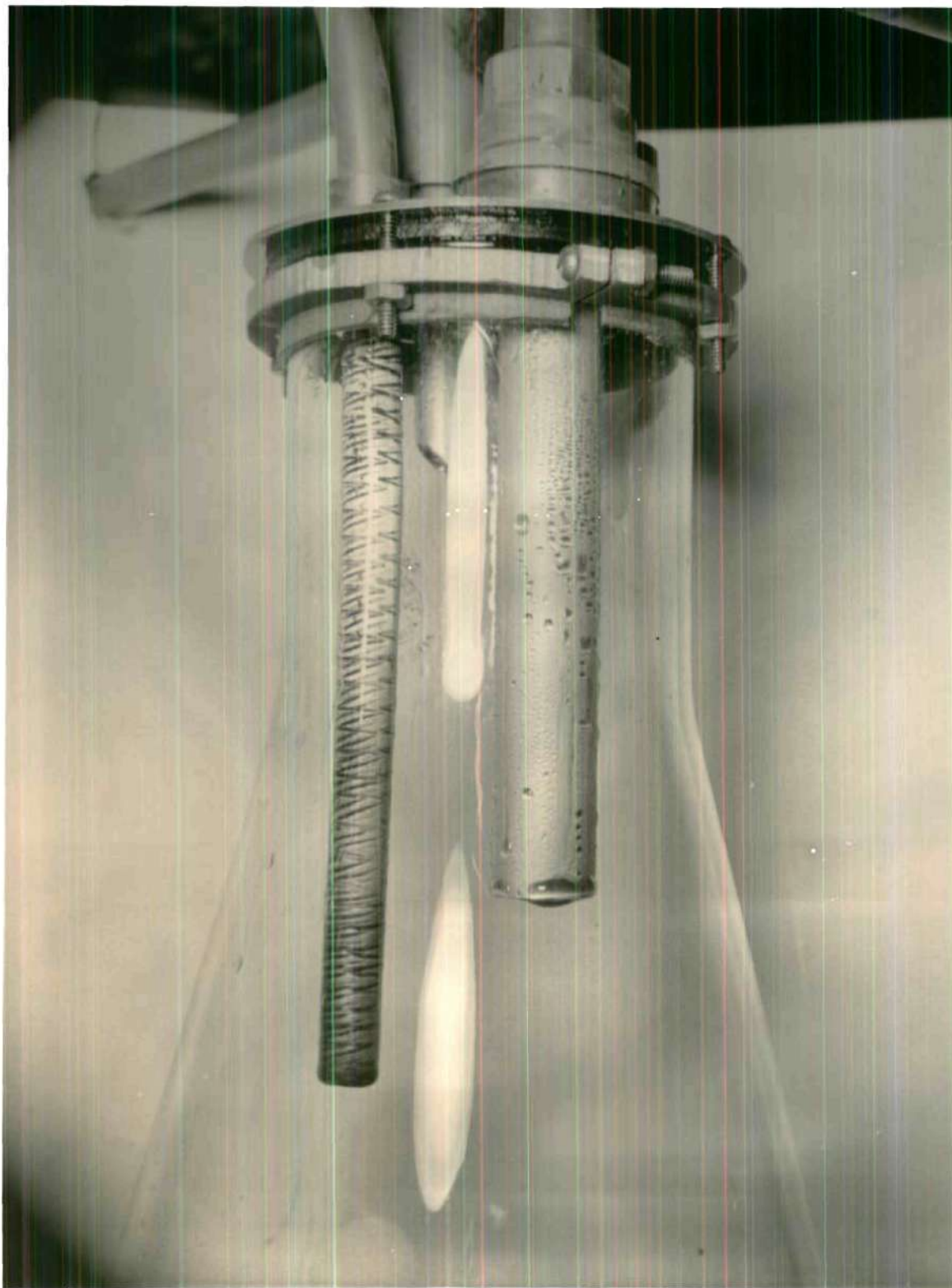
Figure 5. Dropwise Condensation - Aniline with Petroleum Jelly
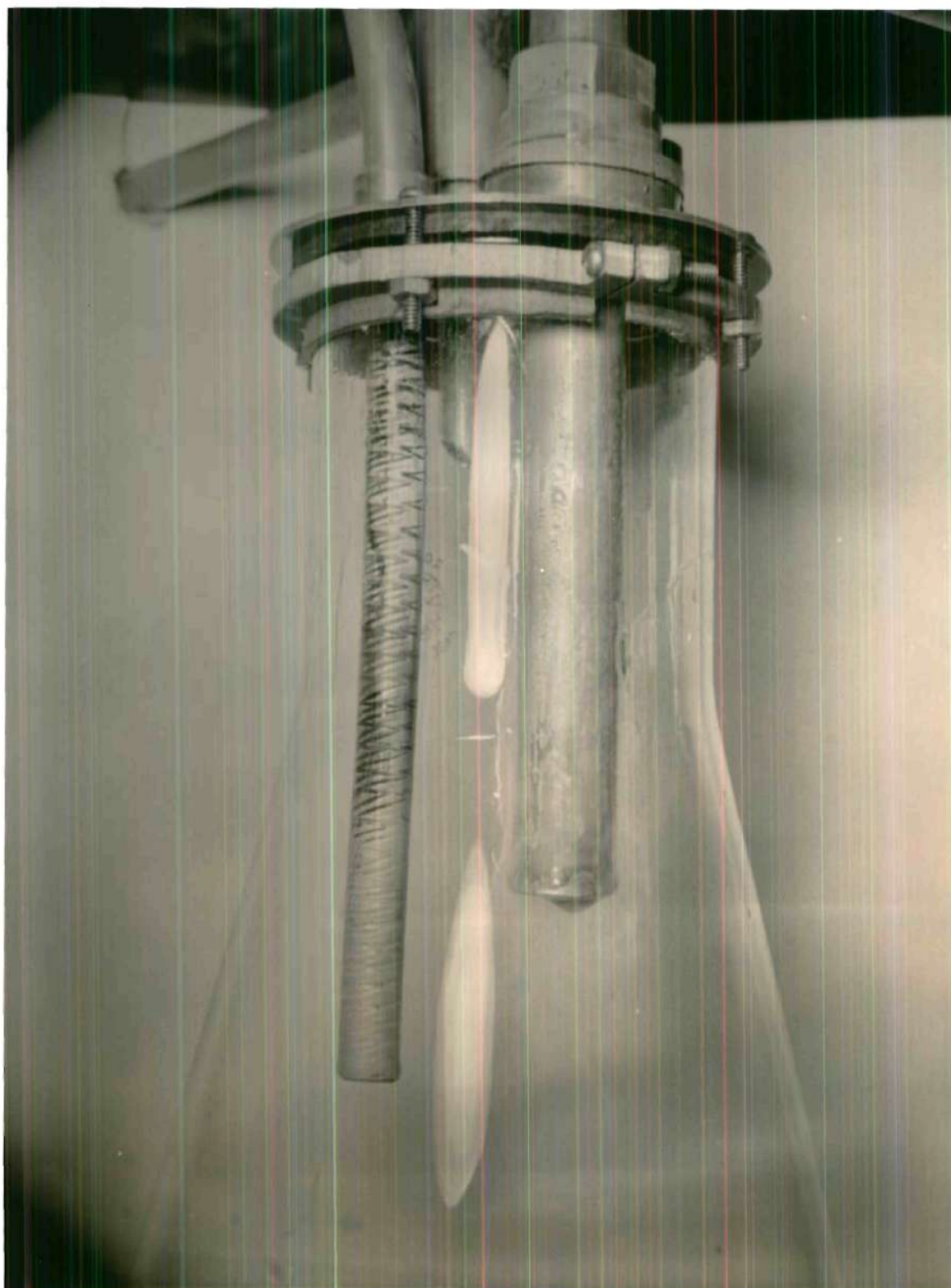
Figure 6. Mixed Condensation - Aniline with Petroleum Jelly
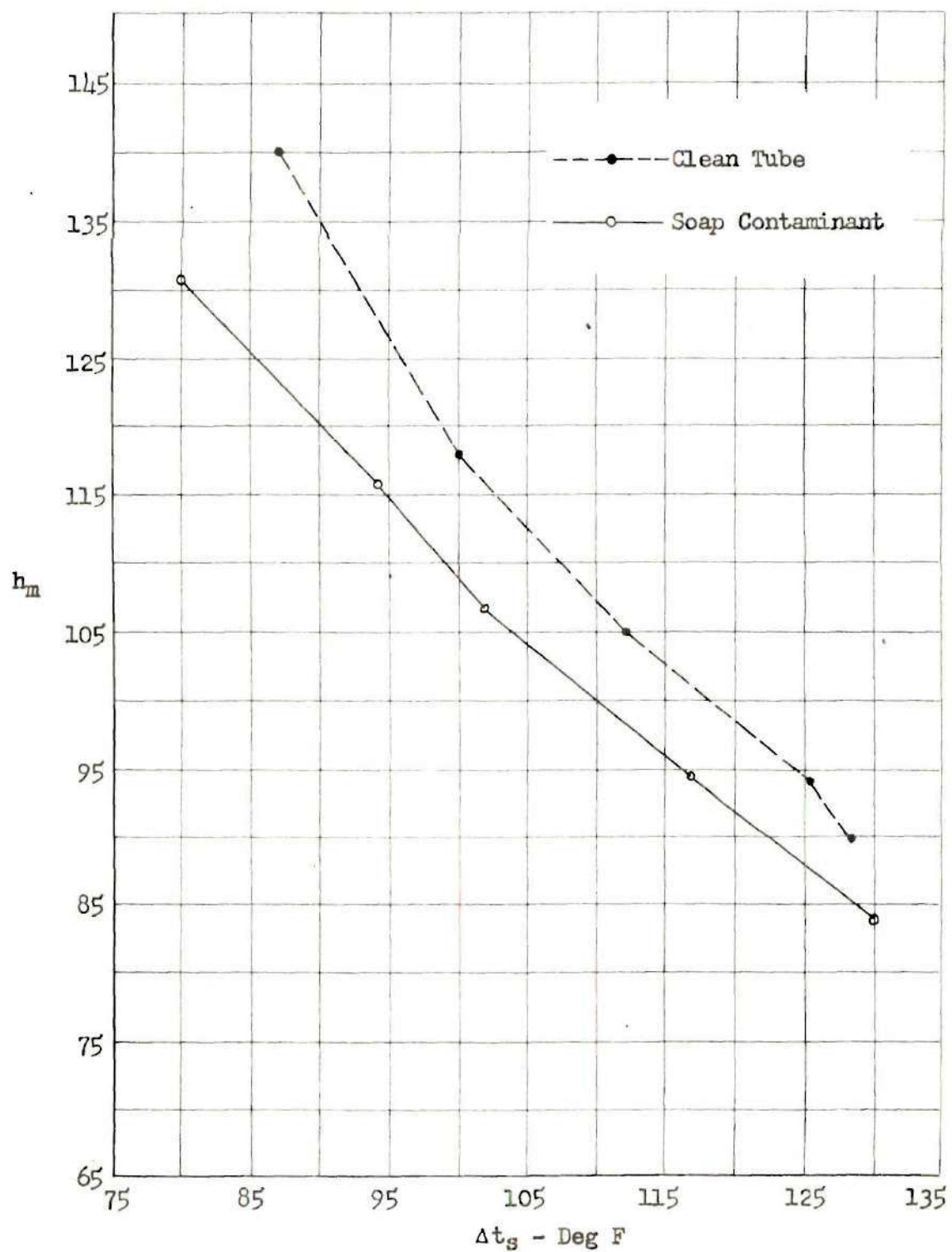
Figure 7 – Octane

Effect of Soap on Vapor-side Coefficient
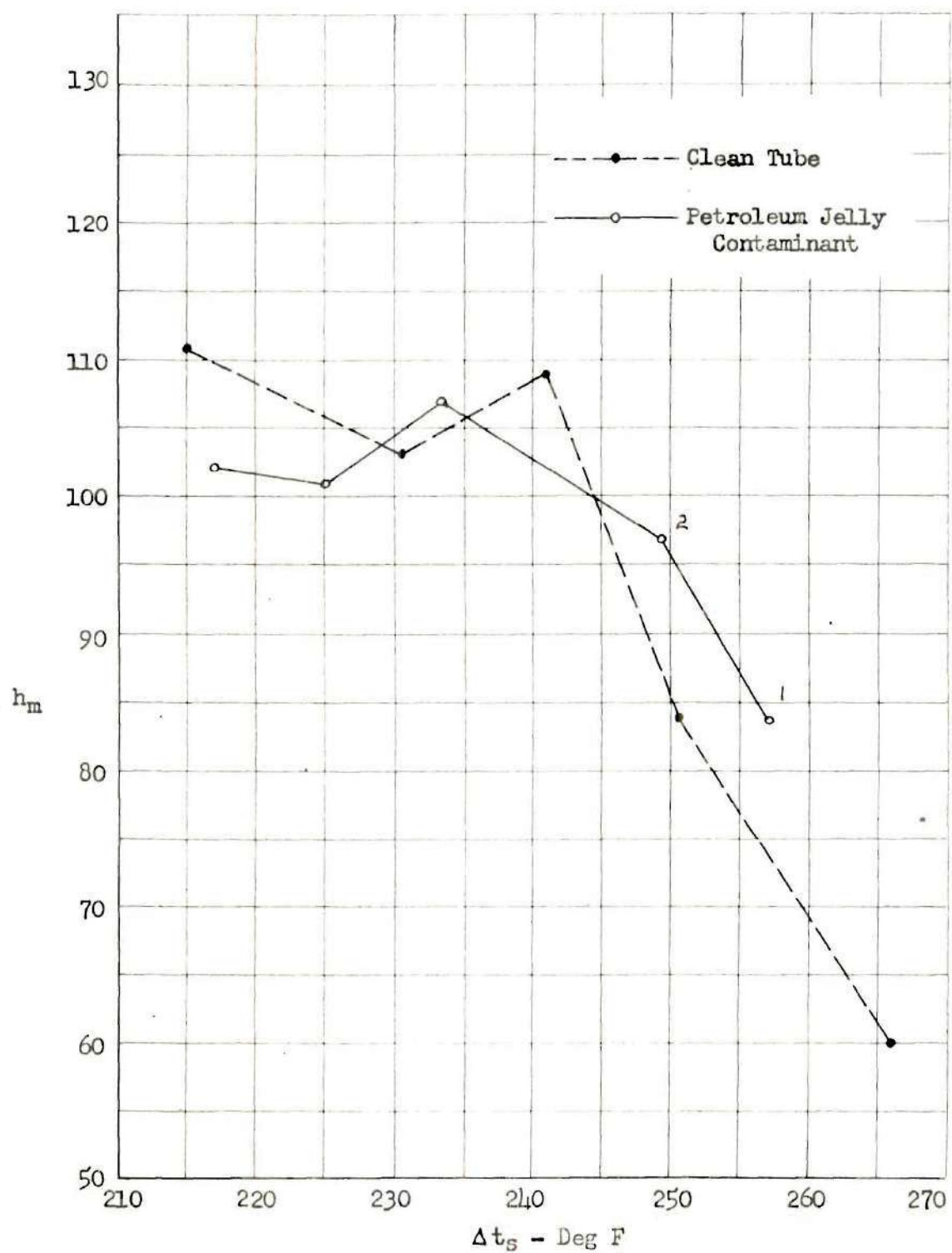
Figure 8 - Aniline

Effect of Petroleum Jelly on Vapor-side Coefficient
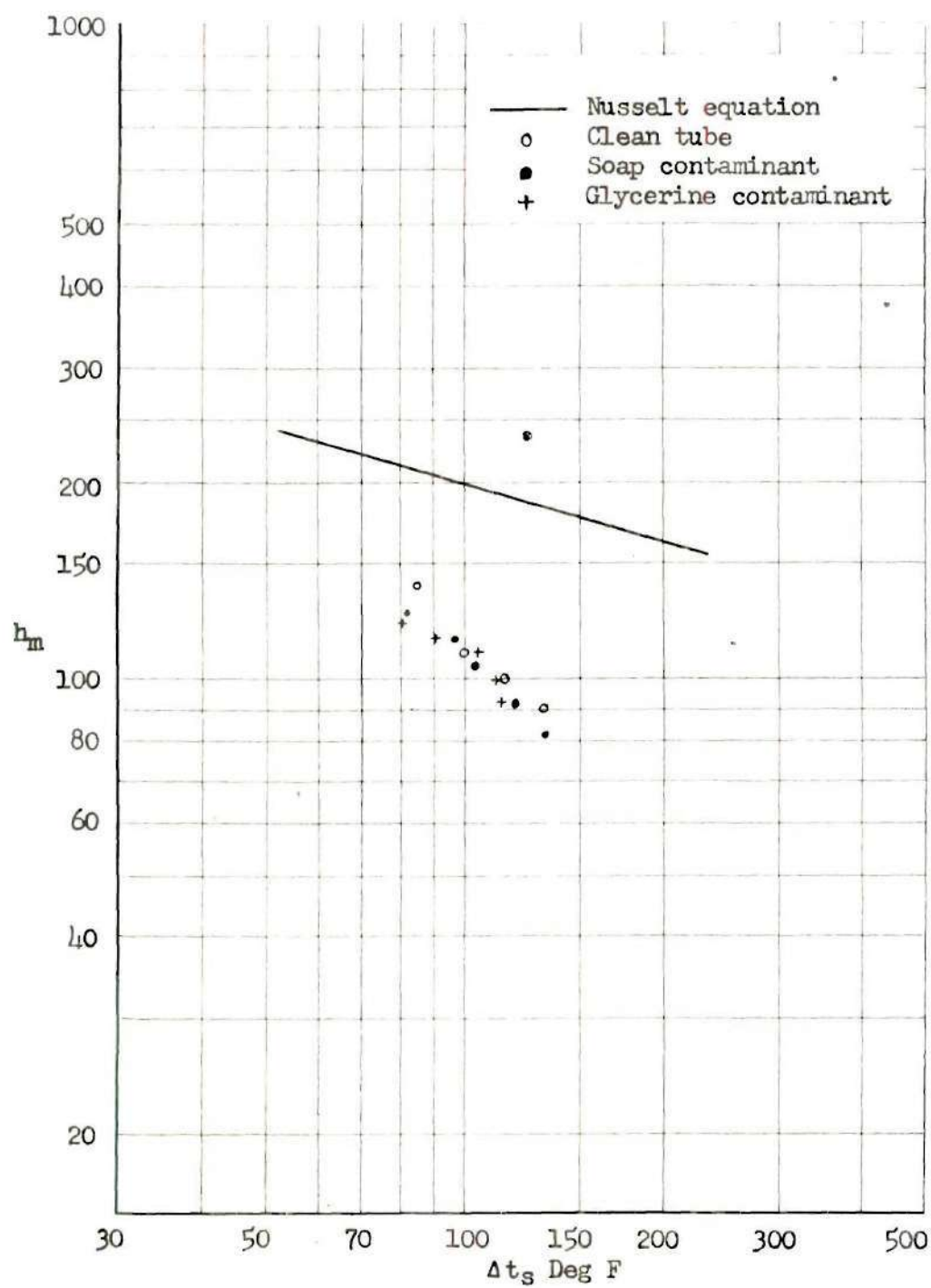
Figure 9 - Octane

Experimental Data Compared with Nusselt Equation
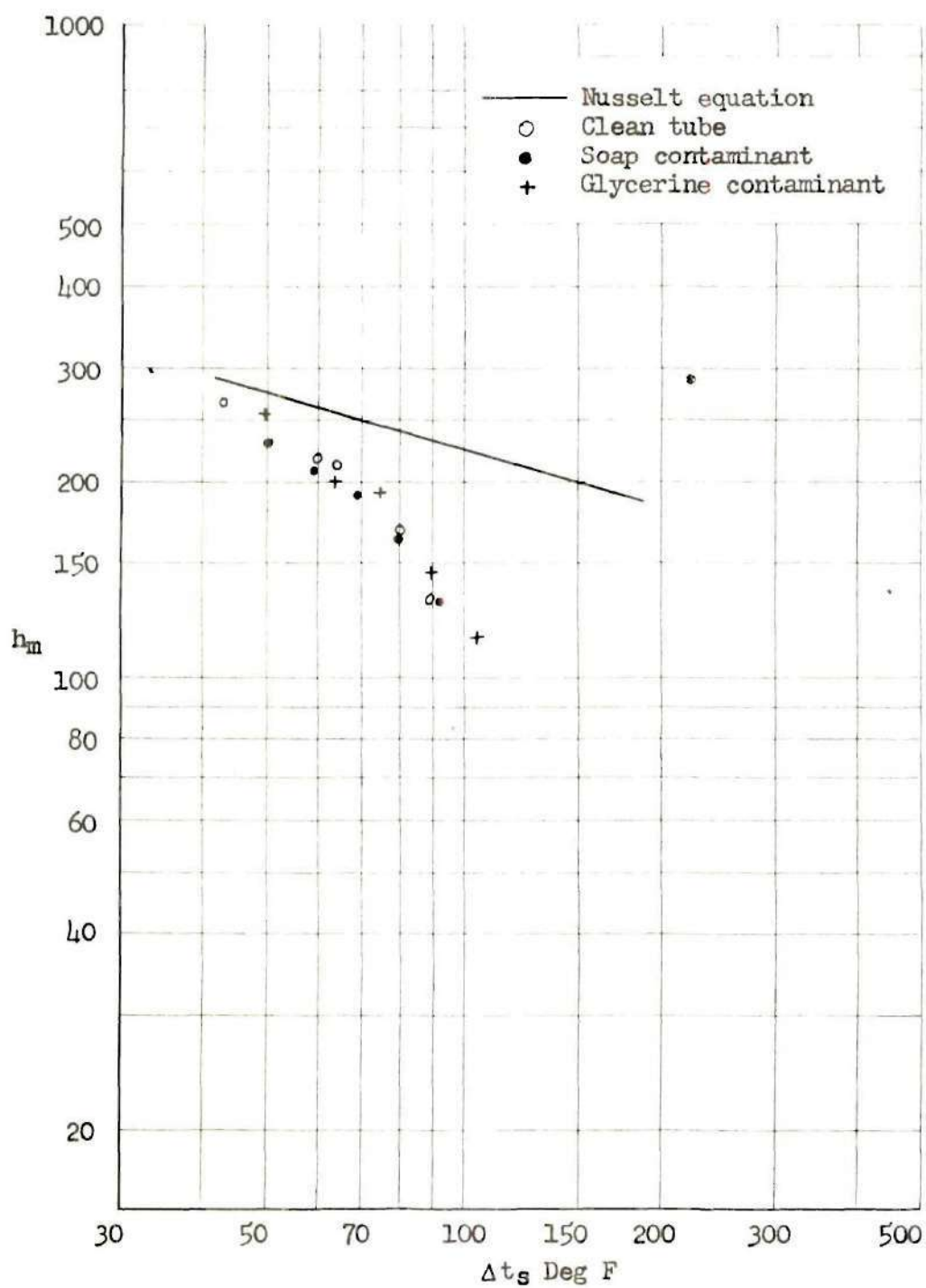
Figure 10 - Benzene

Experimental Data Compared with Nusselt Equation
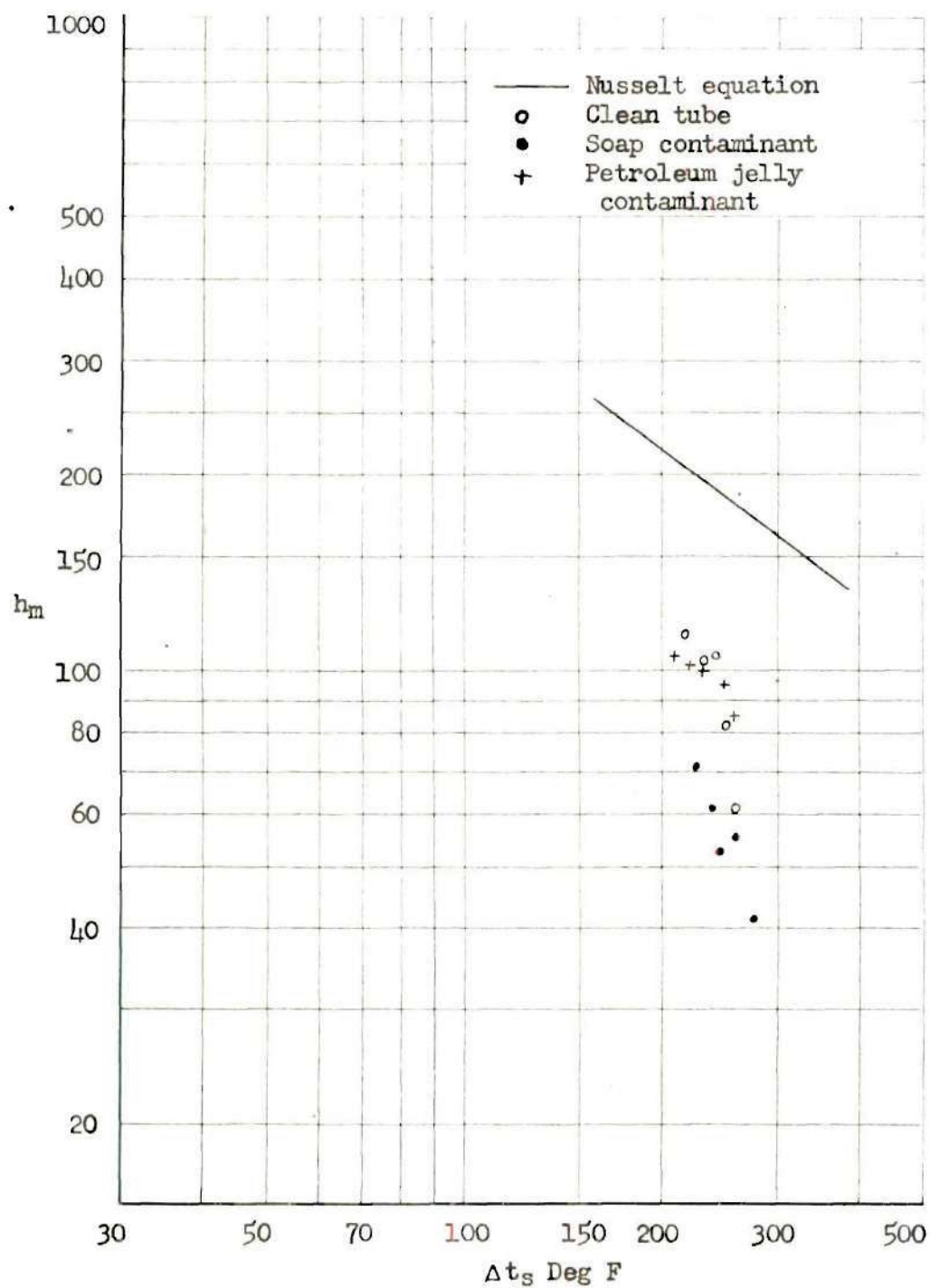
Figure 11 - Aniline

Experimental Data Compared with Nusselt Equation

APPENDIX C

EXPERIMENTAL RESULTS

Table 1. Effect of Contaminants on Octane

W - Surface readily wetted

S - Spreading occurred but showed small affinity

D - Drops formed, no wetting

Contaminant	Result on copper	Result on steel	Result on aluminum
Beeswax	W	W	W
Glycerine	S	S	W
Soap (Ivory)	S	S	S
Detergent (Tide)	W	W	S
Castor oil	W	W	W
Linseed oil	W	W	W
Olive oil	W	W	W
Acetic acid	S	S	S
Oleic acid	W	W	W
Rosin	W	W	W

Table 2. Effect of Contaminants on Benzene

W - Surface readily wetted

S - Spreading occurred but showed small affinity

D - Drops formed, no wetting

Contaminant	Result on copper	Result on steel	Result on aluminum
Beeswax	W	W	W
Glycerine	S	S	S
Soap (Ivory)	S	S	S
Detergent (Tide)	S	S	S
Castor oil	W	W	W
Linseed oil	W	W	W
Olive oil	W	W	W
Acetic acid	W	W	W
Oleic acid	W	W	W
Rosin	W	W	W

Table 3. Effect of Contaminants on Carbon Tetrachloride

W - Surface readily wetted

S - Spreading occurred but showed small affinity

D - Drops formed, no wetting

Contaminant	Result on copper	Result on steel	Result on aluminum
Beeswax	W	W	W
Glycerine	W	W	W
Soap (Ivory)	S	S	S
Detergent (Tide)	W	W	S
Castor oil	W	W	W
Linseed oil	W	W	W
Olive oil	W	W	W
Acetic acid	W	W	W
Oleic acid	W	W	W
Rosin	W	W	W

Table 4. Effect of Contaminants on Acetic Acid

W - Surface readily wetted

S - Spreading occurred but showed small affinity

D - Drops formed, no wetting

Contaminant	Result on copper	Result on steel	Result on aluminum
Beeswax	W	W	W
Glycerine	W	W	W
Soap (Ivory)	W	W	W
Detergent (Tide)	W	W	W
Castor oil	W	W	W
Linseed oil	W	W	W
Olive oil	W	W	W
Petroleum jelly	W	W	W
Oleic acid	W	W	W
Rosin	W	W	W

Table 5. Effect of Contaminants on Aniline

W - Surface readily wetted

S - Spreading occurred but showed no affinity

D - Drops formed, no wetting

Contaminant	Result on copper	Result on steel	Result on aluminum
Beeswax	W	W	W
Glycerine	W	W	W
Soap (Ivory)	D	D	D
Detergent (Tide)	S	S	S
Castor oil	W	W	W
Linseed oil	W	W	W
Olive oil	W	W	W
Petroleum jelly	D	D	D
Oleic acid	W	W	W
Rosin	W	W	W

Table 6. Heat Transfer Data

Vapor – Octane

t_{sv} – 208.6 Deg F

Contaminant – None

A_o – 0.053 Sq Ft

Corrected Barometer – 28.98 In Hg

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/ hr	Q Btu/ hr	t_v Deg F	t_s^e Deg F	Δt_s Deg F	h_m	h_{mt}
1	81.6	84.4	195.4	547.0	203.6	103.2	100.4	102.8	195.0
2	81.3	84.3	195.4	586.0	203.7	103.0	100.7	109.6	
3	80.8	83.5	195.4	527.0	202.8	105.6	97.2	102.2	
4	48.0	53.9	104.1	615.0	202.2	75.4	127.8	91.0	181.0
5	46.3	52.1	104.1	605.0	202.4	73.1	129.3	88.4	
6	44.6	50.6	104.1	625.0	201.2	76.0	125.2	94.2	
7	46.4	52.3	104.1	615.0	198.7	74.9	123.8	93.9	
8	51.4	57.7	104.1	656.0	199.3	85.3	114.0	108.6	
9	62.2	68.6	104.1	666.0	201.2	90.7	110.5	113.8	188.0
10	63.2	68.6	104.1	563.0	201.6	89.7	111.9	95.3	
11	89.5	93.0	189.6	663.0	201.8	115.4	86.4	145.0	
12	90.8	94.3	189.6	663.0	202.7	115.1	87.6	143.0	212.0
13	91.4	94.7	189.6	625.0	202.4	114.5	87.9	134.4	

Table 7. Heat Transfer Data

Vapor — Octane t_{sv} — 208.5 Deg F

Contaminant — Glycerine A_o — 0.053 Sq Ft

Corrected Barometer — 28.922 In Hg

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/ hr	Q Btu/ hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
14	48.1	53.8	101.6	580.0	206.3	90.9	115.4	94.9	
15	49.1	55.1	101.6	610.0	204.1	78.2	125.9	91.5	
16	49.6	55.3	101.6	580.0	204.6	87.5	117.1	93.5	186.0
17	62.6	68.4	101.6	590.0	204.5	94.3	110.2	101.0	190.0
18	64.2	70.5	101.6	640.0	204.2	85.9	118.2	102.1	
19	65.5	71.4	101.6	600.0	204.1	89.6	114.5	99.0	
20	82.5	85.6	189.6	586.0	205.4	100.7	104.7	105.6	
21	82.6	85.9	189.6	625.0	205.4	99.4	106.0	111.3	193.0
22	82.4	85.7	189.6	625.0	205.5	105.1	100.4	117.6	
23	95.9	98.7	189.6	530.0	205.6	117.0	88.6	113.0	
24	95.2	98.1	189.6	549.0	205.7	116.7	89.0	116.5	204.0
25	95.2	98.0	189.6	530.0	205.8	116.6	89.2	112.0	
26	102.1	104.6	197.0	492.0	205.3	122.4	82.9	112.0	
27	101.5	104.2	197.0	532.0	204.5	123.9	80.6	124.6	209.0

Table 8. Heat Transfer Data

Vapor – Octane t_{sv} – 208.6 Deg F

Contaminant – Soap (Ivory) A_O – 0.053 Sq Ft

Corrected Barometer – 28.957 In Hg

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/ hr	Q Btu/ hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
28	46.5	51.6	115.0	586.0	202.3	76.3	136.0	81.4	
29	48.0	53.2	115.0	598.0	202.3	75.1	127.1	88.8	181.0
30	47.0	51.9	115.0	563.0	202.8	74.1	128.7	82.7	
31	63.0	68.1	115.5	589.0	203.2	85.1	118.1	94.0	
32	64.1	69.1	115.5	578.0	204.2	88.0	116.2	94.0	
33	64.9	70.0	115.5	589.0	204.1	86.7	117.4	94.6	186.4
34	82.0	84.8	200.0	560.0	205.3	103.0	102.3	102.1	
35	82.4	85.3	200.0	580.0	205.1	102.9	102.2	107.0	195.3
36	82.4	85.4	200.0	600.0	205.2	103.2	102.0	111.0	
37	89.1	92.5	173.0	588.0	205.3	111.1	94.2	118.0	202.0
38	89.5	93.0	173.0	606.0	205.7	111.7	94.0	121.8	
39	89.5	92.7	173.0	553.0	205.7	111.3	94.4	110.6	
40	108.0	110.8	194.0	543.0	205.9	126.3	79.6	129.0	209.5
41	106.6	109.5	194.0	563.0	205.9	127.2	78.7	135.0	
42	105.9	108.6	194.0	524.0	205.7	125.8	79.9	124.0	

Table 9. Heat Transfer Data

Vapor – Benzene

Contaminant – None

Corrected Barometer – 28.947 In Hg

t_{sv} – 173.6 Deg F

A_o – 0.053 Sq Ft

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/hr	Q Btu/hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
43	49.8	55.7	108.0	637.0	168.8	78.5	90.3	133.2	
44	49.0	55.0	108.0	648.0	169.3	75.6	93.7	130.6	244.0
45	47.6	53.6	108.0	648.0	169.6	73.5	96.1	127.1	
46	61.9	68.2	108.0	680.0	170.8	90.0	80.8	159.0	
47	62.2	68.7	108.0	702.0	170.5	90.0	80.5	164.5	256.0
48	62.6	69.3	108.0	723.0	170.2	90.1	80.1	170.1	
49	81.8	85.4	198.5	715.0	170.5	105.3	65.2	207.0	
50	81.9	85.8	198.5	775.0	170.6	104.3	66.3	221.0	271.0
51	82.1	85.9	198.5	755.0	170.8	104.4	66.4	215.0	
52	91.8	95.2	197.0	670.0	171.2	111.2	60.0	211.0	
53	91.3	95.0	197.0	729.0	171.5	109.8	61.7	223.0	277.0
54	91.3	94.8	197.0	690.0	171.1	109.3	61.8	211.0	
55	111.1	114.1	195.5	586.0	171.8	129.3	42.5	260.0	
56	110.4	113.8	195.5	665.0	171.8	128.7	43.1	292.0	304.0
57	109.6	112.9	195.5	645.0	171.7	125.9	45.8	266.0	

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Table 10. Heat Transfer Data

Vapor – Benzene

t_{sv} – 173.6 Deg F

Contaminant – Glycerine

A_o – 0.053 Sq Ft

Corrected Barometer – 28.947 In Hg

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/ hr	Q Btu/ hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
60	41.0	43.7	233.3	630.0	169.5	64.5	105.0	113.1	237.0
61	42.7	45.8	233.3	723.0	171.9	64.8	107.1	127.2	
62	42.7	45.5	233.3	653.0	170.9	64.9	106.0	106.1	
63	57.4	60.5	225.0	698.0	172.2	82.5	89.7	147.0	250.0
64	58.1	61.1	225.0	675.0	173.2	81.3	91.9	138.8	
65	58.6	61.8	225.0	720.0	172.0	82.1	89.9	151.1	
66	82.7	84.5	413.0	744.0	172.2	96.8	75.4	186.2	
67	82.7	84.5	413.0	744.0	172.1	97.9	74.2	189.0	264.0
68	82.8	84.8	413.0	826.0	172.4	97.5	74.9	208.0	
69	94.2	96.0	413.0	744.0	172.7	107.9	64.8	216.2	
70	94.3	95.7	413.0	579.0	172.6	108.5	64.1	170.5	
71	93.6	95.2	413.0	662.0	171.9	108.4	63.5	196.5	276.0
72	109.8	111.5	406.0	690.0	172.1	121.7	50.4	258.0	
73	110.4	112.0	406.0	650.0	172.1	121.9	50.2	244.5	293.0
74	110.6	112.3	406.0	690.0	172.0	122.1	49.9	261.0	

Table 11. Heat Transfer Data

Vapor - Benzene

$t_{sv} \doteq 173.8$ Deg F

Contaminant - Soap (Ivory)

$A_0 - 0.053$ Sq Ft

Corrected Barometer - 29.052 In. Hg

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/hr	Q Btu/hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
75	49.6	54.9	121.0	641.0	166.5	73.4	93.1	130.0	
76	48.0	53.7	121.0	690.0	168.1	74.5	93.6	139.2	243.0
77	47.6	53.1	121.0	665.0	170.3	76.1	94.2	133.5	
78	59.5	65.2	121.0	690.0	170.6	86.9	83.8	156.3	
79	59.6	65.5	121.0	714.0	170.5	90.3	80.2	168.0	256.0
80	60.0	66.0	121.0	726.0	171.4	90.6	80.8	169.9	
81	81.6	84.9	210.0	693.0	172.4	103.0	69.4	188.5	
82	81.7	85.0	210.0	693.0	171.9	104.4	67.5	194.0	271.0
83	82.1	85.3	210.0	672.0	172.1	105.0	67.0	189.3	
84	94.8	98.1	208.0	686.0	172.2	112.9	59.3	218.1	
85	94.6	97.7	208.0	645.0	172.0	113.5	58.5	208.0	281.0
86	94.4	97.4	208.0	624.0	172.1	112.6	59.5	198.0	
87	110.7	113.6	206.5	600.0	172.2	121.7	50.5	224.0	
88	109.4	112.3	206.5	600.0	172.2	121.6	50.6	223.9	292.0
89	108.0	111.1	206.5	641.0	172.2	120.5	51.7	234.0	

Table 12. Heat Transfer Data

Vapor — Aniline t_{sv} — 356.6 Deg F

Contaminant — None A_o — 0.053 Sq Ft

Corrected Barometer — 29.077 In Hg

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/ hr	Q Btu/ hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
90	47.2	51.3	215.5	884.0	352.8	83.4	269.4	64.3	
91	46.9	50.9	215.5	862.0	349.8	85.9	263.9	61.6	
92	44.2	47.7	215.5	754.0	347.8	82.9	264.9	53.7	173.5
93	55.6	60.9	213.5	1130.0	347.8	96.9	250.9	82.4	
94	57.4	62.8	213.5	1151.0	346.3	93.9	252.4	86.0	180.0
95	81.7	85.4	382.0	1412.0	348.2	107.9	240.3	110.8	
96	82.2	85.8	382.0	1375.0	347.7	104.9	242.8	106.9	186.5
97	94.2	97.4	382.0	1221.0	343.9	113.3	230.6	100.0	
98	93.6	97.0	382.0	1300.0	343.4	113.7	229.7	106.8	
99	106.8	110.1	382.0	1260.0	343.8	128.7	215.1	110.5	
100	107.3	111.2	382.0	1490.0	344.3	127.6	216.7	129.8	199.0

Table 13. Heat Transfer Data

Vapor – Aniline t_{sv} – 356.6 Deg F

Contaminant – Petroleum jelly A_o – 0.053 Sq Ft

Corrected Barometer – 29.077 In Hg

Run No.	t_{wi} Deg F	t_{wo} Deg F	W lbs/ hr	Q Btu/ hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
101	85.9	89.7	168.0	638.0	339.6	109.9	229.7	52.5	
102	51.9	58.8	152.0	1050.0	356.5	100.2	256.3	77.3	
103	49.6	57.2	152.0	1155.0	356.5	100.5	256.0	85.1	183.0
104	47.7	55.7	152.0	1215.0	355.7	96.7	259.0	88.5	
105	59.4	67.6	152.0	1245.0	352.7	104.9	247.8	95.0	
106	59.5	68.0	152.0	1291.0	351.8	102.2	249.6	97.7	
107	60.2	68.5	152.0	1261.0	352.3	104.0	248.3	95.9	186.0
108	82.7	87.5	255.0	1223.0	351.8	116.5	235.3	98.1	
109	83.0	88.2	255.0	1326.0	350.8	118.2	232.6	107.5	194.0
110	82.6	88.2	255.0	1428.0	350.2	117.8	232.4	115.8	
111	95.3	100.3	252.0	1260.0	350.3	124.1	226.2	105.0	197.0
112	94.7	99.7	252.0	1260.0	349.4	123.7	225.7	105.3	
113	94.0	98.5	252.0	1133.0	348.8	125.5	223.3	95.9	
114	105.1	109.7	247.0	1138.0	349.1	130.8	218.3	98.3	201.0
115	104.6	109.8	247.0	1285.0	348.8	130.7	218.1	111.0	
116	104.2	108.6	247.0	1086.0	349.8	133.5	216.3	94.7	

Table 14. Heat Transfer Data

Vapor – Aniline t_{sv} – 356.4 Deg F

Contaminant – Soap (Ivory) A_o – 0.053 Sq Ft

Corrected Barometer – 28.981 In Hg

Run No.	t_{w1} Deg F	t_{wo} Deg F	W lbs/ hr	Q Btu/ hr	t_v Deg F	t_s Deg F	Δt_s Deg F	h_m	h_{mt}
117	49.4	52.8	175.0	595.0	343.3	71.7	271.6	41.4	
118	48.8	52.2	175.0	595.0	343.3	71.0	272.3	41.2	168.0
119	48.4	51.3	175.0	507.0	340.0	68.4	271.6	35.3	
120	60.2	64.6	174.0	766.0	347.6	89.2	258.4	55.9	
121	60.6	65.0	174.0	766.0	350.2	88.7	261.5	55.3	177.3
122	61.2	65.8	174.0	800.0	352.5	89.8	262.7	57.4	
123	84.8	87.9	221.0	686.0	351.3	105.4	245.9	52.6	
124	84.8	87.8	221.0	663.0	350.3	102.5	247.7	50.5	184.5
125	84.9	87.9	221.0	663.0	348.2	104.6	243.6	51.4	
126	95.5	98.9	221.0	752.0	352.6	112.8	239.8	59.2	
127	95.8	99.7	221.0	863.0	351.1	113.3	237.8	68.5	190.5
128	95.0	98.5	221.0	774.0	352.2	113.5	238.7	61.1	
129	106.7	110.4	221.0	818.0	352.7	125.3	227.4	67.9	
130	105.6	109.9	221.0	951.0	352.3	122.4	229.9	78.1	196.0
131	104.3	108.2	221.0	863.0	352.6	122.7	229.9	71.0	

APPENDIX D

CALIBRATION DATA AND CALCULATION METHODS

CALIBRATION DATA

The thermocouples used were made from wire manufactured by Leeds and Northrup Co. and temperature determinations were made from a Leeds and Northrup table of millivolt equivalents. The table was plotted on a large graph to facilitate interpolation. The thermocouple readings were checked for accuracy by the use of a mercury-glass thermometer previously calibrated by the U. S. Bureau of Standards. It was assumed that the thermocouples were functioning properly if they were accurate at any arbitrary check point. All thermocouples were immersed in an insulated water bath and the standard thermometer (with stem thermometer attached) was immersed to the point "0" degrees F. Data was obtained as follows. (All readings are in degrees F.)

Standard thermometer reading	Stem thermometer reading	Stem correction	Actual temperature	Thermocouple reading (millivolts)
51.4	93.0	− 0.19	51.21	51.3 (.4244)
86.0	82.5	0.027	86.03	86.2 (1.195)
110.4	91.6	0.187	110.6	110.7 (1.765)

All thermocouples were found to read the same (within 0.1 degrees Fahrenheit.)

The stem correction was calculated by the following formula, which was found on the certificate accompanying the standard thermometer.

$$K = 0.00009 \ D \ (t_1 - t_2)$$

where;

K = correction in degrees F

D = number degrees exposed filament

t_1 = reading of main thermometer

t_2 = reading of attached thermometer

The boiling points of the test liquids were given at standard atmospheric pressure, hence, it was necessary to apply corrections to find the true boiling points at the existing pressures. This was done by means of the following relation, which is given by Lange in the Handbook of Chemistry.

$$C = K \ (760 - P)(460 + T)$$

where;

C = correction in degrees F

K = 0.000125 for octane and benzene; 0.000118 for aniline

P = barometer reading, mm Hg

T = boiling point as given

CALCULATION METHODS

The outside area of the test surface (A_O) was taken as the product of the circumference times the length of the tube. The area of the plug at the bottom of the tube was neglected, in as much as a similar area near the top of the tube was occupied by a packing gland for the surface thermocouple wires. Hence,

$$A_O = \frac{(3.14)(5/8)(3-7/8)}{(144)} = 0.053 \text{ Sq ft}$$

The rate of heat transfer (Q) was found by multiplying the water rate (W) by the change in the water temperature ($t_{wo} - t_{wi}$). The specific heat (c_p) of water in the range of temperatures used was assumed to be unity. Thus,

$$Q = (W)(t_{wo} - t_{wi}) \text{ Btu per hour}$$

The condensing film coefficient (h_m) was found by dividing the heat transfer rate (Q) by the product of the area (A_O) times the change in temperature across the film ($t_v - t_s$). Thus,

$$h_m = \frac{(Q)}{(A_O)(t_v - t_s)} \text{ Btu/(hr)(sq ft)(deg F)}$$

The theoretical film coefficient (h_{mt}) was found by the use of an equation developed by Nusselt and given by McAdams in the following form.

$$h_{mt} = 0.943 \left(\frac{(k_f)^3 (\rho_f)^2 (g)(\lambda)}{(\mu_f)(L)(t_{sv} - t_s)} \right)^{\frac{1}{4}}$$

The symbols in the above equation are defined on page 31. All numerical values were determined from tables and charts collected by McAdams (17), with the exception of the density (ρ_f), which was determined from the International Critical Tables. For the purpose of these calculations, the Nusselt equation was reduced to the following forms.

For octane, $h_{mt} = 0.943 \left(\dfrac{(1866 \times 10^8)(k_f)^3 (\rho_f)^2}{(\mu_f)(t_{sv} - t_s)} \right)^{\frac{1}{4}}$

For benzene, $h_{mt} = 0.943 \left(\dfrac{(2505 \times 10^8)(k_f)^3 (\rho_f)^2}{(\mu_f)(t_{sv} - t_s)} \right)^{\frac{1}{4}}$

For aniline, $h_{mt} = 0.943 \left(\dfrac{(2882 \times 10^8)(k_f)^3 (\rho_f)^2}{(\mu_f)(t_{sv} - t_s)} \right)^{\frac{1}{4}}$

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