HEAT TRANSFER OF FLOWING GAS-SOLIDS MIXTURES IN A VERTICAL DUCT AT DIFFERENT TEMPERATURE LEVELS

by

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TABLE OF CONTENTS

INTRODUCTION

The study of heat transfer in two phase flow has been given considerable attention in recent years because of the promise of marked increase in the heat transfer coefficient, and because of the many fields in which this phenomenon occurs. The nuclear industry is very interested in increasing the heat transfer coefficient of gas-cooled reactors, and in the rocket industry (especially that dealing with solid-fuel rockets) complicated two phase heat transfer situations occur in the combustion chamber and at the nozzle. In the petroleum industry this phenomena arises in some cracking processes, and it is believed that this industry has a certain amount of unpublished literature on this.

A certain amount of experimental work on the two phase flow heat transfer problem has been published to date; mostly at low temperatures. The amount of theoretical work is still very limited because of its complexity.

This investigation is an experimental study of the behavior of the local heat transfer coefficient for different air-solid ratios in a uniformally heated tube at different temperature levels.

Experimental Work

Systematic experimental work was first reported by Farber and Marley at the University of California in 1957. (4) They passed a mixture of air and aluminum silica catalyst particles (ranging from a few microns to 200 microns in size) through an isothermal heated tube. The average Nusselt number was reported as a function of concentration of particles in air. For mass ratios from zero to one the Nusselt number remained almost constant, for ratios greater than one the Nusselt number increased steadily and had doubled itself at ratios of about 15, the upper limit of the experiment. This work was later extended by Depew (2) who studied the same effects by using uniformally sized glass beads of sizes 200, 70, and 30 microns. He found little change in Nusselt number as a function of concentration for the bigger particles, but the results for 30 micron particles almost matched Farbar's earlier curves. Babcock and Wilcox reported, in 1959 (1), a very extensive study of a two-phase flow experiment carried out for the nuclear industry. They constructed a closed loop, in which a mixture of graphite and nitrogen or helium was pumped, with concentrations as high as 100 to one. They obtained an increase in the overall heat transfer coefficient six times that of gas alone. In 1960, Depew (3) reported on further work in this field. Special attention was given this time to the change in local Nusselt number as a function of concentration. The study was carried out with 200 and 30 micron glass beads, for Reynolds numbers 13,500 and 27,000. For the 200 micron particles he found only a slight increase in Nusselt number as the concentration went up while for the fine particles (30 microns) a strange decrease was observed in the Nusselt number to about 20 per cent below that for pure air for loadings of about one, followed by a steady increase as loading increased. Quan (6) extended this work by using different particle densities. Lead and glass particles of 200 and 30 microns were used. The investigation showed similar results as Depew for glass particles. The small lead particles behaved similar to the glass particles, but the decrease in local Nusselt number was much more and was 60 per cent below that of pure air at its minimum, which occurred at a loading ratio of 1.2.

Theoretical Work

The only known theoretical work on the heat transfer of a flowing fluid-solid mixture was published by Tien in 1961. (10) He analyzed the problem for a tube with constant wall temperature. The analysis is very interesting, but gets extremely involved and many simplifying assumptions were made to obtain a solution. The results do not agree well with Farbara's and Depwe's experimental results for constant wall temperature. Depew (3) extended the theoretical work to a uniformally heated wall and found qualitative agreement with his experimental work.

DESCRIPTION OF EQUIPMENT

The equipment was constructed in such a way that the particles would pass through a continuous cycle (closed loop) thereby reducing the number of particles required. The loop consisted of a uniformally heated heating section instrument to measure the local heat transfer coefficient and an adiabatic section instrumented to measure the bulk temperature and to study the mixing length. After this followed a cooling section to bring the mixture to approximately room temperature before the particles were separated from the air in a high-efficiency cyclone. At the air outlet of the cyclone a calibrated venturi was installed to measure the air flow. The particles were collected in a delay tank for a short period before again being fed into the loop. The air and particles were pumped around the loop by an injection pump driven by compressed air. The pump blew straight into the entrance section to create a good mixture of air and particles before the mixture entered the heating section.

Heating Section

The heater was constructed of a 3/4-inch diameter, 36 inch long, stainless steel tube with an inside diameter of 0.710 inch. The wall thickness was 24 gage. For recording the tube wall temperatures, 30-gage thermocouples were spot welded to the tube at locations shown in Plate II. The thermocouple leads, copper and constantan, were cut into equal lengths, and the two ends were gas welded together into a tiny sphere. The sphere with the leads in a tangential direction to the tube were then carefully spot welded to the tube. Then, electrical tape was placed as close to the joint as possible under the leads and wrapped around the tube one and a half turns covering the thermocouple. At each end of the tube, 1/16 of an inch from the end, a brass flange, 3/16 of an inch thick, was silver soldered to the tube for connecting the power and to ensure a uniform flow of current into the pipe. The leads to the volt meter were also screwed directly onto the brass flange to insure correct voltage readings across the tube. The heating section was electrically insulated from the rest of the system by two reinforced fiber bakelite pieces machined as shown in Plate III. Two holes, 1/8-inch diameter, were drilled perpendicular through each block to provide pressure taps for measuring the pressure drop across the heater.

Adiabatic Section

The adiabatic section was stainless steel tubing, 36 inches long. The thermocouples were welded to the tube in the same fashion as the heating section at positions shown in Plate II.

Insulation

Both the heating section and the adiabatic section were insulated in the same manner. Two 24-gage galvanized sheet steel tubes, 8 inches in diameter were mounted around each section. When every part of the loop had been tested out, the containers were filled with vermiculite.

Cooling Section

The entire length of pipe between adiabatic section and cyclone was made into a cooling section. Three pieces of copper pipe, 3/4 of an inch in diameter with water jackets, were used. When constructing the equipment, it was not known how long the copper pipe bends would last against the eroding effect of the particles. An inspection of the pipes after completion of the experiment indicated little wear.

The Cyclone

The cyclone was constructed in two parts, the upper cylindrical housing was made out of steel to prevent wear. The conic bottom part was made out of glass for visible inspection. The two parts were glued together with Epoxy resin. The cyclone proved to be almost 100 per cent efficient for 30 micron particles. For details, see Plate IV.

Venturi

The venturi was made of 3/4-inch diameter copper pipe by forming it to the proper dimensions on a lathe. The orifice had an area one half the tube diameter which proved sufficient for accurate readings on the manometer. The venturi was calibrated by passing a steady flow of air through it and letting the air fill a gas meter calibration tank. The air temperature and the time for filling the tank were measured together with the pressure drop across the venturi. (See calibration curve, Plate VI.)

Storage Feed Tank

The storage feed tank was constructed out of a poly vinyl flexible tubing 1-1/2 inches in diameter, and 1 foot, 6 inches long. A flexible connection was installed between the cyclone and the feed nozzle. This was vibrated to insure a uniform flow of particles. Unfortunately, this principle gave unsteady flow conditions and was changed to a motor-driven feed mechanism which proved more satisfactory.

Feed Mechanism

A 3/4-inch diameter, 2-inch long copper tube was split 3/16 inch wide and I inch deep at one side, and the tube was placed in the bottom of the feed tank. A rubber ball, 0.68 inches in diameter, was placed inside the tube mounted on a 3/16-inch shaft. The ball had 18 blades cut axially out of it. The shaft was connected to an electric motor, whose speed was controlled by a variac.

Injection Pump

The injection pump was constructed from a 3/4-inch diameter copper elbow through which a 1/4-inch copper pipe air jet nozzle was mounted. The jet blew into a venturi also formed from a 3/4-inch diameter copper pipe. The vacuum created on the upstream side proved adequate to transport particles from the feed inlet to the pump.

Entering Section

The entering section was made of the same stailness steel pipe as the heating section (35 inches long). Three inches from the top, a thermocouple was soldered to the pipe to measure the entering mixtures temperature. The thermocouple joint was insulated from the surroundings with one-inch glass wool insulation covering 6 inches of the tube.

Recorder

A Honeywell high speed electronic recorder with variable sensitivity and range from one to 21 millivolts full scale was used. The recorder was calibrated for each set of runs using a portable millivolt potentiometer. For converting the recorder readings to temperatures, the National Bureau of Standards Reference Table for Thermocouples, Circular 561, was used.

Power Supply

An electric welder was used for energy control to the heating section. For the highest temperature levels, two welders were used in parallel.

Meters

A General Electric precision volt meter with 6-inch full scale deflection was used. The meter had two scales, 0-3 volts and 0-15 volts. Resistance across the meter was 650Ω for the 0-3 volts scale.

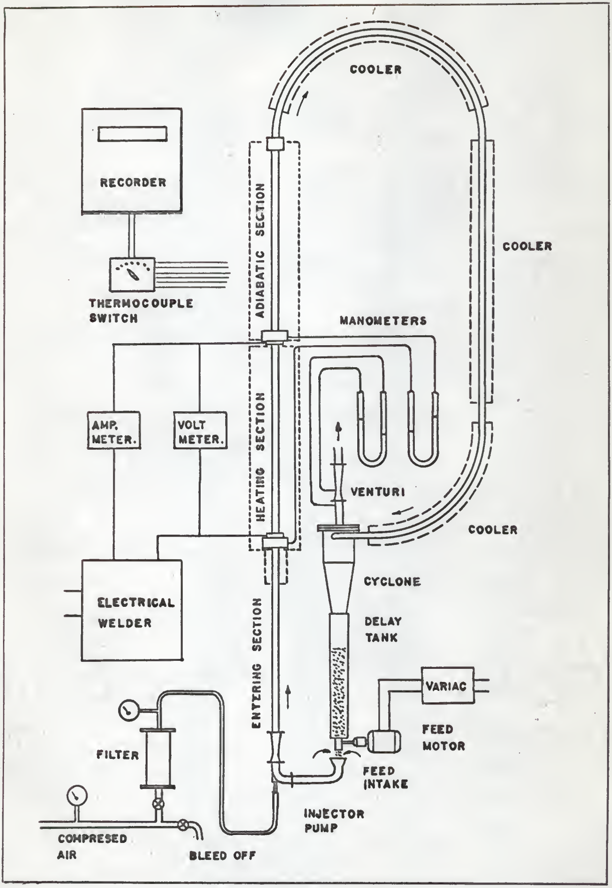
For current measurement, a 50 millivolt full scale volt meter was used across a 300 ampere shunt calibrated for 50 millivolts. Full scale deflection of the meter was 6 inches.

A Meriam manometer with one-hundreths of an inch divisions was used to measure the pressure drop across the venturi.

EXPLANATION OF PLATE I

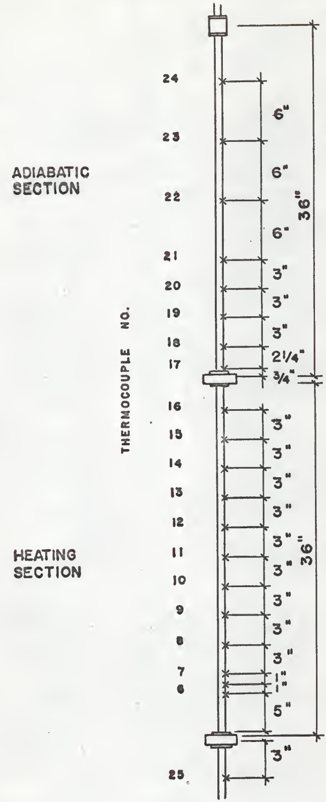
Schematic diagram of the experimental equipment to study heat transfer phenomenon of fluid solid-mixtures.

PLATE I


COOLER
RECORDER
COOLER
ADIABATIC SECTION
THERMOCOUPLE
SWITCH
MANOMETERS
HEATING SECTION
AMP.
METER.
VOLT
METER.
VENTURI
COOLER
CYCLONE
ELECTRICAL
WELDER
ENTERING SECTION
DELAY
TANK
VARIAC
FEED
MOTOR
FILTER
FEED
INTAKE
INJECTOR
PUMP
COMPRESED
AIR
BLEED OFF

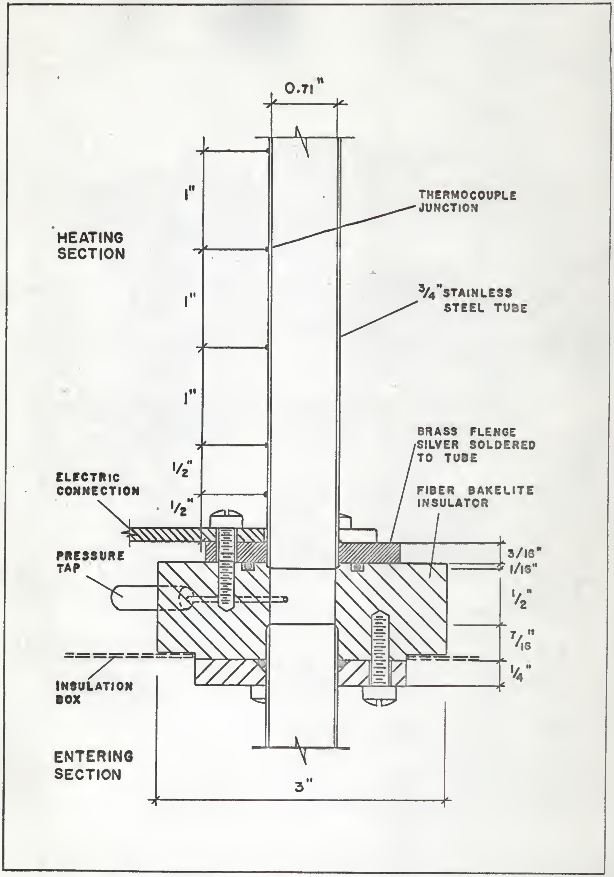
EXPLANATION OF PLATE II

Thermocouple positions for the heating and adiabatic section.


ADIABATIC SECTION
HEATING SECTION
THERMOCOUPLE NO.
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
25
6"
6"
6"
3"
3"
3"
2 1/4"
3/4"
3"
3"
3"
3"
3"
3"
3"
3"
3"
1"
1"
5"
3"
36"
36"

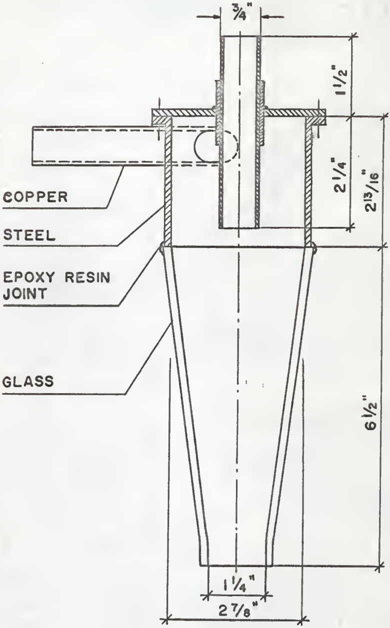
EXPLANATION OF PLATE III

Detailed drawing of the connection between entering and heating sections.


0.71"
1"
1"
1"
1/2"
1/2"
THERMOCOUPLE JUNCTION
HEATING SECTION
3/4" STAINLESS STEEL TUBE
BRASS FLENGE SILVER SOLDERED TO TUBE
FIBER BAKELITE INSULATOR
ELECTRIC CONNECTION
PRESSURE TAP
3/16"
1/16"
1/2"
7/16"
1/4"
INSULATION BOX
ENTERING SECTION
3"

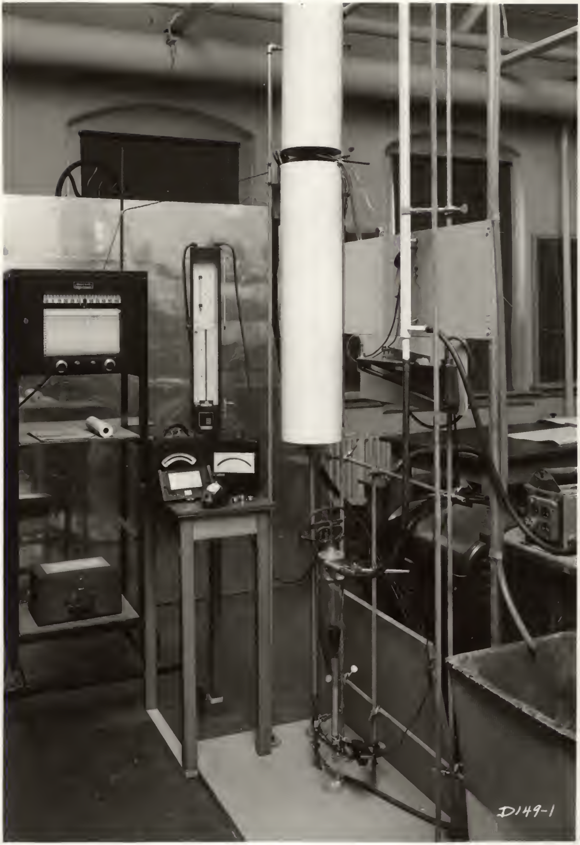
EXPLANATION OF PLATE IV

Detailed drawing of the cyclone.


3/4"
1 1/2"
2 1/4"
2 13/16"
COPPER
STEEL
EPOXY RESIN
JOINT
GLASS
6 1/2"
1 1/4"
2 7/8"

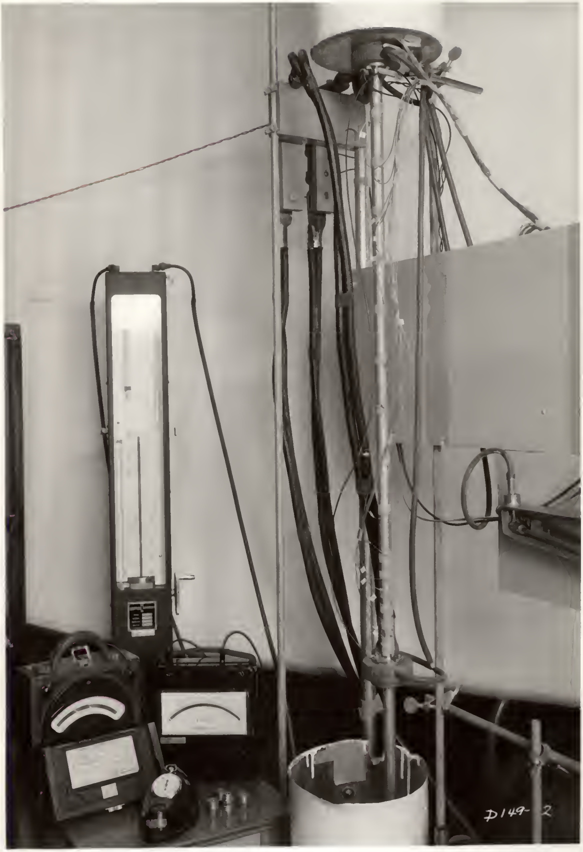
EXPLANATION OF PLATE V

General arrangement of apparatus.


D149-1

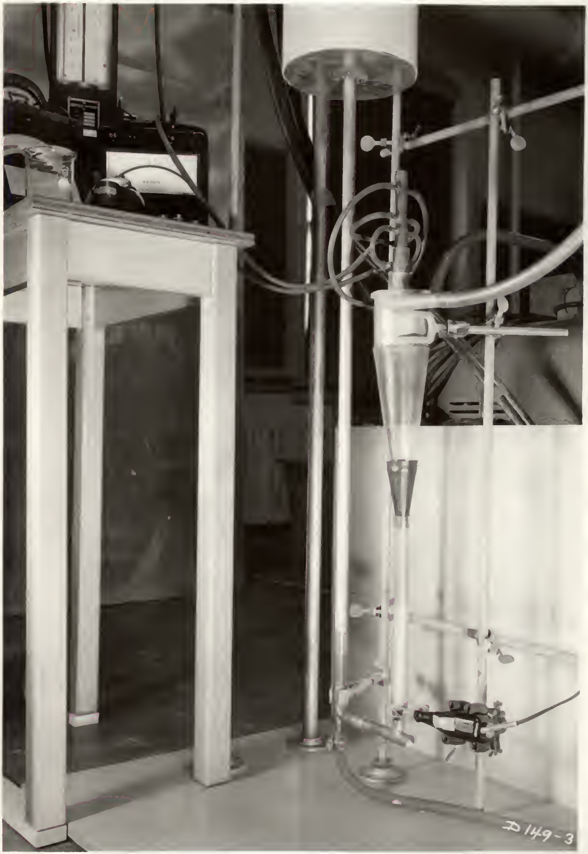
EXPLANATION OF PLATE VI

View of heating section with instrumentation before being insulated.


D149-2

EXPLANATION OF PLATE VII

Close view of cyclone, delay tank, feed mechanism, injector pump and entering section.


D149-3

CALIBRATION OF EQUIPMENT

The heat loss from the heating section was measured by taking off the entrance section and closing the bottom of the heater. A low current was then passed through the section for about 4 hours to insure equilibrium with the surroundings. The temperatures of the tube and the heat flux were recorded. This was carried out a four different temperature levels. Total heat loss was then plotted against the temperature of thermocouple 11, see Plate V. The relationship gave a straight line as expected. It was decided that thermocouple 11 would give the best reference point for the heat loss from this section.

The voltage increase across the tube for a constant current was checked by using the thermocouples as contact points. It was assumed that this increase should be a linear function of tube length. The deviation is shown on Plate VII, Fig. 1, as a percentage of total voltage drop across the tube. Notice the fairly constant deviation of 0.5 per cent between thermocouple 7 and 16. About half of this can be accounted for as tube expansion. The rest might be caused by inaccurate readings of meter or a change in tube wall thickness. The irregularity of junction 14 is believed to be due to a decrease in tube wall thickness.

The heating section was then tested with pure air at the 275° temperature level to check the local Nusselt number at $x/D = 46.8$ against Sparrow's (7) analytical expression.

$$Nu_{\infty} = 0.0245\,(Re)^{0.77} \qquad Pr = 0.7$$

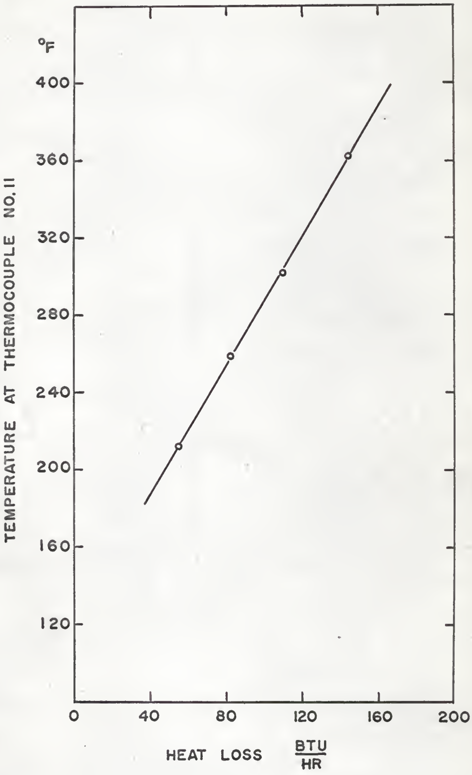
The resulting data checked out to within 1.5 per cent of this equation.

The current passing through the heating section proved to affect some of the thermocouples. It was, therefore, decided to check this effect for each temperature level. The method used was to flip off the current for a short period and record the change in temperature. On an average, the change, if any, was within 1-2 ^{o}F, except for thermocouple 8 which had a 4 degree depression of the temperature. The recorder response to full scale deflection was one second.

To study the grinding effect on the particles, a sample of 300 grams was taken and passed through the loop for one hour at a feed rate of unit mass ratio of air and solids. It was found that 1/3 of the particles had received small fractures on their surface, and a few out of a thousand had cracked.

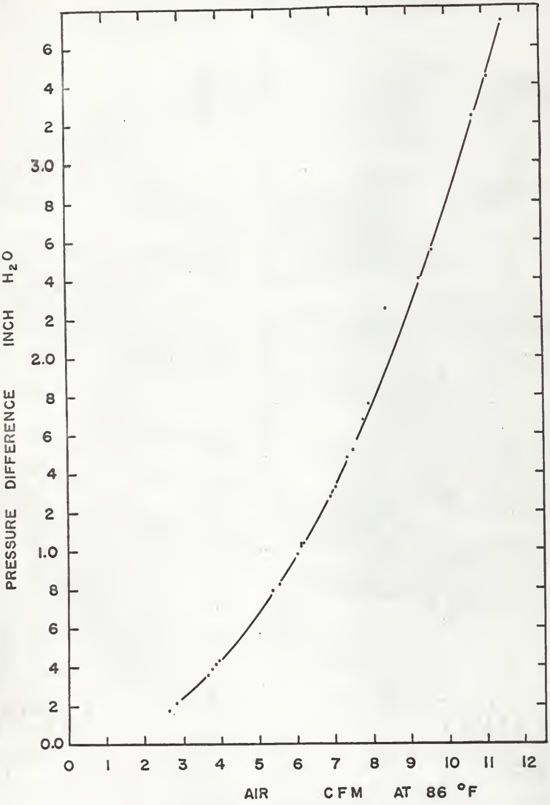
EXPLANATION OF PLATE VIII

Heat loss from heating section as a function of temperature recorded by thermocouple 11.


°F
400
360
320
280
240
200
160
120
TEMPERATURE AT THERMOCOUPLE NO.11
0
40
80
120
160
200
HEAT LOSS $\frac{BTU}{HR}$

EXPLANATION OF PLATE IX

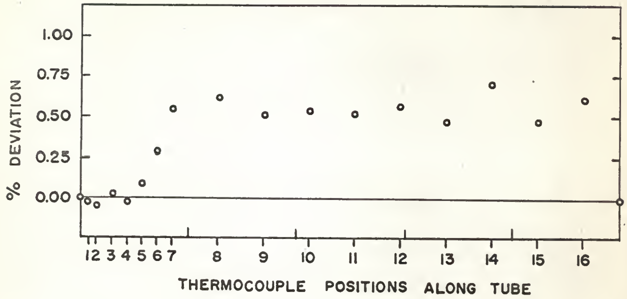
Calibration curve for venturi.

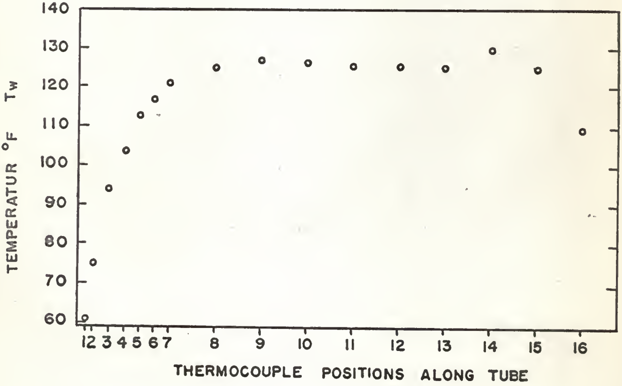

PRESSURE DIFFERENCE INCH H_2O
0.0
2
4
6
8
1.0
2
4
6
8
2.0
2
4
6
8
3.0
2
4
6
0
1
2
3
4
5
6
7
8
9
10
11
12
AIR CFM AT 86 °F

EXPLANATION OF PLATE X

Fig. 1. Percentage deviation of the measured voltage drop across tube compared with an assumed linear drop.

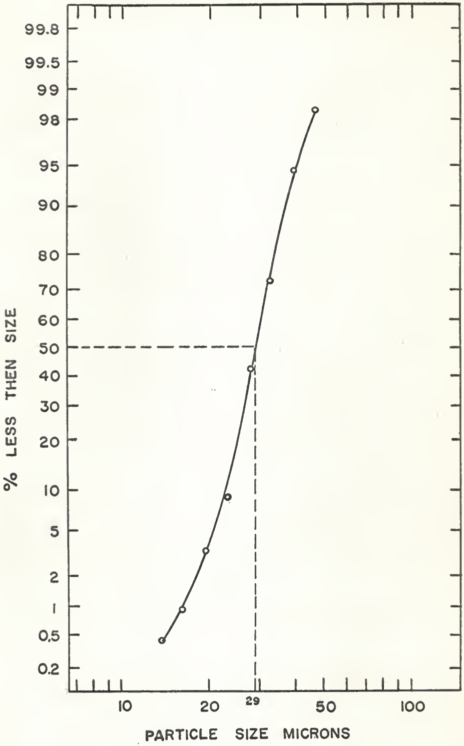
Fig. 2. Temperature profile across tube without air flow.


% DEVIATION
1.00
0.75
0.50
0.25
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
THERMOCOUPLE POSITIONS ALONG TUBE


TEMPERATUR °F Tw
140
130
120
110
100
90
80
70
60
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
THERMOCOUPLE POSITIONS ALONG TUBE

EXPLANATION OF PLATE XI

Size distribution curve of the 30 micron glass beads.


99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
% LESS THEN SIZE
10
20
29
50
100
PARTICLE SIZE MICRONS

EXPERIMENTAL PROCEDURE

The equipment was always started up at least two hours prior to any run to insure equilibrium conditions for all parts. This period was used to adjust air flow, compressor bleed-off, and heater current for the desired temperature level. The cold junction was filled with ice and the recorder calibrated. Thermocouple 16, x/D - 46.8 diameters, was used as temperature level reference point and kept within a few degrees of the selected level.

When the air flow and all temperatures had stayed constant for about half an hour, the first set of readings were taken for pure air. Particles were then fed into the apparatus and pumped around the loop to the delay tank. The loop was operated for an additional ten minutes to allow conditions to stabilize. The particles were then fed into the loop and the air-flow and heat flux adjusted. This took from two to five minutes. At high particle concentrations, it was found harder to adjust the system. Another 15 minutes was allowed to reach equilibrium. The temperature of thermocouple 16 was then recorded followed by readings of the other thermocouples from 1 to 25, and then back to 16 to check for drift, since this took at least five minutes. If everything looked fine, the current, voltage and pressure drop across the heater were recorded and the feed rate was measured. To measure the feed rate, a beaker was passed under the feed mechanism and the sampling time recorded with a 0.2 second division stop watch. At low feed rated, below unit mass ratio, the same sample was used a few times, but at high feed rates, a new sample of particles was used for each run to insure no change in particle quality.

EQUATIONS

The main purpose of this investigation was to study the change in Nusselt number as a function of mass flow ratio for different temperature levels. Three different levels were chosen: 185, 275, and $390^{\circ}F$.

The equations and relationships used are listed below.

The local Nusselt number is taken as

$$Nu_x = \frac{h_x D}{k}$$

where the local heat transfer coefficient is

$$h_x = \frac{q}{T_{w_x} - T_{bm_x}}$$

and the average mixture temperature is given as

$$T_{bm_x} = T_1 + \frac{\pi D \ qx}{WC + W_s C_s}$$

All properties were evaluated at the local bulk temperature except for specific heats, C and C_s, which were evaluated at $100^{\circ}F$. (Change of specific heat was less than one per cent for temperature range used.)

An artificial Reynolds number was used, assuming the mixture properties were the same as for pure air. Total mass air-flow was kept constant throughout the whole experiment. This gave considerable variation of Reynolds numbers for the different temperature levels.

The local Reynolds number

$$Re = \frac{\rho D u_m}{\mu}$$

or

$$Re = \frac{4W}{\pi \mu D}$$

The mass of air and particles were given as a mass ratio,

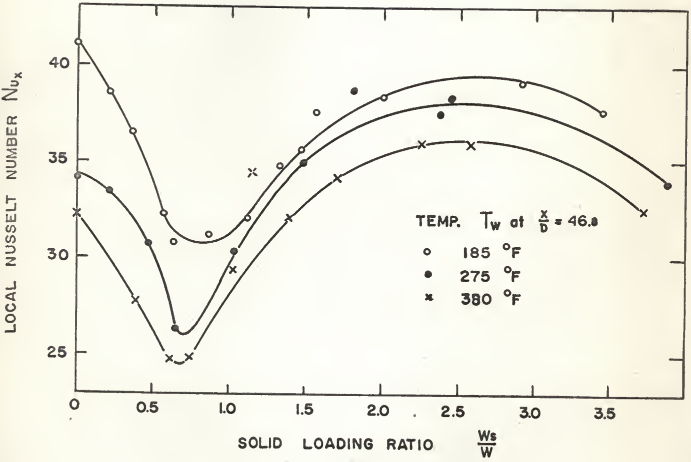
$$\frac{W_s}{W}$$

and axial distance measured from air inlet side of heater as

$$\frac{x}{D} .$$

EXPLANATION OF PLATE XII

Local Nusselt number variation with mass ratio for the three different temperature levels. Mass flow of air constant at 29 lb. per hr.


LOCAL NUSSELT NUMBER Nu_x
40
35
30
25
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
SOLID LOADING RATIO $\frac{W_s}{W}$
TEMP. T_w at $\frac{x}{D}$ = 46.8
185 °F
275 °F
380 °F

EXPLANATION OF PLATE XIII

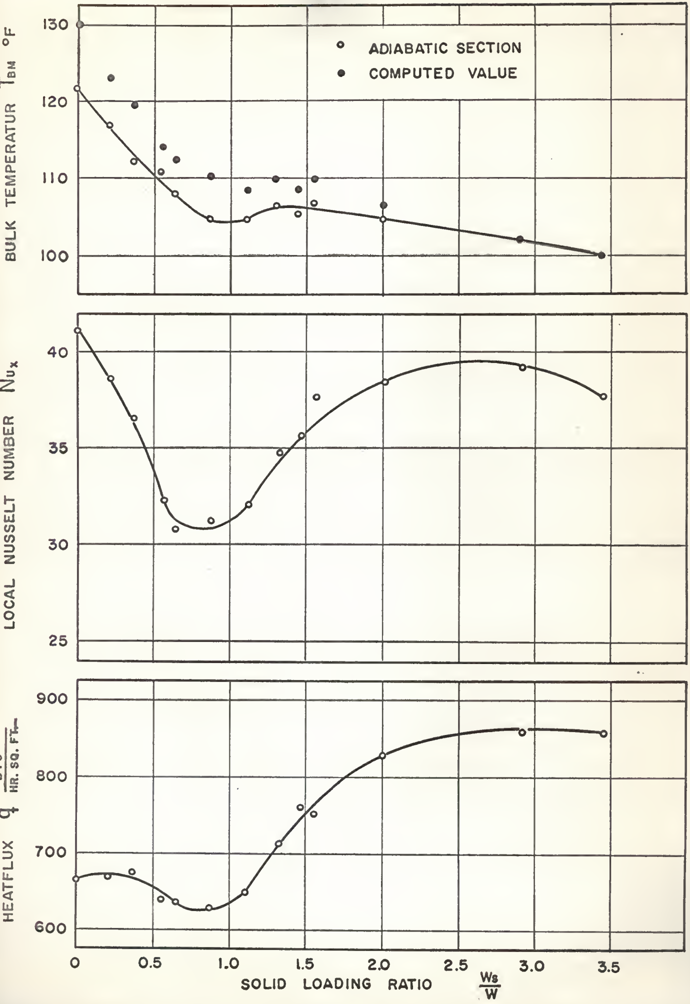
A general picture of the variation of the Local Nusselt number in relation to recorded and computed values, all as a function of mass ratios. Temperature level - $185^{\circ}F$.

Fig. 1. Recorded bulk temperature and computed bulk temperature.

Fig. 2. Local Nusselt number at $x/D = 46.8$.

Fig. 3. Net heat flux to tube.

PLATE XIII



BULK TEMPERATUR T_{BM} °F
130
120
110
100
ADIABATIC SECTION
COMPUTED VALUE
LOCAL NUSSELT NUMBER Nu_x
40
35
30
25
HEATFLUX q $\frac{BTU}{HR. SQ. FT.}$
900
800
700
600
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
SOLID LOADING RATIO $\frac{W_s}{W}$

EXPLANATION OF PLATE XIV

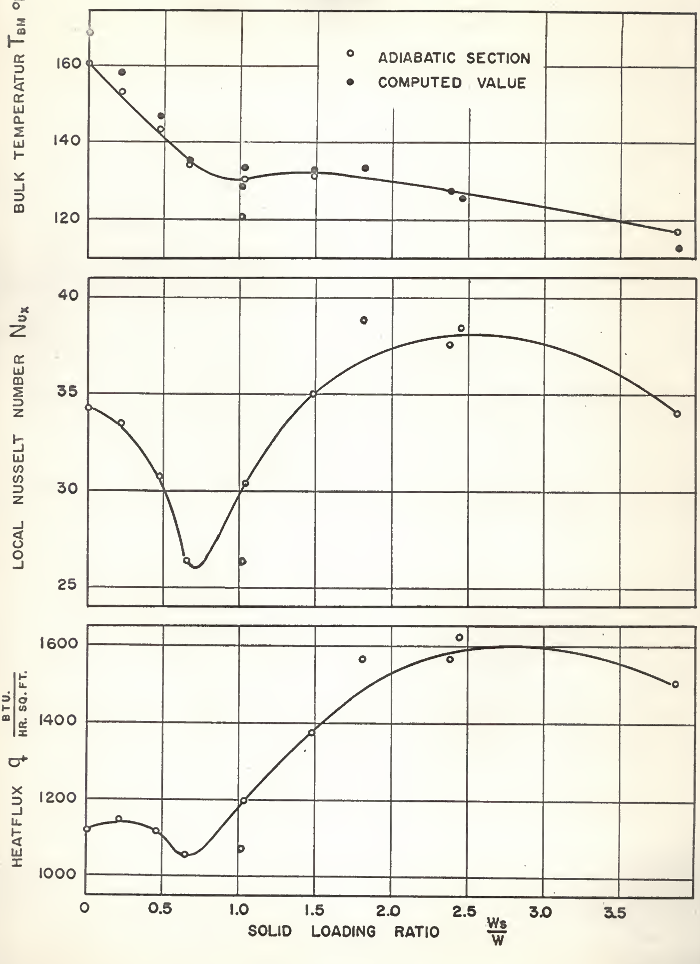
A general picture of the variation of the local Nusselt number in relation to recorded and computed values, all as a function of mass ratios. Temperature level - 275° F.

Fig. 1. Recorded bulk temperature and computed bulk temperature.

Fig. 2. Local Nusselt number at $x/D = 46.8$.

Fig. 3. Net heat flux to tube.

PLATE XIV


BULK TEMPERATUR T_{BM} °F
160
140
120
ADIABATIC SECTION
COMPUTED VALUE
LOCAL NUSSELT NUMBER N_{ux}
40
35
30
25
HEATFLUX q $\frac{BTU.}{HR.\ SQ.\ FT.}$
1600
1400
1200
1000
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
SOLID LOADING RATIO $\frac{W_s}{W}$

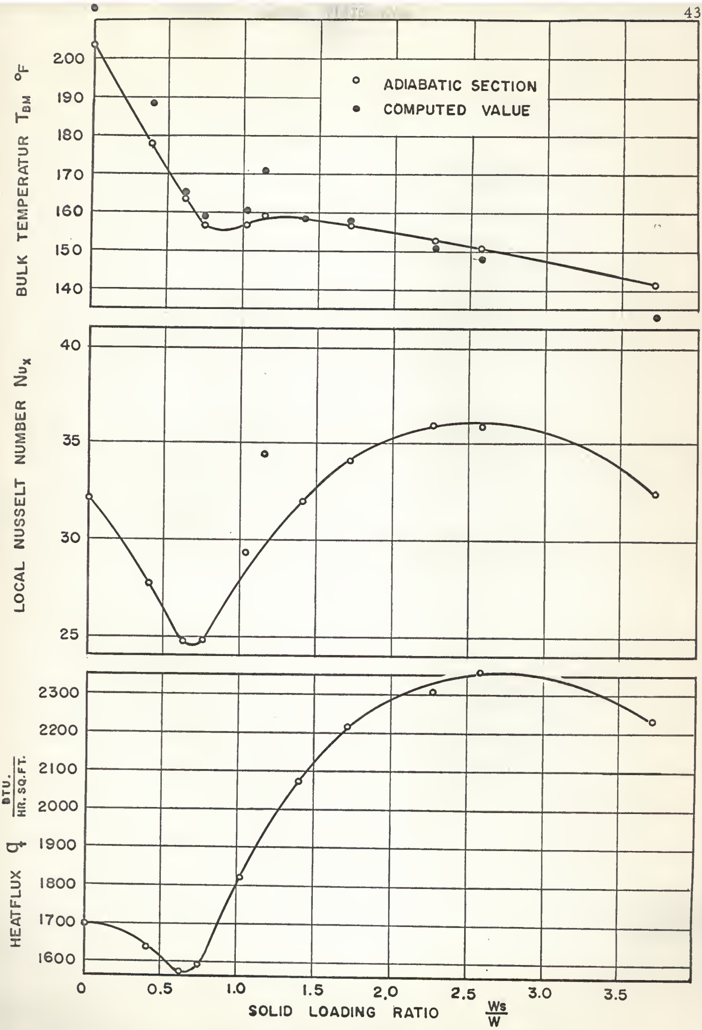
EXPLANATION OF PLATE XV

A general picture of the variation of the local Nusselt number in relation to recorded and computed values. all as a function of mass ratios. Temperature level - 380° F.

Fig. 1. Recorded bulk temperature and computed bulk temperature.

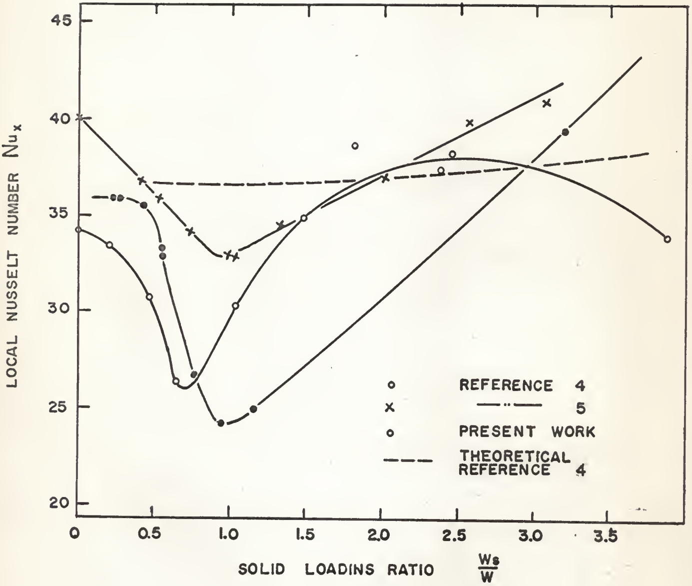
Fig. 2. Local Nusselt number at $x/D = 46.8$.

Fig. 3. Net heat flux to tube.


ADIABATIC SECTION
COMPUTED VALUE
BULK TEMPERATUR T_{BM} °F
200
190
180
170
160
150
140
LOCAL NUSSELT NUMBER Nu_x
40
35
30
25
HEATFLUX q_t $\frac{BTU.}{HR.\ SQ.FT.}$
2300
2200
2100
2000
1900
1800
1700
1600
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
SOLID LOADING RATIO $\frac{Ws}{W}$

EXPLANATION OF PLATE XVI

A comparison of the present experimental work with other experimental and theoretical work.


45
40
35
30
25
20
LOCAL NUSSELT NUMBER Nu_x
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
SOLID LOADINS RATIO $\frac{W_s}{W}$
REFERENCE 4
5
PRESENT WORK
THEORETICAL REFERENCE 4

RESULTS

The main purpose of this experiment was to determine the variation of the local Nusselt number as a function of particle loading for different temperatures in the heating section.

The results of the investigation have been plotted against different parameters to show effects of interest and to compare them with other investigations.

In Plate XII, the results for the three temperature levels are shown. One notices immediately the great decrease in Nusselt number of about 20 - 25 per cent as the mass ratio increases from zero to 0.7, followed by a rapid increase until a mass ratio of about two is reached. From here, it seems to level out or even decrease as the mass ratio approaches 4.0. Four was the upper limit of the feed mechanism.

The Nusselt number shows little change between the three temperature levels as a function of particle concentration. The change in the total value of the Nusselt number is caused by a change in Reynolds number, due to changes in the mean terminal temperature of the mixture.

In Plates XIII, XIV, and XV the local Nusselt number is shown together with the adiabetic section's bulk temperature and the heat flux for different load ratios. The outlet temperature of the heating section is believed to represent the bulk outlet temperature of the heating section to within a few degrees. Notice the steady drop in bulk temperature as the loading ratio goes to 0.7, followed by a slow but constant temperature drop all the way to a loading ratio of four. The calculated bulk temperature given much the same shape, and almost corresponds at high solid loading ratios. This is a good indication of the accuracy of the measured feed rate of particles.

For pure air, the computed bulk temperature is almost 10° F higher than the measured one which indicates that the measured air flow might be too low. An increase of 3.5 per cent of the air flow would correct this difference. Many tests were made to verify this, but without success.

In studying the various results shown in Plates XI, XII, and XIII, it appears as if there are three identifiable regions. In the first part, almost no change in heat flux takes place but a distinguishable drop in mixture bulk temperature is present. In the second region, the heat flux increases very rapidly. Finally, a region in which both the heat flux and bulk temperature remain fairly constant. The reason for these three regions is believed to be due to particle concentration and its interference with the boundary layer.

The results for the 275° F temperature level has, on Plate XV, been compared with other investigator's results. A general agreement is seen with both Depew's (5) and Quan's (4) experimental values for mass ratios up to two. Between 1.5 and 3, most experimental values seem to agree closely with Depew's (5) theoretical values.

DISCUSSION OF RESULTS

It might be worth noting the good agreement for the local Nusselt number at $x/D = 46.8$ for pure air with Sparrow's (7) analytical equation which gave an agreement of 5 per cent for the 380° F temperature level, and 1.5 per cent for the 275° F level. For the 185° F temperature level the agreement was 15 per cent.

In Plate XIV, where the experimental results for the 275° F temperature level is compared with other investigations, it is interesting to note the general agreement of the shape of the curves, although the actual values differ considerably. Quan's results are based on a higher Reynolds number (15,000), which accounts for the higher values of Nusselt number at lower concentrations. The experimental results for all three investigations are fairly close between mass ratio 1.5 and 3, and agree also with Depew's theoretical curve. It should be mentioned that Depew's theoretical function predicts a greater drop in the local Nusselt number, at mass ratios of one, for large particles than for small particles, while experimental work (3), (6) shows the opposite trend.

In studying Plates XIII, XIV, and XV, the following conclusion was drawn to explain the local Nusselt number behavior for different particle to air concentrations.

The definition of the heat transfer coefficient between tube and fluid is defined as the heat flux of the tube divided by the difference between tube wall temperature and the fluid bulk temperature. But the main resistance for heat flow between tube and fluid is the temperature gradient at the wall, in the laminar sub-layer. If a few particles are added to the fluid, their interference with the boundary layer will be very limited. But they will cause a definite change in the mixture bulk temperature.

While the heat flux is expected to stay almost constant because of the small interference with the boundary layer, both of these tendencies are clearly seen from the recorded heat flux and bulk temperature for loadings up to 0.7. As the number of particles increases, they will start to cause an appreciable disturbance of the boundary layer, and increase the temperature gradient at the wall. If the tube wall has to be maintained at a constant temperature, the heat flux must be increased to compensate for the increased heat transfer. This tendency seems definitely to be the case for the heat flux of the tube for loading ratios from 0.7 to 2.5. If this disturbance of the boundary layer is a continuous provess for higher concentrations, it is hard to determine from this experiment. More data are needed to predict what mechanisms might be involved for higher concentrations.

EXPERIMENTAL ACCURACY

The accuracy for each measured quantity has been listed below.

Quantity	Base Value	Estimated Deviation, per cent
L inch	36	0.1
0 inch	0.710	1.0
x inch	20	0.2
Voltage volt	3.00	0.5
Current amp	100.00	0.5
T_1 °F	80	1.0
T_w °F	300	1.0
W lb/hr	29	1.0
Feeding time, sec.	10	2.0
Mass of particles, grams	100	0.01

The estimated accuracy for the local Nusselt number should be 7 per cent.

RECOMMENDATIONS FOR FURTHER WORK

1. It would be of great interest to see if the local Nusselt number would behave the same for particles smaller than 30 microns. All other parameters should be maintained as for this work.

2. To study, experimentally, the particle distribution and the velocity profile in a vertical pipe with turbulent flow. This is a very complex study, and for this reason few investigators have tried it.

CONCLUSIONS

The statements made pertain to a uniformly heated tube through which air and particles are passed having a fully developed velocity profile.

1. The temperature of the tube wall has little effect on the local Nusselt number for the three temperature levels tested, ($185^{o}F$, $275^{o}F$ and 380^{o} F).
2. The decrease in local Nusselt number followed by an increase as concentration of particles increases, can be shown to be related to the definition of the heat transfer coefficient and to the particles increasing interference with the boundary layer as concentration goes up.
3. The local Nusselt number as a function of particle concentration agrees fairly well with the results of other investigators.

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NOMENCLATURE

C = Heat capacity of air BTU/lb F

C_s = Heat capacity of particles BTU/lb F

D = Tube diameter, ft

h = Tube wall heat transfer coefficient BTU/hr sq ft F

k = Air therminal conductivity BTU/hr ft F

N_u = Nusselt number

q = Tube wall heat flux BTU/hr, sq ft

R_e = Reynolds number

T_1 = Mixture entering temperature, ^oF

T_{bm} = Mixture bulk temperature, ^oF

T_w = Tube wall temperature, ^oF

W = Mass flow of air, lb/hr

W_s = Mass flow of particles, lb/hr

ρ = Gas density, lb/ft^3

μ = Viscosity of air, lb/ft sec.

x = Denotes local position along tube

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APPENDIX

Table 1. Summary of heat transfer data and calculations.
Temperature level = 185^{o} F: Air mass flow, 29 lb/hr.

Run No.	Mass Ratio $\frac{W_s}{W}$	Net Heat Flux $q \frac{BTU}{hr.\,sq.\,ft.}$	Inlet Temp. T_1 ^{o}F	Mixtures Bulk Temp. T_{bm_x} $\frac{x}{D} = 46.8$	Wall Temp. T_{w_x} $\frac{x}{D} = 46.8$	Local Heat Trans. Coef. $h_x \frac{BTU}{hr.\,sq.\,ft.\,^{o}F}$	Local Nusselt No. Nu_x $\frac{x}{D} = 46.8$
50	0.000	666.5	77.4	126.7	186.9	11.08	41.2
51	0.2155	668.0	77.4	119.6	184.5	10.31	38.7
52	0.371	675.0	77.9	116.4	186.1	9.69	36.5
53	0.564	640.0	78.8	111.5	186.8	8.50	32.3
54	0.645	637.0	79.0	110.2	188.5	8.14	30.9
55	0.876	630.5	80.6	108.1	184.9	8.21	31.3
56	1.119	651.0	80.8	106.3	184.0	8.39	32.1
57	1.32	715.0	82.0	107.8	186.0	9.15	34.8
58	1.558	752.5	83.3	108.2	184.2	9.90	37.7
59	1.466	760.0	80.2	106.2	187.7	9.33	35.6
60	2.032	829.0	81.0	104.4	186.8	10.04	38.5
61	2.92	859.0	82.0	101.1	185.2	10.21	39.3
62	3.48	857.5	81.3	98.1	186.0	9.76	37.8

Table 2. Summary of heat transfer data and calculations.
Temperature level = 275°F: Air mass flow, 29 lb/hr.

Run No.	Mass Ratio $\frac{W_s}{W}$	Net Heat Flux $q \frac{BTU}{hr.\,sq.\,ft.}$	inlet Temp. T_1 °F	Mixtures Bulk Temp. T_{bm_x} $\frac{x}{D} = 46.8$	Wall Temp. T_{w_x} $\frac{x}{D} = 46.8$	Local Heat Trans. Coef. $h_x \frac{BTU}{hr.\,sq.\,ft.\,°F}$	Local Nusselt No. Nu_x $\frac{x}{D} = 46.8$
80	0.0000	1120	77.9	160.7	277.7	9.58	34.3
81	0.2100	1148	79.6	152.4	275.5	9.32	33.5
82	0.4615	1120	81.1	141.7	274.2	8.45	30.8
85	0.6615	1058	79.7	130.9	280.0	7.09	26.3
84	1.014	1068	81.1	124.7	275.5	7.06	26.3
86	1.042	1200	81.0	129.5	275.8	8.20	30.5
87	1.479	1382	82.4	129.4	275.5	9.46	35.1
88	1.803	1568	83.3	131.0	280.4	10.49	38.8
89	2.373	1564	84.2	124.3	279.4	10.08	37.6
90	2.450	1624	81.2	121.8	280.3	10.23	38.4
91	3.875	1511	81.5	108.9	278.0	8.94	34.1

Table 3. Summary of heat transfer data and calculations.
Temperature level = 380°F: Air mass flow, 29 lb/hr.

Run No.	Mass Ratio $\frac{W_s}{W}$	Net Heat Flux $q \frac{BTU}{hr. sq. ft.}$	Inlet Temp. T_1 °F	Mixtures Bulk Temp. T_{bm_x} $\frac{x}{D} = 46.8$	Wall Temp. T_{w_x} $\frac{x}{D} = 46.8$	Local Heat Trans. Coef. $h_x \frac{BTU}{hr. sq. ft. °F}$	Local Nusselt No. Nu_x $\frac{x}{D} = 46.8$
70	0.0000	1700	77.9	203.7	383.0	9.50	32.2
71	0.4040	1638	78.8	180.6	381.5	8.15	27.4
72	0.6130	1570	80.6	158.7	386.0	6.91	24.7
73	0.7565	1592	80.6	153.5	384.5	6.91	24.8
74	1.037	1820	80.6	154.2	376.5	8.81	29.4
75	1.135	2080	83.3	164.0	378.5	9.70	34.4
76	1.407	2075	80.2	152.6	386.0	8.90	32.0
77	1.702	2185	84.2	153.0	383.0	9.51	34.2
78	2.265	2310	85.1	146.1	378.0	9.93	36.1
79	2.575	2360	86.0	143.3	383.0	9.85	35.8
79B	3.725	2237	85.1	126.9	383.0	8.73	32.5

HEAT TRANSFER OF FLOWING GAS-SOLIDS MIXTURES IN A VERTICAL DUCT AT DIFFERENT TEMPERATURE LEVELS

by

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In recent years, considerable attention has been given to the study of two-phase flow with heat transfer resulting from interest in many fields such as the nuclear industry and rocket industry. The amount of thorough experimental and theoretical work is still fairly limited and much more is required to get a better understanding of the phenomena.

This investigation is an experimental study of the problem carried out in a uniformly heated vertical tube. The apparatus was constructed in the form of a loop through which a mixture of air and glass beads were pumped. It consisted of an entering section to obtain a fully developed velocity profile, a heating section instrumented to measure the local heat transfer coefficient, an adiabatic section to measure the mixture's bulk temperature and mixing length, a cooling section and a cyclone to separate air and particles in order to measure these quantities. An air injection pump was used to pump the mixture around the loop. The air flow was kept constant at 29 lb/hr throughout the experiment. The heating section was operated at three temperature levels - 185, 275, and 380° F, and the particles were spherical glass beads 30 microns in diameter.

The results showed that the local Nusselt number behaved much the same at all three temperature levels, but behaved rather peculiarly as the number of particles increased. The local Nusselt number first decreased as the air to particle mass ratio increased, and at mass ratio 0.7 it was 20-25 per cent below that for pure air. Nusselt number then increased again rapidly as mass ratio was further increased, but at a ratio around two started to flatten out and even decreased for ratios close to four. The reason for these three distinguishing regions is believed to be due to three different particle motions and their interference with the boundary layer and velocity profile.

The results for the 275° F temperature level were compared with the results of other investigators, and a general agreement was found for the local Nusselt numbers for mass ratios up to two. For higher loadings, the experimental results agree somewhat better with the theoretical values obtained by Depew.