THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report

of

Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by Lewis Michael Becker for the degree of Mechanical Engineer. They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Mechanical Engineer.

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Date May 31, 1923

10-20 5M

# A I R   A S   A   C O N D E N S I N G   M E D I U M

# I N   A

# S U R F A C E   C O N D E N S E R

A Thesis Submitted to the Faculty of the

GRADUATE SCHOOL

of the

UNIVERSITY OF MINNESOTA

by

L. M. Becker

In Partial Fulfillment of the Requirements for the

DEGREE OF MECHANICAL ENGINEER



J U N E

1 9 2 3

PREFACE

During the past few years, the necessity for the introduction of some comparatively cheap agent for the absorption of heat or moisture has made itself apparent. One phase of this condition exists chiefly in the laundry and other allied industries where large amounts of moisture are to be absorbed in a short time. At present, this is effected mostly by the use of steam coils which in themselves involve a high initial cost and a tremendous waste of heat energy. For this reason, many modern systems are being installed in which the absorption of heat is accomplished by the recirculation of free air. Needless to say, this new process is meeting with much success.

However, a new field in which free air may be utilized for the absorption heat is the condensation of steam in surface condensers. In view of the fact that so little has been done in this field, the author conducted an extensive series of tests to determine the cooling effect of air on steam when applied to condenser service. The succeeding pages of this paper will explain the methods employed to carry out the tests and to calculate the desired data.

INDEX

D R A W I N G S   O F   A P P A R A T U S

# PRELIMINARY DISCUSSION

The recovery of condensation water from power plants is an important matter. Ordinary methods of condensing the steam by means of a water-cooled condenser are almost prohibitive in cost, particularly if cooling towers or similar devices are used, since the latter involve a loss of water about equivalent to the amount of condensation. In addition to this, the high fuel cost enters as a factor, rendering it desirable to secure the additional economy due to the use of condensing engines, operating only against condenser pressure. It becomes necessary, therefore, to consider other means for recovering the condensation under such unfavorable conditions. The question has been asked, what can be done with air?

The use of air as a condensing medium in a surface condenser has been given little consideration by the engineering profession, certainly not with the idea of making such a problem practical. This condition may be attributed to the thought that it was unnecessary except in remote regions where fuel and water are scarce. The city of Kalgoolie, in Western Australia, furnished such a condition, and, up to the present time, the only example of an air cooled installation. Here was built an electric central station for furnishing power and lighting current to the neighboring gold mines. The units consisted of three 1500 Horse Power engines provided with surface condensers of a special design, which were cooled by air instead of by water. The cooling effect was produced by three large fans seven feet in diameter and running normally at 320 R.P.M. The average vacuum obtained was about 18 inches thruout the year, ranging from 0 inches on very hot days to 22 inches in colder weather. However, there are no data available as to the relative proportions of air used to steam condensed in this installation.

## OBJECT OF TESTS

The primary object of these tests as run in the laboratory was to determine the number of pounds of air necessary to condense one pound of exhaust steam flowing thru the condenser. This could be determined in two ways, but the methods employed in these tests were to compare the number of pounds of steam actually condensed with the number of pounds of air flowing thru the condenser per unit of time.

Inasmuch as the tests furnished the requisite data, additional calculations were made to determine the value of the Coefficient of Transmission "C" of the condenser.

# DESCRIPTION OF CONDENSER

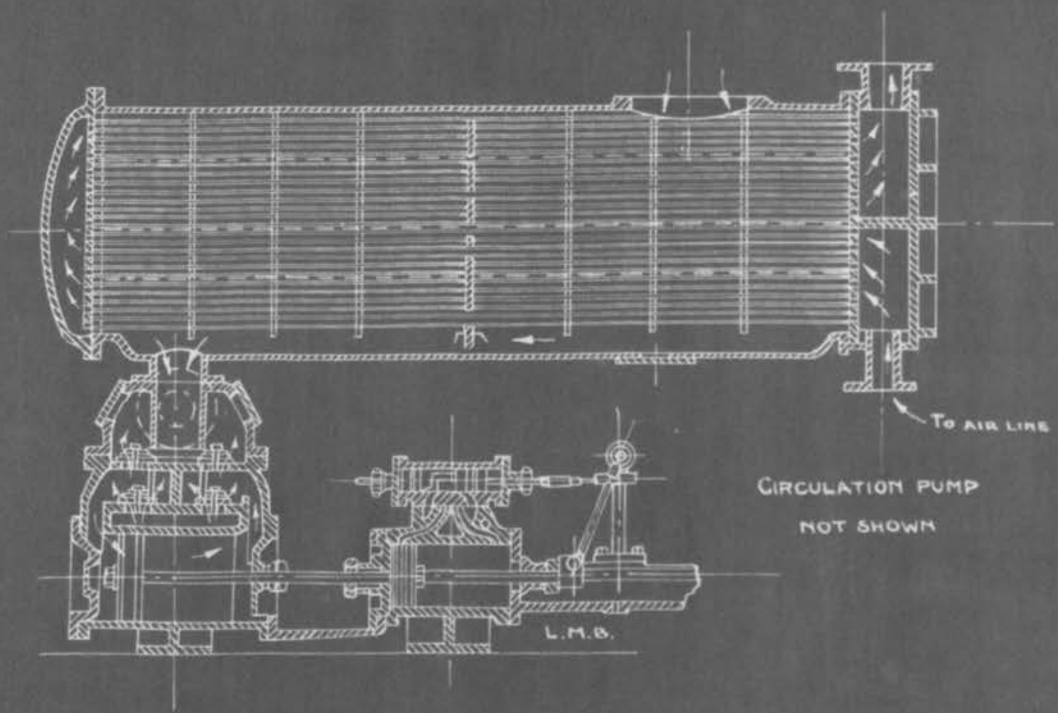
The tests were run on a regular Wheeler Surface Condenser as shown in Fig. 1, Page 6. This condenser was designed for the condensation of steam by water rather than air. For the purposes of these tests, the circulating pump was dispensed with and the main body of the condenser was supported on framework. This condenser was of the double flow type and consisted of a cast iron chamber fitted with a number of small, seamless brass tubes thru which the cooling air was circulated under pressure. The exhaust steam from the engine entered at the top and after passing thru a throttle valve was prevented from coming into direct contact with the tubes by means of baffle-plates, which also served to distribute the steam more evenly over the cooling surface. The steam in passing thru between the tubes, was condensed and fell to the bottom of the chamber from which it was removed together with the entrained air by a vacuum pump.

The air chamber between the tube sheet and the head end was divided into two compartments, the partition being so arranged that the air flowed first from the lower set of tubes and then thru the upper set in the opposite direction. In this way, the temperature of the cooling air increased and reached a maximum where the exhaust steam entered. Condensation of the steam began as soon as the vapor entered the condenser, and the surfaces of the tubes were at once covered with a thin film of water flowing downwards from tube to tube.

# GENERAL DIMENSIONS
# OF
# THE CONDENSER

The general dimensions and other data pertaining to the condenser were as follows:

| | |
|---|---|
| Number of tubes | 250 |
| Number of tubes in upper division | 126 |
| Number of tubes in lower division | 124 |
| Outside diameter of tubes - inches | 0.62 |
| Inside diameter of tubes - inches | 0.52 |
| Length of tubes - feet and inches | 5-4 5/16 |
| Diameter of end plates - inches | 18 |
| Total cooling surface - square feet | 220.5 |
| Length of radiating surface - feet and inches | 5-2 |
| Circumference of body - feet and inches | 5-8 |
| Radiating surface - square feet | 29.298 |




Wheeler Surface Condenser and Vacuum Pump

Fig. 1

# THEORY OF VENTURI METER

The Venturi Meter for measuring air is in principle nothing but an orifice placed in a pipe line and thru which the air to be measured is forced. The contracted passage increases the velocity of the fluid and causes a pressure loss, converted into velocity. This pressure loss may be measured and from this the rate of flow thru the pipe may be calculated.

The Venturi Meter as used in these tests is shown in cross-section in Fig. 2, Page 9. It consists in reality of two converging nozzles placed end to end with the smaller ends joined. The end thru which the fluid enters i s usually called the "up-stream" end, the other is designated the "down-stream" end, while the section of smallest diameter is known as the "throat". The up-stream end and the throat section are surrounded by pressure chambers at A and B, with which the respective sections communicate by means of a number of small openings. By connecting the chambers to the two ends of a U-Tube manometer as in Fig. 2, the reading of the latter will indicate the loss of pressure head between the up-stream section and the throat, this difference being represented by H in the Figure.

For accurate work, the Meter required calibration. Once calibrated, the error in weight readings for a given temperature should not exceed one percent for capacities within the working range of the manometer. This particular Meter was calibrated and an expression derived for the flow of air in pounds per second. This equation took the form

$$W = C_1\left[\frac{P\Delta p}{T_1}\right]^{\frac{1}{2}} \left[1 - C_2\left[\frac{\Delta p}{P}\right] + C_3\left[\frac{\Delta p}{P}\right]^2\right]$$

# EQUATION CONSTANTS AND NOMENCLATURE

The values of the constants as expressed in the equation for the flow of air thru a Venturi Meter, Page 7, are as follows:

$$C_1 = F_2 \left[ \frac{2gST_o}{P_o(1 - a)} \right]^{1/2} = 0.00338$$

$$C_2 = \frac{z + a}{4z(1 - a)} = 0.53962$$

$$C_3 = \frac{29 + 110a + 5a^2 - 40z + 32az + 8a^2z}{96z^2(1 - a^2)} = -0.13915$$

The symbols in the above constants are represented by the following nomenclature:

$F_2$ = area of the throat in sq. ft.

a = ratio of throat areas = $\frac{F_2}{F_1}$

$P_o$ = atmospheric pressure in lbs. per squ. ft.

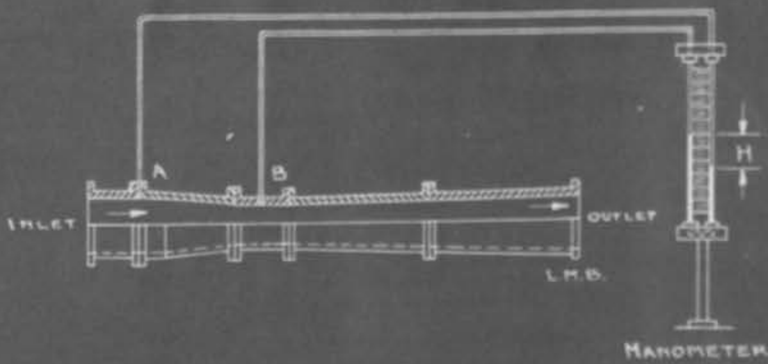
P = absolute pressure of the air at the throat in lbs. per squ ft.

$\Delta p$ = difference in mercury level of the manometer.

S = weight of air per cu. ft. at $P_o$ pressure.

z = ratio of specific heats at constant pressure and at constant volume.

$T_1$ = absolute temperature of air after passing thru the throat




VENTURI METER

FIG. 2.

## T H E   A I R   C O M P R E S S O R

The compressed air was furnished by a two stage compressor manufactured by the Ingersoll-Sargeant Drill Co., of New York. This compressor drew in the free air from the outside and compressed it up to a high pressure in the cylinders from which it was forced into the storage tank.

In addition to furnishing the air, the engine driving the compressor furnished the exhaust steam to the condenser, thereby making the whole system a self contained unit.

The location of this unit in the system is clearly shown in the layout, Figure 3, Page 14.

## T H E   A U X I L I A R Y   C O O L E R

The auxiliary coller consisted of a cast iron chamber containing a coil of tubes about which cold water circulated. The air, after passing thru the Venturi Meter, flowed directly thru this coil and then into the condenser.

The function of this cooler was to somewhat reduce the temperature of the air before it flowed thru the condenser.

# M E A S U R I N G   I N S T R U M E N T S

In addition to the apparatus described in Pages 4, 7, 10, and 11, the following measuring instruments were used to carry out the tests:

1 Pressure Gage

4 Mercury Manometers

1 Water Manometer

2 Separating Calorimeters

10 Fahrenheit Thermometers

3 Weighing scales

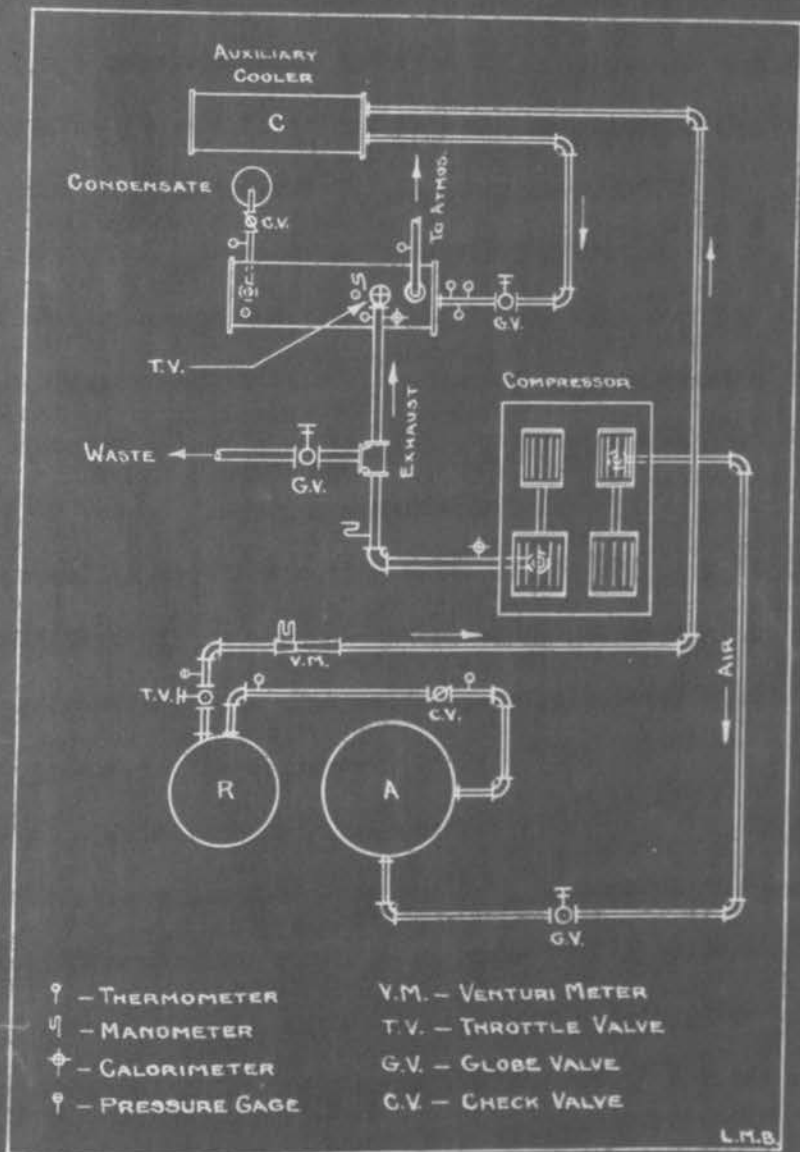
1 Weighing Tank

By referring to the code at the bottom of Page 14, it is seen that each of the above instruments is represented by a certain symbol on the layout of the apparatus.

## L O C A T I O N   O F   A P P A R A T U S

The location of the condenser, auxiliary cooler, air compressor, tanks and measuring instruments is clearly shown in the accompanying diagram, Fig. 3, Page 14. This lay-out is the result of several different arrangements and was found to work satisfactorily and to give the best results.

The original piping lay-out and position of the apparatus was essentially the same as that shown with the exception that at first the air was not led thru the auxiliary cooler but flowed directly to the condenser.




·DIAGRAM·

OF

·LOCATION OF APPARATUS·

FIG. 3.

## METHOD OF PROCEDURE

The plan of operation was as follows: The compressor forced the air into the receiving tank "A" from which it passed thru the reservoir "R", thru the Venturi Meter and into the auxiliary cooler, from which it flowed thru the condenser into the atmosphere. Without the use of the auxiliary cooler, it was found that the temperature of the air as it entered the condenser was too great to have much cooling effect.

The pressure of the air was adjusted to some extent by a throttle valve before it passed thru the Venturi Meter. Here the pressure was measured by means of a mercury manometer, the difference in leg levels being controlled by the throttle valve in the air line at the condenser. The temperature of the air was taken before going into the Meter and also after passing thru. The wet and dry bulb temperatures were taken at the entrance to the condenser.

The exhaust steam from the compressor entered the condenser thru another throttle valve which was employed to control the amount of steam entering. Corresponding readings of pressure and temperature of the steam were taken before throttling and after entering the condenser. The back pressure on the engine was held constant by means of a by-pass valve in the exhaust line.

A number of trial tests were run first so as to get constant readings. Each test was run for about two hours and readings taken at 10 minute intervals. The final tests gave results which agreed very closely and the data recorded in pages 16, 17, 18, 19, and 20 is taken from the best of these tests.

DATA SHEET

CALORIMETER AT ENGINE

| Time | Weight of Condensate lbs. | Reading of Gage Glass lbs. | Difference * in Hg. Level in. | Height of * water leg in. |
|---|---|---|---|---|
| 9:00 | ----- | ----- | ----- | ----- |
| 9:10 | ----- | 0.172 | 4.0 | 9.125 |
| 9:20 | 11.53 | 0.177 | 4.0 | 10.25 |
| 9:30 | 11.84 | 0.185 | 4.0 | 10.875 |
| 9:40 | 12.11 | 0.190 | 4.0 | 11.064 |
| 9:50 | 12.35 | 0.195 | 4.0 | 11.75 |
| 10:00 | 12.73 | 0.20 | 4.0 | 12.375 |
| 10:10 | ----- | ----- | ----- | ----- ** |
| 10:20 | 13.3 | 0.21 | 3.125 | 1.0 |
| 10:30 | 13.52 | 0.215 | 2.75 | 1.125 |
| 10:40 | 12.11 | 0.22 | 3.25 | 1.125 |
| 10:50 | 12.41 | 0.225 | 3.125 | 2.375 |
| Averages | | | 3.625 | 7.10 |
| 1st Total | 0.82 | 0.023 | | |
| 2nd Total | 0.79 | 0.015 | | |
| 3rd Total | 0.30 | 0.005 | | |
| Sums | 1.91 | 0.043 | | |

* Measurements of exhaust pressure

** Water blown from manometer

# DATA SHEET

## CALORIMETER AT CONDENSER

| Time | Weight of Condensate lbs. | Gage Glass Reading lbs. | Hg. Level Difference in. | Height * of water in. | Barometer* Reading in. Hg. |
|---|---|---|---|---|---|
| 9:00 | 75.3 ** | 0.015 | 5.2 | 13.25 | 29.26 |
| 9:10 | 75.8 | 0.019 | 5.2 | 13.25 | " |
| 9:20 | 79.58 | 0.024 | 4.5 | 13.00 | " |
| 9:30 | 80.12 | 0.028 | 4.2 | 12.75 | " *** |
| 9:40 | 98.8 | 0.030 | 4.2 | 12.75 | " |
| 9:50 | 94.7 | 0.038 | 4.1 | 12.85 | " **** |
| 10:00 | 95.08 | 0.042 | 4.0 | 12.65 | " |
| 10:10 | 95.62 | 0.045 | 4.1 | 12.75 | " |
| 10:20 | 96.20 | 0.048 | 3.8 | 12.55 | " |
| 10:30 | 96.70 | 0.053 | 3.6 | 12.50 | 29.28 |
| 10:40 | 97.22 | 0.056 | 4.25 | 12.75 | " |
| 10:50 | 97.71 | 0.059 | 3.75 | 12.50 | " |
| Averages | | | 4.25 | 12.79 | 29.265 |
| 1st Total | 5.16 | 0.015 | | | |
| 2nd Total | 3.01 | 0.021 | | | |
| Sums | 8.17 | 0.036 | | | |

* Measurement of exhaust pressure before throttling

** Tare weight of weighing tank

*** Added 18.34 pounds of water

**** Changed water in can

# DATA SHEET

## CONDENSER AND STEAM

| Time | Condenser Temper. deg. F. | Entering Steam Temp. deg. F. | Hot well Temp. deg. F. | Condenser Vacuum in.Hg. | Weight of Condensate lbs. |
|---|---|---|---|---|---|
| 9:00 | 165 | 217 | 149 | 17.714 | 239.5 * |
| 9:10 | 170 | 220 | 147.5 | 17.014 | |
| 9:20 | 180 | 220.5 | 146.2 | 14.014 | |
| 9:30 | 171.5 | 218 | 145 | 15.164 | |
| 9:40 | 170 | 218 | 142 | 16.164 | |
| 9:50 | 169 | 218 | 139 | 16.414 | |
| 10:00 | 168.7 | 218 | 136 | 17.214 | |
| 10:10 | 170.5 | 218.4 | 135.4 | 17.364 | |
| 10:20 | 168 | 218 | 135 | 17.614 | |
| 10:30 | 167 | 217 | 138 | 17.514 | |
| 10:40 | 170 | 218 | 141.5 | 17.714 | |
| 10:50 | 175 | 216.5 | 140 | 15.814 | 327.0 ** |
| Averages | 170.4 | 218.1 | 141.2 | 16.644 | |
| Net weight of condensate | | | | | 87.5 |

* Beginning of test

** End of test

Average pressure of the steam at the condenser before throttling - in. Hg. = 3.357

# DATA SHEET

## CONDENSER AND AIR

| Time | Entering air Pressure in.Hg. | Entering air Temperature deg. F. | Leaving air Pressure in.Hg. | Leaving air Temperature deg.F. | Temperature at end of 1st pass deg. F. |
|---|---|---|---|---|---|
| 9:00 | 2 | 57.5 | 7.75 | 157 | 131.5 |
| 9:10 | 2 | 57 | 7.75 | 155 | 142.5 |
| 9:20 | 2 | 57.5 | 7.7 | 158 | 130 |
| 9:30 | 2 | 58 | 7.8 | 156 | 124 |
| 9:40 | 2 | 58 | 8 | 157 | 133.3 |
| 9:50 | 2.05 | 58 | 7.95 | 156 | 129 |
| 10:00 | 2 | 59 | 7.25 | 157 | 138 |
| 10:10 | 2 | 59 | 7.15 | 157.5 | 137.6 |
| 10:20 | 2 | 59 | 6.7 | 157 | 144.7 |
| 10:30 | 1.6 | 59 | 5.5 | 157 | 144.5 |
| 10:40 | 2 | 58 | 7.25 | 157 | 146.8 |
| 10:50 | 2 | 59 | 7.5 | 157 | 143.5 |
| Averages | 1.97 | 58.25 | 7.358 | 156.79 | 137.11 |

Average temperature of dry bulb = 60.0°

Average temperature of wet bulb = 58.5°

Average temperature of outside = 67.0°

DATA SHEET

VENTURI METER

| Time | Pressure at Throat lbs/sq.in. | Pressure in Throat in.Hg. | Temperature of entering air deg.F. | Temperature of leaving air deg.F. |
|---|---|---|---|---|
| 9:00 | 49.2 | 133.5 | 24.25 | 131 |
| 9:10 | 56.0 | 136 | 26.2 | 133 |
| 9:20 | 55.1 | 139.5 | 25.75 | 136.5 |
| 9:30 | 56.0 | 142 | 26.7 | 139.5 |
| 9:40 | 57 | 144 | 27.1 | 141 |
| 9:50 | 56.2 | 145 | 26.75 | 143 |
| 10:00 | 53.2 | 146 | 25.4 | 144 |
| 10:10 | 53 | 146 | 25.25 | 144 |
| 10:20 | 49.5 | 145 | 23.7 | 142 |
| 10:30 | 44.5 | 142 | 21.65 | 140 |
| 10:40 | 53 | 139.5 | 24.75 | 138 |
| 10:50 | 54 | 141 | 25.25 | 138.5 |
| Averages | 53.06 | 141.6 | 25.23 | 139.2 |

# EXPLANATION
# OF
# TABULATION AND COMPUTATIONS

The data as read from the data sheets and the computed results will be grouped under the following headings:

Average steam Data and results

Average Air Data and results

Average Venturi Meter Data and results

Summary of General Results

For convenience, the average data and and results will be recorded in tabular form first, after which the methods of calculation will be explained in detail. In the calculation of any one result involving values as found for some other result, only the Item No. will be referred to. This method will be readily understood in the pages of calculations.

Goodenoughs' Steam Tables used.

# A V E R A G E   S T E A M   D A T A

# A N D

# R E S U L T S

| Item No. | | |
|---|---|---|
| 1. | Number of tests run | 10. |
| 2. | Average duration of each test - hours | 1.83 |
| 3. | Barometer pressure - in.Hg. | 29.265 |
| 4. | Barometer pressure - lbs/sq. in. abs. | 14.369 |
| 5. | Weight of dry steam passing thru the calorimeter at engine - lbs. | 1.91 |
| 6. | Weight of moisture collected in calorimeter at engine - lbs. | 0.043 |
| 7. | Total weight of steam passing thru the calorimeter at engine - lbs. | 1.953 |
| 8. | Quality of the steam at the engine exhaust - %. | 97.79 |
| 9. | Weight of dry steam passing thru the calorimeter at condenser - lbs. | 8.17 |
| 10. | Weight of moisture collected in calorimeter at condenser - lbs. | 0.036 |
| 11. | Total weight of steam passing thru the calorimeter at condenser - lbs. | 8.206 |
| 12. | Quality of the steam entering the condenser - %. | 99.56 |
| 13. | Temperature of the steam at the condenser before throttling - deg. F. | 218.1 |
| 14. | Pressure of the steam at the condenser before throttling - in. Hg. | 3.357 |
| 15. | Pressure of the steam at the condenser before throttling - in. Hg. abs. | 32.622 |
| 16. | Pressure of the steam at the condenser before throttling - lbs/sq. in. abs. | 16.01 |
| 17. | Vacuum in the condenser - in.Hg. | 16.644 |
| 18. | Vacuum in the condenser - lbs/sq.in. | 8.172 |

| Item No. | | |
|---|---|---|
| 19. | Vacuum in the condenser - lbs/sq. in. abs. | 6.197 |
| 20. | Temperature of the steam entering condenser - deg. F. | 170.4 |
| 21. | Absolute temperature of the steam entering the condenser - deg.F. | 630 |
| 22. | Total pressure of one pound of steam and entrained air in the condenser - in. Hg. | 12.621 |
| 23. | Partial pressure of the steam in condenser - in.Hg. | 12.310 |
| 24. | Temperature of the steam corresponding to the partial pressure of the steam - deg.F. | 171.475 |
| 25. | Volume of one pound of steam at the partial pressure of the steam - cu. ft. | 61.576 |
| 26. | Latent heat of one pound of steam at the condenser before throttling - B.t.u. | 964.816 |
| 28. | Total heat in one pound of steam at the condenser before throttling - B.t.u. | 1149.148 |
| 27. | Heat of the liquid of one pound of steam at the condenser before throttling - B.t.u. | 184.332 |
| 29. | Total heat in one pound of mixture of steam and air in condenser after throttling - B.t.u. | 1151.495 |
| 30. | Temperature of the hot well - deg.F. | 141.2 |
| 31. | Absolute temperature of the hot well - deg.F. | 600.8 |
| 32. | Partial pressure of the steam at the temperature of the hot well - lbs/sq. in. | 2.969 |
| 33. | Total heat in one pound of condensate above 32 deg.F. - B.t.u. | 109.2 |
| 34. | Total weight of condensate - lbs. | 87.5 |
| 35. | Weight of condensate per hour - lbs. | 47.8 |
| 36. | Total heat given up by the steam per minute per pound - B.t.u. | 828.4 |

# A V E R A G E  A I R  D A T A

# A N D

# R E S U L T S

| Item No. | | |
|---|---|---|
| 37. | Average temperature of outside air - deg.F. | 67.0 |
| 38. | Average dry bulb reading - deg.F. | 60 |
| 39. | Average wet bulb reading - deg.F. | 58.5 |
| 40. | Temperature of the air entering condenser - deg.F. | 58.25 |
| 41. | Pressure of the air entering condenser - in.Hg. | 1.97 |
| 42. | Temperature of the air leaving condenser - deg. F. | 156.79 |
| 43. | Pressure of the air leaving condenser - in. Hg. | 7.358 |
| 44. | Increase in temperature - deg. F. | 98.54 |
| 45. | Specific heat of air at constant pressure | 0.24 |
| 46. | Specific heat of air at constant volume | 0.18 |
| 47. | Partial pressure of the air entrained in the steam in the condenser - in.Hg. | 0.311 |
| 48. | Weight of air entrained per pound of steam - lbs. | 0.0401 |
| 49. | Partial pressure of the air in the liquid at the temperature of the hot well - lbs/sq.in. | 11.40 |
| 50. | Volume of one pound of air at the partial pressure of the air - cu.ft. | 19.52 |
| 51. | Partial pressure of the air in the liquid at the temperature of the hot well - lbs/sq. ft. | 1641.6 |
| 52. | Heat absorbed by one pound of air going thru the condenser - B.t.u. | 23.649 |
| 53. | Intrinsic energy of the entrained air at the temperature of the hot well - B.t.u./lb. | 0.788 |
| 54. | Latent heat of vaporization of the air at the temperature of the wet bulb - B.t.u. | 1058.97 |
| 55. | Weight of saturated vapor per pound of dry air - lb. | 0.01047 |

| Item No. | | |
|---|---|---|
| 56. | Humidity of the air entering the condenser - %. | 91.5 |
| 57. | Weight of moisture actually mixed with one pound of dry air - lbs. | 0.01013 |
| 58. | Heat content of moisture in the air - B.t.u. | 0.475 |
| 59. | Heat added per pound of air and moisture supplied, B.t.u. | 24.124 |
| 60. | Dew point at the temperature of the wet and dry bulb thermometers - deg.F. | 57.55 |

# A V E R A G E  V E N T U R I  M E T E R  D A T A

# A N D

# R E S U L T S

| Item No. | | |
|---|---|---|
| 61. | Pressure of the air at the throat - lbs/sq.in. | 53.06 |
| 62. | Pressure of the air in the throat - in.Hg. | 141.6 |
| 63. | Pressure of the air in the throat - lbs/sq.in. | 69.52 |
| 64. | Drop in pressure thru throat - lbs/sq.in. | 16.46 |
| 65. | Drop in pressure thru throat - lbs/sq. ft. | 2363.04 |
| 66. | Temperature of air entering throat - deg. F. | 25.23 |
| 67. | Temperature of air leaving throat - deg. F. | 139.2 |
| 68. | Absolute temperature of air leaving throat - deg.F. | 598.8 |
| 69. | Weight of air passing thru the Venturi Meter per minute - lbs. | 34.14 |
| 70. | Weight of air passing thru the Venturi Meter per hour - lbs. | 2048.4 |

# SUMMARY

# OF

# GENERAL RESULTS

Item No.

| | | |
|---|---|---|
| 71. | Air required per pound of steam condensed - lbs. | 42.94 |
| 72. | Radiation loss from the condenser per hour - B.t.u. | 4300.0 |
| 73. | Coefficient of transmission for condenser B.t.u./hr./sq.ft./deg. difference | 1.49 |
| 74. | Steam condensed per square foot of heating surface of the condenser - lbs. | 0.216 |

# C A L C U L A T I O N S

# O F

# S T E A M   R E S U L T S

Item 2. The duration of the test was 1 hour and 50 minutes or 110 minutes.

$$110/60 = 1.83$$

Item 3. Value taken from Data Sheet, page 17.

Item 4. Item 3 x 0.491 = 29.265 x 0.491 = 14.369

Item 5. Value taken from Data Sheet, Page 16.

Item 6. Value taken from Data Sheet, Page 16.

Item 7. Item 5 + Item 6 = 1.91 + 0.043 = 1.953.

Item 8. Item 5/Item 7 = 1.91/1.953 = 0.9779 or 97.79 %.

Item 9. Value taken from Data Sheet, Page 17.

Item 10. Value taken from Data Sheet, Page 17.

Item 11. Item 9 + Item 10 = 8.17 + 0.036 = 8.206.

Item 12. Item 9/Item 11 = 8.17/8.206 = 0.9956 or 99.56 %.

Item 13. Value taken from Data Sheet, Page 18.

Item 14. Value taken from Data Sheet, Page 18.

Item 15. Item 3 + Item 14 = 29.265 + 3.357 = 32.622.

Item 16. Item 15 x 0.491 = 16.01.

Item 17. Value taken from Data Sheet, Page 18.

Item 18. Item 17 x 0.491 = 16.644 x 0.491 = 8.172.

Item 19. Item 4 - Item 18 = 14.369 - 8.172 = 6.197.

Item 20. Value taken from Data Sheet, Page 18.

Item 21. Item 20 + 459.6 = 170.4 + 459.6 = 630.0.

Item 22. Item 3 - Item 17 = 29.265 - 16.644 = 12.621.

Item 23. The partial pressure of the steam in the condenser is that pressure corresponding to the temperature of the steam as it enters the condenser. The partial pressure corresponding to a temperature of 170.4 deg. F. (Item 20) = 12.310 in.Hg. from the steam tables.

Item 24. The temperature of the steam corresponding to a partial pressure of 12.310 in.Hg. from the steam tables is 171.475 deg.F.

Item 25. From the steam tables, the volume corresponding to a pressure of 12.310 in.Hg. (Item23) = 61.576 cu. ft./lb.

Item 26. Pressure of steam at condenser before throttling = 16.01 lbs/sq.in. Latent heat of one pound of steam at this pressure = 969.08B.t.u. Quality = 99.56 % (Item 12)

0.9956 x 969.08 = 964.816 B.t.u.

Item 27. Heat of the liquid at 16.01 lbs/squ.in. = 184.332 B.t.u. per pound.

Item 28. Item 26 + Item 27 = 964.816 + 184.332 = 1149.148 B.tu. per pound.

Item 29. In order to find the total heat in one pound of the steam at the condenser before throttling, the heat content of the entrained air must be considered.

$$\text{Total heat} = \text{Item } 28 + (U_a + AP_aV_a)$$

$$U_a = \text{intrinsic energy of the air} = c_v dtW$$

$$= 0.18\ (\text{Item } 20 - 32) \times \text{Item } 48$$

$$= 0.18\ (170.4 - 32) \times 0.0401 = 0.998$$

$$P_a = \text{Item } 47 \times 0.491 \times 144 = 21.918 \text{ lbs/sq.ft.}$$

$$V_a = \text{Item } 25$$

$$A = \text{reciprocal of Joules' equivalent} = \frac{1}{778}$$

$$AP_aV_a = \frac{21.918 \times 61.576}{778} = 1.349 \text{ B.t.u.}$$

$\therefore$ Total heat in one pound of steam

$$= 1149.148 + 0.998 + 1.349 = 1151.495 \text{ B.t.u.}$$

Item 30. Value taken from the Data Sheet, Page 18.

Item 31. Item 30 + 459.6 = 141.2 + 459.6 = 600.8.

Item 32. From the steam tables, the partial pressure of steam at a temperature of 141.2 deg.Fs (Item 30) = 2.969 lbs/sq.in.

Item 33. Item 30 - 32 = 141.2 -32 = 109.2 B.t.u.

Item 34. Value taken from Data Sheet, Page 18.

Item 35. Item 34/Item 2 = 87.5/1.83 = 47.8.

Item 36. To find the net total heat given up per pound of steam, the total heat in one pound of condensate above 32 deg.F. and the heat content of the vapor at the temperature of the hot well must be subtracted from the total heat of one pound of the steam at the condenser before throttling.

$$H = \text{Item } 29 - \text{Item } 33 - (\text{Item } 53 + A \times \text{Item } 51 \times \text{Item } 50 \times \text{Item } 48)$$

$$= 1151.495 - 109.2 - 8.788 - \frac{1641.6 \times 19.52 \times 0.0401}{778}$$

$$= 1039.865$$

Net total heat given up per minute =

$$\frac{1039.865 \times 47.7}{60} = 828.4 \text{ B.t.u.}$$

# CALCULATIONS

## OF

## AIR RESULTS

Item 37. Value taken from Data Sheet, Page 19.

Item 38. Value taken from Data Sheet, Page 19.

Item 39. Value taken from Data Sheet, Page 19.

Item 40. Value taken from Data Sheet, Page 19.

Item 41. Value taken from Data Sheet, Page 19.

Item 42. Value taken from Data Sheet, Page 19.

Item 43. Value taken from Data Sheet, Page 19.

Item 44. Item 42 - Item 40 = 156.79 - 58.25 = 98.54.

Item 47. Item 22 - Item 23 = 12.621 - 12.310 = 0.311.

Item 48. By using the characteristic equation, PV = WRT, the weight of air per pound of steam may be calculated, where

P = partial pressure of the entrained air in

lbs/sq.ft. = Item 47 x 0.491 x 144

= 0.310 x 0.491 x 144 = 21.918

V = Item 25 = 61.576

T = Item 21 = 630.0

R = 53.35

$$\therefore W = \frac{PV}{RT} = \frac{21.918 \times 61.576}{53.35 \times 630.0} = 0.0401$$

Item. 49. Item 4 - Item 32 = 14.369 - 2.969 = 11.40

Item 50. In calculating this value, the equation PV = RT must be used where

$T$ = Item 31 = 600.8

$P$ = Partial pressure of the air in the condensate in lbs/ sq. ft.

= Item 51 = 1641.6

$R = 53.35$

$$\therefore\ V = \frac{RT}{P} = \frac{53.35 \times 600.8}{1641.6} = 19.52$$

Item 51. Item 49 x 144 = 11.40 x 144 = 1641.6

Item 52. Item 45 x Item 44 = 0.24 x 98.54 = 23.649

Item 53. $C_v$ (Item 30 - 32) Item 48 = 0.18 (141.2 - 32) 0.0401

= 0.788

Item 54. Value taken from the steam tables at a temperature of 58.5 deg. F. (Item 39).

Item 55. Value taken from the tables of mixtures of air and saturated water vapor at a temperature of 58.5 deg.F. (Item 39).

Item 56. Value taken from the Psychrometric Tables for a dry bulb temperature of 60 deg. F. (Item 38) and a wet bulb temperature of 58.5 deg.F. (Item 39).

Item 57. In determining the weight of moisture actually mixed with one pound of dry air, the formula $W = \frac{r'W' - 0.24(t - t')}{r' + 0.476(t - t')}$

must be used where

$r' = \text{Item } 54 = 1058.97$

$W' = \text{Item } 55 = 0.01047$

$t = \text{dry bulb temperature} = \text{Item } 38 = 60$

$t' = \text{wet bulb temperature} = \text{Item } 39 = 58.5$

$$\therefore \quad W = \frac{1058.97 \times 0.01047 - 0.24\,(60 - 58.5)}{1058.97 + 0.476\,(60 - 58.5)}$$

<u>Item 58</u>. Item 57 x 0.476 x Item 44

$= 0.01013 \times 0.476 \times 98.54 = 0.475$

<u>Item 59</u>. Item 52 + Item 58 = 23.649 + 0.475 = 24.124

<u>Item 60</u>. Value taken from the Psychrometric Tables for a temperature of 60 deg.F. dry bulb and 58.5 deg.F. wet bulb.

# CALCULATIONS OF VENTURI METER RESULTS

Item 61. Value taken from Data Sheet, Page 20.

Item 62. Value taken from Data Sheet, Page 20.

Item 63. Item 62 x 0.491 = 141.6 x 0.491 = 69.52.

Item 64. Item 63 - Item 61 = 69.52 - 53.06 = 16.46.

Item 65. Item 64 x 144 = 16.46 x 144 = 2363.04.

Item 66. Value taken from Data Sheet, Page 20.

Item 67. Value taken from Data Sheet, Page 20.

Item 68. Item 67 + 459.6 = 139.2 + 459.6 = 598.8.

Item 69. The equation as derived for the Venturi Meter is given on Page 7, the value of the constants being worked out on Page 8.

$$C_1\left[\frac{P\,\Delta p}{T_1}\right]^{\frac{1}{2}} = C_1\sqrt{\frac{(\text{Item 4} + \text{Item 61})144 \times \text{Item 65}}{\text{Item 68}}}$$

$$= 0.00338\sqrt{\frac{(14.369 + 53.06)144 \times 2363.04}{598.8}}$$

$$= 0.662$$

$$C_2\left[\frac{\Delta p}{P}\right] = C_2\left[\frac{\text{Item 65}}{(\text{Item 4} + \text{Item 61})144}\right]$$

$$= 0.53962\left[\frac{2363.04}{(14.369 + 53.06)144}\right]$$

$$= 0.131$$

$$C_3\left[\frac{\Delta p}{P}\right]^2 = C_3\left[\frac{\text{Item 65}}{(\text{Item 4} + \text{Item 61})144}\right]^2$$

$$= -0.13915\left[\frac{2363.04}{(14.369 + 53.06)144}\right]^2$$

$$= -0.0082$$

$$\therefore\ W = 0.662\ (1 - 0.131 - 0.0082)$$

$$= 0.569 \text{ lbs/sec.}$$

$$= 60 \times 0.569 = 34.14 \text{ lbs/min.}$$

Item 70. Item 69 x 60 = 34.14 x 60 = 2048.4

# CALCULATIONS
# OF
# GENERAL RESULTS

Item 71. Item 70/Item 35 = 2048.4/47.8 = 42.94

Item 72. In calculating the radiation loss from the condenser, the transmission coefficient "k" for cast iron must be calculated. From Harding and Willard, "Mechanical Equipment of Buildings", this value of "k" at 150 deg.F. = 1.9 B.t.u. per sq. ft. per degree difference in temperature. For any other temperature, this value of "k" is expressed as 1.9 - 1.9 x 0.002 (150 - 88.8) = 1.668, where 88.8 is the mean difference in temperature of the condenser.

Knowing the value of "k", the radiation loss of the condenser may be calculated from the expression, $R = kS_o(t - t_o)$, where

$S_o$ = the radiating surface of the condenser

= 5.167 x 5.667 = 29.298 sq. ft. (Page 5)

$t - t_o$ = mean temperature difference of the condenser

= 88.8

$\therefore R = 1.668 \times 29.298 \times 88.8 = 4300$

Item 73. In calculating the coefficient of transmission "C" of the condenser, the expression $C = \frac{WH}{ST_m}$ must be used where

W = Item 70 = 2048.4

H = Item 59 = 24.124

S = Heating surface of the condenser = 220.5 (Page 5)

$$T_m = \frac{T_2 - T_1}{\log_e \dfrac{T_3 - T_1}{T_3 - T_2}}$$ In this expression,

$T_1$ = Item 40 = 58.25

$T_2$ = Item 42 = 156.79

$T_3$ = Item 20 = 170.4

$$\therefore \quad T_m = \frac{156.79 - 58.25}{\log_e \dfrac{170.4 - 58.25}{170.4 - 156.79}} = 147$$ and

$$C = \frac{2048.4 \times 24.124}{220.5 \times 147} = 1.49$$

Item 74. Item 35/220.5 = 47.8/220.5 = 0.216

## DISCUSSION OF RESULTS

By proper and careful manipulation of the apparatus it was possible to secure some results which were far below those estimated. It may be said that very few assumptions of any kind were made in the calculations of the results. Every little item which was thought to have some bearing on the outcome of the tests was carefully considered and worked out.

The results of the test show that it required 42.94 pounds of air to condense one pound of steam. This amount could no doubt be considerably reduced thru the use of a specially designed condenser for using air as a condensing agent rather than water.

# C O N C L U S I O N S

The use of the auxiliary cooler to lower the temperature of the air before entering the condenser may lead to criticism of the methods employed. However, it may be said that this is only one means of cooling the air. In case of an actual installation of air condensing equipment, suitable means would be provided to prevent the air from going into the condenser at too high temperatures.

The condensation of steam by means of air has great possibilities. It is to be hoped that, during the next few years, the engineering profession will be more willing to consider the idea and develop it to a state of perfection where it could take its place along side other modern methods of recovering the condensation water from power plants.

# B I B L I O G R A P H Y

Air Cooled Surface Condensers, Engineering News,
Oct. 1902, page 271, ibid., vol. 49, page 203.