HEAT TRANSFER IN A BATCH FLUIDIZED BED

by

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Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Chemical Engineering at the Massachusetts Institute of Technology

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487 Commonwealth Ave.
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May 26, 1953

Professor Earl B. Millard
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Dear Professor Millard:

In accorcance with the regulations of the Faculty, the attached thesis entitled "Heat Transfer in a Batch Fluidized Bed" is hereby submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Chemical Engineering.

Respectfully submitted,

Signature redacted

Richard T. Miskinis

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I. SUMMARY

Information on the transfer of heat within fluidized beds is necessary in their design for use in exothermic and endothermic reactions. The primary purpose of this thesis has been to investigate thermal effects within a fluidized bed.

The apparatus used in this work was constructed by the author and consisted of a 2 inch inside diameter column. It was heated at the bottom with an external heater and cooled at the top by a water jacket. The solid used was a mixture of No.'s 11, 13, 15, and 17 glass beads.

The procedure consisted of imposing a vertical temperature gradient across the column. When equilibrium had been reached the necessary measurements were taken and the conductivity was calculated using Fourier's law, $Qw = kA\Delta T/L$. Studies of temperature profiles and temperature fluctuations within the bed were also made.

The thermal conductivity was found to be independent of the distance between the heater and cooler sections, heat input to the bed, temperature drop across the test section and temperature level in the bed within the following range of variables:

Distance between heater and cooler	14 inches to 26 inches
Heat input by heater	492 to 1340 BTU/hr.

Temperature drop across the test section	4.8 to 23.0°F
Temperature at the test section bottom	116.1 to 275.7°F
Superficial air velocity	0.405 to 0.940 ft./sec.
Thermal conductivity	1700 to 11810 BTU/hr.- ft.-°F

It was a function of the superficial air velocity through the bed and is represented by the following equation:

$$k = (V_B - 0.51)\ 25000.$$

Vertical temperature profiles within the bed were found to be linear. Temperature fluctuations were found to decrease as distance upward from the heater increased. Fluctuations in the temperature difference across the test section were found to decrease with increasing air velocity.

II. INTRODUCTION

A. General: Since the use of fluidized beds in the catalytic cracking of petroleum in 1942, the applications of these beds in industrial processes has been steadily increasing. They are now also used in the Fischer-Tropsch synthesis of hydrocarbons, the gasification of coal, and the distillation of shale oil. (6)

A fluidized bed is a suspension of finely divided solid particles in a fluidizing medium. The fluidizing medium may be either a gas or a liquid. In the following discussion, only a gas was used as the fluidizing medium.

There are four noticeable stages in the fluidization process. (6)

1. At low gas velocities, there is no fluidization and the particles are supported by resting upon each other.
2. At somewhat higher air velocities, the quiescent stage is reached. Here the fluid velocity just balances the gravitational force on the particles, and they are supported by the fluidizing medium.
3. At still higher air velocities the turbulent stage is reached. This stage is characterized by rapid mixing of the solid particles. The mixing pattern is generally believed to consist of upward flow in the center of the column and downward flow along the walls. This stage is the

one ordinarily used in industrial processes.

4. Finally, at the highest air velocities, the particles are lifted up and carried out of the bed by the air.

The primary advantage of fluidized beds is the excellent temperature control which can be obtained. This is possible because of the excellent mixing of the solids in the bed. These solids carry most of the heat, resulting in a practically uniform temperature throughout the bed. Since most industrial processes have an optimum temperature at which they give a maximum yield, the importance of this close temperature control is readily recognizable.

Another advantage is the ease of removal or addition of solids from or to the bed. The solid particles may be used either as a catalyst for a reaction or as one of the reactants in a reaction. When the reactants are used as the solid particles, the removal of reaction products from the bed and the addition of fresh reactant is made easier. When the particles are used as a catalyst in a reaction, addition of fresh catalyst and removal of spent catalyst is greatly simplified.

A third advantage is the high rate of heat transfer within a fluidized bed. This enables rapid removal of heat from the bed in highly exothermic reactions, and rapid addition of heat to the bed for endothermic reactions.

One disadvantage is possible back mixing of reaction products with the fresh reactants. This dilutes the reactants and lowers the yield from the maximum obtainable.

B. Object: Although fluidized beds have been in industrial use for approximately ten years, much of the data necessary for the design and analysis of these systems is still lacking. In particular, little work has been done in the field of internal heat transfer in fluidized beds. It is obvious that control of the temperature level and rate of heat flow is necessary for competent design.

In the past few years, several workers at M.I.T. have made studies of internal heat transfer in fluidized beds. It was the purpose of the author to try to substantiate the results of the previous workers and also to increase the number of variables studied by varying the distance between the heating and cooling elements. A second purpose was to obtain temperature fluctuation data to help make more clear the mixing patterns within these beds.

C. Previous Work:

1. Mixing Phenomena: The general pattern of solid mixing in fluidized beds has been shown to be vertical upward flow in the center of the bed(core) and vertical downward flow along the bed walls(annulus). This pattern is modified by various amounts of cross mixing between the core and annulus.

Bart (2), by means of a tracer technique, investigated the mechanics of mixing. Using a three inch diameter column, he initially charged the tracer solid to the bottom half of the column and bulk solid to the other half. The fluidizing air was then turned on for a definite time interval, and was then shut off. Sections of the bed were then analyzed for the various amounts of tracer and bulk solid. He concluded that for column diameters of less than three inches and superficial air velocities of less than 1.5 feet per second, circulations followed the core and annulus pattern. The velocities of the solids upward in the core was on the order of three times as great as the solid velocity downward in the annulus. For the assumption of steady flow in a batch system, the amount of fluidized solid at a cross section must remain the same. To account for this, he proposed that either the cross-sectional area of the annulus be three times the cross-sectional area of the core, or that the solid density in the annulus be three times the solid density in the core, or more likely, a combination of the two. He found that increases in air velocity resulted in a greater amount of side mixing probably due to turbulence, and that decreasing time of contact decreased net side mixing.

Carlsmith and Freund (3), using silica gel microspheres as the solid, found that at low velocities, core and annulus flow up the center and down the walls with side mixing between the two was most important. They also found that at lower air velocities, rate of circulation increases with decreasing particle size and increasing air velocity. At higher air velocities the main effect of increased air velocity was to increase turbulence and side mixing. They state that the core to annulus area ratio is considerably less than one.

However, they found the core and annulus theory to be at best a crude approximation, dependent on three questionable assumptions:

1. Constant solid velocity across the core.
2. Constant solid velocity across the annulus.
3. Constant rate of side mixing between core and annulus.

2. Heat transfer: Trilling (9), found that heat transfer coefficients in fluidized beds were from 2 to 150 times larger than those of empty tubes or fixed beds with the same particle to tube diameter ratios at the same gas velocity. He suggested two possible reasons for this:

1. Solid particle motion increases the gas stream turbulence, eliminating core resistance and decreasing the thickness of the laminar film along the heat transfer surface.
2. The solid particles act as carriers of heat, transporting it both radially and longitudinally throughout the bed.

He found that in all cases, the heat transfer coefficients increase with decreasing particle size. Also, at low solid concentrations, an increase in solid concentration generally increased heat transfer rates. Diameter of the containing vessel seemed to have no effect.

Bakal (1), using a two inch inside diameter glass column with air as the fluidizing medium and No. 13 glass beads as the solid particles, found that the axial thermal conductivity of the fluidized bed increased with increasing superficial gas velocity. The column was heated internally at the bottom and cooled at the top. He found k, the heat transfer coefficient to vary from 2750 to 10600 BTU/hr.-ft.-°F. The heat transfer coefficient was calculated using Fourier's Law:

$$Q_w = kA\frac{\Delta T}{L}$$

where Q_w is the heat transfered in the bed from the heating to the cooling section (heat carried out by the cooling water) in BTU/hr.

A is the cross sectional area of the column in square feet.

T is the temperature drop across the test section in °F.

L is the length of the test section in feet.

k is the heat transfer coefficient or thermal conductivity in BTU/hr.-ft.-°F.

McCord (8), used the same column as Bakal, again heating at the bottom and cooling at the top. Air was fluidizing medium and silica gel microspheres and glass beads were used as the solid particles. He found the thermal conductivity to be independent of the heat input to the bed, temperature level of the bed, temperature driving force through the bed, length of bed, and weight of solids in the bed. He found that the thermal conductivity was a function of the superficial gas velocity, and recommended the use of the following equations.

For glass beads: $k = 5700 V_B^{1.7}$ (V_B from 0.8 to 1.5 ft./sec.)

For microspheres: $k = 7000 V_B^{0.35}$ (V_B from 0.1 to 0.6 ft./sec.)

He found that the solids did not circulate in a smooth manner. For microspheres, they circulate up the center and down the sides, with considerable cross mixing. For glass beads under slugging conditions, violent cross mixing masks any circulation pattern. Three mechanisms of solid mixing were proposed:

1. The solids move up the center and down the sides in spurts.
2. The core of upflowing solids changes its radial position from time to time.
3. Cross mixing occurs as slugs of solids transported from one radial position to another.

Camp and Eissenberg (4), used the same two inch inside diameter glass column as Bakal and McCord, with the heater at the bottom and the cooler at the top. They used air as the fluidizing medium, and microspheres and No. 13 glass beads as the solid particles. The equations they arrived at are:

For glass beads: $k = 6000V_B^{2.1}$

For microspheres: $k = 6900V_B^{0.38}$

They found that changing the length of the test section had no apparent effect on the vertical thermal conductivity.

Christensen (5), using a three inch inside diameter glass column with a 29 inch test section, heater at the bottom and the cooler at the top, found the vertical thermal conductivity to be independent of the heat input to the bed, the temperature level of the bed, the temperature difference across the test section, and the amount of solid within the bed. It was a function of the superficial gas velocity. The equations he obtained for microspheres are:

$k = 3500 + 4500\ V_B$ (for V_B of 0.2 to 1.4 ft./sec.)

$k = 6500 + 1700\ V_B$ (for V_B of 1.4 to 2.9 ft./sec.)

He noted a discontinuity at 1.4 ft./sec., but made no attempt to explain it. He found that vertical temperature profiles within the bed were linear.

D. Nature of the Work: The fluidized bed was a two inch inside diameter column with an external heater located at the bottom and a cooler located at the top. The fluidizing medium was air and the solid particles used were a mixture of No.'s 11, 13, 15, and 17 glass beads.

Two distances between the heater and cooler, 14 inches and 26 inches, were used. Temperature measurements were taken at the centerline of the bed. Vertical thermal conductivities have been calculated and plotted, and temperature fluctuation data has been plotted.

III. APPARATUS

The apparatus used in this work (as shown in Fig. 1) was constructed by the author. It consisted of a two inch inside diameter column. The bottom calming section was 15 inches in height and was made of glass. It was packed with quarter inch glass beads to insure even distribution of the air. Above these beads was a 200 mesh screen to support the bed and further distribute the incoming air. Before the air entered the calming section, it was passed through a filter packed with glass wool to eliminate any entrained oil in the air. Also preceding the calming section were an orifice to measure air flow rate and a thermometer to measure entrance air temperature. A pressure tap was located at the air orifice to record static air pressure at the orifice.

The heater section was 15 inches long and was constructed of copper tubing. It was wound with Nichrome resistance wire and insulated by mica sheet. A voltmeter and an ammeter were introduced into the circuit to measure the power input, and a slide wire resistance enabled variation of the power input.

Two test sections were used. Both were made of glass, but one was 12 inches long and the other was 24 inches long. They were interchangeable on the column and were fastened to the heater and cooler sections with metal sleeves.

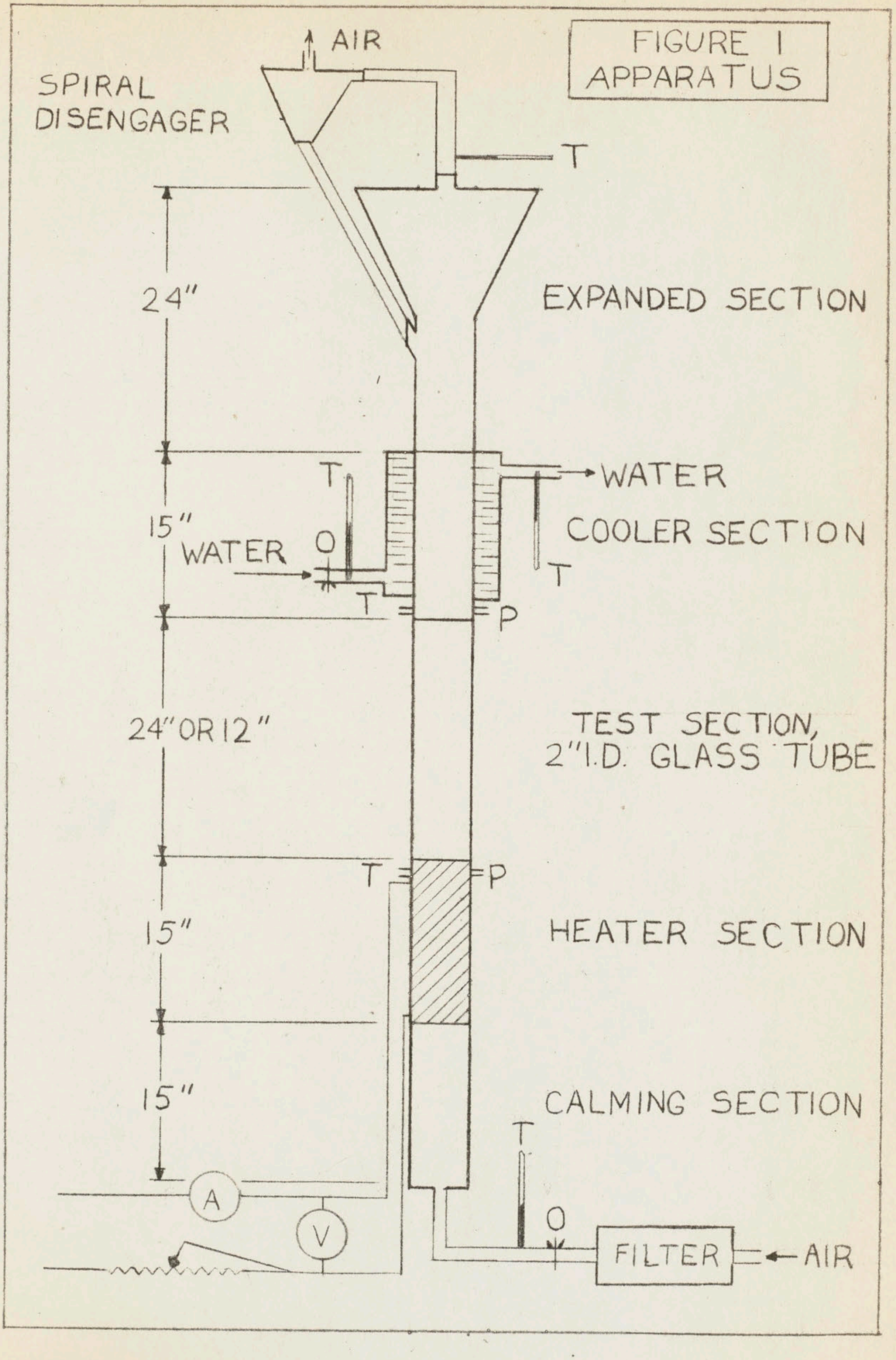
FIGURE 1
APPARATUS
AIR
SPIRAL
DISENGAGER
T
24"
EXPANDED SECTION
15"
WATER
O
T
WATER
COOLER SECTION
T
T
P
24" OR 12"
TEST SECTION,
2" I.D. GLASS TUBE
T
P
15"
HEATER SECTION
15"
CALMING SECTION
T
A
V
O
FILTER
AIR

The cooler section was made of copper, and was 15 inches long. It was well baffled to insure complete mixing of the cooling water and minimize variations in the exit water temperature. An orifice was used to measure the water flow rate. Thermometers were placed at the entrance and exit of the cooling section to record entrance and exit water temperatures.

The expanded section was 24 inches in overall length, and consisted of 12 inches of glass column directly over the cooler and 12 more inches of the expander itself. The purpose of the expanded section was to drop the solids back into the bed and eliminate solid entrainment. A thermometer was located at the top of the expanded section to record exit air temperature. The air from the expanded section was then sent to a cyclone separator, to disengage any solid that left the expanded section. These solids were then returned to the bed through a tube.

The heater and cooler sections were interchangeable, that is, the heater could be removed and the cooler could be placed in the position occupied by the heater.

Pressure taps and thermocouple probes were located just below the cooling section and just above the heating section. Iron-Constantan thermocouple wire was used. The temperatures were recorded by a standard potentiometer and a photoelectric potentiometer.

The entire column was insulated with a two inch layer of fiberglass pipe. Glass wool was placed in the cracks in the fiberglass pipe. This helped to reduce heat losses from the column.

IV. PROCEDURE

When it was desired to make a run, the bed was first filled with enough solid so that the level of the bed after the air was turned on was above the top of the cooling section. After this was done the heat input and the water flow rate were then set at the desired values. At least three hours was then allowed for the bed to reach equilibrium. Equilibrium was determined by taking temperature readings within the bed. When the temperature at a given position in the bed was found to be reproducible, equilibrium was assumed. Then the following measurements were taken:

1. Temperature at the test section bottom.
2. Temperature at the test section top.
3. Pressure drop across the air orifice.
4. Entrance and exit air temperatures.
5. Static pressure at the air orifice.
6. Pressure drop across the water orifice.
7. Entrance and exit water temperatures.
8. Power input to the heater.
9. Pressure at the top and bottom of the test section.

Temperatures in the test section were obtained by averaging the values for a number of readings at five second intervals. This was necessary because the temperature in the bed fluctuated constantly.

Pressure drops across the air orifice also had to be taken as the average of a number of readings because the values recorded by the manometer fluctuated constantly. An attempt was made to damp these fluctuations by pinch-clamping the air line just before it entered the column, but fluctuations still persisted.

In runs 1 through 15 the distance between the heating and cooling sections was 26 inches, while in runs 16 through 25 it was 14 inches.

The vertical temperature profiles were obtained by taking temperature readings at five different vertical points within the bed. These temperatures were all taken at the centerline by means of a movable central thermocouple which ran the length of the test section.

Fluctuations in the bed temperature were obtained at the bottom of the test section and at 14 inches above the test section bottom. The values were taken at the centerline at five second intervals and read from a standard potentiometer.

Fluctuations in the vertical temperature difference across the test section were also recorded. Thermocouples at the test section bottom and at 26 inches above the test section bottom, at the centerline of the bed, were bucked against each other. Readings were taken at five second intervals with a photoelectric potentiometer which recorded temperature differences.

V. RESULTS

The results of this investigation are presented graphically in Figures 2 through 7. A complete tabulation of data and results is included in the appendix.

In Figure 2, the thermal conductivity k for glass beads is plotted against the superficial air velocity through the column for the 25 runs. The glass beads were under slugging conditions in all these runs. In runs 1 through 15, the distance between the heating and cooling sections was 26 inches. In runs 16 through 25, the distance between the two sections was 14 inches. The superficial air velocity was varied from 0.405 to 0.940 ft./sec. Temperatures at the bottom of the test section ranged from 116.1°F to 275.7°F. The water flow rate was varied from 95 pounds/hr. to 192 pounds/hr. A straight line has been fitted to the data. Its equation is:

$$k = (V_B - 0.51)\ 25000$$

In figure 3, two vertical temperature profiles are presented. Both profiles were taken when the distance between the heater and the cooler was 26 inches. The temperatures were taken at five points in the bed, all points being at the bed centerline but at varying vertical positions.

In Figures 3 and 4, instantaneous temperature fluctuations have beenplotted. The readings were taken with a standard potentiometer at five second intervals. The average value of the potentiometer readings corresponds to the zero ordinate on the graphs with deviations from the average plotted as positive and negative deflections. In both figures, the distance between the heater and cooler was 14 inches. The fluctuation data was taken at the bottom of the test section and at 14 inches above the bottom. In Figure 4, the superficial air velocity was 0.635 ft./sec., while in Figure 5 it was 0.775 ft./sec.

In Figures 6 and 7, fluctuations in the temperature difference across the test section have been plotted. In these runs, the distance between the heater and cooler was 26 inches. Thermocouple probes at the centerline position and with vertical positions at 0 inches and 26 inches above the test section bottom were bucked against each other. Readings were taken at five second intervals with a photoelectric potentiometer which measured temperature differences. The average value of the fluctuations corresponds to the zero ordinate on the graphs, with deviations from the average plotted as positive and negative deflections. The superficial air velocities used were 0.653, 0.706, 0.776 and 0.859 ft/sec.

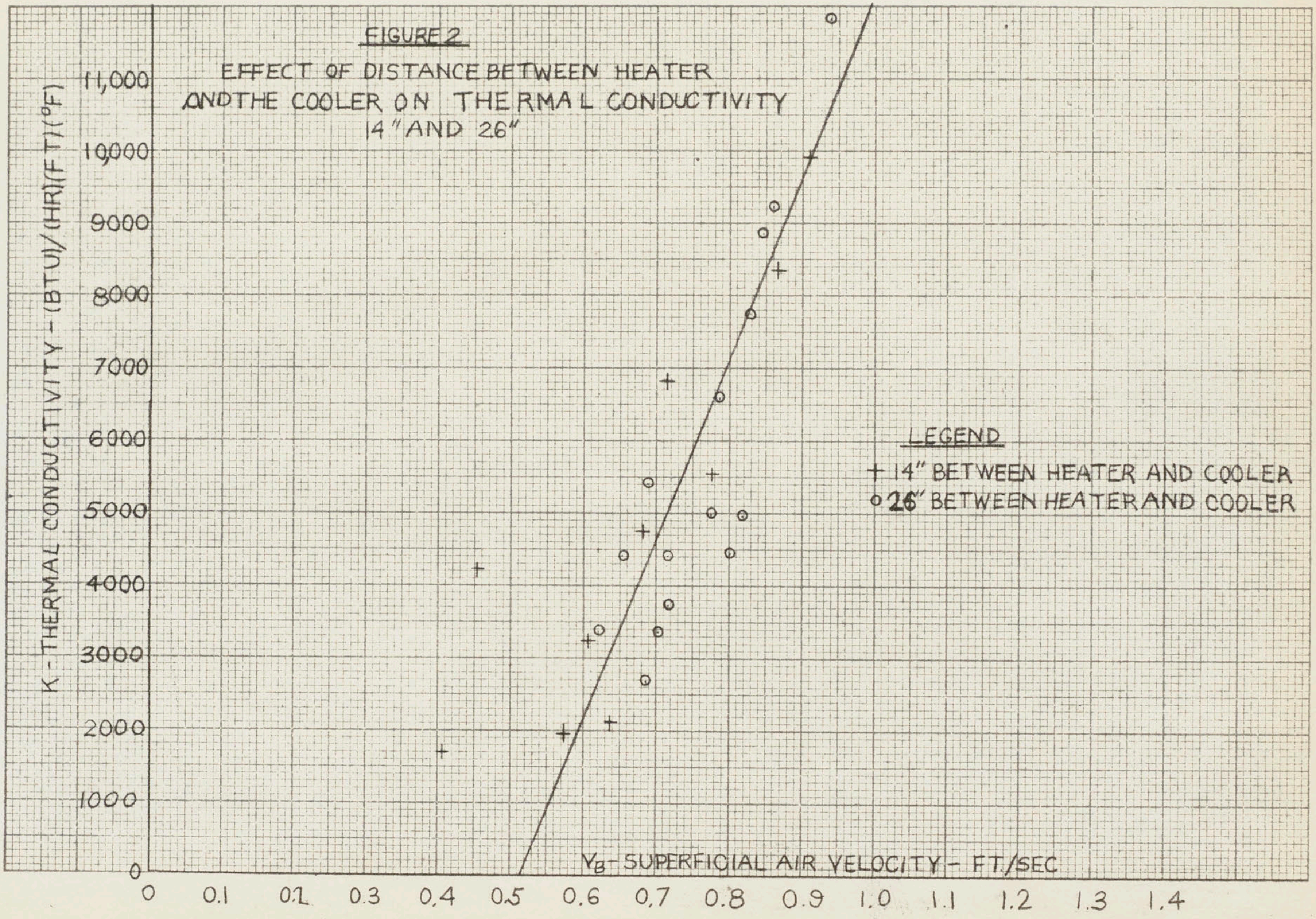

FIGURE 2

EFFECT OF DISTANCE BETWEEN HEATER AND THE COOLER ON THERMAL CONDUCTIVITY 14" AND 26"

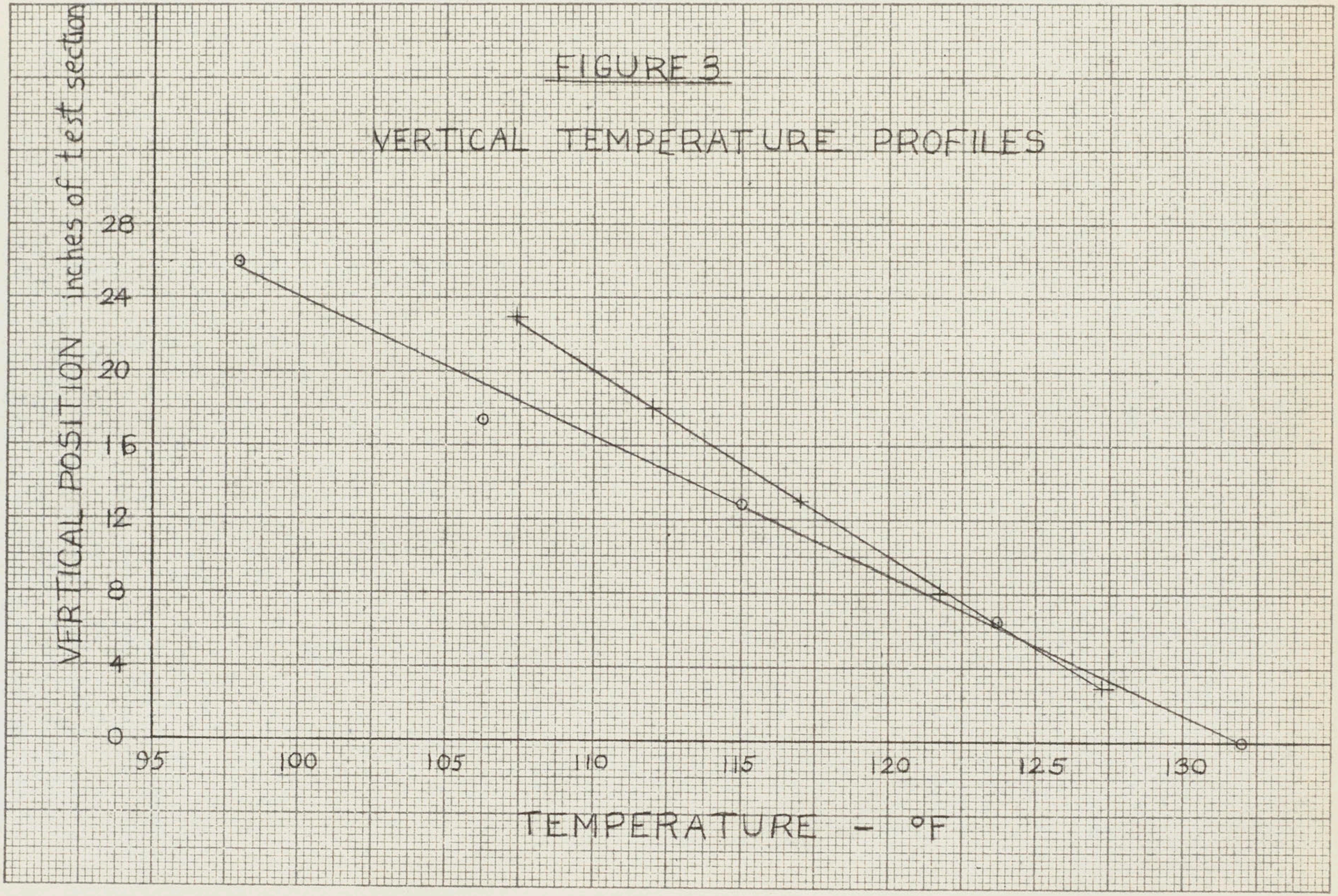
FIGURE 3
VERTICAL TEMPERATURE PROFILES
VERTICAL POSITION inches of test section
28
24
20
16
12
8
4
0
95
100
105
110
115
120
125
130
TEMPERATURE - °F

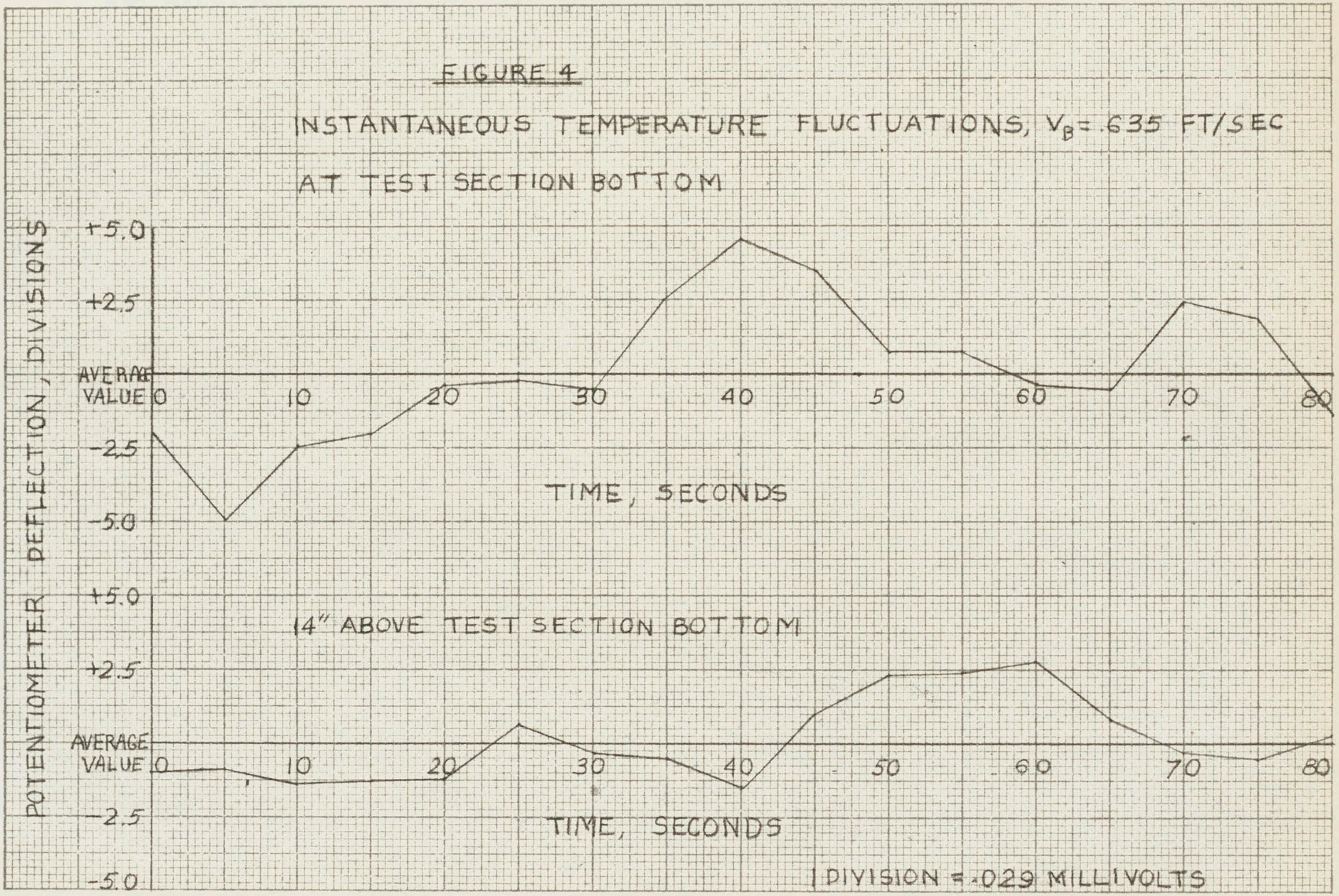

FIGURE 4

INSTANTANEOUS TEMPERATURE FLUCTUATIONS, V_B = .635 FT/SEC

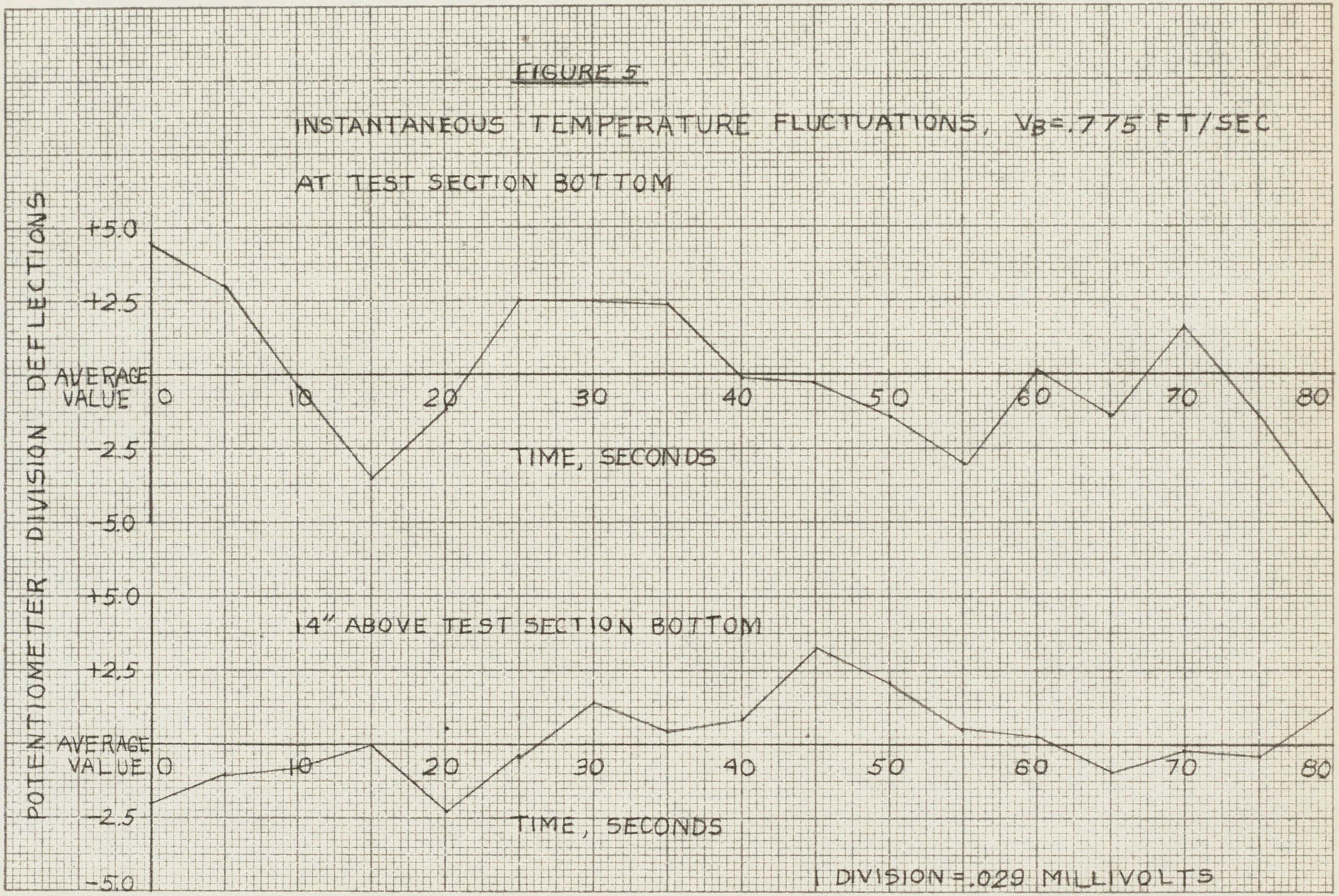

FIGURE 5

INSTANTANEOUS TEMPERATURE FLUCTUATIONS, $V_B = .775$ FT/SEC

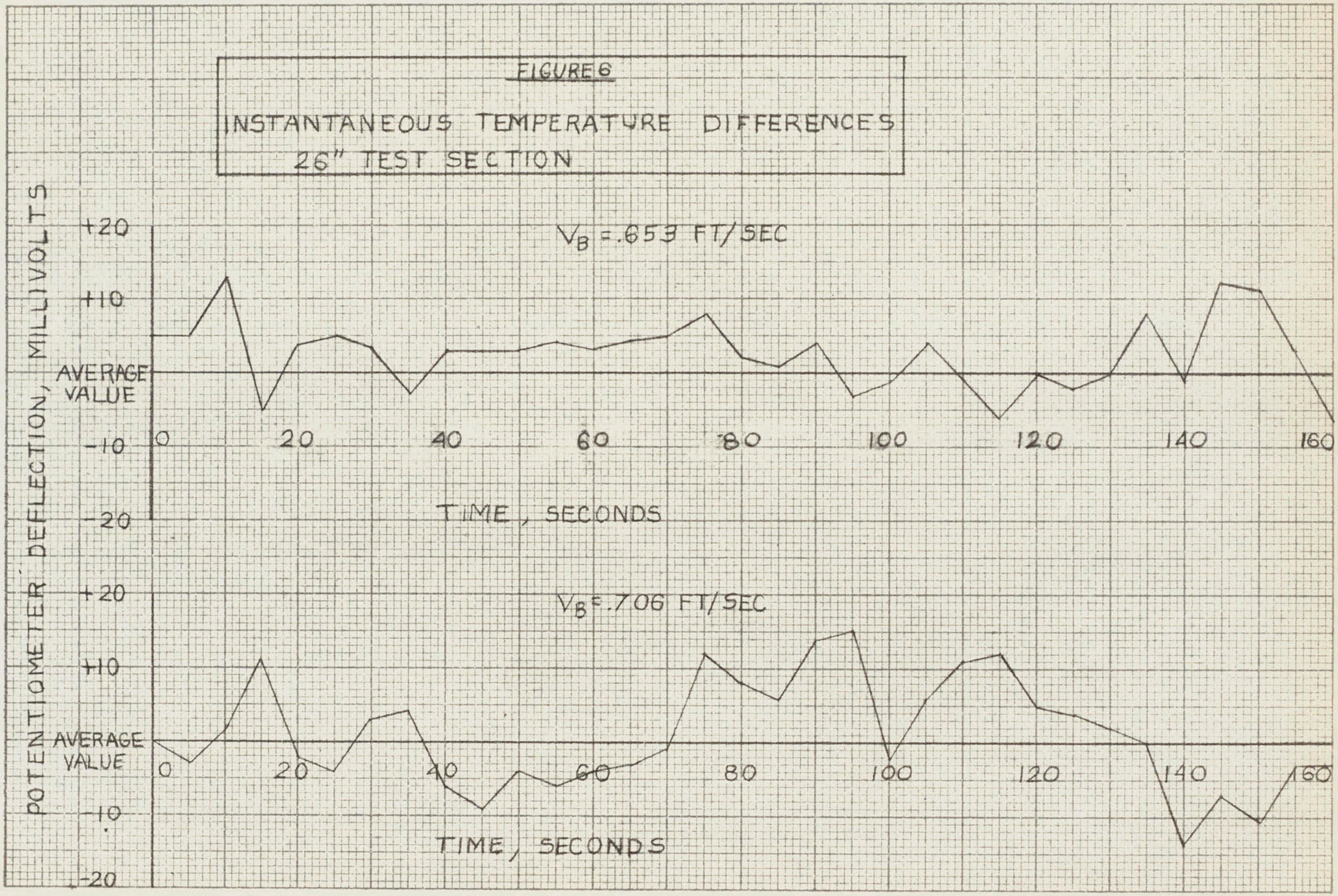
FIGURE 6
INSTANTANEOUS TEMPERATURE DIFFERENCES
26" TEST SECTION
POTENTIOMETER DEFLECTION, MILLIVOLTS
V_B = .653 FT/SEC
+20
+10
AVERAGE VALUE
-10
-20
0
20
40
60
80
100
120
140
160
TIME, SECONDS
V_B = .706 FT/SEC
+20
+10
AVERAGE VALUE
-10
-20
0
20
40
60
80
100
120
140
160
TIME, SECONDS

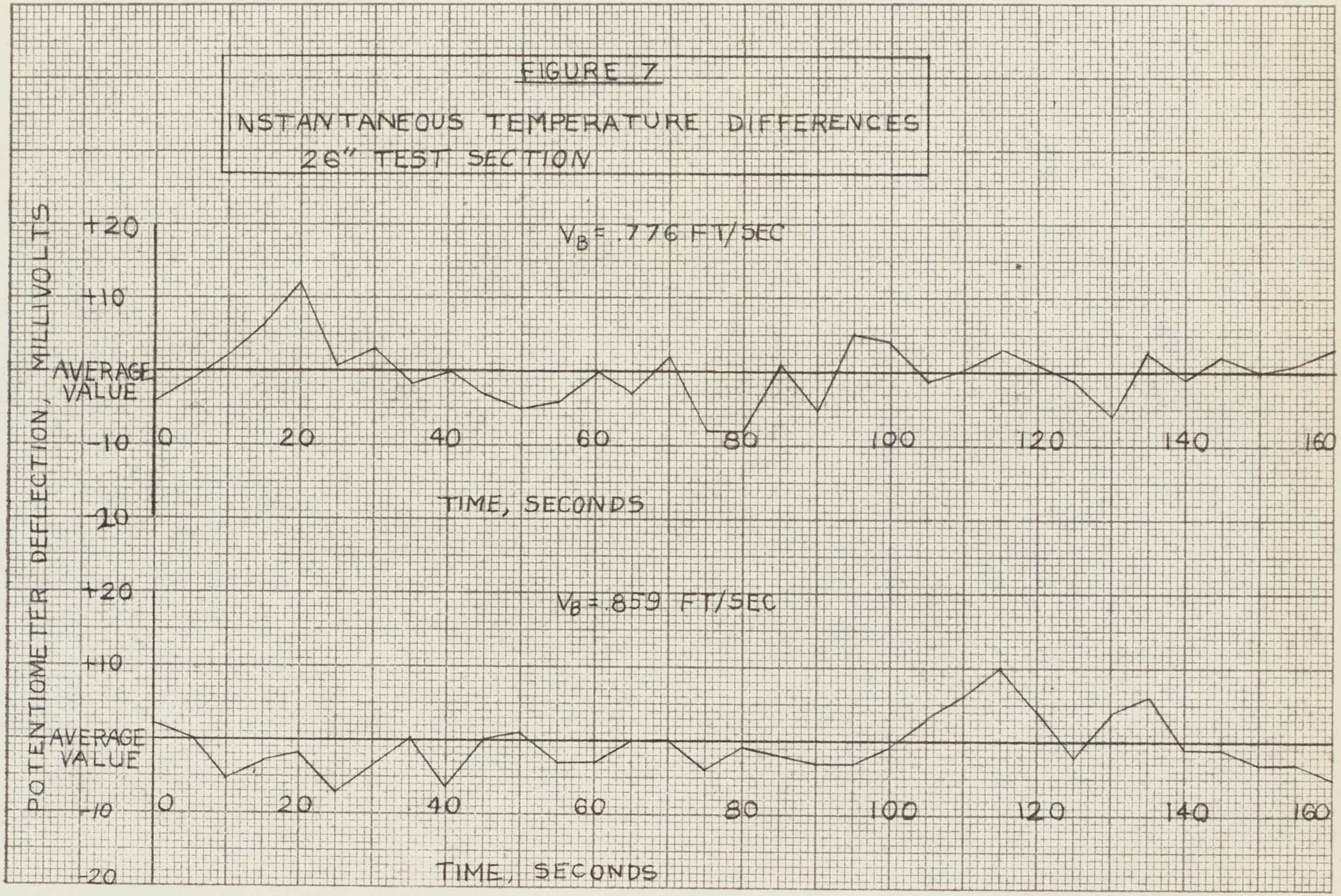
FIGURE 7
INSTANTANEOUS TEMPERATURE DIFFERENCES
26" TEST SECTION
POTENTIOMETER DEFLECTION, MILLIVOLTS
V_B = .776 FT/SEC
+20
+10
AVERAGE VALUE
-10
-20
0
20
40
60
80
100
120
140
160
TIME, SECONDS
V_B = .859 FT/SEC
+20
+10
AVERAGE VALUE
-10
-20
0
20
40
60
80
100
120
140
160
TIME, SECONDS

VI. DISCUSSION OF RESULTS

A. Quantitative Results: In this study, the conductivity has been calculated using Fourier's law and considering the fluidized bed as a solid rod along which the heat is transferred. The heat carried out by the cooling water has been considered as the heat transferred vertically upward through the test section. This is justified because heat balances show the heat carried out by the cooling water to be on the order of 85% of the heat input from the heater, with the exception of a few runs which show higher heat loss to the surroundings. The bed temperatures used in the calculations were taken at the bed centerline.

The values of thermal conductivity have been plotted against the superficial air velocity in Figure 2. A straight line has been fitted to the data. Its equation is:

$$k = (V_B - 0.51)\ 25000$$

If the two scattered points at the left are discarded, the maximum deviation from the equation is 36%, and the average deviation is 18%. The largest deviations are found at the lower air velocities. This may partly be due to the fact that the bed was slugging in all runs, and the readings on the air orifice manometer fluctuated constantly. Consequently, an average pressure drop reading had to be taken. Errors in the manometer reading tend to make for greater errors in the superficial air velocities at low velocities thanat higher ones because of the smaller absolute manometer readings at the lower air velocities. Also, the thermal conductivity is a very strong function of the superficial air velocity here, and small changes in the superficial air velocity represent much larger changes in the conductivity.

In this study, the thermal conductivity was a much stronger function of the superficial air velocity than in the investigations of Camp and Eissenberg (4), and McCord (8). Both of these other studies used a 2 inch inside diameter column with No. 13 glass beads as the solid. In this study , a 2 inch inch diameter column was also used, but the solid particles were a mixture of No.'s 11, 13, 15, and 17 glass beads with the majority of the solids being in the smaller particle size range. Also, the other workers had an internal heater while in this study an external heater was used. The above differences in the experimental conditions may explain the variance between the results of this study and the previous studies.

Within the range of variables studied, the thermal conductivity has been found to be independent of the distance between the cooling and heating sections, the heat input to the bed, temperature drop across the test section, and the temperature level in the bed. The conductivity increases in a linear fashion with increasing superficial air velocity. The ranges of the variables studied were:

Distance between heater cooler.	14inches and 26 inches
Heat input by heater.	492 to 1340 BTU/hr.
Temperature drop across the test section.	4.8 to 23.0°F
Temperature at the test section bottom.	116.1 to 275.7°F
superficial air velocity.	0.405 to 0.940 ft./sec.
Thermal conductivity	1700 to 11810 BTU/hr.-ft.°F

B. Qualitative Results: Figure 3 shows the vertical position in inches of test section plotted against the temperature at the position in °F. These temperatures were taken at the centerline for five different vertical positions within the bed. The distance between the heater and cooler was 26 inches. The temperature profiles show a practically linear decrease as the distances above the heater increase.

A study of temperature fluctuations in the bed at the bottom of the test section and at 14 inches above the test section bottom is presented in Figures 4 and 5. The distance between the heater and cooler was 14 inches. The temperatures were taken only at the centerline. The average fluctuation decreases at the further distance from the heater. A probable explanation, assuming that the air is at the same temperature as the solid, is that these fluctuations are due to variations in solid temperature. As the hotter solid rises up from the heater there is local overheating of the solid which has been in contact with the heater walls. This solid begins to mix with the colder solid returning from the cooler. This mixing is probably not very complete at the lower positions in the bed, and the greater difference in temperatures of the solids at these lower positions results in greater temperature fluctuations as the solids come in contact with the thermocouple bead. As the height above the heater increases, the hotter and colder solids are more thoroughly mixed and are more likely to be at the same temperature for a given position in the bed, resulting in smaller temperature fluctuations.

In Figures 6 and 7, fluctuations in the temperature difference across the 26 inch test section at five second intervals are presented. The thermocouples were located at the centerline, 26 inches apart in vertical distance. They were bucked against each other and the fluctuations were obtained from a photoelectric potentiometer which read the temperature difference.

These fluctuations are shown for four different superficial air velocities. The fluctuations in temperature difference tend to decrease at increasing superficial air velocities. Since the bed was under slugging conditions, this decrease in fluctuations at higher air velocities is probably due to greater turbulence in the bed at the higher air velocities. The solid is better mixed at higher air velocities and hence at a more uniform temperature for any portion of the bed. Thus individual temperatures tend to fluctuate less at any given point in the bed, and therefore the sum or difference of two fluctuating temperatures tends on the average to be smaller.

VII. CONCLUSIONS

1. Within the limits of this work, the thermal conductivity has been found to be independent of the distance between the heating and cooling sections, the heat input to the bed, the temperature drop across the test section, and the temperature level in the bed. The thermal conductivity is a function of the superficial air velocity through the bed. The relation is represented by the equation:

$$k = (V_B - 0.51)\ 25000$$

2. Vertical temperature profiles at the center-line of the bed are linear, the temperature decreasing with increasing distance from the heater.

3. Temperature at any point in the bed fluctuated continuously. These fluctuations decrease in size as the distance from the heating section is increased.

4. Fluctuations in the temperature difference across the test section decrease with increasing superficial air velocity in the bed.

VIII. RECOMMENDATIONS

1. Further work should be done using the same apparatus with the positions of the heater and cooler reversed to determine what effect this has on the thermal conductivity.

2. Further work should be done using microspheres and different sizes of glass beads to determine what the effect of particle size is on the thermal conductivity.

3. Work should be done with columns having different cross-sectional areas to determine the effect of cross-sectional area on the conductivity.

4. Additional vertical temperature profiles, and also radial temperature profiles, should be obtained.

5. Additional work should be done on the study of temperature fluctuations within the bed.

6. The experimental conditions, such as size distribution of the solid particles, should be varied in an effort to stop slugging and obtain good fluidization within the bed.

7. The pressure taps to the bed should be modified to prevent their clogging up with solid during operation.

A P P E N D I X

APPENDIX A. NOMENCLATURE

A	Cross-sectional area of the column.	sq. ft.
E	Voltage input of heater.	volts
I	Current input of heater.	amperes
k	Thermal conductivity.	BTU/hr.-ft.-°F
L	Length over which conductivity is calculated.	ft.
P_B	Average pressure in the bed.	cm. water
P_C	Static pressure at air orifice during Calibration.	cm. Hg
P_o	Static pressure at air orifice during operation.	cm. Hg
Q_H	Heat input by heater.	BTU/hr.
Q_L	Heat loss to surroundings.	BTU/hr.
Q_W	Heat out in cooling water.	BTU/hr.
Ri_i	Inside radius of insulation.	ft.
Ri_o	Outside radius of insulation.	ft.
T	Refers to specific bed temperature.	°F
T_B	Average temperature in bed.	°F
T_C	Temperature at air orifice during calibration.	°R
T_o	Temperature at air orifice during operation.	°R
Tw_i	Temperature of entrance cooling water.	°C
Tw_o	Temperature of exit cooling water.	°C
V_B	Superficial air velocity in the bed.	ft./sec.
W_c	Flow rate of air under orifice calibration conditions.	#mols/min.
W_o	Flow rate of air under orifice operating conditions.	#mols/min.

W_w	Mass flow rate of water.	#/hr.
Δh_a	Pressure drop across air orifice.	cm. water
ΔT	Temperature drop across bed.	°F

Subscripts

B	Refers to bed.
C	Refers to air orifice calibration conditions.
i	Refers to insulation.
H	Refers to heater.
o	Refers to air orifice operating conditions.
w	Refers to cooling water.

APPENDIX B. SAMPLE CALCULATIONS

1. Calculation of k (all figures based on run No. 8)

$Q_W = W_W \times 1.8 \times (Tw_o - Tw_i)$

$= 156 \times 1.8 \times (26.3 - 24.0)$

$= 640$ BTU/hr.

$T = 9.3°F$

$L = 2.17$ ft.

$A = 0.0225$ sq. ft.

$$k = \frac{Q_W \times L}{A \times \Delta T} = \frac{640 \times 2.17}{0.0225 \times 9.3} = 6590 \text{ BTU/hr.-ft.-°F}$$

2. Calculation of superficial air velocity

$\Delta h_a = 21.2$ centimeters water

$W_c = 0.00183$ pound mols per minute(from Fig. 9)

$$W_O = 0.00183\sqrt{\frac{P_O \times T_C}{P_C \times T_O}} = 0.00183\sqrt{\frac{93.5 \times 546}{78.3 \times 547}}$$

$= 0.00200$ pound mols per minute

$$AV_B = 0.00200 \times 359 \times \frac{760 \times 695}{783 \times 460} = 1.056 \text{ ft.}^3\text{/min.}$$

$$V_B = \frac{1.056}{0.0225 \times 60} = 0.786 \text{ ft./sec.}$$

3. Heat input by the heater

$Q_h = 3.41 \times E \times I = 3.41 \times 69 \times 3.0 = 720$ BTU/hr.

APPENDIX C. ESTIMATION OF HEAT LOSS FROM THE COLUMN

All calculations based on run No. 8.

1. Heat input: $Q_h = 3.41 \times E \times I = 720$ BTU/hr.

2. Heat to cooler: $Q_c = 1.8 \times W_w \times (T_{w_o} - T_{wi})$

   $= 640$ BTU/hr.

3. Losses through test section and heater section:

   A. Temperature of glass wool

   inner $= 230°F$

   outer $= 80°F$

   B. Thermal conductivity of glass wool

   $k = 0.028$ BTU/hr.-ft.-°F

   C. Area of heat transfer

   $$A = \frac{2\pi(Ri_o + Ri_i)L}{2}$$

   $$= 3.14 \times (40/12) \times (4/12 + 2/12) = 5.23 \text{ sq. ft.}$$

   where Ri_o is the outside radius of the insulation, Ri_i is the inside radius of the insulation, and L is the length of the section under consideration.

   D. Estimated heat losses from the column

   $$Q_L = \frac{k\,A\Delta T}{L} = \frac{0.028 \times 5.23 \times 150}{3.33} = 65 \text{ BTU/hr.}$$

Another source of heat loss is in the wires outside the bed leading to the heater. Also, the heat loss through the insulation around the heater is probably greater than here indicated because the heater is probably at a temperature considerably higher than 230°F

APPENDIX D. SUMMARY OF DATA AND RESULTS

Run Number	1	2	3	4	5	6	7
Test section length, inches	26	26	26	26	26	26	26
Water flow rate, #/hr.	132	136	129	132	140	140	95
Change in water temperature, °C	1.9	2.1	2.0	4.7	2.8	4.4	4.1
Heat out in water, BTU/hr.	449	504	470	622	700	616	702
Pressure drop across air orifice, cm. water	14.3	16.1	19.4	26.1	29.9	38.2	29.8
Static pressure at air orifice, cm. Hg	12.8	13.3	15.1	15.3	17.1	19.2	18.1
Temp. at bottom of test section, °F	236.2	215.9	218.2	227.6	200.1	185.6	202.3
Temp. at top of test section, °F	220.0	205.0	210.0	220.0	193.0	180.0	195.0
Temp. drop across test section, °F	12.6	10.9	8.2	7.6	7.7	5.6	7.3
Superficial air velocity, ft./sec.	0.625	0.653	0.688	0.827	0.845	0.940	0.854
Voltage of input, volts	62.0	62.0	68.0	68.5	69.5	69.0	69.0
Current of input, amperes	2.85	2.80	2.80	3.00	3.00	3.00	3.00
Heat input of heater, BTU/hr.	600	592	650	700	712	709	720
Thermal conductivity, BTU/hr.-ft.-°F	3390	4410	5410	7740	8860	11810	9920
Heat lost to surroundings, BTU/hr.	151	88	180	78	12	93	18

Run Number	8	9	10	11	12	13	14	15	16	17	18
Test section length, inches	26	26	26	26	26	26	26	26	14	14	14
Water flow rate, #/hr.	156	123	142	129	153	172	185	185	192	168	171
Change in water temperature, °C	2.3	2.3	2.9	1.6	1.4	1.8	1.7	1.8	1.6	1.9	2.3
Heat out in water, BTU/hr.	640	508	612	372	384	557	550	598	553	574	710
Pressure drop across air orifice, cm. water	21.2	22.7	15.6	15.3	23.6	17.8	23.8	16.8	19.2	14.3	8.2
Static pressure at air orifice, cm. Hg	16.9	16.1	14.0	13.3	15.3	14.6	15.2	13.6	20.4	18.4	15.3
Temp. at bottom of test section, °F	239.3	239.2	275.7	259.0	223.5	230.9	205.6	248.1	120.0	132.3	126.3
Temp. at top of test section, °F	230.0	230.0	260.0	240.0	215.0	215.0	195.0	235.0	102.7	117.8	126.3
Temp. drop across test section, °F	9.3	9.2	15.7	12.9	8.3	15.9	10.6	13.1	17.3	15.0	8.7
Superficial air velocity, ft./sec.	0.786	0.818	0.718	0.686	0.801	0.706	0.776	0.716	0.635	0.572	0.456
Voltage of input, volts	69.0	73.5	69.0	56.5	58.5	63.0	62.0	68.0	68.0	84.0	70.5
Current of input, amperes	3.00	3.00	3.00	2.55	2.50	2.85	2.85	2.80	3.05	3.50	3.05
Heat input of heater, BTU/hr.	720	752	705	492	500	612	602	650	707	1000	733
Thermal conductivity, BTU/hr.-ft.-°F	6590	4990	3720	2690	4430	3360	4970	4400	2110	1980	4220
Heat lost to surroundings, BTU/hr.	80	244	93	120	116	55	52	52	154	426	23

Run Number	19	20	21	22	23	24	25
Test section length, inches	14	14	14	14	14	14	14
Water flow rate, #/hr.	171	192	185	123	185	142	172
Change in water temperature, °C	1.5	2.0	1.5	4.0	3.8	2.5	2.2
Heat out in water, BTU/hr.	755	1035	500	883	1250	674	675
Pressure drop across air orifice, cm. water	5.8	22.8	16.2	44.1	38.2	28.3	20.0
Static pressure at air orifice, cm. Hg	13.4	21.2	18.3	20.0	18.9	19.3	17.4
Temp. at bottom of test section, °F	168.0	137.1	129.3	116.1	129.5	131.4	133.7
Temp. at top of test section, °F	145.0	129.3	121.3	111.3	121.7	125.1	126.3
Temp. drop across test section, °F	23.0	7.8	8.0	4.8	7.8	6.3	7.4
Superficial air velocity, ft./sec.	0.405	0.714	0.604	0.909	0.864	0.774	0.682
Voltage of input, volts	73.5	87.0	73.0	77.0	96.0	71.0	72.0
Current of input, amperes	3.20	3.75	3.20	3.50	4.10	3.10	3.20
Heat input of heater, BTU/hr.	801	1110	796	925	1340	750	785
Thermal conductivity, BTU/hr.-ft.-°F	1700	6850	3240	9910	8340	5520	4720
Heat lost to surroundings, BTU/hr.	46	75	296	43	90	76	110

APPENDIX E. ORIFICE CALIBRATIONS

The water orifice was calibrated by timing the discharge of a known weight of water. Fig. 8 gives the results as pounds of water per hour plotted against pressure drop across the orifice in centimeters of mercury.

The air orifice was calibrated using the gasometer in room 3 - 054 at M. I. T. The pressure drop across the orifice in centimeters of water was plotted on logarithmic paper (Fig. 9) against the flow rate of air in pound mols per minute. The superficial air velocity through the bed can then be obtained by the following method:

W_c is obtained from the plot. Then,

$$W_o \simeq W_c \sqrt{\frac{P_o \times T_c}{P_c \times T_o}}$$

where P_o is the pressure at the orifice during operation in centimeters of mercury,

P_c is the pressure at the orifice during calibration in centimeters of mercury,

T_o is the temperature at the orifice during operation in °R,

T_c is the temperature at the orifice during calibration in °R. Then,

$$AV_B \simeq W_o \times 359 \times \frac{76.0 \times T_B}{P_B \times 460}$$

where AV_B is the volume of air flowing through the test section in cubic feet per minute.

P_B is the average bed pressure in centimeters of mercury.

T_B is the average bed temperature in °R. Then

$V_B = \frac{AV_B}{A}$, giving the superficial air velocity through the bed.

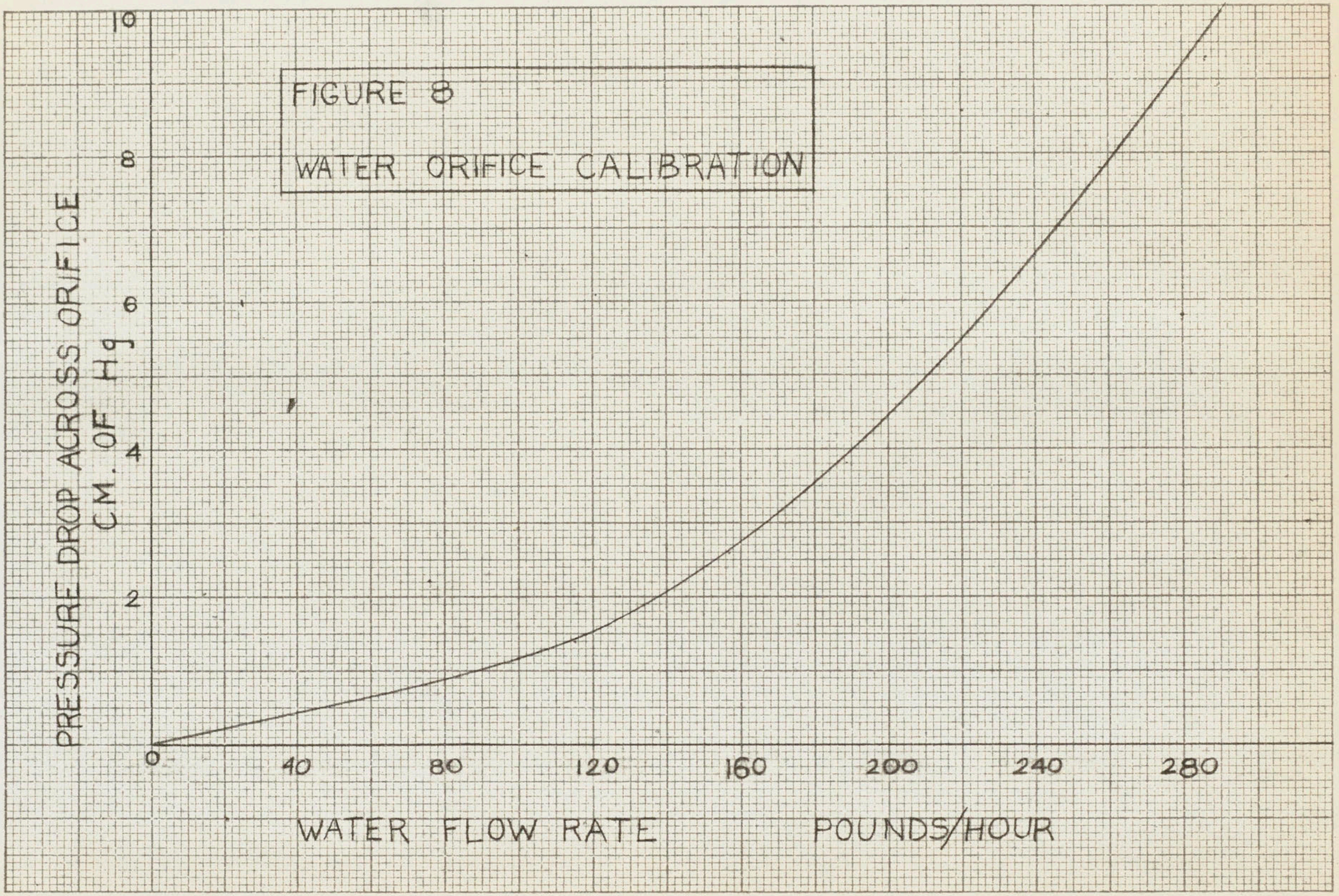

FIGURE 8

WATER ORIFICE CALIBRATION

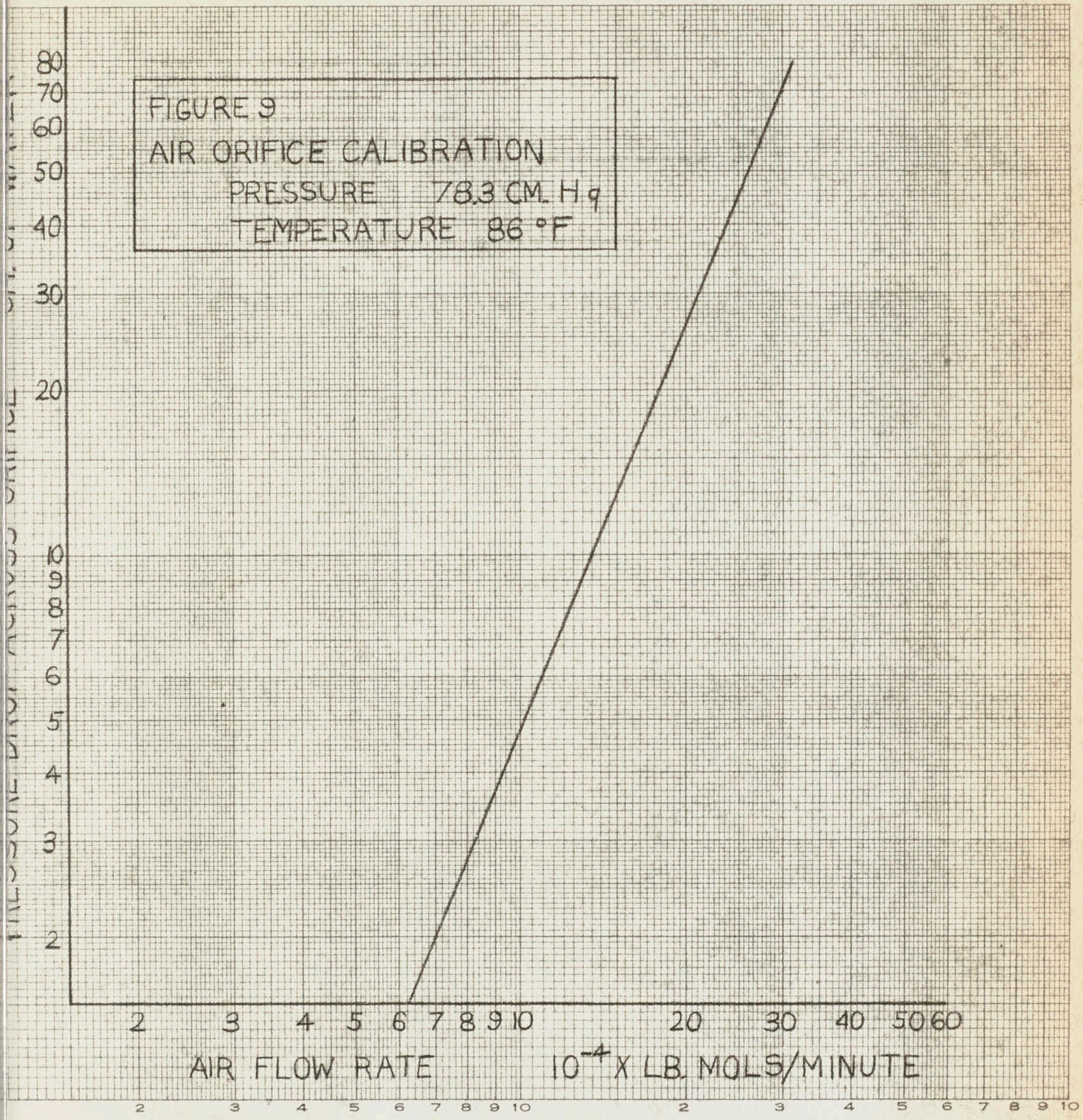

FIGURE 9
AIR ORIFICE CALIBRATION
PRESSURE 78.3 CM. Hg
TEMPERATURE 86 °F

APPENDIX F. SUPPLEMENTARY INFORMATION

1. Solids: Screen analysis

80 - 100 mesh	33.3 gms.	14.7%
115 - 150 mesh	28.7 gms.	12.7%
150 - 200 mesh	109.9 gms.	48.6%
Finer than 200 mesh	54.4 gms.	24.0%
	226.3 gms.	100.0%

The solids were a mixture of No.'s 11, 13, 15, and 17 glass beads.

2. Column:

The column diameter was 2.06 inches.

APPENDIX G. LITERATURE CITATIONS

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