THE EFFECT OF UNSATURATION IN C_{18} FATTY ACIDS ON STEAM CONDENSATION

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
Robert Alexander Brandon
1961

This is to certify that the

thesis entitled

The Effect of Unsaturation in C_{18} Fatty
Acids on Steam Condensation

presented by

Robert Alexander Brandon

has been accepted towards fulfillment
of the requirements for

M.S. **degree in** Chemical Engineering

Major professor

Date February 20, 1961

O-169

ABSTRACT

THE EFFECT OF UNSATURATION IN C_{18} FATTY ACIDS ON STEAM CONDENSATION

by Robert Alexander Brandon

Steam condenses by two distinctly different mechanisms, drop condensation or film condensation, or by a combination of the two called mixed condensation. Much higher heat transfer coefficients are obtained for drop condensation than for film condensation, but the occurrence of drop condensation requires that the condensing surface be coated with a layer of chemical promoter. This layer must be at least one molecule thick, and preferably only one molecule thick. All effective promoters of drop condensation have an electron-rich polar part which bonds to the metal condenser surface and a hydrophobic hydrocarbon part which stands away from the condenser surface making the surface nonwettable.

The present investigation was undertaken to determine the influence, if any, of unsaturation on a compound's effectiveness as a promoter of drop condensation of steam. To accomplish this, the overall heat transfer coefficients in Btu/(hr)(ft^2)(°F) resulting from drop condensation promoted by four C_{18} fatty acids (stearic, oleic, linoleic, and linolenic; all identical except for degree of unsaturation) were determined and compared at several different cooling water rates.

The determinations were made with a copper finger-type condenser inserted through a treated cork into the vapor space of a flask containing boiling water. The promoters used were of the highest purity available and were handled with extreme care to prevent contamination or oxidation before they were dropped into the water in the flask or rubbed on the condenser surface. The overall heat transfer coefficients were calculated from measurements of the cooling water rate and its temperature at the inlet and outlet of the condenser, and knowledge of the steam temperature and the surface area of the condenser. Much care was taken to obtain accurate measurements and to minimize the effects of outside influences.

The results of the investigation showed no correlation between the degree of unsaturation in a compound and its effectiveness as a promoter of drop condensation of steam, but they did contain some very unusual graphs of overall heat transfer coefficient versus cooling water rate. They also showed that promoters, when rubbed on the condenser surface, can result in an overall heat transfer coefficient lower than that obtained with an unpromoted surface. Appearance of the copper salts of the various acids on the condenser surface and in the flask after addition of the acid indicated that the promoter was reacting with copper or copper oxide from the condenser surface. It is recommended that several changes be made in the apparatus and that the study of the effect of unsaturation on a compound's ability to promote drop condensation be continued.

THE EFFECT OF UNSATURATION IN C_{18} FATTY ACIDS ON STEAM CONDENSATION

By

Robert Alexander Brandon

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Chemical Engineering

1961

[illegible]
7/25/[illegible]

ACKNOWLEDGEMENT

The author wishes to thank his major professor, Dr. C. C. DeWitt of the Department of Chemical Engineering, Michigan State University, for his invaluable aid in obtaining the materials for this study, for his counsel during operations, and for his encouragement during the preparation of this paper. Thanks are also due to Dr. C. V. Foster of Continental Oil Company for advice and encouragement given during preparation of the paper, to Dr. M. F. Obrecht of Michigan State University, who was instrumental in initiating the study, to Dr. C. F. Gurnham of the Department of Chemical Engineering, Michigan State University, for his help while acting as major professor after Dr. DeWitt's retirement, to Mrs. Barbara Judge for typing, and to Shirley Brandon for her aid in making calculations.

The financial aid of the scholarship given by the Dow Chemical Company is very much appreciated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

INTRODUCTION

A saturated vapor, such as steam, may condense on a cooled surface by either of two distinctly different mechanisms, or by a mixture of the two (Figures 1, 2, 3). The most commonly occurring mechanism is called film condensation. It occurs when the condensate completely wets the condensing surface and forms a continuous liquid film over the entire surface. The second mechanism is known as drop condensation and occurs on a non-wettable surface. Here the condensate forms in droplets ranging in size from microscopic to diameters of one-eighth inch or more. When the condensing surface is partially wettable, a combination of film and drop condensation called mixed condensation occurs. It is characterized by areas of drop and areas of film condensation occurring side by side on a condensing surface. The relative amount of each type of condensation varies according to the wettability of the surface.

When film condensation occurs, a layer of liquid condensate builds up on the condensing surface. The thickness of this layer depends on the density and viscosity of the condensate, the vapor friction, the rate of condensation, and the distance from the top of the condenser; the last due to the increase in volume of condensate runoff on the lower portions of the condensing surface. Liquids are poor conductors of heat. Since all the heat given up by the condensing vapor must pass through the liquid condensate layer, its presence reduces the amount of heat transferred and, therefore, the condensation rate.

Drop condensation originates in many tiny droplets of uniform size and shape. These droplets grow by condensation on their surfaces and by coalescence with neighboring droplets until they reach a critical size determined by the viscosity

FILM CONDENSATION

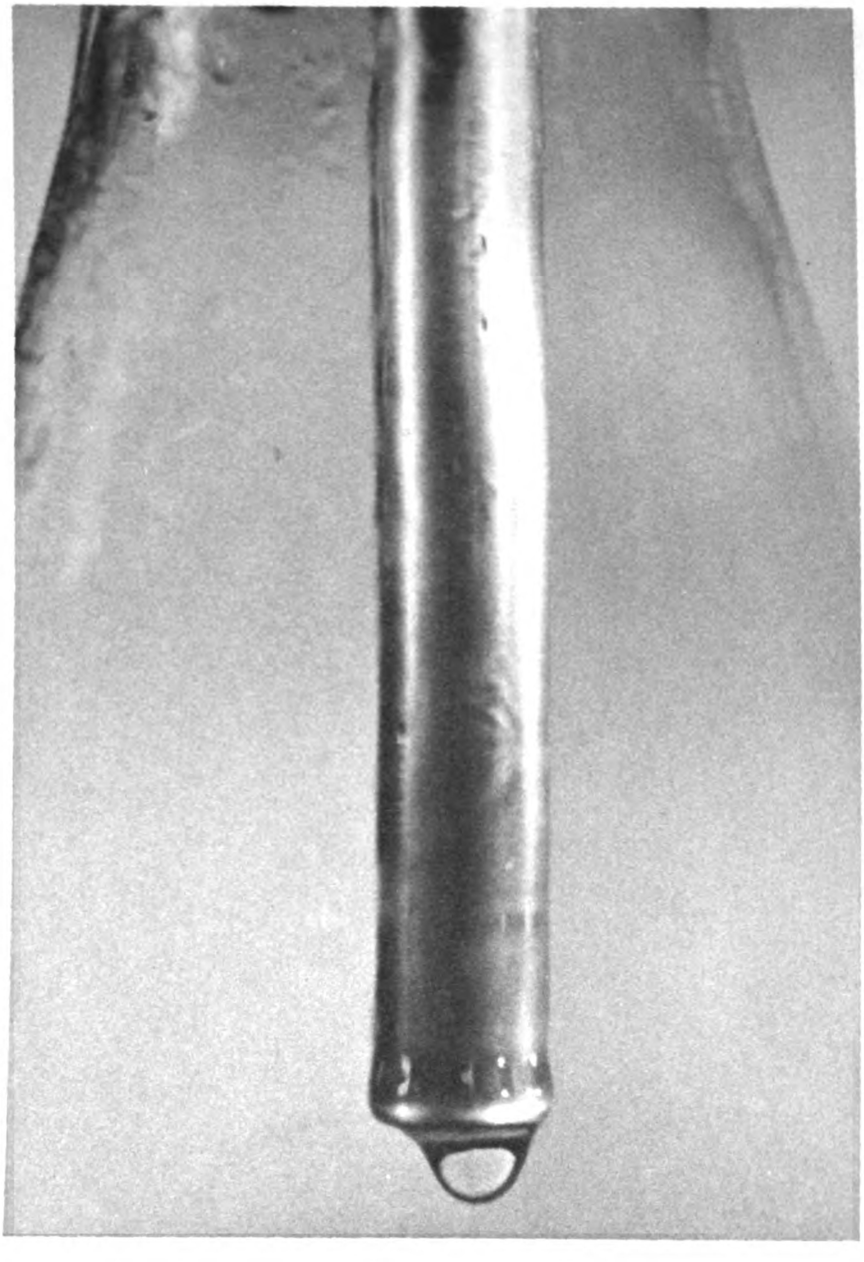


Figure 1

DROP CONDENSATION

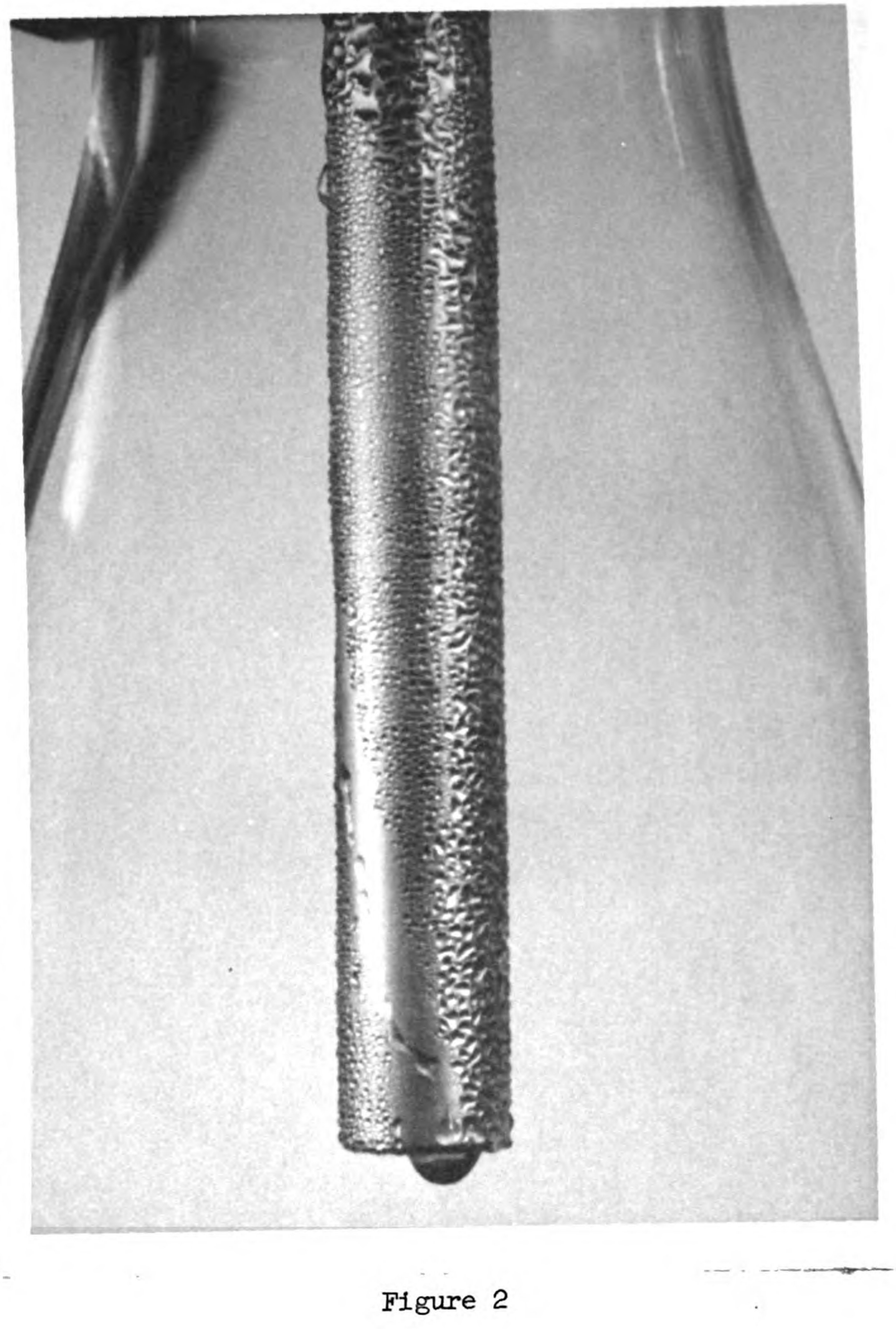


Figure 2

MIXED CONDENSATION

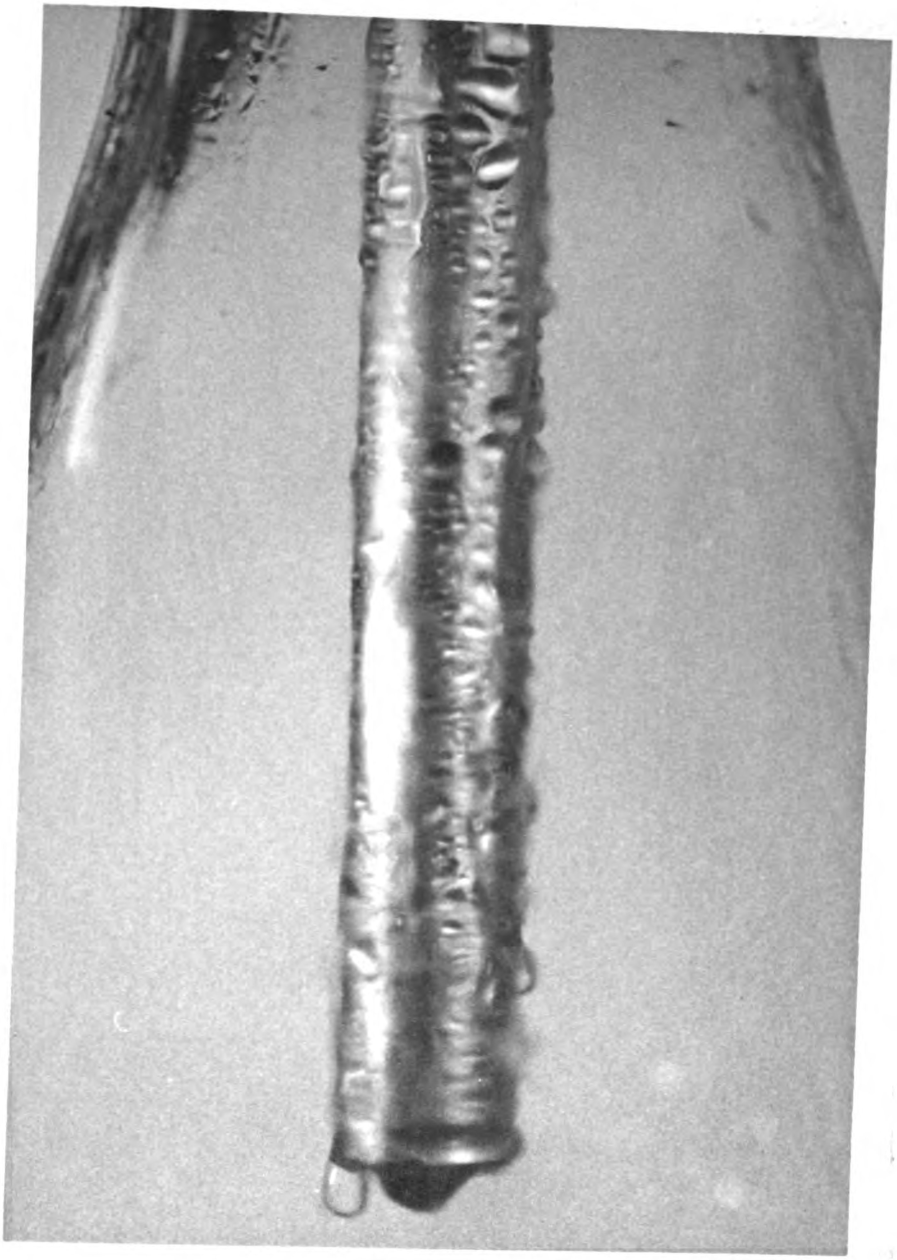


Figure 3

and density of the condensate, the vapor friction, and the relative surface tensions. The droplets then roll down the condensing surface sweeping with them all droplets in their path and leaving a bare surface behind them. New droplets of condensate form on the bare surface, and the cycle repeats. Droplets cover only about 45% of the condensing surface at any one time during drop condensation. The large free area results in a much larger temperature difference through the condenser wall and give local heat transfer coefficients ten to twenty times larger than those obtained for film condensation.

Film condensation is much more prevalant than drop condensation because, although many compounds will render a surface nonwettable, only those which are not removed by the scouring action of the steam and condensate are efficient drop promoters. All efficient drop promoters are compounds having molecules composed of a long hydrocarbon chain attached to an active polar group. The polar group bonds to the metal condensing surface leaving the hydrocarbon chain standing away from it. When a monomolecular layer of these molecules forms on a condensing surface, only the long nonwettable hydrocarbon chains are exposed to the condensing vapor and drop condensation results.

Stearic acid and oleic acid, both C_{18} fatty acids having no double bond and one double bond respectively, are good promoters of drop condensation. The purpose of this investigation was to determine the effect of double bonds on a compound's ability to promote drop condensation. To make this determination a comparison was made of the overall heat transfer coefficient, U, obtained from a condenser when treated with each of the following C_{18} fatty acids: stearic, oleic, linoleic (two double bonds), and linolenic (three double bonds).

HISTORY

Pioneers in the study of drop condensation of steam were Schmidt, Schurig, and Sellschopp (23). In 1930 they reported on studies of condensation on the face of a vertical copper disc 1 mm thick by 15 cm in diameter cooled by a high velocity jet of water directed against the rear center of the disc. A glass section in the steam chest permitted observation of the condensing surface while measurements of the disc temperatures and the inlet and outlet water temperatures permitted calculation of heat transfer coefficients. The investigators discovered that complete film condensation occurred when the copper disc had been etched with zinc chloride dissolved in HCl. They obtained drop condensation on a freshly polished disc (the method of polishing was not mentioned) and on the etched disc after long use. The drop condensation on the polished plate, however, changed to film condensation in areas where iron rust from the steam accummulated. Their condensation rates for drop condensation were 1.9 to 2.5 times those obtained for film condensation. They stated that the change to drop condensation on their etched plate was "produced possibly by dirt or little drops of oil brought in with the steam," but concluded that steam condenses as a continuous film on "dirty surfaces and surfaces roughened by etching" and condenses as drops on "clean and smooth surfaces."

In 1931, Spoelstra (25) published the results of his investigations on the condensation of steam on tubes taken from evaporators in Javanese sugar mills. He had observed that a lower heat transfer coefficient resulted after using naphtha to clean tubes fouled with a scale containing 15 to 30 percent oily substances. Subsequent investigations showed that the presence of oil in scale markedly increased the heat transfer coefficient over that obtainable with the same scale when oil free, and even over that obtainable with a clean tube if the scale used for comparison was thin and very oily. A slightly oily scale resulted in a decreased coefficient. He also showed that injection of oil into steam condensing on oil-free tubes would cause some increase in the heat transfer coefficient for badly pitted tubes but would cause a marked increase in the coefficient for smooth tubes. After the appearance of the paper by Schmidt, Schurig, and Sellschopp, Spoelstra built an apparatus permitting observation of the condensation and found that drop condensation accompanied the increased heat transfer coefficients. He also found that drop condensation would occur on slightly roughened tubes but not on badly fouled and pitted tubes.

In 1932, Jakob (11) reported that qualitative measurements indicated that film condensation occurs when steam flows parallel to the cooling surface at high velocities but that mixed condensation usually appears at low steam velocities; both conditions, however, being dependent on the cleanliness and characteristics of the condensing surface. A year later Jeffrey and Moynihan (15) concluded from a series of tests that a tube had to be "chemically" clean to obtain film condensation and that "commercially" clean tubes contain a contaminant, probably an oily film, that renders the surface nonwettable, causing drop condensation even on etched or slightly oxidized surfaces. They obtained much higher overall heat transfer coefficients for drop condensation.

The results of an extensive study of the mode of condensation were published in 1932 by Nagle and Drew (19). They had observed during the operation of a falling film condenser that the heat transfer coefficient increased with time. To investigate this, two small falling film condensers with pyrex steam jackets were built. Operation of these showed that the increasing coefficient obtained with the larger condenser was due to a change from film to drop condensation caused by a contaminant in the steam. The small condensers were then used to investigate condensation on tubes of different metals, each being tested with different degrees of surface roughness and with different oils or fats rubbed on the surface. The metals used were: copper, brass, nickel, Monel metal, steel, aluminum, chromium-plated copper, chromium-plated brass, and 18-8 chromium-nickel steel. The oils and fats were: Russian mineral oil, fuel oil, kerosine, mutton tallow, beeswax, olive oil, stearic acid, oleic acid, and the fatty binders of two commercial buffing compounds. Condensation resulting from the different combinations of metals and surface coatings varied from 100 percent drop to 100 percent film, with many degrees of mixed condensation being found between. Steel and aluminum were judged unsuitable for a study of drop condensation because corrosion rapidly roughened their surfaces. Oleic acid was found to be the best promoter of drop condensation.

A patent was issued to Nagle (17) in 1935 covering the method of improving condenser efficiency by forming on the condensing surface a film of material which tenaciously resists removal by the normal action of the vapor and its condensate and is nonwettable by the condensate. The film-forming materials were to be organic compounds having a non-polar part attached to a polar part. They included fatty acids, dithiophosphates, mercaptans, and organic compounds containing bivalent sulfur along with a polar part and a non-polar part. The patent also covered condensing apparatus having such a film on the condensing surface.

Nagle and Drew (18) in 1935 co-authored a paper with Bays and Blenderman in which they reported steam-side heat transfer coefficients having values 15 to 19 times the value predicted by the Nusselt equation. The coefficients were obtained from a copper falling-film condenser, chromium plated on the steam side, and promoted with oleic acid.

In a second paper published in 1935, Drew, Nagle, and Smith (3) tabulated the results of various combinations of condenser metal and promoter used in their own and most of the previous investigations on drop condensation of steam. The metals listed were generally those mentioned above in connection with an earlier paper by Nagle and Drew (19). The promoters listed were: mineral oils, fatty acids, soap, fats and waxes, alcohols, sulfides and mercaptans, xanthates, dithiophosphates, sulfur compounds, nitrogen compounds, and halides. Drew, Nagle, and Smith concluded:

"1. Clean steam, whether or not it contains noncondensable gas, always condenses in a film on clean surfaces, rough or polished.

2. Dropwise condensation of steam does not occur unless the cooling surface is in someway contaminated.

3. Although numerous substances, while actually on the surface, will make it nonwettable, only those that are strongly adsorbed or otherwise firmly held are significant as drop promoters on a condenser. Some contaminants seem to depend for their activity as promoters on the amount of noncondensable gas present. Some contaminants are specifically effective on certain metals (e.g., mercaptans on copper alloys); others are quite generally effective (e.g., fatty acids). Boiler steam at the M. I. T. naturally contains drop-promoters which are effective on some metals but not on others.

4. Dropwise condensation is induced and maintained more easily on smooth surfaces than on rough."

Basing his ideas on the work of previous investigators, Jakob (12) in 1936 proposed a mechanism for condensation revolving around the idea that the steam condenses on the dry cooling surface to form a very thin layer which is continually drawing up to form droplets. He concludes that the thickness of the layer depends principally on the behavior of the surface and of the nuclei initiating the condensation. He presents calculations to determine the limits on the thickness of the layer.

Since all previous investigations on drop condensation had been performed on short tubes, Fitzpatrick, Baum, and McAdams (8) in 1938 presented experimental evidence of benzyl mercaptans effectiveness for promoting increased heat transfer coefficients on copper and admiralty metal tubes of commercial length (ten feet).

Emmons (4) in 1939 proposed molecular mechanisms for drop and film condensation based on published studies of the behavior of molecules on surfaces. He noted the conditions favorable to drop condensation and listed the following properties as characteristic of a good drop promoter:

"1. Part of the (promoter) molecule must have very small affinity for the vapor molecules.

2. Another part of the molecule must have a large affinity for the cooling surface.

3. These parts must be so combined that a monomolecular layer has one active surface and one inactive surface."

Emmons states that drop condensation will occur when a monomolecular layer of such a promoter is deposited on the cooling surface with the inactive side exposed to the vapor, and that only one layer of molecules, i.e., a monomolecular layer, is responsible for drop promotion. Data gathered from a finger type condenser similar to the one used by Drew, Nagle, and Smith (3), and an apparatus which deposited a single layer at a time of calcium stearate on the condenser surface are presented to support his statements.

The effects of steam velocity, length of vertical condensing surface, and heat load on film condensation and benzyl mercaptan promoted drop condensation were studied by Shea and Krase (24) in 1940. They condensed steam on a vertical copper plate backed by a water jacket divided into five separate sections, each 4 inches wide and 4.6 inches high, and each equipped with a means of controlling and measuring the cooling water flow rate, and of measuring inlet and outlet temperatures of the cooling water. Their results indicated a change in heat transfer coefficient with length of condenser, steam velocity, and heat load; though the effect of heat load is slight. For drop condensation, their data showed an increase in coefficient with steam velocity until the condensate runoff reached a certain level after which it dropped with increasing steam velocity. The data also showed a constant increase in resistance to heat transfer with length thus permitting prediction of average coefficients for longer tubes.

A mechanism for drop condensation differing somewhat from that proposed by Emmons (4) appeared in an article by Fatica and Katz (6) in 1949. In this paper the authors developed a theoretical equation relating the average heat transfer coefficient between the vapor and the metal condensing surface to the fraction of condensing area covered by droplets, the advancing and receding contact angles, the angle of inclination of the condensing surface, the thermal conductivity of the condensate, and the surface tension of the condensate. Experimental data was presented to prove the soundness of the equation.

Hampson (9) in 1951 published results of a study of condensation on a flat copper or brass surface which could be set at various angles with the horizontal. For drop condensation on a copper surface promoted with oleic acid, he found that the heat transfer coefficient decreased as the surface was tilted from the vertical to the horizontal, but found an increase for film condensation on a horizontal surface facing downward. Contrary to the results obtained for film condensation, Hampson's data showed little decrease in the coefficient with increasing heat load for drop condensation. He found also that the presence of a given amount of noncondensable gas would cause a much larger percentage drop in the heat transfer coefficient for drop condensation than for film condensation but that the reduced coefficient was still greater than that for film condensation.

The results of a study on the duration of drop condensation were published by Hampson (10) in 1955. In his study he used condensing surfaces of brass, copper, stainless steel, and chromium-plated steel. These were promoted with either pure benzyl mercaptan, pure oleic acid, mixed oleic acid and benzyl mercaptan, oleic acid mixed with light lubricating oil, or benzyl mercaptan mixed with light lubricating oil. He found that:

1. Drop condensation lasts appreciably longer on a mirror-finished surface than on rougher finishes.

2. Mixed promoters promote drop condensation longer than any single substance in the mixture.

3. The presence of a noncondensable gas increases the life of a drop-giving surface more than would be expected from the reduction of the condensation rate due to the presence of the gas.

4. The cleanliness of the metal surface before treatment with promoter appreciably affects the life of the drop condensation.

5. The life of a drop-giving surface is decreased as the rate of condensation is increased.

The study also presented further evidence in support of the conclusions reached earlier by Nagle and Drew (19) that promoters have different effects on different metals and that a promoter is necessary to produce drop condensation.

An investigation of drop condensation of steam was initiated at Michigan State University in 1955 by Erickson (5) and Squire (26) in two separate studies. Each used a copper finger type condenser similar to that used originally by Drew, Nagle, and Smith (3), and introduced the promoters by rubbing them on the surface of the condenser. Squire found that both octadecylamine acetate and stearic acid gave an overall heat transfer coefficient about 10% higher than that obtained for pure steam. Erickson's results indicated that stearic acid was more effective in increasing the overall heat transfer coefficient that either octadecylamine or dodecylamine, the latter being somewhat less effective than the former. His test with octylamine produced an overall coefficient lower than that obtained for distilled water exhibiting complete film condensation in spite of the fact that octylamine exhibited the best drop condensation obtained in his investigations. A resistance due to the formation of a copper-amine complex was proposed.

Packer (21) continued the investigation at Michigan State University in 1956 using the apparatus of Erickson and Squire with some modifications. Overall heat transfer coefficients calculated for a cooling water velocity of about two feet per second show the following order, greatest to least, of effectiveness of the promoters studied by Packer: stearic acid (rubbed on), dodecanethiol, tridecane-nitrite, octanoic acid, 1-octanol, 1-dodecanol, stearic acid, and lauric acid. 1-Octadecanol exhibited a coefficient lower than that exhibited by the distilled water control. Except as noted above, the promoter was carried to the condenser in the steam. At the two foot per second water velocity, the coefficient for condensation promoted by stearic acid rubbed on was about twice that calculated for pure water but the increase varied inversely with water velocity. Also, the order of effectiveness of the different promoters varied somewhat with water velocity.

The latest work to appear on drop condensation is that of Blackman, Dewar, and Hampson (1), who in April of 1957 published the results of a study using copper and brass surfaces promoted by specially synthesized compounds containing divalent selenium or sulfur as the surface-active atoms. Thirty-seven compounds were tested for periods of 500 to 3530 hours without deterioration of the drop condensation. Nearly as many more were tested for two hours similarly without deterioration of the drop condensation. The long periods of perfect promotion prevented the desired correlation between structure of the compound and its life as a promoter. The study showed, however, that the drop-promoting effectiveness of compounds having their hydrophobic hydrocarbon chain hindered by a hydrocarbon chain of similar length attached to the same surface-active atom and ending in a polar group varied directly with the ratio of the length of the hydrophobic chain to the length of the polar chain. Also, compounds containing sulfur atoms with all their valency electrons in use were found ineffective as drop promoters. Finally, Blackman, Dewar, and Hampson found on two separate occasions that promoted condensation starting on rough, badly corroded tubes changed from mixed or poor quality drop to perfect drop in three to four days and that the badly discolored surfaces brightened to very near the color of new metal within two weeks.

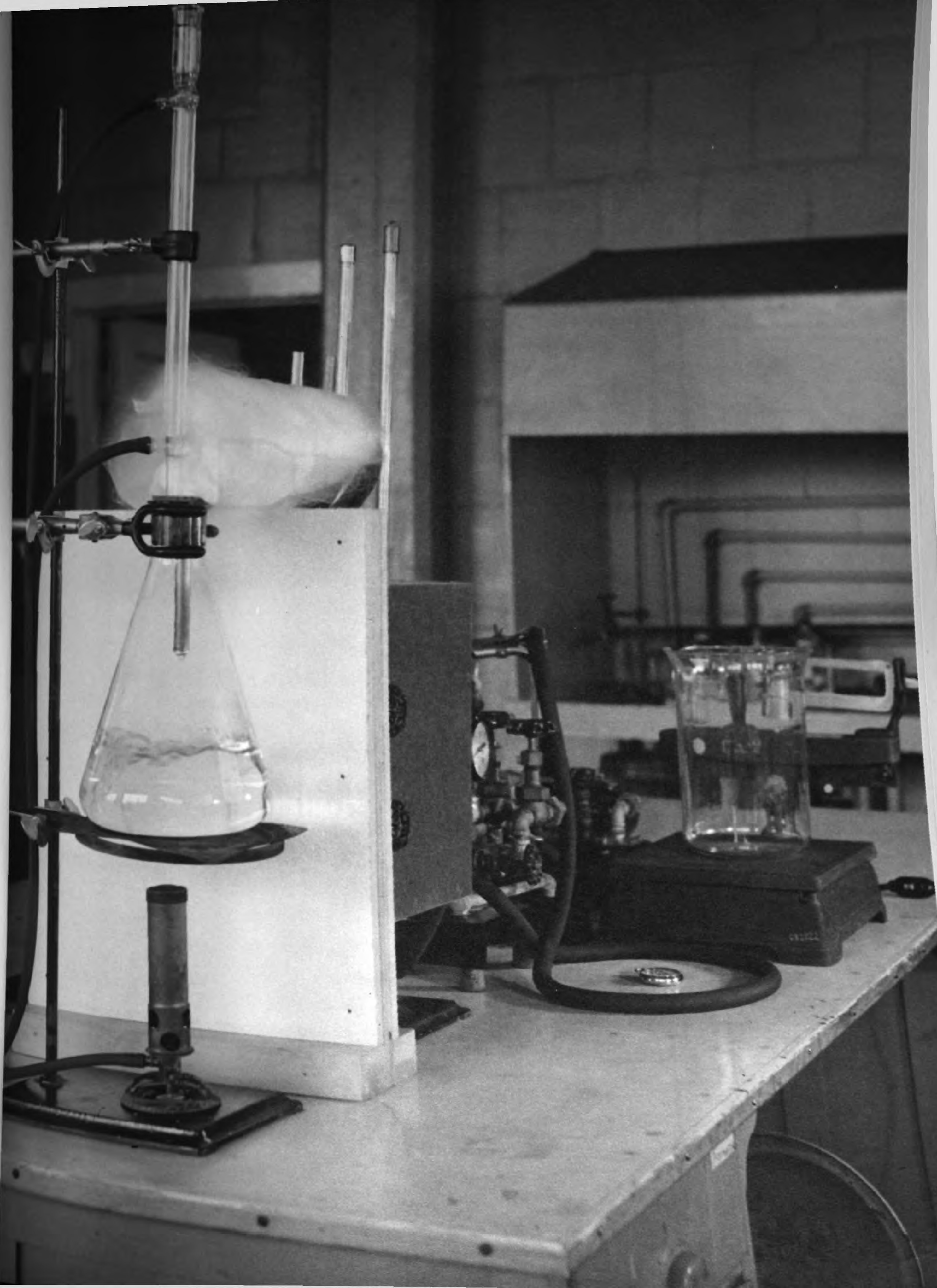
APPARATUS

The condenser (Figure 5) used for this study was similar to the modification made by Drew, Nagle, and Smith (3) of Spoelstra's (25) original finger-type condenser, subsequent modifications also being made by Emmons (4), Erickson (5), Packer (21), and Squire (26). It consisted of two concentric copper tubes and an outlet arm, the outer tube having an outside diameter of 0.496 inch and an inside diameter of 0.437 inch, and the inner tube having an outside diameter of 0.250 inch and an inside diameter of about 3/16 inch. The top of the larger tube was drawn down into a collar which fitted snugly around the outside of the smaller tube. The smaller tube was positioned and soldered into the collar so that its lower end was 1/8 inch above the lower end of the larger tube. A circular copper plate slightly less than 0.496 inch in diameter, soldered in place, closed the lower end of the larger tube, and a piece of the smaller tubing soldered into an opening 5-3/4 inches above the bottom of the 6 inch long outer tube formed the outlet arm. Two 1/4 to 1/2 inch copper expansion couplings soldered to the outer ends of the outlet arm and inner tube for hose connections completed the condenser. All joints were silver soldered. During operation the cooling water flowed down through the inner tube, back up through the annulus, and out through the outlet arm.

After the condenser had been assembled, it was cleaned inside and out with nitric acid (20 percent by volume) to remove any oxide film or other contaminants. Then, to even the copper surface, it was thoroughly buffed on a soft moter-driven buffing wheel using a commercial buffing compound. Before use, it was cleaned and polished further. The procedure for this operation is given in detail in the section on procedure.

CONDENSATION APPARATUS

Figure 4



FINGER-TYPE CONDENSER

(ACTUAL SIZE)

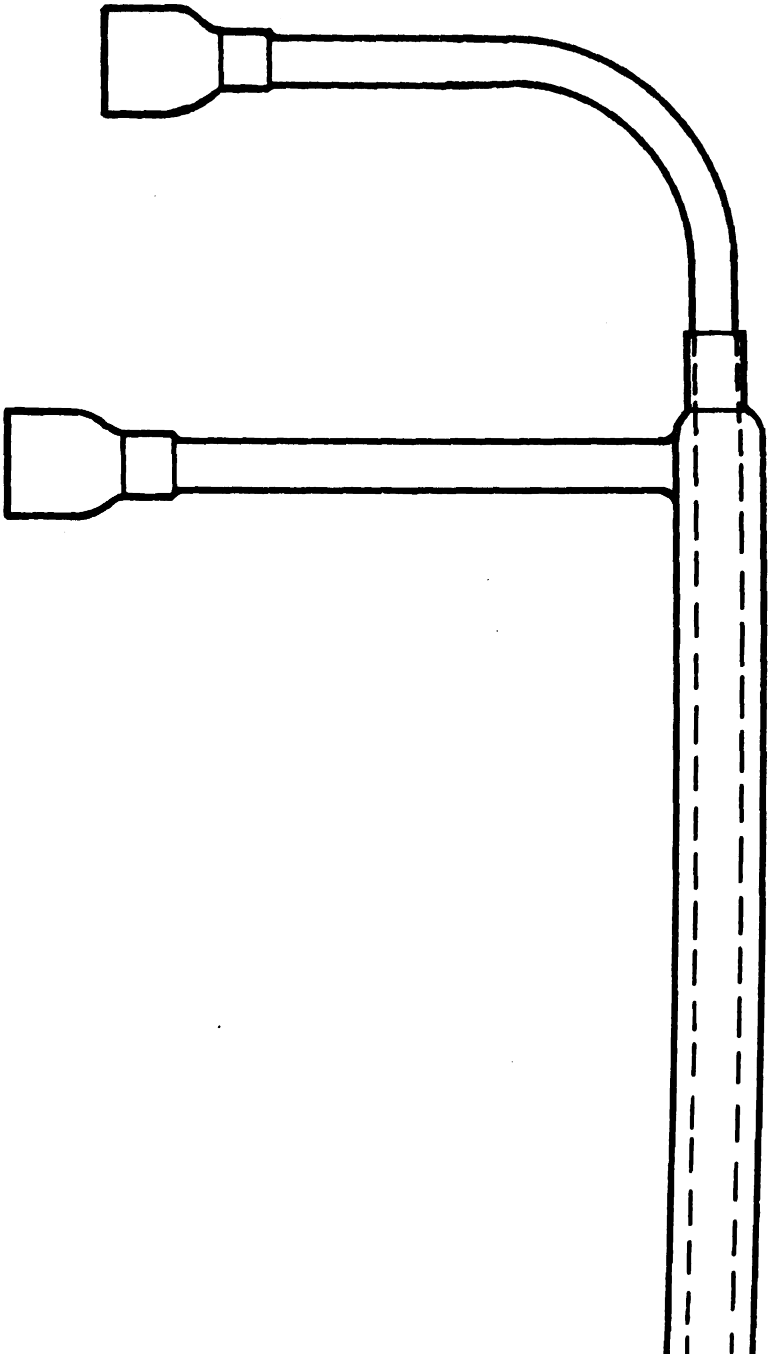


FIGURE 5

A two-liter Erlenmeyer flask served both as the steam jacket for the condenser and as the boiler. A cork with two holes drilled through it held the copper condenser in place in the neck of the flask, and a Bunsen burner heated about a liter of distilled water in the bottom of the flask to provide steam. Four "Boileezers" were placed in the flask to promote even boiling. A glass reflux condenser inserted in the second hole of the cork condensed any excess steam and provided an opening to the atmosphere for removal of noncondensable gases in the system and for maintenance of atmospheric pressure inside the flask.

The corks used to close the mouth of the flask and to hold the two condensers in place were drilled and then boiled repeatedly in clean distilled water until the water remained clear after several hours of boiling. This treatment was to remove water- or steam-soluble compounds in the corks, and to prevent their contaminating the high purity system needed for these experiments.

Cooling water for the copper condenser was drawn from a tap into a jug of about two liters capacity equipped with a hose connection at the bottom. From this connection two pumps, Eastern Industries Models D-11 and D-6, connected in series forced the water through the condenser and thermometer wells and into the drain. Each of the pumps was piped with a by pass which could be closed. The outlet line from the second pump was equipped with a globe valve and, beyond this, a pressure gage. Rubber tubing having inner and outer diameters of 1/2 and 3/4 inch respectively connected the various components of the cooling water system. During operation, the tap on the water main was adjusted so the water overflowed continually from the top of the jug to provide a cooling water source at a constant pressure.

Beckman thermometers were used to measure the inlet and outlet temperatures of the cooling water. The thermometers were secured in wells by inserting them through a hole in a rubber stopper and pressing this firmly into the top of the well.

The wells were made of 3/4 inch galvanized pipe, the cooling water flowing in at the bottom, up through an annulus between the thermometer and a straight section of pipe, and out through the side arm of a tee at the top. One well was connected into the inlet line between the second pump and the condenser and the second was connected into the outlet line. The well in the outlet line was provided with a bypass so the flow of water through it could be diverted and the thermometers changed in case the temperature of the outlet water moved out of the range of a thermometer. Both wells were clamped into a specially built box packed with glass wool to insulate the wells from the surroundings and from each other. The portion of the copper condenser projecting above the cork and the cooling water lines attached to the condenser were also insulated with glass wool to prevent heat transfer with the surroundings. A rectangular shield approximately 18 inches high and 15 inches wide, made of two sheets of 3/4 inch Celotex insulating board mounted one on each side of a 3/4 inch sheet of plywood, was placed between the Bunsen burner and the thermometer wells to reduce the heat transfer between the burner and the wells. One of the three Beckman thermometers used was standardized in a constant temperature bath against a standard platinum resistance thermometer and the other two were standardized by comparison with the first in a constant temperature bath.

Temperatures read from the Beckman thermometers are accurate to ± 0.005°C which corresponds to a maximum possible error of 2 percent for the minimum observed temperature rise of approximately 0.5°C. The time measured during the collection of cooling water for weighing has a maximum possible error of 0.2%; the weight is in error by no more than 0.03%.

PROCEDURE

Keeping the system absolutely free of contaminants was the most important consideration in developing the procedure for this experiment.

An exhaustive search was made for the purest C_{18} acids available and those offered by the Hormel Foundation, Austin, Minnesota, were selected. An analysis supplied by the Hormel Foundation of each of the acids used appears in the Data section of the Appendix. The acids, except the stearic which was received in flake form in a serum bottle with a biological seal, were received in sealed glass ampoules and before use were transferred to serum bottles with biological seals. The transfers were made in large polyethylene bags which were thoroughly flushed with nitrogen before use to prevent oxidation of the acids. One end of the bag was open just enough for admittance of the operator's hands, and a steady stream of nitrogen was maintained from the closed end of the bag over the working area and out the open end. Each ampoule was thoroughly cleaned, placed in the bag, its neck creased and knocked off with a file and the acid poured into a serum bottle which previously had been thoroughly cleaned, dried and flushed with nitrogen. The bottle was capped with a biological seal and removed from the bag. Each acid was transferred in a clean bag.

The first step in the experimental procedure was removal of the steam-soluble compounds in the corks used to hold the condensers. Three new drilled corks were placed in a 1000-ml beaker filled with distilled water and equipped with devices to hold the corks beneath the water and to hold the water level constant. The corks were boiled in the water for a period, the water drained, the beaker filled with fresh water, and the boiling resumed. This cycle was repeated a number of times in an attempt to boil the corks until they no longer colored the water. It was found that the corks colored each succeeding change of water less up to a point at which the trend reversed itself and each succeeding batch extracted more colored material. Continuation of the process resulted in the corks shriveling up and eventually cracking without the cessation of the evolution of the colored material. After drying, these corks were hard, shrunken, cracked, and useless. The corks used in the runs reported in this work were boiled until the amount of color seemed to be at the minimum. They were then placed in clean beakers covered with watch glasses for drying at room temperature and storage until use. Corks for the entire series of runs were boiled and allowed to dry before the runs were begun.

The first step taken for a run was removal of the black oxide film from the inner surfaces of the condenser. To do this the condenser was filled with a solution of 5 weight percent sulfuric acid and 5 weight percent potassium dichromate in distilled water and allowed to stand with intermittant agitation for two minutes. The solution was drained from the condenser, discarded, and the condenser washed out thoroughly with tap water.

Next the outside of the condenser was scrubbed with a hot detergent (Tide) solution and scoured with cleanser (Ajax) on a small cheesecloth pad until the surface was uniformly bright and tap water would drain away leaving an unbroken film. It was then immersed in distilled water, boiled for ten minutes, and rescrubbed with cleanser until the surface was again uniformly bright and distilled water would drain away leaving a continuous film. The condenser was immersed in distilled water until the system was ready for assembly.

The glass reflux condenser, Erlenmeyer flask, and all other glassware used were thoroughly scrubbed with laboratory brushes and a hot Tide solution containing Ajax until, after a thorough rinsing with tap water, distilled water would drain away leaving an unbroken film.

A piece of aluminum foil was scrubbed with Tide and Ajax until distilled water would drain from it leaving an unbroken film. This foil was carefully wrapped around the lower part of the condenser, taking care not to touch any surface likely to be in contact with the steam, and the combination inserted into a hole in the cork so that the aluminum foil formed a sleeve completely surrounding the copper condenser where it passed through the cork. A knife was used to fold the part of the sleeve projecting below the cork back away from the condenser and down flat against the bottom of the cork. The condenser was then inserted as far as possible into the cork and the portion projecting through the cork again cleaned with Ajax cleanser taking care to keep the cork free of cleanser and not to touch any surfaces likely to come into contact with the steam. Use of this procedure with the aluminum sleeve with its lower end turned back against the cork resulted in minimum contamination of the condenser by the cork.

Approximately 1000 ml of distilled water was measured into the 2-liter Erlenmeyer flask from a clean graduate and the flask clamped into position over the Bunsen burner. The copper condenser was positioned so that it extended exactly 3.50 inches below the bottom of the cork and its surface was wetted with distilled water to make certain that it had not become contaminated. If the water did not drain leaving an unbroken film, the condenser was recleaned.

The glass reflux condenser used had its lower end cut off at an angle of about 45 degrees. It was positioned so that its tip projected below the bottom face of the cork while the top of the angled opening was still above the bottom of the cork. The cork with the two condensers in place was then forced securely into the neck of the Erlenmeyer flask. The cooling water hoses were attached and secured to their respective connections on the condensers taking care not to disturb the positions of the condensers in the cork.

The water to the condensers was turned on and the flow to the copper condenser adjusted to an intermediate rate. The

Bunsen burner was lighted and after the boiling started, the flame was adjusted to produce about one drop of condensate every two seconds from the tip of the reflux condenser. The flask was then allowed to boil for two hours or longer to expel any noncondensable gas in the flask.

At the end of the two hour period the cooling water rate to the copper condenser was adjusted to the exact desired value by means of the globe valve on the pump outlet, first approximating the valve setting by the pump discharge pressure, and then setting it exactly according to the weight of about four liters of water collected at the outlet to the drain during a timed interval. Care was taken to maintain the outlet at the same level both during measurement of flow and during the intervals of operation between. The D-6 pump was operated only to obtain the highest of the three flow rates and was bypassed during operation at the other two. The flame was adjusted to give exactly one drop of condensate from the reflux condenser every two seconds when averaged over a two to four minute period. This rate was difficult to set and the drops had to be counted for at least two minutes to obtain reasonable reproducability. After the rates were set, the system was run for twenty minutes before any readings were taken.

The cooling water outlet temperature fluctuated continuously, so to obtain a reading, the inlet and outlet temperatures were read at the beginning and end of a random one minute interval and the average of the two inlet temperatures and the two outlet temperatures were entered in the data as the inlet and outlet temperatures respectively.

After the adjusted system had operated for twenty minutes, temperature readings were taken at five minute intervals until three successive readings agreed. Three more readings were then taken and these entered in the data. The water rate was measured immediately after completing each of the three final temperature readings by collecting approximately four liters of the coolant discharge stream, timing the period of collection and weighing the water collected. The steam temperature was taken to be that of saturated steam at the ambient atmospheric pressure.

At least three temperature and cooling water rate readings were taken at each of three or more different water rates during each run, and the above procedure was followed after each change in water rate.

When the three sets of readings had been taken for the new cork and uncontaminated distilled water, the system was allowed to cool. A small amount of the acid to be studied was withdrawn from its serum bottle into a clean, dry, nitrogen-flushed hypodermic needle and the needle with its contents weighed. The cork with its condensers was loosened and lifted a short distance out of the neck of the flask. About 0.005 g of acid was dropped into the flask from the needle, the cork and condensers secured back in the neck, and the hypodermic needle reweighed to determine the exact amount of acid added. Boiling was resumed and a run made using the above procedure to obtain three sets of readings for the acid-containing system.

The system was broken down after the acid-containing run, the cork carefully removed maintaining the aluminum sleeve intact and placed in a clean beaker covered with a watch glass for later use. A run using pure distilled water to determine the effects of the cork on the results immediately followed by a steam-distilled acid run was made for each acid.

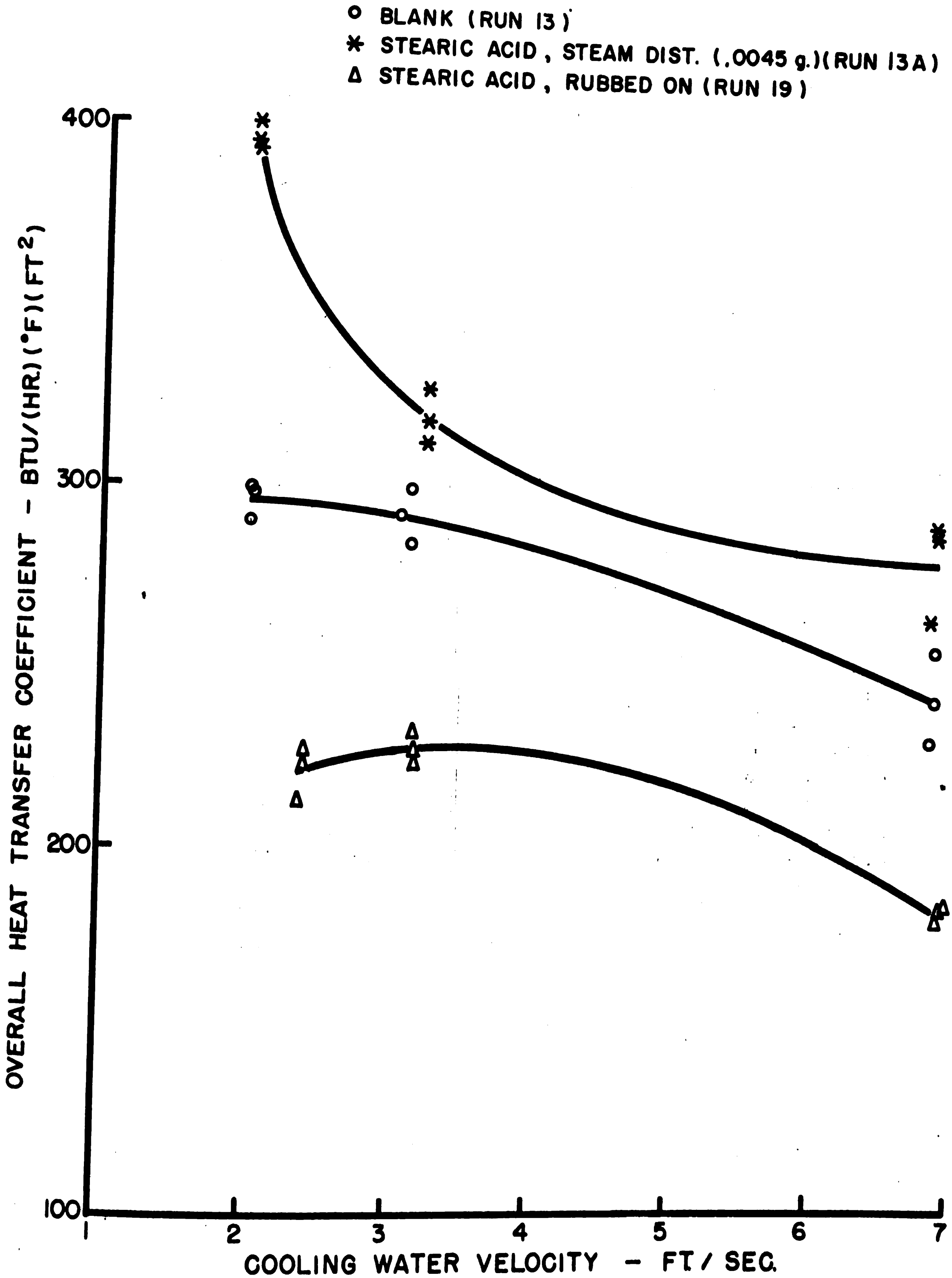
To study the effects of the acids when rubbed on the condenser surface, the cork used for the acid in question in the previous runs was re-used. The other components of the system were cleaned in the usual manner, the flask set in place, and about 1200 ml of distilled water poured into it. The water was then boiled gently for at least 20 minutes to dispel air from the flask. The copper condenser was removed from the beaker of distilled water and thoroughly dried with clean filter paper. A quantity of acid was withdrawn from the serum bottle in a clean hypodermic needle and three drops from the needle placed on the surface of the condenser (one drop equals about 0.005 g). The acid was spread over the entire surface of the condenser with a clean filter paper and the excess removed by wiping with another clean filter paper. The condenser was then positioned in the cork carefully, trying not to disturb the aluminum sleeve. The system was assembled, allowed to operate for two hours, and readings taken as previously described. The aluminum foil, if torn or seriously disturbed, was replaced using the procedure for placing the original sleeve. Stearic acid when used was removed from its serum bottle with a spatula rather than with a hypodermic needle.

Overall heat transfer coefficients and cooling water velocities in the annulus of the condenser were calculated for each reading taken in this experiment. The values were tabulated and plotted one against the other. A sample calculation appears in the Appendix.

RESULTS


OVERALL HEAT TRANSFER COEFFICIENT – BTU/(HR)(°F)(FT²)

FIGURE 6


○ BLANK (RUN 13)
* STEARIC ACID, STEAM DIST. (.0045 g.)(RUN 13A)
Δ STEARIC ACID, RUBBED ON (RUN 19)
400
300
200
100
1
2
3
4
5
6
7
OVERALL HEAT TRANSFER COEFFICIENT - BTU/(HR.)(°F)(FT²)
COOLING WATER VELOCITY - FT./ SEC.

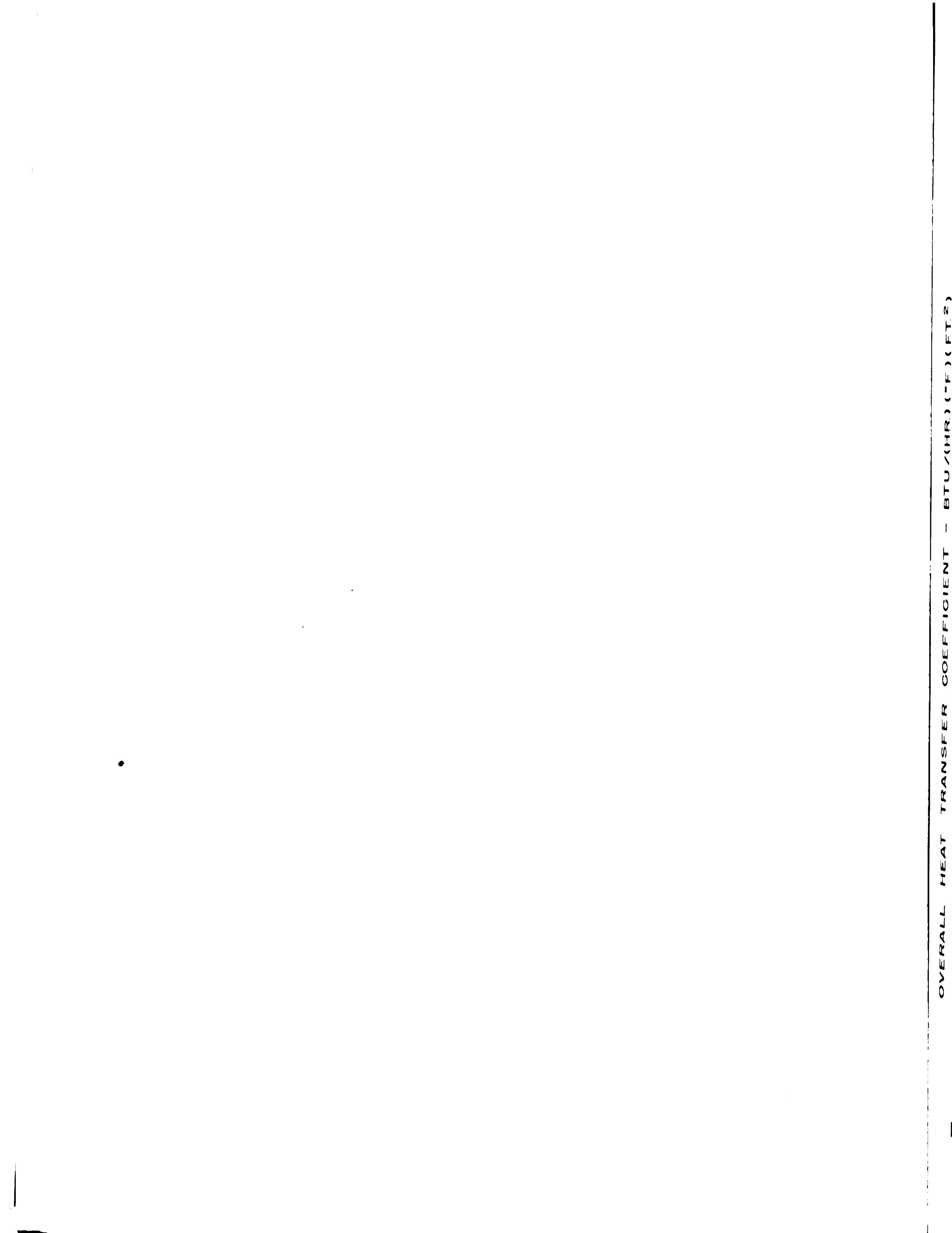
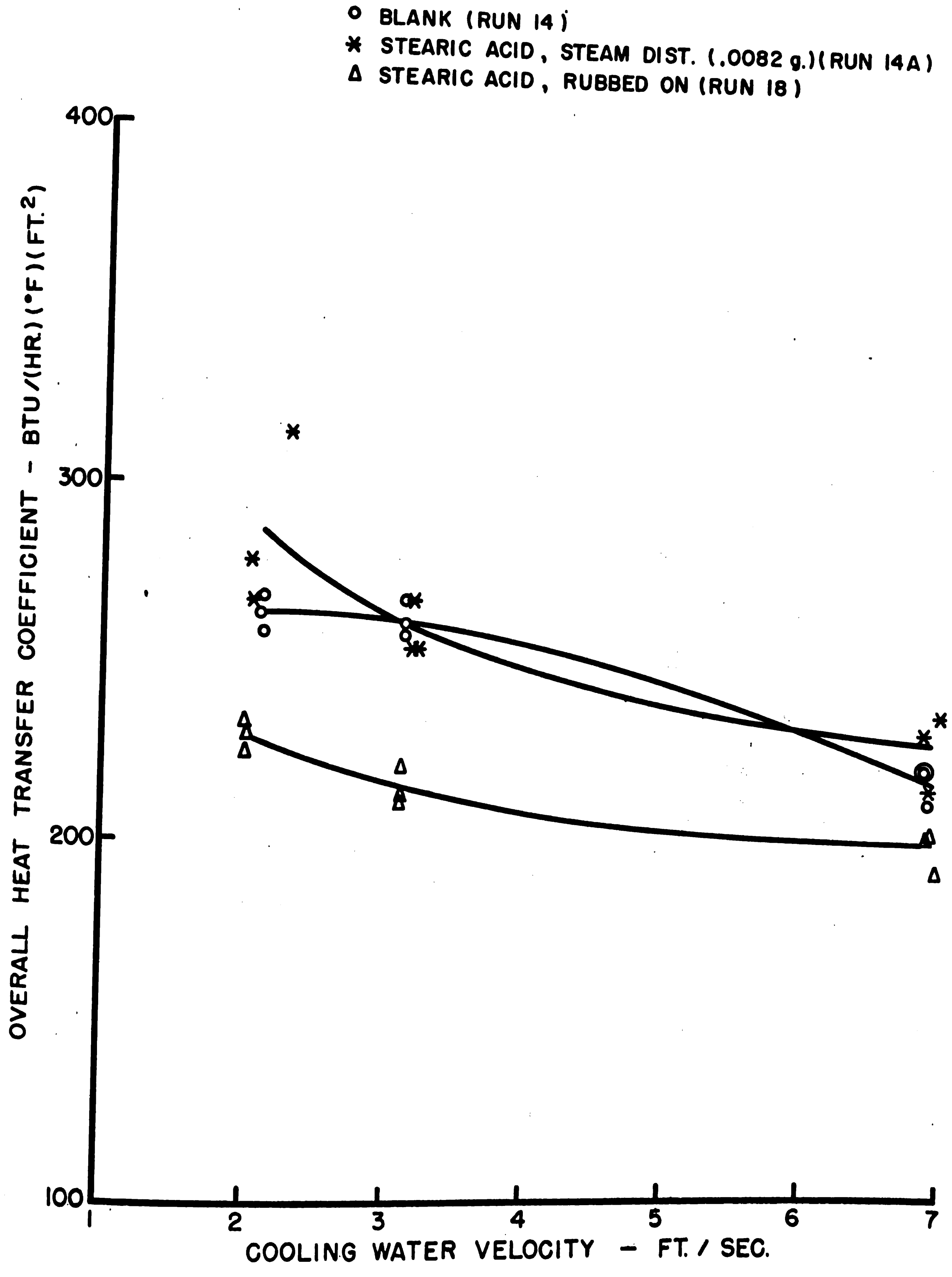
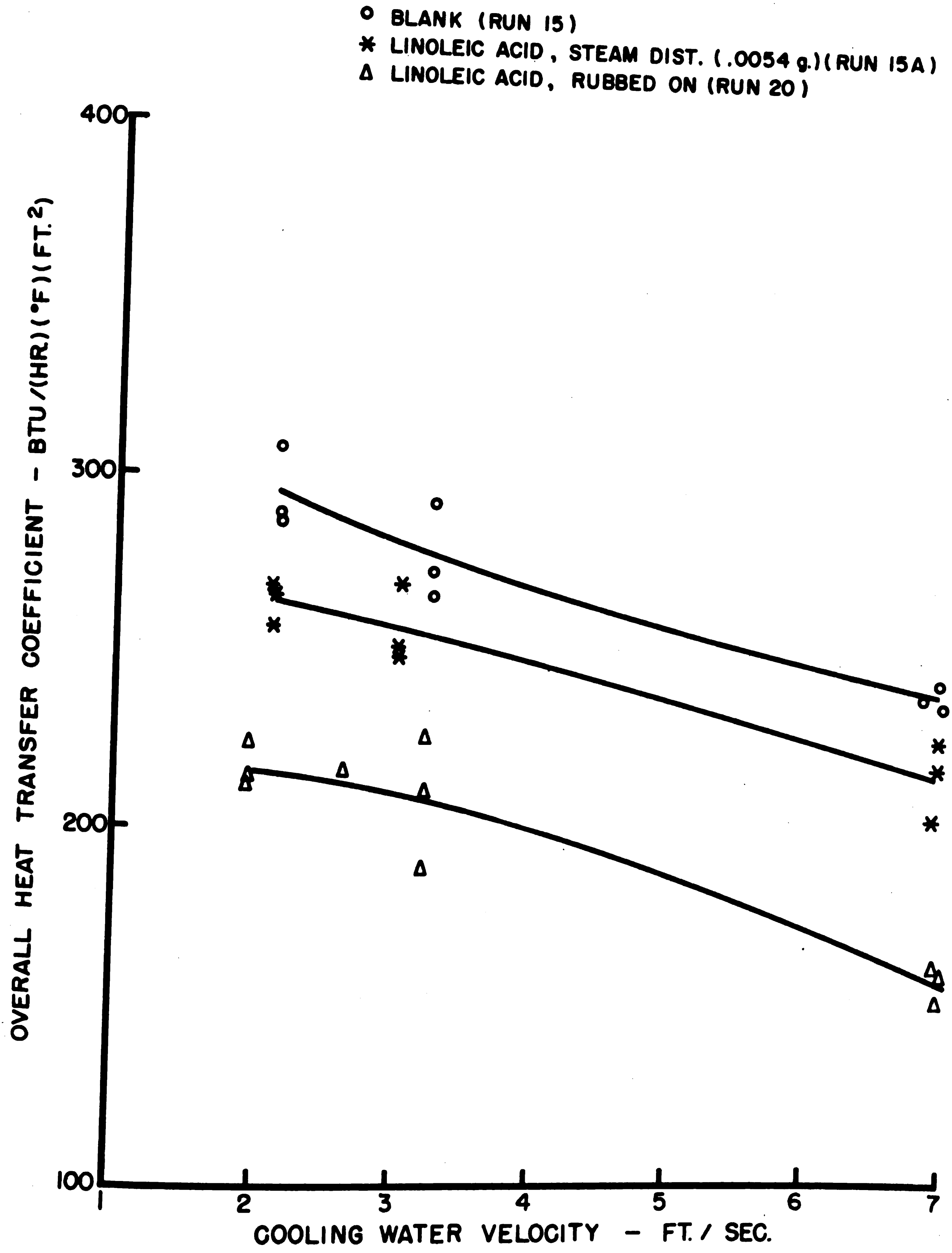

OVERALL HEAT TRANSFER COEFFICIENT - BTU/(HR)(°F)(FT²)

FIGURE 7


○ BLANK (RUN 14)
* STEARIC ACID, STEAM DIST. (.0082 g.)(RUN 14A)
Δ STEARIC ACID, RUBBED ON (RUN 18)
OVERALL HEAT TRANSFER COEFFICIENT - BTU/(HR.)(°F)(FT.^{2})
400
300
200
100
1
2
3
4
5
6
7
COOLING WATER VELOCITY - FT. / SEC.

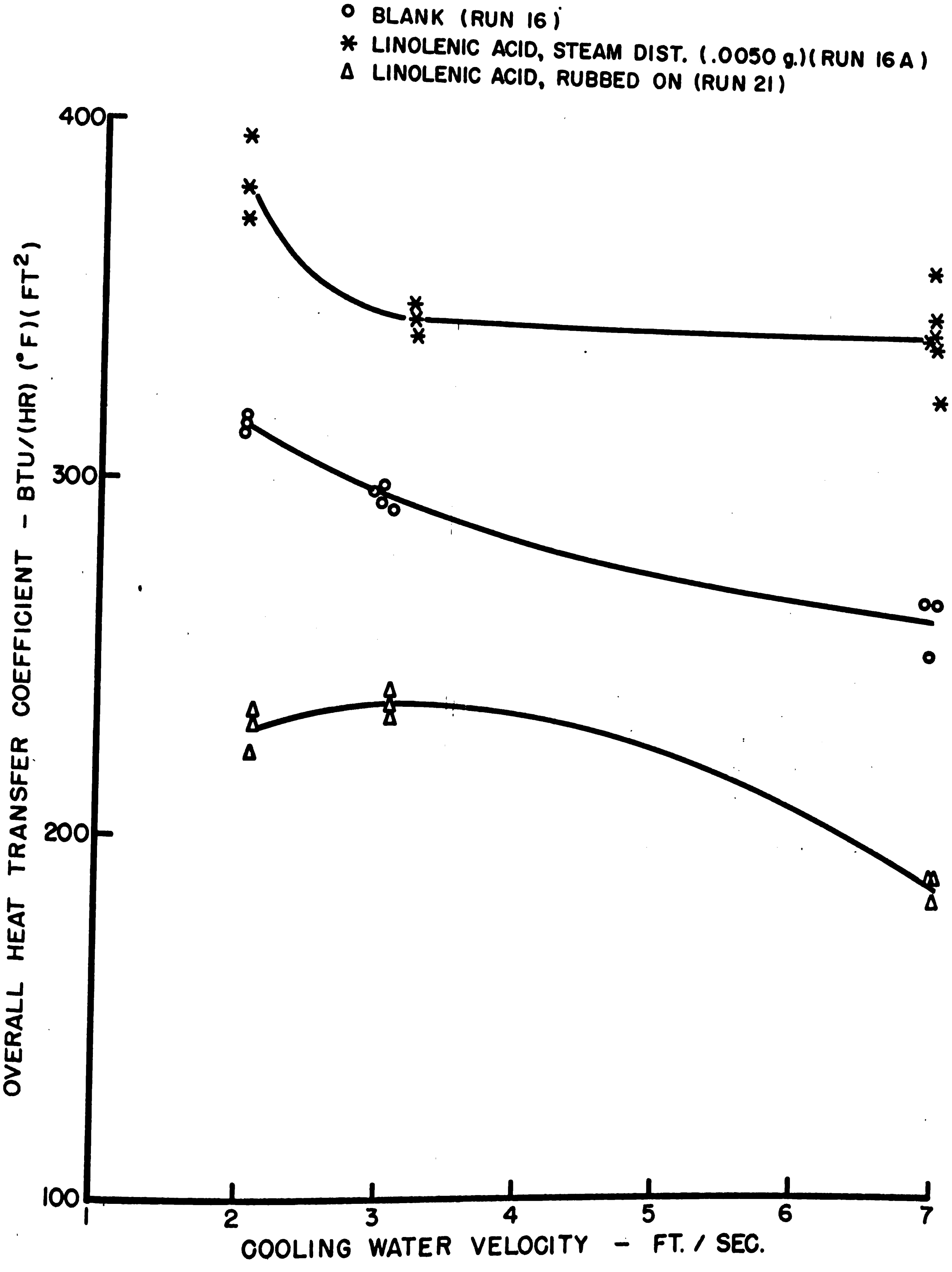

OVERALL HEAT TRANSFER COEFFICIENT

FIGURE 8



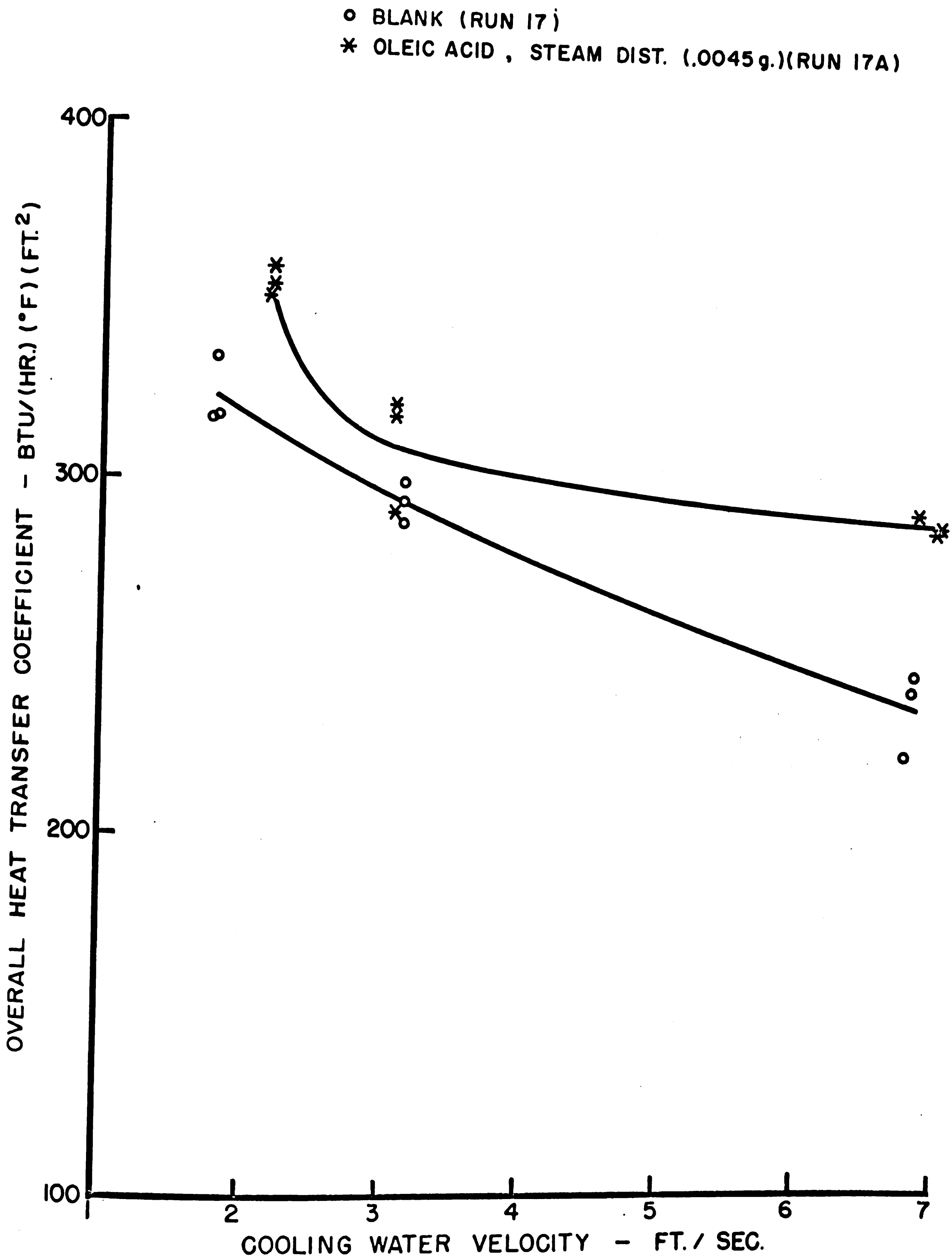
○ BLANK (RUN 15)
✱ LINOLEIC ACID, STEAM DIST. (.0054 g.)(RUN 15A)
Δ LINOLEIC ACID, RUBBED ON (RUN 20)
400
300
200
100
OVERALL HEAT TRANSFER COEFFICIENT - BTU/(HR.)(°F.)(FT.^{2})
1
2
3
4
5
6
7
COOLING WATER VELOCITY - FT./SEC.

FIGURE 9



○ BLANK (RUN 16)
✱ LINOLENIC ACID, STEAM DIST. (.0050 g.)(RUN 16A)
Δ LINOLENIC ACID, RUBBED ON (RUN 21)
400
300
200
100
OVERALL HEAT TRANSFER COEFFICIENT - BTU/(HR) (°F)(FT^2)
1
2
3
4
5
6
7
COOLING WATER VELOCITY - FT. / SEC.

FIGURE 10


o BLANK (RUN 17)
* OLEIC ACID, STEAM DIST. (.0045 g.)(RUN 17A)
OVERALL HEAT TRANSFER COEFFICIENT - BTU/(HR.)(°F)(FT.²)
400
300
200
100
1
2
3
4
5
6
7
COOLING WATER VELOCITY - FT./SEC.

In each run, the condenser containing the rubbed-on acid exhibited complete drop condensation when first inserted into the warm flask but the condensation soon changed to mixed. The mixed form gave way to complete film condensation early in the run containing linoleic acid, Run 20. In the run with linolenic acid, only a very small area of drop condensation remained after 40 minutes operation. Run 19 with stearic acid exhibited about 50 percent film condensation shortly after boiling began. The relative amounts of the two types of condensation, film and drop, remained nearly constant during the remainder of the run. The run with oleic acid, Run 18, produced only a small area of film condensation.

Shortly after starting operation of the blank runs, the bright polished copper surface dulled to a color suggestive of cuprous oxide, Cu_2O. A bright ring about 1/16 inch wide remained just below the cork. A black ring of similar width appeared immediately below it. Both of these rings were apparently due to contamination from the cork, because if a crack in the foil shield on the face of the cork around the condenser extended back close to the condenser, the width of the rings increased at that point. These rings were also observed in irregular widths to 1/2 inch or more in runs made with unshielded corks.

In all runs containing acid dropped into the flask from a hypodermic needle, the blue-green color of the copper salt of the acid appeared indicating a definite reaction between the acid and the copper. A brightening of the dulled copper surface was also usually noticed making it likely that the acid reacted with the oxidized surface. Blue-green flecks of copper stearate appeared on the walls of the flask and in the boiling water soon after Run 13A was begun. Film type condensation was obtained throughout this run. In the runs with oleic acid, Runs 14A and 17A, the green-blue color appeared immediately in spots where acid touched the condenser during addition. The color later appeared in the areas giving drop condensation. These occupied approximately the bottom one-third of the condenser and were divided by rivulets of condensate running down from the film condensation above. The best drop condensation was observed in these two runs. Another interesting phenomenon observed in the two runs was the apparent solidification of acid on the condenser. A milky white film of acid formed over the condenser when the cooling water was turned on and then slid down to form a great water-containing sac around the bottom of the condenser. The sac slowly diminished in size and disappeared after about two hours boiling.

In Run 15A with linoleic acid the blue-green color appeared only at places where acid touched the condenser during addition. These places gave drop condensation for a time but reverted to film. Only the bottom plate and a small area around the bottom of the condenser seemed to remain nonwettable. Run 16A with linolenic acid behaved very nearly the same as Run 15A. A nonwettable area about one inch wide appeared around the wall of the flask just above the level of the boiling water in all five runs employing steam distilled acid. It was very difficult to remove when cleaning the apparatus.

The calculated results failed to produce straight lines when plotted by the method of Wilson (27) so they were plotted as cooling water velocities, V, versus overall heat transfer coefficients, U, to avoid unnecessary complications. The curves were drawn by calculating the average overall heat transfer coefficient and the average cooling water velocity for each cooling water rate setting in each run, plotting these points, and drawing a smooth curve through them. To obtain an indication of the relative effect of the different acids on the overall coefficient, U, the percent change of the average overall coefficient for an acid from the average overall coefficient for the blank was calculated at each water velocity for each acid. The three percentages calculated for an acid were averaged.

The results for the steam distilled acids are: linolenic acid, 23.1% increase; stearic acid, 19.6% increased; oleic acid, 6.2% (Run 14A) and 12.5%(Run 17A) increases; and linoleic acid, 8.4% decrease.

Data taken but not reported in this paper showed that results obtained from a given system could be exactly duplicated when the system was shut down, allowed to stand overnight, and rerun before disassembly. It was also shown that two newly assembled identical systems using the same cork would yield nearly duplicate results.

The apparatus used in this experiment has a number of distinct advantages and a number of very serious faults. Chief among the advantages are its simplicity and ease with which it can be disassembled and all surfaces in contact with the steam thoroughly cleaned. Furthermore, it is possible to observe all surfaces to check for cleanliness and it is possible to observe all parts of the copper condensing surface during operation. The unit is a self-contained closed system which makes it easier to obtain and maintain a constantly pure source of steam and a constant concentration of promoter.

The first fault recognized in the system was the use of corks to close the neck of the flask. Previous investigators (5, 21, 26) have reported successful use of corks extracted with boiling water in a manner similar to that described in the procedure but all attempts to prevent contamination of the present system by corks failed. These attempts included various boiling procedures, wrapping the corks in foil, and coating them with polyester resin. It was noticed in the first runs of this study that it was difficult to insert a clean, completely wettable condenser through a cork and have it remain wettable after insertion. These nonwettable areas exhibited drop condensation in the flask.

The results of these first runs, each made with a clean, newly assembled boiled cork and distilled water containing no acid, could not be made to agree with one another. A number of runs were made, none of them reported in this paper. A definite correlation was noticed between the overall heat transfer coefficients calculated from the data taken and the amount of and the persistency of the drop condensation induced by the cork. The runs exhibiting the greatest amount of, or the most persistent drop condensation produced the largest heat transfer coefficients. The operating procedure adopted for the runs reported attempted to find the effect of the contaminant from the cork on the heat transfer coefficient and add to it the effect of the acid promoter.

The second major fault in the system was the continual fluctuation of the thermometer in the cooling water outlet line. It is possible that insufficient mixing and channeling of the cooling water as it passed through the condenser and on to the thermometer caused the fluctuation but this does not seem likely because the water after leaving the condenser and before reaching the thermometer flowed through one sudden contraction, two sudden expansions, four 90-degree ells, and several sweeping bends (in the rubber tubing). Removing the thermometer from the well and placing it in a deep cylinder with the cooling water directed against the bottom of the cylinder and then overflowing from the top caused no noticeable change in the amount of fluctuation. The fluctuations, therefore, seem to be caused by irregular heating of the cooling water due to irregular steam currents and temperatures in contact with the condenser. This is supported by Packer's (21) observations of fluctuations in the reading of a thermometer placed in the steam.

The system's third fault was its inadequate boilup rate control. The method of control, as explained in the procedure, made the rate difficult to adjust and measure accurately. A small change in rate was found to cause an appreciable change in the heat transfer coefficient.

A peculiarity of the system, but not necessarily a fault, is its production of overall heat transfer coefficients, U, which are inversely proportional to the condenser cooling water velocity. The overall coefficient is usually directly proportional to the cooling water velocity and has been found to be so in the three previous studies (5, 21, 26) made at Michigan State University on apparatus similar to that used in the present study. The condenser used in the present study, however, was made especially for the study from the drawings of Packer (21). It is similar to the condenser used in the three previous studies at Michigan

State University but certainly not identical to it. The flow patterns in the two condensers could, therefore, be quite different.

Reynolds numbers of 2500, 4000, and 8500 were calculated for the three cooling water rates used in this study. These numbers, especially the lowest, are only slightly above the so-called critical Reynolds number of 2100 below which flow is streamline and above which flow is usually but not necessarily turbulent (22). Therefore, there is no guarantee that the flow was turbulent during any given reading taken in the experiment, and the data point to some unusual combination of dimensional characteristics of the equipment and fluid which produced turbulent flow at the low velocities and streamline flow at the high velocities. This effect would result in a mechanism of heat transfer for the high velocities which would give a much lower value of the overall heat transfer coefficient than would have been obtained from turbulent flow. This would result in an inversion of the usual relationship between the overall coefficient and the condenser water rate exactly as has happened in this study. The inversion of the relationship was also aided by slightly higher average cooling water temperatures at low water velocities.

In view of his experiences, the author would like to suggest a number of improvements to be made in the apparatus should it be used for future study. First, eliminate the corks from the system and support the copper condenser from a sheet of Teflon or similar inert material having low thermal conductivity. Clamp this sheet to the top of the steam chamber. Second, adapt one or more sections of three-inch Pyrex pipe to replace the flask as boiler and steam chamber. The length of the pipe should be sufficient to allow all entrainment to settle and all steam currents to diffuse assuring a constant steam supply to the condenser. More than one section of pipe could be used with a screen, packed section or similar distributor placed between the condenser and the boiler water. The three-inch diameter would serve to remove the condenser from the cooling effects of the walls and allow a large area for passage of steam to the upper extremities of the condenser.

As a third improvement, replace the Bunsen burner with electric heaters controlled by a Variac or similar autotransformer. Immersion heaters could easily be supported from a metal plate clamped to the bottom of the pipe, or better, a Pyrex cap fitted with a heating mantle or wrapped with heating tapes could be used for the boiler. Fourth, eliminate the reflux condenser and regulate the boil-up rate by holding a constant steam pressure. The pressure should be measured on a manometer or very accurate gauge connected to a pressure tap set into the Teflon sheet closing the top of the boiler or to a side arm near the top of the Pyrex chamber by a small bore (to prevent refluxing) tube of inert material that can be thoroughly cleaned. Finally, rebuild the copper condenser enlarging the inner tube to give higher velocities in the annulus without increasing the water mass flow rates. No change is contemplated for the cooling system except possible installation of a mixing chamber between the condenser and the outlet thermometer and the use of one large pump rather than two small ones.

CONCLUSIONS

1. A definite chemical reaction takes place between the C_{18} fatty acids and a slightly oxidized copper surface.
2. The area covered by this investigation and possibly the areas covered by the previous investigations at Michigan State University should be studied further using apparatus free of sources of contamination (i.e., containing no corks) and capable of supplying an accurately controlled unvarying flow of steam to all parts of the condenser.

APPENDIX

BIBLIOGRAPHY

1. Blackman, L. C. F., Dewar, M. J. S., and Hamspon, H., "An Investigation of Compounds Promoting the Dropwise Condensation of Steam," J. Appl. Chem. (London), 7, 160-71 (1957).
2. Brown, G. G., and Associates, "Unit Operations," pp. 448-53, John Wiley and Sons, Inc., New York, 1950.
3. Drew, T. B., Nagle, W. M., and Smith, W. Q., "The Conditions for Dropwise Condensation of Steam," Trans. Am. Inst. Chem. Engrs., 31, 605-21 (1935).
4. Emmons, H., "The Mechanism of Drop Condensation," Trans. Am. Inst. Chem. Engrs., 35, 109-23 (1939).
5. Erickson, W. D., "A Study of Dropwise Condensation as Related to Normal Alkyl Amines," A Thesis for the Degree of Master of Science, Michigan State University, 1955.
6. Fatica, N., and Katz, D. L., "Dropwise Condensation," Chem. Engr. Progr., 45, 661-74 (1949).
7. Fishenden, M., "Heat Transfer in the Condensation of Steam," Engineering, 145, 643-5 (1938).
8. Fitzpatrick, J. P., Baum, S., and McAdams, W. H., "Dropwise Condensation of Steam on Vertical Tubes," Trans. Am. Inst. Chem. Engrs., 35, 97-107 (1939).
9. Hampson, H., "Condensation of Steam on a Metal Surface," pp. 58-81, Proceedings of the General Discussion on Heat Transfer, Inst. Mech. Engrs., London, and Am. Soc. Mech. Engrs., New York, 1951.
10. Hampson, H., "Dropwise Condensation on Metal Surface," Engineering, 179, 464-9 (1955).
11. Jakob, M., Z. Ver. deut. Ingr., 76, 1161 (1932).
12. Jakob, M., "Heat Transfer in Evaporation and Condensation," Mech. Eng., 58, 729-38 (1936).
13. Jakob, M., "Heat Transfer," pp. 658-96, John Wiley and Sons, Inc., New York, 1949.

14. Jakob, M., and Hawkins, G. A., "Elements of Heat Transfer and Insulation," pp. 161-2, John Wiley and Sons, Inc., New York, 1949.

15. Jeffrey, J. O., and Moynihan, J. R., "Drop Versus Film Formation in the Condensation of Steam on Condenser Tubes," Mech. Eng., 55, 751-4 (1953).

16. McAdams, W. H., "Heat Transmission," 3rd ed., pp. 347-51, McGraw-Hill Book Co., New York, 1954.

17. Nagle, W. M., U. S. Patent 1,995,361 (March 26, 1935).

18. Nagle, W. M., Bays, G. S., Blenderman, L. M., and Drew, T. B., "Heat Transfer Coefficients During Dropwise Condensation of Steam," Trans. Am. Inst. Chem. Engrs., 31, 593-604 (1935).

19. Nagle, W. M., and Drew, T. B., "The Dropwise Condensation of Steam," Trans. Am. Inst. Chem. Engrs., 30, 217-55 (1933-34).

20. Nusselt, W., Z. Ver. deut. Ingr., 60, 541-609 (1916).

21. Packer, J. E., "Dropwise Condensation of Steam Relative to N-Alkyl Alcohols and Acids," A Thesis for the Degree of Master of Science, Michigan State University, 1956.

22. Perry, J. H., "Chemical Engineers' Handbook," 3rd ed., p. 383, McGraw-Hill Book Co., New York, 1950.

23. Schmidt, E., Schurig, W., and Sellschopp, W., Tech. Mech. u. Thermodynam., 1, 53 (1930).

24. Shea, F. L., and Krase, N. W., "Dropwise and Film Condensation of Steam," Trans. Am. Inst. Chem. Engrs., 36, 463-90 (1940).

25. Spoelstra, H. J., "Arch. Suikerind. Ned.-Indie," 39, 905-56 (1931).

26. Squire, D. D., "The Effect of Octadecylamine Acetate on the Over-all Heat Transfer Coefficients," A Thesis for the Degree of Master of Science, Michigan State University, 1955.

27. Wilson, E. E., "A Basis for Rational Design of Heat Transfer Apparatus," Trans. Am. Soc. Mech. Engrs., 37, 47-82 (1915).

NOMENCLATURE

A = Active area of finger condenser, ft^2.

A' = Area of condenser annulus, ft^2.

A_i = Inside active area of finger condenser, ft^2.

A_o = Outside active area of finger condenser, ft^2.

A_b = Active bottom area of finger condenser, ft^2.

C_p = Specific heat of water, Btu/(lb)(°F).

d = Density of water, lb/cu ft.

Q = Heat flux, Btu/(hr)(ft^2).

t_a = Arithematic average cooling water temperature, °F.

t_i = Cooling water inlet temperature, °F.

t_o = Cooling water outlet temperature, °F.

t_s = Steam temperature, °F.

U = Overall heat transfer coefficient, Btu/(hr)(ft^2)(°F).

V = Cooling water velocity, ft/sec.

W = Cooling water mass flow rate, lb/hr.

W' = Cooling water mass flow rate, lb/min.

DATA

Hormel analysis of acids:

Stearic acid.

No analysis furnished.

Oleic acid.

Lot No. 3.

Iodine value (Wijs) 89.8 (theoretical value 89.87).

Analysis according to Brice, Swain, Schaeffer and Ault (Oil and Soap, <u>22</u>, 219; 1945), expressed as percentage C_{18} fatty acids.

	Conjugated Acids	Non-conjugated Acids
Saturated	--	0.27
Monoenoic	--	99.7
Dienoic	0.02	0.02
Trienoic	none	none
Tetraenoic	none	none

Linoleic acid.

Lot No. 6-N.

Iodine value (Wijs) 181.0 (theoretical value 181.03).

Conjugated polyunsaturated constituents (from ultraviolet absorption data) expressed as percentage of C_{18} fatty acids.

Dienoic: not more than 0.15%

Trienoic: not more than none

Tetraenoic: not more than none

Linolenic acid.

Lot No. 9.

Iodine value (Wijs) 272.5 (theoretical value 273.51).

Conjugated polyunsaturated constituents (from ultraviolet absorption data) expressed as percentage of C_{18} fatty acids.

Dienoic: not more than 0.25%

Trienoic: not more than none

Tetraenoic: not more than trace

Run 13

Acid: none

Steam temperature: 210.60°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	17.91	6.83	59.11	60.30	231.15
2	18.00	6.86	58.69	60.01	256.39
3	17.99	6.86	58.64	59.88	241.97
4	8.00	3.05	60.15	63.46	291.97
5	8.19	3.12	60.24	63.39	284.26
6	8.19	3.12	60.08	63.39	298.69
7	5.24	2.00	60.22	65.21	289.67
8	5.24	2.00	60.22	65.37	299.18
9	5.31	2.02	60.13	65.37	297.54

Run 13A

Acid: .0045 gm. Stearic

Steam temperature: 210.63°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	17.89	6.82	58.48	59.85	264.92
2	18.02	6.87	58.42	59.90	287.87
3	17.98	6.86	58.46	59.95	290.82
4	8.44	3.22	58.75	62.13	311.64
5	8.44	3.22	58.60	62.06	318.03
6	8.44	3.22	58.68	62.22	326.56
7	5.27	2.01	59.02	65.88	400.00
8	5.28	2.01	59.02	65.75	392.79
9	5.28	2.01	59.09	65.84	393.93

Run 14A

Acid: .0082 gm. Oleic

Steam temperature: 210.73°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	8.31	3.17	58.66	61.47	253.93
2	8.31	3.17	58.68	61.48	253.93
3	8.31	3.17	58.68	61.63	267.21
4	5.34	2.04	59.25	63.99	278.03
5	5.92	2.26	59.23	64.06	313.93
6	5.35	2.04	59.22	63.75	266.56
7	17.95	6.85	58.57	59.76	230.66
8	18.06	6.89	59.00	60.10	215.08
9	18.27	6.97	59.13	60.31	235.57

Run 15

Acid: none

Steam temperature: 210.68°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	17.82	6.80	58.64	59.88	239.67
2	18.14	6.92	58.64	59.88	243.97
3	18.21	6.95	58.66	59.86	237.70
4	8.44	3.22	58.91	61.88	273.77
5	8.44	3.22	58.91	62.10	293.44
6	8.44	3.22	58.89	61.79	266.56
7	5.49	2.10	59.29	64.38	308.20
8	5.52	2.10	59.29	64.06	289.67
9	5.56	2.12	59.27	63.97	287.38

Run 15A

Acid: .0054 gm. Linoleic

Steam temperature: 210.67°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.04	6.88	59.52	60.57	204.92
2	18.13	6.92	59.52	60.67	227.38
3	18.11	6.91	59.31	60.42	219.67
4	7.81	2.98	59.18	62.13	251.97
5	7.81	2.98	59.14	62.06	248.85
6	7.81	2.98	59.40	62.55	269.51
7	5.44	2.07	59.34	63.84	269.02
8	5.45	2.08	59.29	63.59	257.54
9	5.46	2.09	59.25	63.68	266.06

Run 16

Acid: none

Steam temperature: 210.47°F

Reading No.	Water Rate (lb/min)	(ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.02	6.87	58.62	59.99	267.05
2	18.13	6.91	59.16	60.44	251.97
3	18.21	6.95	59.32	60.67	266.56
4	8.00	3.05	59.11	60.51	291.47
5	7.81	2.98	59.36	62.83	297.87
6	7.75	2.96	59.20	62.65	293.61
7	7.63	2.91	59.11	62.65	296.23
8	5.22	1.99	58.20	64.26	312.62
9	5.23	1.99	58.64	64.11	314.43
10	5.25	2.00	58.69	64.18	317.21

Run 16A

Acid: .0050 gm. Linolenic

Steam temperature: 210.40°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.13	6.91	58.66	60.42	347.38
2	18.06	6.89	58.73	60.57	360.49
3	18.01	6.87	58.60	60.35	341.64
4	8.31	3.17	58.82	62.65	349.18
5	8.31	3.17	58.89	62.67	344.26
6	8.38	3.19	58.84	62.55	340.00
7	5.18	1.97	59.40	65.88	371.97
8	5.20	1.98	59.13	65.73	380.49
9	5.23	1.99	59.27	66.07	394.75
10	18.25	6.96	58.33	59.97	324.10
11	18.10	6.90	58.39	60.13	342.79
12	18.12	6.91	58.33	60.06	339.34

Run 17

Acid: none

Steam temperature: 209.89°F

Reading	Water Rate		Inlet Temp.	Outlet Temp.	U
No.	(lb/min)	(ft/sec)	(°F)	(°F)	(Btu/hr/ft^2/°F)
1	17.89	6.82	58.91	60.17	245.74
2	17.71	6.76	59.20	60.35	222.79
3	17.86	6.81	58.78	60.08	241.31
4	8.19	3.12	58.75	61.99	287.70
5	8.19	3.12	58.59	61.86	293.77
6	8.19	3.12	58.73	62.06	299.02
7	4.68	1.79	59.34	65.75	333.61
8	4.73	1.81	59.14	65.19	317.54
9	4.65	1.77	59.40	65.52	316.39

Run 17A

Acid: .0045 gm. Oleic

Steam temperature: 209.89°F

Reading No.	Water Rate (lb/min)	(ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.30	6.98	58.30	59.74	286.23
2	18.33	6.99	58.66	60.10	287.54
3	17.93	6.84	58.35	59.85	291.15
4	8.00	3.05	57.97	61.56	290.16
5	8.00	3.05	57.96	61.63	320.82
6	8.00	3.05	57.94	61.57	317.70
7	5.68	2.17	58.57	64.29	359.18
8	5.66	2.16	58.59	64.20	351.15
9	5.69	2.17	58.59	64.22	353.77

Run 18

Acid: Oleic

Steam temperature: 210.35°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.05	6.89	58.75	59.77	200.98
2	18.22	6.91	58.75	59.77	201.80
3	18.21	6.95	58.73	59.70	191.97
4	8.13	3.10	59.00	61.38	210.82
5	8.13	3.10	58.98	61.47	220.33
6	8.13	3.10	58.96	61.36	212.29
7	5.22	1.99	58.86	62.94	233.93
8	5.26	2.00	58.89	62.87	229.51
9	5.26	2.01	58.80	62.71	225.08

Run 19

Acid: Stearic

Steam temperature: 210.48°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.20	6.94	58.98	59.92	184.92
2	18.01	6.90	58.91	59.83	180.33
3	18.14	6.92	58.93	59.86	184.26
4	8.31	3.17	59.00	61.56	231.97
5	8.31	3.17	58.96	61.43	223.61
6	8.31	3.17	58.96	61.47	226.88
7	6.19	2.36	58.64	61.79	212.79
8	6.25	2.39	58.55	61.88	227.21
9	6.23	2.38	58.75	62.02	222.95

Run 20

Acid: Linoleic

Steam temperature: 210.56°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.14	6.92	58.75	59.58	162.62
2	18.23	6.95	59.00	59.77	153.11
3	18.30	6.98	58.60	59.41	160.33
4	6.81	2.60	59.04	61.95	217.05
5	8.38	3.19	58.84	61.16	211.80
6	8.38	3.19	58.77	60.84	188.85
7	8.38	3.19	58.78	61,27	226.56
8	5.06	1.93	59.13	63.00	214.92
9	5.07	1.93	59.11	63.16	225.25
10	5.03	1.92	59.04	62.91	212.95

Run 21

Acid: Linolenic

Steam temperature: 210.57°F

Reading No.	Water Rate (lb/min)	Water Rate (ft/sec)	Inlet Temp. (°F)	Outlet Temp. (°F)	U (Btu/hr/ft^2/°F)
1	18.27	6.97	59.43	60.35	182.46
2	18.21	6.94	59.56	60.51	188.69
3	18.24	6.96	59.25	60.21	189.18
4	8.00	3.05	58.30	61.07	240.98
5	8.00	3.05	58.19	60.91	236.06
6	8.00	3.05	58.30	60.98	233.11
7	5.46	2.08	58.53	62.40	230.98
8	5.45	2.08	58.53	62.47	234.75
9	5.45	2.08	58.51	62.28	223.61

METHOD OF CALCULATION

Calculation of the overall coefficient, U.

The overall heat transfer coefficient, U, was calculated through use of a heat balance between the heat transferred to the cooling water, Q_w, and that given up by the condensing steam, Q_s.

$$Q_s = UA\ (t_s - t_a) = Q_w = WC_p\ (t_o - t_i)$$

To calculate the overall coefficient, U, the temperatures of the cooling water entering, t_i, and leaving, t_o, the condenser were read; the steam temperature, t_s, determined from a barometer reading; the water rate, W, calculated from a timed weight; and the condenser area, A, calculated from its dimensions. The specific heat of water, C_p, is a known quantity.

$$U = \frac{WC_p\ (t_o - t_i)}{A\ (t_s - t_a)}$$

$$A = \frac{A_o - A_i}{\ln\ (\frac{A_o}{A_i})} + A_b$$

$$A_i = 3.1416\ (\frac{.437}{12})\ (\frac{3.50}{12}) = .03337\ ft^2$$

$$A_o = 3.1416\ (\frac{.496}{12})\ (\frac{3.50}{12}) = .03786\ ft^2$$

$$A_o = 3.1416\ \frac{(.437/12)^2}{4} = .00104\ ft^2$$

$$A = .03556 + .00104 = .03660\ ft^2$$

$$C_p = 1\ Btu/(lb)(°F)\ at\ 15°C.$$

$$U = \frac{W'(60)(1)(t_o - t_i)}{.0366\ (t_s - t_a)} = 1639.34\ W'\ \frac{(t_o - t_i)}{(t_s - t_i)}$$

By substituting the measured values of the variables into the above equation the value of the overall heat transfer coefficient, U, can quickly be determined for any set of conditions.

Calculation of cooling water velocity, V.

To calculate the cooling water velocity in the condenser, the area of the annulus was calculated, the weight rate converted to a volume rate, and the latter divided by the former.

$$V = \frac{W' \; A'}{60 \; (d)}$$

$$d = 62.40 \text{ lb/ft}^3 \text{ at } 15^\circ\text{C.}$$

$$A = \frac{3.1416}{4} \left[\left(\frac{.437}{12}\right)^2 - \left(\frac{.25}{12}\right)^2 \right] = .0007007 \text{ ft}^2$$

$$V = .3814 \; W'$$

By substituting the measured water rate into the above equation, the water velocity in the condenser is readily calculated.