AN ABSTRACT OF THE THESIS OF

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Title: TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER AS A FUNCTION OF CONCENTRATION OF SODIUM SULFATE

Abstract Approved: __________

{Major Professor}

There is a demand, by commercial interests, for information regarding the effects of high concentrations of soluble salts in boiler water on boiler efficiency and temperature drop from heating surface to boiler water. In order that this information be obtained, a research program, dealing with the problem, has been initiated at Oregon State College under the supervision of R. E. Summers. Several years may be required to complete the program, as much time is necessary to build special equipment and to make necessary tests.

It has been the privilege of the writer to carry on that research work during this school year, and the purpose of this paper is to present the work he has done on the problem, to point out the more important findings, and to make suggestions for further research.

The determination of temperature drop from heating surface to boiler water as a function of solution concentration was the goal of this year's work. The only salt solutions examined were those made with sodium sulfate. Concentrations ranged from distilled water to 120,000 parts per million sodium sulfate. Work was of a pioneering nature in an unexplored field and provisions were not made for extremely accurate measurements, prior
to a determination of some general approximations. It has been hoped that
more or less general knowledge could be obtained and that the results
thereof would furnish a basis for more accurate and more definite work
to be carried on later. Many difficulties were encountered, however, and
even general accuracy of results has not been definitely established.

Much labor has gone to a preliminary investigation of methods.

Tentative results of investigations of Na₂SO₄ concentrations are:

(1) An indicated "critical point" probably caused by change in
the form of Na₂SO₄ occurring at about 148 pounds gage pressure, in
boilers.

(2) The apparent finding that for pressures below 148 pounds
gage, concentrations of Na₂SO₄ investigated have little effect, while
at pressures greater than 148 pounds gage they may have pronounced effect
on temperature drop from heating surface to boiler-water solution.
For pressures above 148 pounds gage, concentrations greater than
approximately 25,000 parts per million (depending on surface conditions)
have appeared to cause an increase in temperature differential while
concentrations less than that have appeared to cause even a decrease
in temperature drop.

When this research is continued, or in correlating it with other
related studies, two major problems should be seriously weighed before more
data are obtained. First, major difficulties thus far have been with tempera-
ture measuring apparatus. An accurate and reliable means of measuring
temperature drop from heating surface to boiler water should be devised and
proven. Second, the condition of heating surface apparently has a large
effect on results obtained. A method of conditioning and grading heating
surface should be established and coordinated with the temperature measuring
means employed.
TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER 
AS A FUNCTION OF CONCENTRATION 
OF SODIUM SULFATE

by

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This problem was suggested by Professor R. E. Summers of Oregon State College and it was through his efforts that the model test boiler was made available.

The writer wishes to thank him and also other staff members for their kind help and criticism.

The generous cooperation of Mr. B. W. DeGeer in behalf of the Great Northern Railway Company is also deeply appreciated.
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TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER AS A FUNCTION OF CONCENTRATION OF SODIUM SULFATE

INTRODUCTION

Considerable interest and controversy have arisen within the past few years concerning effects of high concentrations of soluble salts in boiler water on boiler efficiency and temperature drop from heating surface to boiler water. Opinions concerning the subject are very much in disagreement and experimental data which might provide an answer are lacking. Some persons, among them Professor W. L. Badger of the University of Michigan, contend that soluble salt concentration has negligible effect on temperature drop from heating surface to solution (1) while others believe that an increase in boiler-water concentration causes an increased temperature drop. This latter group includes many operators of steam-boiler equipment who resort to extensive blow down to prevent possibility of burning out boiler water-tubes. Delays and damage due to failure of water tubes are costly but excessive blow down is also uneconomical. The true facts concerning this subject of dispute should be known, as safety and economy of operation could probably be greatly improved if "guessing" were eliminated from boiler-water control.

It may seem strange at first thought that this problem has not already been thoroughly investigated, inasmuch as
steam boilers have been in use for many years. Effects due to solution concentration have, however not been as important in the past as they now are and they were not always apparent as at present, with boilers now being operated at higher pressures and greater loads than ever before (2). It is important that engineers know the temperature at which boiler metal will operate as in many cases the metal must work at a stress near its maximum tensile strength for the temperature encountered.

R. E. Summers, Assistant Professor of Mechanical Engineering at Oregon State College, has for several years been interested in the action of solution concentration on boiler performance for he has found through contacts with operators of railway and power plant equipment that there is a demand for information concerning safe concentrations in boilers and that more knowledge is desired concerning the relation of boiler efficiency to soluble salt concentration. Because of his interest in the problem, Mr. Summers has encouraged and aided experiment and investigation at Oregon State College which might provide additional information on the subject, and under his supervision, a research program has been initiated which should ultimately answer existing questions.

Several years of research and study may be necessary before a complete knowledge of the problem can be obtained. It is necessary to investigate numerous concentrations of
soluble salts and combinations of soluble salts. Also the action of various types and positions of heating surface must be studied, as well as the influence of various rates of heat flow from the heating surface to the solution. All of these effects must be determined for a wide range of boiler pressures. The magnitude of the problem becomes apparent when the numerous possible combinations of variable factors are considered, and particularly so when it is realized that much new equipment must be constructed in order that the necessary tests can be carried on.

Last year Lawrence Hall, Graduate Student in Mechanical Engineering at Oregon State College, worked on the problem through making a theoretical study of the variation of viscosity of boiler salines with concentration (3). The results of his work indicated that boiler efficiency should decrease with an increase in concentration of dissolved solids but the experimenter did not have sufficient special equipment available, at the time, to check results of his work with actual experimental data. He succeeded in building a falling-sphere high-temperature viscosimeter, however, with which relative kinematic viscosities of boiler-water solutions were measured under various conditions of temperature and pressure.

Under the direction of Professor Summers, there were also worked out detailed plans for an experimental boiler with which actual measurements of boiler efficiency could
be made. One major transcontinental railway company was sufficiently interested in the problem to build the experimental boiler for the use of the College (3) but was prevented from doing so by regulations of the Interstate Commerce Commission. However a much modified "model boiler", of smaller design, was built by commercial interests during the Spring of 1936. That apparatus is now at Oregon State College in the Department of Mechanical Engineering.

In September 1936, C. H. Whisler, a Graduate Student, began work with the equipment. The first problem confronting Mr. Whisler was that of installing heaters and test instruments in the boiler and otherwise preparing it for operation. This problem proved to be rather difficult as commercial equipment of the type desired was not available and much construction work had to be done in the laboratory. After several failures were experienced while attempt was being made to build a water heater of the type desired, efforts were discontinued and a commercial immersion heater was used temporarily in order that some trial runs might be made with solutions of certain salts.

Two preliminary tests and two regular tests had been completed by December 10, 1936, at which time Mr. Whisler withdrew from school to reenter commercial work and could no longer continue with the research. At that time the present writer replaced him and has carried on the research work to the present date.
Progress has been slow as much experimenting and construction work was done in an effort to get best results from the equipment. Much trouble was experienced with heaters and with temperature measuring devices and a large portion of the available time was devoted to eliminating these troubles. Some results were obtained, however, and the preliminary investigations completed should prove valuable as further work is done in this field.

It is the purpose of this paper to present the work done on the problem by the present writer and to point out the more important findings made by him, and to make suggestions for further research.
CHAPTER 1

THE PROBLEM

A brief outline of boiler-water troubles will be presented in order that there may be established a relation of the problem under consideration to the other problems in the field. No specific boiler ill is entirely independent of others, as treatments for one difficulty usually produce quite definite effects on the remaining ones.

Boiler water difficulties (4) may be classified into the following five groups:

(1) Incrustation; the deposition of scale, sludge, or sediment.

(2) Foaming and priming; excessive carryover of moisture in steam.

(3) Corrosion; rusting or pitting of metal.

(4) Embrittlement; metal cracking and failure.

(5) Excessive blow down.

The first four of the boiler troubles named foregoing have received considerable study and may be quite satisfactorily controlled by practical treatments developed in recent years. Excessive blow down, the fifth boiler ill mentioned, has not received as much careful study and blow down schedules have been devised either for control of foaming and priming, as a rough safety precaution against burning out of water-tubes, or from habit, with little consideration of the best possible economic balance of
costs. This unfortunate condition has necessarily existed in many places because information is not available on which to set up an optimum schedule of blow down. The amount of blow down required for water-tube protection is not known for boiler water solutions encountered in present industry and, if known, would represent only a limit to which blow down must be carried for safety. Similarly, the amount of blow down necessary for control of foaming and priming and sludge deposition would be another lower limit of regulation.

It has been reported (3) in several instances that an increase in the amount of blow down has caused a corresponding increase in boiler efficiency. If such is the case an optimum blow down schedule could be devised with an economic balance between efficiency gain from increased blow down and losses due to loss of boiler water, loss of heat with boiler water, and probable loss of boiler-water treating chemicals or alkalinity. And, as mentioned previously, limiting factors would be: minimum blow down for control of foaming and priming; tendency toward sludge deposition; and the requirements of boiler-metal protection. Heat exchangers are now sometimes used to considerably reduce heat losses with boiler water. To work out an ideal schedule requires a rather exact knowledge of the rate of increase of boiler efficiency with rate of change of concentration and composition of solution and a knowledge
of the limiting solution concentration allowable for control of any boiler-water problem.

At the present time very little that is practical is known regarding the rate of change of boiler efficiency with change in concentration and composition of boiler water and, as has been previously stated, probably less is known of the limiting allowable concentrations for boiler-metal safety. These two problems are very closely related, however, as will be seen from the following considerations.

Let $T_b$ represent the temperature of the metal boiler heating surface and let $T_s$ denote the boiler water temperature. Then $(T_b-T_s)$ will be the temperature drop from heating surface to boiler water which will determine directly the temperature at which the boiler tubes must operate. This, $(T_b-T_s)$, may be chiefly a function of solution concentration and solution composition, but it may also be influenced by shape and position of heating surface and by boiler pressure, as well as by rate of heat flow to boiler water.

The temperature difference $(T_b-T_s)$ is also a controlling factor in the efficiency problem. If the Newton equation $H = K(T_b-T_s)A$ is assumed to represent the heat flow from heating surface to solution where:

- $H$ is total heat flow per unit time,
- $K$ is coefficient of heat transfer for conditions existing, and
- $A$ is area through which heat is being transmitted,
then the factor $T_b$ (heating surface temperature) must be of prime importance. Heat energy is arriving at the heating surface continually in the form of sensible heat of furnace gases, or by radiation, and the smaller the amount of heat being absorbed by the boiler the higher will be the temperature of the gases leaving the boiler. This change in sensible heat in the stack gases causes changes in boiler efficiency and general observations have shown that an increase in flue gas temperature of 40 Fahrenheit degrees is equivalent to a loss in boiler efficiency of approximately 1 per cent, due to boiler tubes not absorbing heat from the furnace gases.

If a boiler-water concentration is reached which causes a decrease in the flow of heat through the heating surface it is apparent that some form of heat insulating layer may exist at the surface of the heating wall, on the water side. It is also apparent that this condition would cause an increase in the temperature, $T_b$, of the heating surface metal and of the stack gases, and that an increase in $T_b$ and $(T_b-T_s)$ can be associated with a loss in boiler efficiency. As $T_b$ has also a limiting value for boiler-tube safety it is seen that the problems of heating-surface protection and boiler efficiency are inter-related and that a remedy for one would be, equally, a remedy for the other.

It should be realized that this is not a problem in conventional heat transfer and that the factor $K$ (coef-
efficient of heat transfer for conditions existing) of the foregoing heat transfer equation might probably vary considerably with changes in solution concentration, pressure, etc. Its changes must be considered, as well as changes in the factor \((T_b - T_s)\), for a complete knowledge of the effect of solution concentration upon boiler efficiency.

As research work on a certain problem progresses it is necessary to build up data and results step by step. Success depends very largely on selecting phases of the work for study in their proper sequences in order that advancement may continue with the smallest possible amount of trouble and interruption. The goal of this research work, at the present, is the determination of the temperature difference factor \((T_b - T_s)\) for varying concentrations and compositions of boiler water under different conditions of pressure and heating surface. This factor is considered basic and the most important element of the problem under consideration and when its behavior is fully determined the controversy of concentration of non-scale-forming matter in boiler water will have been advanced a long way toward settlement. The next step in the research program will then logically be a quantitative study of variation in boiler efficiency due to changes in boiler-water concentration.
Model Boiler

The major piece of apparatus used in making this experimental study was the model boiler constructed for use of the school by outside commercial interests. Outstanding features of the boiler are shown in the general assembly drawing, Figure 1, and by the photographs, Figures 2 and 3. Figure 2 shows the boiler and apparatus assembled for operation with the exception of the front oven door and front boiler insulating cover. These have been removed to show inner construction. In Figure 3 the apparatus is shown completely assembled and ready for a test run.

It may be seen that the model boiler consists of a heat insulated cylindrical pressure vessel horizontally placed inside of a well insulated oven. Sample boiler-water solutions placed within the pressure vessel are heated during tests by electric immersion heaters of one kilowatt capacity. Five 500-watt electric strip heaters are used to add heat to oven air, the temperature of which is measured by two 0 to 600 degree F. mercury-in-glass thermometers. One thermometer is placed near the top and the other near the bottom of the oven in order that an average temperature reading be obtained. A fan and motor (shown in Figure 2) are used to circulate oven air. The temperature variation
FIGURE 1

GENERAL ASSEMBLY OF MODEL BOILER
SIDE ELEVATION
Figure 2

Figure 3

TEST APPARATUS
TEST INSTRUMENTS

Figure 4
of that air, from top to bottom of oven, is usually less than 5 Fahrenheit degrees. The oven itself has outside dimensions of 30 inches by 36 inches by 36 inches and is of welded construction. The walls are built of 3/32-inch steel sheets spaced 3 inches apart and filled between with asbestos insulating filler. The pressure vessel within the oven has an inside length of 18 inches and an approximate inside diameter of 8 inches. As is shown in Figure 1, it has a removable head on each end, each head being held in place by eight 3/4-inch bolts. The rear removable head has been drilled and tapped in three places to receive 1/2-inch pipe fittings but thus far these openings have not been used and are fitted with plugs. The front head has provisions at two points for 1/2-inch pipe fittings and at one point for a 2-1/2-inch fitting. It is by means of the 2-1/2-inch pipe tap that immersion heaters are installed, and one of the 1/2-inch pipe size openings on the front has been used for mounting a chromel-alumel thermocouple in the boiler in order that solution temperature may be determined. The vessel was designed for a maximum operating gage pressure of 400 pounds per square inch but it has not been used at pressures that high to date. Surrounding the pressure vessel is a two inch thickness of asbestos insulation. Two pipes are welded into the top of the vessel. One, an extra heavy 1/4-inch pipe, leads to the pressure gage; the second, an extra heavy 1-inch pipe, leads to a condenser which may
be used to load the boiler. Condensate from the condenser returns by gravity.

**Boiler-Water Heaters**

The electric immersion heater used in the boiler water must provide the heating surface from which the factor, temperature drop from heating surface to solution, is determined. It is necessary, therefore, that the shape, condition, and material of the heater surface, and the rate of flow of heat through that surface, be taken into account in evaluating results of the test. By using a variable resistance in series with the heater it is possible to control the rate of heat flow through the surface from zero to a maximum value dependent upon heater capacity. In order to study surface effects, and in an effort to obtain best test results, the following described different heaters were used:

- **Heater No. 1** - Standard General Electric immersion heater of the hairpin type; copper surface.
  - Capacity 1 kilowatt.
  - Active heating surface 16.6 square inches approx.
  - Type of surface, circular cross-section copper tube, outside diameter 11/32 inch.

- **Heater No. 2** - Heater constructed in college laboratory, cat-tail type, steel surface.
  - Capacity 1 kilowatt
Active heating surface 33 square inches.
Type of surface, circular cross-section steel tube, 1 inch outside diameter.
Heater No. 3 - Heater built by Great Northern Railway Company, cat-tail type, steel surface.
Capacity 1 kilowatt.
Active heating surface 27 square inches approx.
Type of surface, elliptical steel tube, ellipse 1/2 inch by 7/8 inch.
Heater No. 4 - Heater constructed in college laboratory, cat-tail type, steel surface.
Capacity 1 kilowatt
Active heating surface 39 square inches approx.
Type of surface, circular cross-section, steel tube, 1 inch outside diameter.

More detailed information on heaters and heater construction will be found in Appendix A.

Temperature Measuring Devices for Heaters and Solutions

All heaters were equipped with thermocouples for measuring surface temperature, and heaters 1, 2, and 3 were also provided with a second thermocouple placed in the boiler solution approximately one inch from the heating surface. These second thermocouples were connected differentially with the first and provided means for measuring temperature difference between heating surface and solution.
The solution thermocouples were shielded so that radiated energy from the heater could not affect their readings. Heater No. 1 was equipped with copper-nickel thermocouples while heaters 2 and 3 were fitted with nickel-steel thermocouples. Heater No. 4 had, for measuring surface temperature, a chromel-alumel thermocouple welded into its surface. The leads of this thermocouple were placed inside of the heater tube rather than in the solution in order that possible electrical leakage between leads could not occur. When heater No. 4 was used the temperature of the boiler-water solution was measured by a chromel-alumel thermocouple inserted in the boiler independent of the heater (for additional information on the construction and calibration of these thermocouples refer to Appendix B).

Miscellaneous Other Equipment

Other important equipment used regularly was as follows:

Bristol recording pressure gage;

Range 0 to 500 pounds per square inch gage.

Smallest division of reading 5 pounds.

Bourdon test gage;

Range 0 to 250 pounds per square inch gage.

Smallest division of reading 1 pound.

Laboratory wattmeter and variable resistance; used for controlling power input to immersion heater.
Direct reading potentiometer (5); for measuring electromotive force of thermocouples.

Special surface gage; for measuring liquid level in boiler.

The special surface gage, mentioned in the foregoing paragraph, was constructed to make possible checking of the quantity of solution in the boiler without removing that solution. It consisted of a pointed brass rod connected in series with two common dry cells, a millivoltmeter, a postoffice-type resistance box, and the boiler. Contact between the point of the rod and the solution surface closed the electrical circuit allowing a small current to flow and causing the millivoltmeter to indicate a potential drop across its terminals. The brass rod was placed inside of a small rubber tube so that it would not make contact with metal when being lowered through the condenser tube in which it was used. The rod was calibrated and marked so that a fixed distance from the top of the condenser tube to the solution surface could be used to indicate a proper level (corresponding to ten liters of solution). The variable resistance was necessary in the circuit to balance unlike resistances of different solutions in order that millivoltmeter readings would be on scale.
CHAPTER 3

WORK DONE AND TEST PROCEDURE

Work done on the research problem during the school year, within the scope of this thesis, includes:

(1) Setting up the experimental model boiler and equipping it with necessary measuring apparatus.

(2) Construction of immersion heaters for test use (see Appendix A).

(3) Construction and calibration of thermocouples for measuring temperature drop from heating surface to boiler solution (see Appendix B).

(4) A study of the methods for determining solution concentration in order that a best method be found (see Appendix C).

(5) The taking of data from some actual tests (see problem statement) for a range of sodium sulfate \((\text{Na}_2\text{SO}_4)\) concentrations in water.

Phases (1), (2), (3), and (4) of the work done are discussed in detail elsewhere in this paper and no further description will be necessary here. Actual test procedure will be explained at this point, however.

At the beginning of each test, ten liters of solution of the required composition and concentration were placed in the boiler and that was closed except for a vent in the top of the condenser tube. Oven heaters and the immersion
heater were then set in operation and heat application was continued until the solution reached a steaming point. This warming period required approximately two and one-half hours and readings were taken only Occasionally as this part of the run was not accorded much importance. At the conclusion of the warming period the solution was allowed to steam until all air had been driven from the boiler through the vent. The vent was then closed with a pipe plug and pressure was allowed to rise above atmospheric.

Readings were taken at approximate ten-minute intervals throughout the period of pressure increase to the maximum pressure allowed. About four and one-half hours were required for the pressure to rise through the investigated range, from 0 to 250 pounds per square inch gage. A different set of readings was recorded when using heaters 1, 2, and 3 than when using heater No. 4 because unlike temperature measuring systems were employed (see Chapter 2 and Appendix B).

Readings taken while using heaters 1, 2, and 3, were:

(a) Boiler gage pressure, pounds per square inch.
(b) Oven temperature, degrees Fahrenheit.
(c) E.M.F. of differential thermocouple, millivolts.
(d) Immersion heater input, watts.

The pressure vessel was covered with approximately two inches of asbestos insulation. Nevertheless, oven air
temperature was at all times maintained as nearly equal to boiler solution temperature as was possible in order that heat transfer through the pressure vessel walls would be negligible. In order that this regulation of oven temperature could be effected, solution temperature was approximated by readings from the steam tables. Temperatures corresponding to boiler pressure were assumed. This procedure disregarded vapor pressure lowering due to salt in solution. The error caused by making this assumption was considered not large enough to be of importance as, first, a few degrees temperature difference between oven and solution temperature should not affect results of the test and, second, a check of solution temperature with a thermocouple indicated that values of temperature taken from the steam tables were roughly applicable to the solutions studied.

Differential thermocouple readings were converted into values of temperature drop from heating surface to boiler water by employing a calibration curve previously prepared in the laboratory.

Immersion heater input was maintained at 900 watts for the major part of the study because large variations in line voltage of the electric power supply made it impossible to maintain, at all times, an input of 1000 watts, the usual heater rating. Readings at inputs other than 900 watts were obtained, but this phase of the problem was not
extensively studied and no large amount of data was taken. Some investigations were made however with an input of 450 watts in order that the general effect of heat input variation might be discovered.

As previously stated, a few readings different from those described foregoing were taken when heater No. 4 was employed. With that heater readings recorded were:

(a) Boiler gage pressure, pounds per square inch.
(b) Oven temperature, degrees Fahrenheit.
(c) E.M.F. of solution thermocouple, millivolts.
(d) E.M.F. of heating surface thermocouple, millivolts.
(e) Immersion heater input, watts.

Heater and solution thermocouples used with heater No. 4 were most carefully calibrated in the laboratory, and the matter of obtaining temperature difference between heating surface and boiler water from observed data was merely one of subtraction, after calibration curves had been prepared for the couples.

Test results were, in all cases, expressed in the form of curves. Values of temperature drop from heating surface to boiler water have been plotted as ordinates against values of boiler pressure as the independent variable. Separate curves apply to the different immersion heater inputs and to different boiler solutions.

The only salt solutions investigated this year were
those made with sodium sulfate (Na₂SO₄) and distilled water. Concentrations of this salt were varied from distilled water to a maximum of 120,000 parts per million. Actually no tests were run with pure distilled water because serious rusting would probably result were this done. To reduce rusting, 100 parts per million of sodium hydroxide (NaOH) were added to the distilled water runs. It was believed that the added alkalinity would somewhat retard excessive metal rusting and at the same time not greatly affect the readings obtained for distilled water, as the amount of sodium hydroxide in solution was very small. This amount of sodium hydroxide was present in all runs made, for the water of the distilled water runs was used to make up the solutions of sodium sulfate tested. In order that runs could be carried forward without unnecessary loss of salt and distilled water, ten liters of water (plus the 100 parts per million of NaOH to prevent rusting) were usually tested first. Salt was then added to the solution for succeeding runs, causing the solution concentration to become increasingly greater.

Designation of tests was according to a simple system. A series of tests included all of the runs made with a certain filling of distilled water and its several salt quantities. Subscripts were used, along with a series number, to signify the particular run of that series. For instance, 3e denotes run "e" of the third series of tests.
Between trials the boiler was thoroughly cleaned by first circulating tap water through it for several hours and then removing the front pressure-vessel head and drying the inner surfaces with clean rags.
CHAPTER 4

RESULTS OF WORK

Work done this year with present equipment has led to a general knowledge of what additional apparatus and improvements are needed for carrying on the research study. The model boiler was found to be quite satisfactory for determining the temperature difference factor but will probably not be satisfactory for determining variations in boiler efficiency with changes in solution concentration.

Boiler heaters used were constant sources of trouble but a method of heater construction (see Appendix A) was finally devised which gave good results and had an additional advantage that heating elements could be replaced without disturbing other parts of the heater.

Thermocouple applications used this year were not altogether satisfactory. However, certain elements of construction were found successful and may prove of value in future work. It was found that a good thermocouple junction of large area could be made by either electroplating a surface of one metal upon another (nickel was electroplated directly on steel for heater No. 2 and on copper for heater No. 1) or by applying a layer of one metal on another with an acetylene welding torch (nickel was thus applied to steel for heater 3). Difficulty was experienced in attempting to electroplate nickel directly on steel (see Appendix B) but the process should be quite
easily carried out if a thin layer of copper is first plated on the steel. This layer of copper will not affect the thermocouple reading (6).

Results of tests with the model boiler and with the several heaters in different aqueous solutions are shown by the curves in Figures 5, 6, 7, 8, and 9. Five series of tests were made by the writer, three with heater No. 1, one with heater No. 2, and one with heater No. 4. The heating element of heater No. 3 burned out before data could be obtained with that, and, because of the heater construction, repairs could not be made. Since heater No. 4 has been completed time has not been available, prior to the present writing, for more than two test runs. These constitute the fifth series.

Solution concentration, heater used, power input of immersion heater to solution, and other pertinent data, are given on the curve sheets for each series.

In order that results with different heaters might be compared more closely, density of heat flow through heater surface has been calculated as well as possible for each heater. That was found to be as follows, for 900 watts input:

Heater No. 1 26,630 B.t.u. per sq. ft. per hr.
Heater No. 2 15,400 B.t.u. per sq. ft. per hr.
Heater No. 3 16,380 B.t.u. per sq. ft. per hr.
Heater No. 4 11,340 B.t.u. per sq. ft. per hr.
It is customary to rate a boiler on the basis that 10 square feet of heating surface under normal operating conditions are considered capable of evaporating 34.5 pounds of water per hour from and at 212 degrees F. For comparison, percentage ratings of boiler heating surface were calculated for each heater. Results are as follows:

<table>
<thead>
<tr>
<th>Heater No.</th>
<th>Percentage Boiler Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>795</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>490</td>
</tr>
<tr>
<td>4</td>
<td>339</td>
</tr>
</tbody>
</table>

The foregoing boiler ratings are based on a heater input of 900 watts.
CURVES SHOWING EFFECT OF
BOILER PRESSURE ON
TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER
AS DETERMINED BY
FIRST SERIES OF TESTS
NOVEMBER 1936

HEATER NO 1
INPUT 900 WATTS
ALL SOLUTIONS CONTAIN 100 PPM NaOH

FIGURE 5
CURVES SHOWING EFFECT OF BOILER PRESSURE ON TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER AS DETERMINED BY SECOND SERIES OF TESTS JANUARY 1937

HEATER NO I

ALL SOLUTIONS CONTAIN 100 PPM NaOH

FIGURE 6
CURVES SHOWING EFFECT
OF
BOILER PRESSURE
ON
TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER
AS DETERMINED BY
THIRD SERIES OF TESTS
APRIL 1937

HEATER No 1
INPUT 900 WATTS
ALL SOLUTIONS CONTAIN 100 PPM NaOH

FIGURE 7
CURVES SHOWING EFFECT OF BOILER PRESSURE ON TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER AS DETERMINED BY FOURTH SERIES OF TESTS APRIL 1937

HEATER NO 2 INPUT 900 WATTS ALL SOLUTIONS CONTAINED 100 PPM NaOH

\[ \text{TEMPERATURE DROP - F DEGREES} \]

\[ \text{BOILER GAGE PRESSURE - LB PER SQ IN} \]

FIGURE 8
CURVES SHOWING EFFECT
OF
BOILER PRESSURE
ON
TEMPERATURE DROP FROM HEATING SURFACE TO BOILER WATER
AS DETERMINED BY
FIFTH SERIES OF TESTS
MAY 1937

HEATER NO 4
INPUT 900 WATTS
RUN S₄- DISTILLED WATER PLUS 100 PPM NaOH
RUN S₅- DISTILLED WATER PLUS 100 PPM NaOH
PLUS 60,000 PPM Na₂SO₄

FIGURE 9
CHAPTER 5

CONCLUSIONS

As stated in the foregoing discussion, this research was carried on as a part of a larger effort. The general desire has been, as was also stated, discovery of the effect, if any, of boiler-water concentration on temperature drop from heating surface to boiler water. Study has been limited this year, in the work of the present writer, to certain investigations of sodium sulfate concentrations. Enough tests have been made to show considerable information useful at least in further studies, if not of certain direct practical value. Results obtained with each heater will be discussed separately, as each was equipped with a different temperature measuring device and somewhat different results were obtained with each. These have to be considered in relation to the means used for the determination, and are here so presented:

Considerations of First, Second, and Third Series of Runs (heater No. 1, copper-nickel differential thermocouple)

An examination of graphically presented data for the first three series of test runs reveals certain indications. They are as follows:

(a) Below 148 pounds to the square inch, gage
pressure, solution concentration does not seem to have a pronounced effect on temperature drop from heating surface to boiler water. Average values of temperature drop obtained for distilled water below 148 pounds per square inch gage pressure check quite closely the findings of Max Jacob (2).

(b) At boiler pressures above 148 pounds, gage, concentrations greater than approximately 25,000 parts to the million (depending on heating surface condition) of Na₂SO₄ apparently cause a larger temperature drop than does pure distilled water.

(c) At boiler pressures above 148 pounds, gage, concentrations less than approximately 25,000 parts to the million (depending on heating surface condition) of Na₂SO₄ apparently cause a somewhat smaller temperature drop than does distilled water.

(d) The data indicate that a critical point occurs at about 148 pounds gage pressure. Above this pressure solution concentration has a marked effect while below this pressure concentration is not so important for the solutions studied. That this critical point is due to a change in form of dissolved Na₂SO₄ appears to be the most logical explanation as work on solubility of Na₂SO₄ (7) has shown that a change in form does occur at approximately 148 pounds per square inch, gage pressure.
(e) Data obtained from the second and third series of runs should check fairly closely for concentrations below 40,000 parts per million Na₂SO₄, as this range is covered by both series and both were made with same heater (No. 1) and with the same power input. It will be seen, however, that the second and third series of runs do not check each other closely; a greater temperature drop is associated with a given solution strength in the third series than in the second. As test conditions for the two runs were not changed by the operator it was thought that the heating surface, which had been exposed to the salt solution for several days between runs, had become corroded and that this corrosion was responsible for the observed difference in the temperature drop factor (2). This action of surface condition might be eliminated in future research if some standardized means of conditioning and grading the surface could be adopted. It is apparent that surface condition is an important phase of this study.

(f) The effect of variation in heater input, as shown by Figure 6, is not large for the heat input range investigated. This result is checked by research on evaporation (2) which shows that a great change in temperature drop will not result from a corresponding change in heat input at the higher rates of heat.
transfer but at low rates of heat transfer (below the range investigated in this work) a large change in temperature drop does result from a small change in input.

The manner in which dissolved salt causes changes in temperature drop has not yet been determined. Consideration of the effect of conventional heat transfer as a function of Reynolds number, etc., does not indicate that there will be a pronounced increase in temperature drop with increase in concentration (8). Two years ago, however, Professor Summers suggested a theory of soluble scale formation which might account for the increase in temperature difference. This theory is briefly restated as follows:

"Imagine that during rapid steam formation at a boiler surface, a portion of the boiler plate is blanket ed with steam bubbles. Within those bubbles, or on the surface of formation on which they have grown, are probably deposits of salt thrown out of solution by rapid evaporation of water from a very much, and non-uniformly, concentrated solution in contact with the heat transfer surface. Shut down and inspection of the boiler would disclose no such salt deposits, even though they might exist in appreciable thickness during steaming. Their existence would be in the nature of spotty deposits, first in one place and then in another, during steaming, or one might think of them as being formed and at the same time being dissolved in great numbers. If this theory is correct, you may expect to find the reduction of heat transfer at high concentrations more pronounced on those surfaces, or in those boilers, through which heat transfer is chiefly by convection."

Considerations of Fourth Series of Runs

(Heater No. 2)
Data for the fourth test series were obtained with a nickel-steel differential thermocouple and it is apparent that results are, perhaps, poor. However the "critical point" existing at a boiler pressure of approximately 148 pounds gage is indicated by this series of runs and an increase in temperature drop is shown to result from an increase in concentration, for boiler pressures above 148 pounds gage. These results correspond to results obtained with heater No. 1 fitted with a copper-nickel differential thermocouple.

Errors in the data of the fourth series are undoubtedly caused by an improper calibration of the differential thermocouple. The calibration curve was prepared with a cold junction temperature of 80 degrees Fahrenheit, whereas in actual operation the cold junction (or solution thermocouple) reached a temperature in excess of 400 degrees Fahrenheit. A possible difference in composition of the steel at the two junctions could cause considerable error in readings under these conditions.

As the copper-nickel differential thermocouple of heater No. 1 was calibrated in this same manner the accuracy of the first, second, and third series data may be questioned, although the results should be relatively correct.

Considerations of Fifth Series of Runs
(Heater No. 4)
The data for the fifth series of tests were obtained with two carefully calibrated chromel-alumel thermocouples, one welded into the heating surface of heater No. 4 and the other placed in a thermocouple well in the solution. The thermocouple junction for measuring heating surface temperature was welded into the surface from the inside as explained in Appendix B. Leads from this junction were brought out through insulators inside the heater tube in order that they would not be in contact with the solution at any point. This was done so that readings would be free of any effects of solution upon the leads, such as electrical leakage and tendency of solution to build up a potential between leads as in a voltaic cell. Similarly, the junction of the solution thermocouple was welded into the surface of a metal thermocouple well and its leads were not in contact with the boiler water. The major objection to this temperature measuring system is that it measures only a spot temperature on the heating surface whereas the hot junction used with the differential thermocouples consisted of large areas of plated-on or welded-on metal. If steam bubbles are forming rapidly at different spots over a large area, there may be a considerable variation in temperature of heating surface temperature over that area, and, the temperature of a given point may also fluctuate as bubbles form. If a single spot thermocouple is used the reading obtained is not liable to be as representative as if the
thermocouple junction is made to include a large area.

The data obtained for the distilled water run check fairly well with results from the first, second, and third series, but run 5b does not check data obtained with a corresponding concentration when heater No. 1 was used in run 2b. No conclusions can be based on results of series 5, as not sufficient tests were completed to check the data obtained.

Summary of Conclusions

(A) Work described herein was of a pioneering nature in an unexplored field and provisions were not made for extremely accurate measurements, prior to a determination of some general approximations. It has been hoped that more or less general knowledge could be obtained and that the results thereof would furnish a basis for more accurate and more definite work to be carried on later. Many difficulties were encountered, however, and even general accuracy of results has not been definitely established. Much labor has gone to a preliminary investigation of methods.

(B) Tentative results of investigations of Na₂SO₄ concentrations are:

(1) An indicated "critical point" probably caused by change in the form of Na₂SO₄ occurring at about 148 pounds gage pressure, in boilers.

(2) The apparent finding that for pressures below
148 pounds gage, concentrations of Na₂SO₄ investigated have little effect, while at pressures greater than 148 pounds gage they may have pronounced effect. For pressures above 148 pounds gage, concentrations greater than approximately 25,000 parts per million (depending on surface condition) have appeared to cause an increase in temperature differential while concentrations less than that have appeared to cause even a decrease in temperature drop.

(C) When this research is continued, or in correlating it with other related studies, two major problems should be seriously weighed before more data are obtained. First, major difficulties thus far have been with temperature measuring apparatus. An accurate and reliable means of measuring temperature drop from heating surface to boiler water should be devised and proven. Second, the condition of heating surface apparently has a large effect on results obtained. A method of conditioning and grading heating surface should be established and coordinated with the temperature measuring means employed.
APPENDIX A

IMMERSION HEATER CONSTRUCTION
The problem of immersion heater construction is interrelated with that of design and construction of temperature measuring systems for determining temperature drop from heating surface to boiler water. This is true because the heater and the surface-temperature measuring apparatus must be built in one unit. In order to better explain each, however, problems of the two will be presented separately. Heater construction is discussed in this Appendix and temperature measuring systems are dealt with in Appendix B.

It was originally the desire to obtain experimental data with rates of heat transfer through the heating surface approximately equal to those found in actual boilers. The average modern boiler was arbitrarily assumed to operate at outputs ranging to about 900 per cent rating, which corresponds to a heat flow through the heating surface of approximately 30,000 British thermal units per square foot per hour. Calculations were made to show that a heater of 1 kilowatt capacity would have 16.4 square inches of heating surface to produce the indicated heat emission density.

A standard General Electric immersion heater (heater No. 1, Figure 10) of the hairpin type was obtained and, as elsewhere stated, was used for the first three series of tests. This heater had a heating surface area of 16.6
IMMERSION HEATERS

Figure 10
square inches, practically the amount desired. However, the heating tube of this heater was made of copper, a material not satisfactory for contact with caustic solutions. Under conditions of high temperature, copper would be severely attacked by the caustic solutions and the heating surface would become badly corroded. As heating surface condition has a large effect on results obtained it was desired to have a heating surface of either nickel or steel. Pure nickel was favored as it is not easily corroded and has certain advantages for installation of temperature measuring devices (plating on thermocouples). However a nickel tube of the required size and shape was not readily available so a steel tube was used. As steel is ordinarily the metal used for boiler construction, however, perhaps the choice was a good one.

Instead of building a heater of the hairpin type, as was heater No. 1, plans were made for building one of the "cat-tail" type (see heater No. 2, Figure 10). The problem of construction of a heater of 1 kilowatt capacity with only 16.4 square inches of heating surface was very difficult as the heating element necessarily used was composed of 27.8 feet of 18 gage Chromel "A" resistance wire wound in the form of a helix, a rather bulky element. Gage 20 heating element wire could have been used, had it been available, and only 17.8 feet would have been necessary. The problem would have been greatly simplified with this
smaller wire and in future construction this is the kind that will probably be most adaptable.

By varying heat input during tests with the commercial heater No. 1 it was found that representative results could be obtained with a smaller input, the only difference being that a small percentage decrease was found in the temperature drop values obtained. Because this was the case, it was decided to increase the amount of heating surface of the proposed heater and make construction simpler.

A satisfactory steel cased heater (No. 2) of 33 square inches of heating surface was finally completed. It was made as follows: A 12-inch length of 3/4-inch steel pipe was fitted into a pipe bushing to form the body of the heater as shown in Figure 10. A cap was then welded over the free end of the pipe to make the heater a closed thimble capable of preventing solution under pressure from escaping to the outside of the boiler. The assembly was centered on a lathe and the pipe was turned to a smooth bright surface. The resistance element wire was wound in the form of a helix approximately 9/32 inch in outside diameter and 11 inches in length. As leads of the element were to be attached at the outer end of the helix, a 1/8-inch steel rod was run through the center of the coil and welded to the heating element wire to make contact with the inner end. The steel rod was insulated from the coil.
by refractory insulators. The entire heating element was held in position and insulated from the heater body by alundum cement. Some difficulty was experienced at first in placing a stiff mix of this cement in the heater but it was found that filling was easily accomplished through application to the case to a concrete vibrator. During the placing of the cement, the heating element was spaced from the closed end of the heater tube by mica disks and was centered in the tube by hand. After being placed in position, the cement was dried in an oven at 230 degrees F. for about 20 hours, and was then further dried by operating the heater at a low input for several hours.

The heating element of heater No. 2 may be removed, for repairs or replacement, by holding the heater in a vertical position with the closed end up and tapping with a hammer. Of course, it is necessary to re-cement the element in position when replacing it.

Heater No. 4 was built similarly to No. 2 except that a 15 inch length of 3/4-inch steel pipe was used for the heating surface and the heating coil was stretched to a length of about 12 inches. Also, insulated thermocouple leads were brought out through the inside of the heater tube, the thermocouple junction being welded into the heating surface.
APPENDIX B

TEMPERATURE MEASURING SYSTEMS
TEMPERATURE MEASURING SYSTEMS

Surface temperatures of condenser tubes or boiler tubes have been measured by the following methods:

(a) By thermocouples welded, silver soldered, electro-plated, or peened to the heat transferring surface.

(b) By resistance thermometers embedded in the surface.

(c) By measurement of electrical resistance of a given section of the heating surface itself and correlation of that resistance with temperature.

Each method has certain advantages and disadvantages. Thermocouples, whether welded, electroplated, peened, or silver soldered to a surface must have leads coming away from that surface, and these leads may effect steam bubble formation or may conduct heat into the boiler water causing a change in temperature of the point where the thermocouple is applied. Also, unless the junction covers a large area, spot temperatures instead of average values may be recorded. The chief advantage of thermocouples is their ease of construction.

Resistance thermometers are valuable for accurate work but difficult of installation in boiler heating surface. Once constructed and calibrated, however, they should provide a reliable means of measuring heating surface temperature.
The method of measuring the resistance of the tube itself is little applied to the case under consideration. Salt solution conductance would act in parallel with that of the tube and interpretation of results would be difficult. The method has possibilities, however.

It was decided to use thermocouples for temperature measurement for research this year. Time was limited and rapid construction of thermocouples was possible, and the equipment was simpler than for the other methods.

Heater No. 1 was the first to be fitted with a temperature measuring device. For measuring surface temperature a nickel wire was plated onto the copper surface forming, on the heater, a nickel-copper junction. A large area of nickel (about 1-1/2 square inches) was plated on in order that average temperature values and not spot temperatures would be measured. At another point on the copper heating surface, a copper wire was silver soldered to the surface. This copper wire and the nickel wire formed the leads from the junction.

Solution temperature, for use in connection with readings of surface temperature of heater No. 1, was measured with a second nickel-copper thermocouple placed approximately 1 inch from the heater surface and shielded from direct radiation by a thin metal sheet. This couple was connected differentially with the first in order that readings of temperature difference might be obtained.
directly. Leads from this differential system of thermocouples were carried to the outside of the boiler through two insulated bolts running through the pipe bushing on the heater. Heater No. 1 is shown in Figure 10 without the temperature measuring thermocouples attached. Heater No. 2 is shown equipped with a differential thermocouple system, however, which is almost the same as that used for heater No. 1. The only differences were, first, nickel-steel couples were used instead of nickel-copper couples (because heating surface was steel), and second, instead of having a plated-on heating surface junction, heater No. 2 had a welded-on junction. A reducing flame and flux was used, when welding, to prevent the oxidation of nickel when melted. The finished junction was turned down in a lathe to an even smooth layer of nickel and presented an area of about 1-1/2 square inches.

Calibration of the differential thermocouple was effected by placing the solution couple in one beaker of water and the heater and surface couple in another beaker of water. Solution couple temperature was held at 80 degrees F. while the temperature of the heater junction was increased to 212 degrees F. Readings of temperature difference and of differential thermocouple potential were recorded at frequent intervals in order that data might be obtained for the relation of temperature difference to differential thermocouple potential.
couple similar to that of heater No. 2 with the exception that nickel was plated on the steel heating surface instead of being placed on with a welding torch. The plated-on nickel did not remain attached to the steel very well but that trouble was expected, in some measure, since no copper under plating was used.

Heater No. 4 was equipped with a chromel-alumel wire thermocouple for measuring heating surface temperature. A small hole was drilled in the heating tube and the chromel-alumel wire junction was pushed through from the inside. The flame of an acetylene torch was then used to weld the heating surface and the junction together and to close the opening in the heater case. After welding, the tube was smoothed with a file to give a uniform surface. The thermocouple leads were strung through small refractory insulators and brought between the heating element and tube wall to the outside of the boiler. Heater No. 4 and the thermocouple leads are shown in Figure 10. A separate chromel-alumel thermocouple was used for measuring solution temperature (see Figure 11) when heater No. 4 was used.

The two chromel-alumel thermocouples were calibrated in an actual boiler test on distilled water. At regular periods, immersion heater input was reduced to zero so that the heating surface would assume the temperature of the distilled water. Gage pressures were read and corresponding distilled water temperatures were taken from steam
tables. There temperatures were then plotted against solution thermocouple and heating surface thermocouple potentials to obtain calibration curves. The two thermocouples were made of wire from the same coils and their calibrations were identical.
SOLUTION THERMOCOUPLE

Figure 11
Sodium sulfate used for making solutions was of the technical grade obtained in 400 pound barrels for commercial boiler-water control. Because the amount of hydration of the salt was not known, it was necessary to test each solution made to determine actual concentration. Average findings indicated that the salt existed in an almost completely dehydrated form. Methods experimented with for determining solution concentration were as follows:

(a) Specific gravity of the solution was determined with a Nalco hydrometer and sodium sulfate concentration was read directly from a calibration chart supplied with that hydrometer. This method did not appear to give correct results and was not applied in the actual test work.

(b) A chemical method of analysis by benzidine titration was tried. It was a rapid and an apparently accurate method but, because some doubt existed as to the exact strength of some of the laboratory reagents used this method was considered applicable only for rough checking.

(c) Specific gravity of the solution was measured with a specific gravity bottle and values of corresponding \( \text{Na}_2\text{SO}_4 \) concentration were obtained from tables in a handbook of physics and chemistry. This
method required more time than the others but was the one used, because of its accuracy.

(f) An electric concentration meter, loaned by the National Aluminate Corporation, was used to obtain approximate values of solution concentration prior to application of method (c). It provided a very rapid means of determining Na₂SO₄ concentration, after being calibrated for that salt.
APPENDIX D

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