Fluidisation

Baran Anil

CE20238

Chemical Engineering Skills Practice and Design 2

Laboratory Investigation 3A

Group 16

10 - 03 – 2022

Abstract

This experiments main objectives were to find the experimental values for the Superficial velocity and voidage at minimum fluidization and the particle size. As well as this collect data to show the relationship between the superficial velocity and pressure drop or heat transfer. The superficial velocity value obtained was 0.129 m s^{-1} and the voidage around 0.468. The particle size was then calculated to be 297 µm, which then concluded that the powder in the rig was Grade 56 Aluminium Oxide. The results of the collected data created graphs that were similar to the theoretical graphs, which shows that they were comparable. Unfortunately, there were some errors occurring due to many factors and limitations such as interpretations of graphs and other physical phenomena.

Introduction and Theory

The aim of this experiment is to calculate the superficial velocity, the voidage at minimum fluidization and the particle diameter for Aluminium Oxide powder in a fluidized bed. Both the theoretical and empirical data will be obtained, in which they will later be compared to one another to assess the accuracy of the results. As well as this, the relationship between the fluidized bed behavior and the heat transfer will be analyzed, to assess the heat transfer between the solids and the fluid flowing within the rig. Fluidized beds are used in specific processes in industry, some of which are Fluid Catalytic Cracking (FCC), where in the petroleum industry, the longer hydrocarbon molecules are broken into smaller and lighter ones. Other methods may include (Shilton and Niranjan, 1993) freezing and cooling, drying, puffing, freeze drying, spray drying, classification and blanching and cooking. These processes involve heat and mass transfer to or from the food material, which can be rapidly achieved from fluidization

The basic principle of fluidization is the stationary solid particles will be placed into a dynamic state by the upwards stream flow of fluid. This means that the solid particles, usually powder form, will show behaviour similar to a fluid in an upward direction due to the superficial velocity of the gas flowing from underneath. The point where the upwards drag force is enough to keep the particles floating at the same height on the rig is called the point of minimum fluidization. Particles will be floating in a steady position. When it comes to the heat transfer between hot fluid and a fixed bed, it occurs mainly through heat conduction. Due to the movement of the particles, the fluid and the particles are very well mixed in the fluidised bed. To calculate the heat transfer coefficient, Equation 1 was used:

$$h = \frac{Q}{A\Delta T} \qquad \text{Eq. 1}$$

The first problem faced will be calculating the theoretical values for the superficial velocity, which is the velocity of the fluid flowing through a given cross-sectional area treating the fluid as the only fluid present in the area, hence a hypothetical value and the voidage, which is basically a ratio of the unoccupied volume in a container to the total volume of the container. The equation used to calculate voidage is seen below with Equation 2:

$$-\frac{\Delta P}{l} = (1 - \varepsilon_{mf})(\rho_s - \rho)g \qquad \text{Eq.2}$$

The point before minimum fluidisation the pressure drop, which has a linear increase in pressure drop, can be calculated via the Carman-Kozeny equation. Equation 3, as seen below, can be used in both laminar and turbulent flow conditions:

$$\Delta P = 180 \frac{\mu u_{mf} h_{mf}}{{d_p}^2} \frac{(1-\varepsilon_{mf})^2}{{\varepsilon_{mf}}^3} \qquad \text{Eq.3}$$

Once these parameters are calculated, it is used to calculate the particle diameter via the Ergun equation which is only valid in the turbulent flow region. Unlike the Equation 3, this gives a quadratic equation which is Equation 4 and is displayed below:

$$\frac{\Delta P}{l} = 150 \frac{\mu}{{d_p}^2} \frac{(1-\varepsilon_{mf})^2}{{\varepsilon_{mf}}^3} u_{mf} + 1.75 \frac{\rho_f}{d_p} \frac{(1-\varepsilon_{mf})}{{\varepsilon_{mf}}^3} {u_{mf}}^2 \qquad \text{Eq.4}$$

From this equation, we proceed to find the particle diameter, which we then can understand better what grade of aluminium oxide powder we are working with.

<u>Method</u>

Before the flowrate is increased from nothing, the measurements should be taken of the initial conditions, these measurements are bed height, pressure drop and the flowrate of the fluid through the fluidised bed. When recording the bed height, one should take 3 measurements and take the average.

Once the flowrate is increased from nothing, the point of minimum fluidisation should be found by slowly increasing the flowrate, until the first movement can be seen with the powder which is in the fluidised bed. Once this point is found, the various measurements already talked about should be taken.

Proceed to gradually increase the flowrate gradually and record the measurements at 10 different flowrates. The 10 flowrates should be 3 below, one close to and 6 above below the minimum fluidisation point. Repeat the process with decreasing flowrate once the highest flowrate is achieved on the rig.

For the next part, electrical power is supplied to the heating element, the voltages preferable are between 10V to 20V for the first set of data, and 20V and 30V for the second set of data. For each set of data, carry out measurements for 3 different flowrates, one below, one close to and one above minimum fluidisation point.

Between each measurements, leave 5 minutes before recording the temperature to allow for equilibration of the temperature, allowing for the temperature to stabilise. Take 3 measurements of temperature for each: T_1 = Temperature of the bed, T_2 = Temperature of the heating element and T_3 = Temperature of the fluid in the rig.

As well as the temperatures, record the measurements of: voltage supplied, current supplied, flowrate, bed height and pressure drop.

Proceed to turn off the rig once all the raw data is obtained.

<u>Results and Calculations</u>

Initially, the flowrate was obtained from a graph that shows the relationship between the pressure tube reading the air flowrate, which can be found in Appendix 1.6. Once the flowrates were obtained, it was divided by the inner cross-sectional area of the fluidised bed, which gave our experimental superficial velocity, after this our pressure values that were obtained. The Superficial velocities were calculated via Equation 5 below:

$$u_{mf} = \frac{Q}{A} \qquad \text{Eq. 5}$$

The graph that was plotted, was the relationship between the logarithmic values of superficial velocity and the pressure drop as can be seen in Figure 1 below:

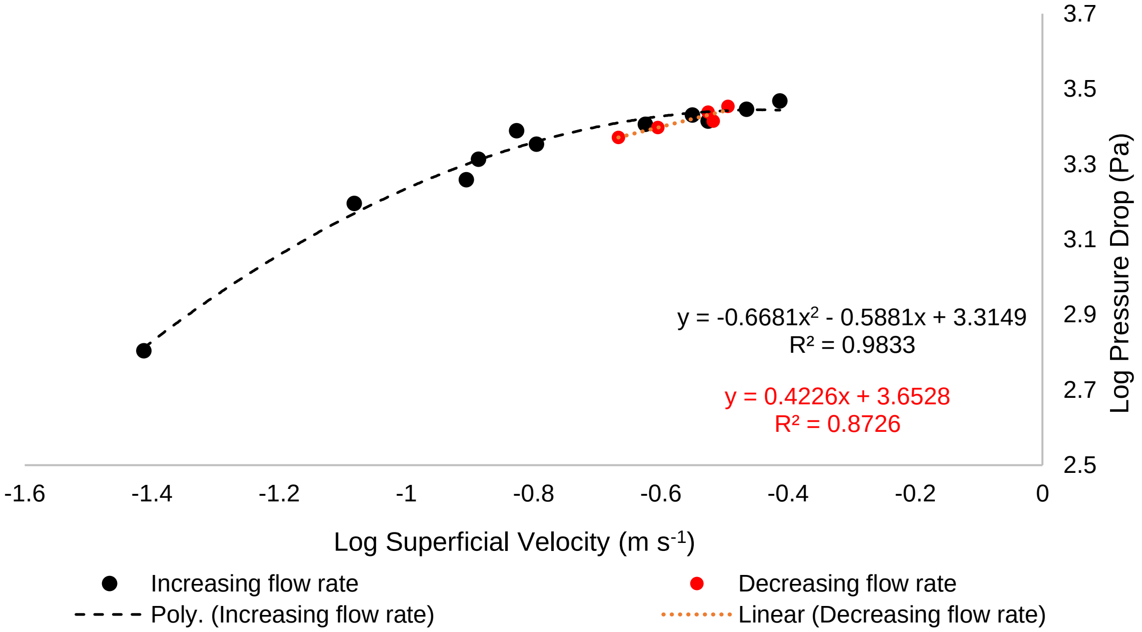


Figure 1: : Relationship between Superficial Velocity and Pressure Drop

The next graph was produced exclusively to calculate our superficial velocity and was done only by dividing our pressure drop values by the fluidised bed height, from this the graph below, Figure 2:

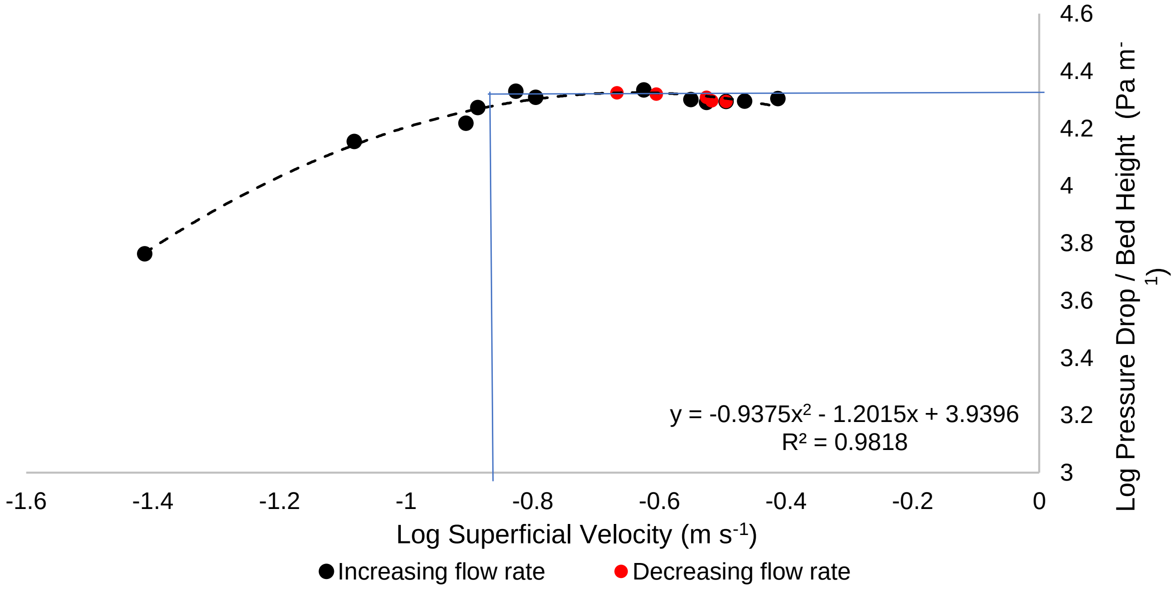


Figure 2: Relationship between Superficial Velocity and Pressure Drop / Bed Height to find the Velocity at minimum fluidisation

From this graph, a logarithmic value for our experimental value for superficial velocity, by estimating when the maximum pressure drop on Figure 2, a finding the corresponding logarithmic superficial velocity on the x-axis, from Figure 2, which was -0.89. From this the velocity value obtained was:

$$u_{mf} = 10^{-0.89} = 0.129\, m\, s^{-1}\ (to\ 3\ s.f.)$$

This value then can be used to calculate the experimental value for voidage of the Fluidised bed, via Equation 2. The values obtained for the density of air is around 1.184 kg m^{-3} (*Knovel - Interactive Table Viewer*, 2022) , the density of the solids being around 3982.6 kg m^{-3} (*Knovel - Interactive Table Viewer*, 2022) and the viscosity of the air around 1.1×10^{-5} kg m^{-1} s^{-1} (Blevins, 1984, pp.324, 325).

The pressure drop divided by the bed height can be calculated via the equation of the second order polynomial equation in Figure 2, as seen below:

$$\log\left(\frac{\Delta P}{l}\right) = -0.9375(-0.89)^2 - 1.2015(-0.89) + 3.9396 = 4.318$$

$$\therefore -\frac{\Delta P}{l} = -10^{4.318} = -32960.97\, Pa\, m^{-1}$$

therefore the voidage can now be calculated, using Equation 2:

$$-32960.97 = \left(1 - \varepsilon_{mf}\right)(3982.6 - 1.184) \times -9.81$$

$$\therefore \varepsilon_{mf} = 0.468$$

The last part for out mass transfer results was the particle diameter, which was done by rearranging the Ergun equation, Equation 3:

$$1701.5d_p^2 + 0.738d_p - 3.03 \times 10^{-5} = 0$$

When solved for d_p, the answer obtained is given as:

$$d_p = 0.000297\, m = 297\, \mu m$$

When comparing the calculated value of our average particle size to the results on the lab manual, one can see that this size of a particle lies between 54 and 60 grade Aluminium Oxide. From here, linear interpolation was applied to calculate the specific grade of the particles:

$$Grade = 60 + (297 - 250)\left(\frac{54 - 60}{320 - 250}\right) = 56.0$$

Therefore, we have a grade 56 Aluminium Oxide powder.

In the next stage, the heat transfer within the fluidised bed was analysed, where the superficial velocity was plotted against the heat transfer coefficient. An example of the calculation of the heat transfer coefficients from the raw data for different flowrates can be seen below:

$$Q = 15V \times 0.215A = 3.225W$$

$$\Delta T = 53°C - 29.5°C = 23.5°C = 296.65K$$

It is already given that the area of the heat source being 1.6×10^{-3} m^2, the final step in the calculation of the heat transfer coefficients is inserting our parameters into Equation 1:

$$h = \frac{3.225}{(1.6 \times 10^{-3}) \times 296.65} = 85.77\, W\, m^{-2}K^{-1}$$

This was applied to the calculation of all of the heat transfer coefficients, which lead to the formation of Figure 3 below:

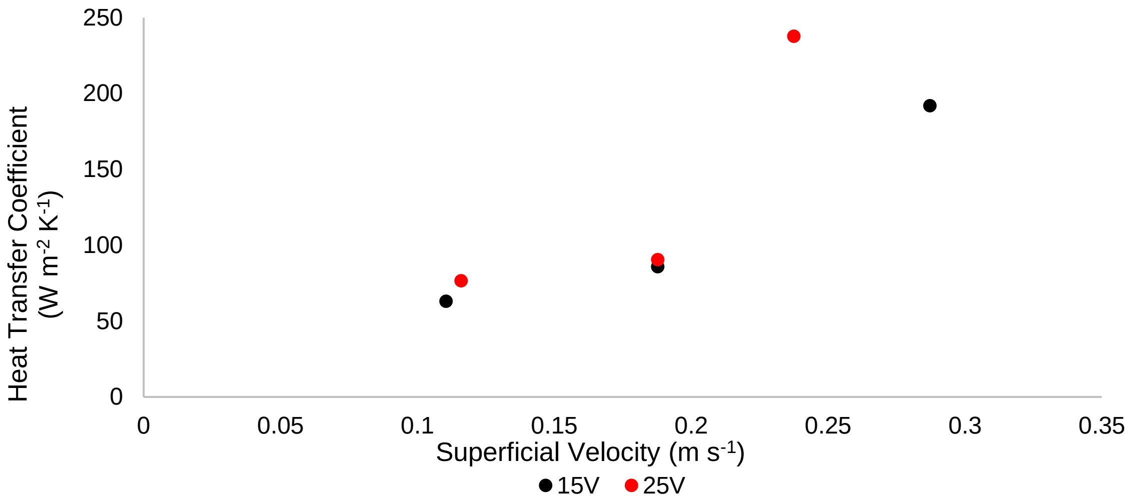


Figure 3: Relationship between Heat Transfer Coefficient and the Superficial Velocity

This leaves us with a final comparison of the for experimental and theoretical data, the results can be seen in Table 1 below:

Table 1: Table comparing the experimental and theoretical values from the fluidisation process

Parameter	Experimental	Theoretical
$u_{mf}\ (m\ s^{-1})$	0.129	54 Grade: 0.505 100 Grade: 0.119
ε_{mf}	0.468	54 Grade: 0.568 100 Grade: 0.608

Discussion

The main aim of this experiment was to calculate the experimental and theoretical values for the Superficial velocity, Voidage at minimum fluidisation and the particle size of the Aluminium Oxide powders. When comparing these values one can clearly see the difference between them, where: When looking at Table 1, one can see the significant difference between the experimental and theoretical values, the differences may have risen from the numerous assumptions of the Ergun equation and Equation 2, as well as the errors within the procedure of the experiment. When looking at Figures 1 and 2, one can also see that the relationship between the velocities and pressures seem to be correct, with the pressure difference increasing and peaking at the point of minimum fluidisation, before decreasing slightly and levelling off and stabilising at a point. This is what is expected of such a graph therefore one can conclude that this part of the experiment was successful. For Figure 3, the relationship between the heat transfer coefficient and the superficial velocity was also as expected, as the heat transfer for the higher voltages were higher due to a higher overall heat transfer. Also, higher superficial velocities were expected to have higher heat transfer coefficient, which is also apparent in Figure 3, therefore one can further conclude that this part of the experiment was also successful. Although these results are successful to some degree, there are still errors that prevented them from becoming ideal results.

The superficial velocity calculated from the experiment shows error due to the approximation of the point of minimum fluidisation, where the highest point on Figure 2 is approximated. This leads to errors in the calculation of the superficial velocity at minimum fluidisation, in which then this error is carried forward with the next 2 calculations of the voidage and the particle size. The use of the polynomial line of best fit wasn't the best procedure either because the line of best fit does not behave in the same manor that an actual graph for this relationship would and does not have the peak the one would usually use to find the velocity, the line of best fit also did not pass through the point of minimum fluidisation which meant that using the equation to calculate $\frac{\Delta P}{l}$ lead to the errors in the continuing calculations, hence the approximation of the point of minimum fluidisation was one of the biggest errors. Another error relating to the velocities can be spotted when comparing the increasing and decreasing flowrates in Figure 1, where

Another error present in the results could be that the pressure drop after the minimum fluidisation point not being constant, after reducing past the point of minimum fluidisation. The theory would state that the data should be linear after this point because the fluidised bed would act as a packed bed before fluidisation occurred, in which a sudden increase in the area of the fluid flow would cause a pressure drop and once stabilised, the area of this fluid flow would remain constant to some degree due to the pressure drop becoming independent from the fluid velocity after this point. This would explain why the pressure drop would need to be stable after the point of minimum fluidisation. However, this simply is not the case with this experiment as some fluctuations can be seen in Figure 2 and 3. The reasoning for this could be that (Richardson, J.F. Harker, J.H. Backhurst, J.R., 2002) there was channelling or likely the effect particle-wall friction instead. Another reason could be (Srivastava and Sundaresan, 2002) due to the presence of lateral nonuniformities in the bed density, where the bed height was higher on one end than the other. The present non-uniformity of the bed height also lead to difficulties in the recording of the bed height data as from different perspectives, the bed height seemed to change by 0.1 or 0.2 cm.

Moving onto Figure 3, the analysis of the heat transfer and superficial velocity for 2 different voltages of 15V and 25V. In Figure 3, the ranges of the heat transfer coefficients vary from 63.0 to 192.0 W m^{-2} K^{-1} and 76.6 to 237.6 W m^{-2} K^{-1}, for 15V and 25V respectively. This shows that the change in heat transfer coefficient with velocity increases with higher voltages and happens at a minimum before the point of m.f. and increases more steadily after this point. Industrial processes undergo fluidisation at significantly higher processes, therefore comparison between this experiment and industrial processes can be difficult to confirm the validity of the results. Also, the fact that there is a notable difference in the heat transfer coefficients after the point and at the point of minimum fluidisation increases the margin of error within these results. The best procedure to eliminate such errors would be to take multiple readings above and below the point of minimum fluidisation and take multiple readings of temperature, voltage and current at each one of these points for an average which could potentially reflect a much more accurate graph, where the point of increase in difference can be further analysed.

Looking at the average particle size of the Aluminium Oxide particles, although there could have been an error carried forward with the initial calculation of the superficial velocity, other errors may include the clumping of the particles, affecting the average particle size by adding more variation to the individual size of the particles hence more deviation from the mean particle size. This occurs when the bed has not been fluidised for long enough amount of time, however, in this experiment, plenty of time was given before proceeding with the experiment.

<u>Conclusion</u>

In this experiment, the values for the Superficial Velocity and voidage were calculated at minimum fluidisation as well as the particle diameter to further determine what grade of Aluminium Oxide powder was present in the process. The value for Superficial Velocity found from the experiment was 0.129 m s^{-1}. This was slightly higher than the 100 Grade Aluminium Oxide, which caused some insecurities about the accuracy of the result as the calculated grade was 56. The value obtained for the voidage was around 0.468, this value seemed to be closer to the voidage for 54 grade powder hence showed some degree of accuracy within the results and one can conclude that there were no significant errors within the calculations or apparatus. The final calculated value was the grade, which was calculated at around 56, this value is quite low and displays the fact that this form of Aluminium Oxide powder was low quality and would not be preferred in industrial use. Overall, the calculated parameters deemed to be accurate and can be compared to further repetitions of this experiment to study the effect of fluidisation with Aluminium Oxide powders.

References

Knovel - Interactive Table Viewer, 2022. [Online]. Available from: https://app.knovel.com/web/view/itable/show.v/rcid:kpPMHPFCPA/cid:kt01212G31/viewerType:itble//root_slug:pocket-manualheat-processing/url_slug:table-10-21-properties/?start=0&columns=1,2,3,4,5 [Accessed 7 March 2022].

Knovel - Interactive Table Viewer, 2022. [Online]. Available from: https://app.knovel.com/web/view/itable/show.v/rcid:kpYCPDCECD/cid:kt00BKAOL1/viewerType:itble//root_slug:yaws-criticalproperty/url_slug:table-20-density-solid/?start=0&columns=1,2,3,4,5 [Accessed 7 March 2022].

Blevins, R.D., 1984. *Applied fluid dynamics handbook*. 1st ed. Malabar, Florida: Krieger Publishing Company

Srivastava, A. and Sundaresan, S., 2002. Role of wall friction in fluidization and standpipe flow. *Powder Technology* [Online], 124(1-2), pp.45–54. Available from: https://doi.org/10.1016/s0032-5910(01)00471-5 [Accessed 9 March 2022].

Richardson, J.F. Harker, J.H. Backhurst, J.R. (2002). Coulson and Richardson's Chemical Engineering Volume 2 - Particle Technology and Separation Processes (5th Edition) - 6.1.4 Minimum Fluidising Velocity in Terms of Terminal Failing Velocity. Elsevier.

Shilton, N.C. and Niranjan, K., 1993. Fluidization and its Applications to Food Processing. *Energy Procedia* [Online], 75, pp.1752–1757. Available from: https://doi.org/10.1016/j.egypro.2015.07.453 [Accessed 9 March 2022].

Nomenclature

A	Heating element Surface Area (m)
d_p	Particle Diameter (μm)

g	Gravitational Acceleration (m s^2)
h	Heat Transfer Coefficient (W m^{-2} K^{-1})
ε_{mf}	Voidage at Minimum Fluidisation
l	Bed Height (cm)
l_{mf}	Bed Height at Minimum Fluidisation (cm)
ΔP	Pressure Drop (cmH_2O)
ρ_s	Particle Density (kg m^{-3})
ρ_{pour}	Pour Density (kg m^{-3})
ρ_f	Fluid Density (kg m^{-3})
Q	Power (W)
T_1	Temperature of Bed (K)
T_2	Temperature of Heating Element (K)
μ	Fluid Viscosity (kg m^{-1} s^{-1})
u_{mf}	Superficial Velocity (m s^{-1})

Appendix

1.1) Table for the Raw Data collected from the Mass Transfer part of the experiment

Rotameter		Flow Rate [L/min]	Pressure Drop, dH [cm H20]	Bed Height [cm]			
Reading	Type			1	2	3	Avg.
0.4	24A	26	0	11	11	11	11
1.1	24A	29	23	11.1	11.1	11	11.1
5.7	14XA	7	6.5	11	11	11	11
13.6	14XA	15	16	11	11	11	11
17.9	14XA	22.5	18.5	11	11	11	11
19.8	14XA	23.5	21	11	11	11	11
25.1	14XA	27	25	11.5	11.4	11.6	11.5
3	24A	43	26	12	12	11.5	11.83333
5.2	24A	54	26.5	13.5	13.5	13	13.33333
5.65	24A	51	27.5	13.5	13.5	13.5	13.5
7.45	24A	62	28.5	14	14.5	14	14.16667
8.1	24A	70	30	14.5	15	14.4	14.63333
7.2	24A	58	29	14.5	14.3	14.6	14.46667
6.5	24A	54	28	14	13	13.5	13.5
5.4	24A	55	26.5	13	13	13.5	13.16667
3.3	24A	45	25.5	12	12	12	12
2.4	24A	39	24	11	11	11.5	11.16667

1.2)Table for the Processed Data collected from the Mass Transfer part of the experiment

u (ms-1)	log u [ms-1]	log PD [Pa]	log PD/bed [Pa m-1]
0.143605	-0.842830938	N/A	N/A
0.160175	-0.795406288	3.353241869	4.30791889
0.038663	-1.412706246	2.804427389	3.763034704
0.082849	-1.081713027	3.195634015	4.15424133
0.124273	-0.905621768	3.258685761	4.217293076

0.129797	-0.886736424	3.313733327	4.272340642
0.149128	-0.826440522	3.389454041	4.328756201
0.2375	-0.624335831	3.406487381	4.333380282
0.298256	-0.525410526	3.414759907	4.28982117
0.281686	-0.55023411	3.430846726	4.300512958
0.342442	-0.465412597	3.446358893	4.295091217
0.386628	-0.412706246	3.468635287	4.303292022
0.320349	-0.494376293	3.453912031	4.293543556
0.298256	-0.525410526	3.438672064	4.308338296
0.303779	-0.517441597	3.414759907	4.295284066
0.248547	-0.604591772	3.398054213	4.318872967
0.215407	-0.666739679	3.371725274	4.323801722

1.3) Table for the Raw Data collected from the Heat Transfer part of the experiment (Part 1)

Voltage [V]	Current [A]	Rotameter		Flow Rate	Pressure Drop
		Reading	Type		
15	0.215	17	14XA	20	19
	0.215	2	24A	34	23.5
	0.215	5	24A	52	27
25	0.365	18.5	14XA	21	19
	0.365	2	24A	34	25
	0.365	4.5	24A	43	30

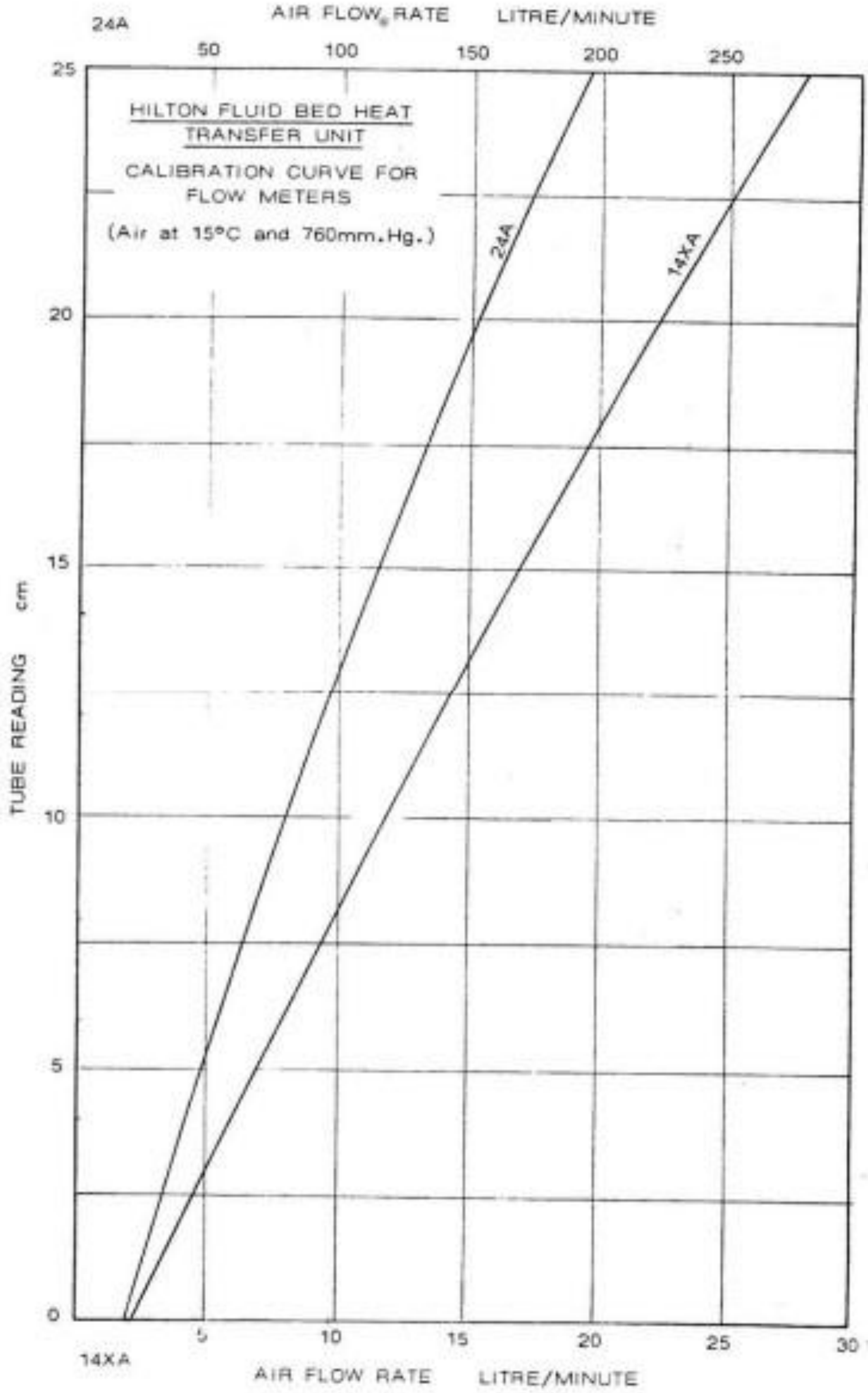
1.4) Table for the Raw Data collected from the Heat Transfer part of the experiment (Part 2)

Bed Beight			Temp [C]		
1	2	3	t1	t2	t3
11	11	11	27	59	23
11.1	11.1	11.1	29.5	53	27
13	13	13	30	40.5	29
11	11	11	32	106.5	27.5
11.1	11	11.1	34	97	26
13.1	13.2	13.3	37	61	25

1.5) Table for the Processed Data collected from the Heat Transfer part of the experiment

u (ms-1)	log u [ms-1]	q [W]	h
0.110465258	-0.95677429	3.225	62.98828
0.187790938	-0.726325369	3.225	85.77128
0.28720967	-0.541800942	3.225	191.9643
0.11598852	-0.935584991	9.125	76.55201
0.187790938	-0.726325369	9.125	90.52579
0.237500304	-0.624335831	9.125	237.6302

1.6) Graph showing relationship between Pressure Drop and Flowrate



24A
AIR FLOW RATE LITRE/MINUTE
50
100
150
200
250
25
20
15
10
5
0
HILTON FLUID BED HEAT TRANSFER UNIT
CALIBRATION CURVE FOR FLOW METERS
(Air at 15°C and 760mm.Hg.)
24A
14XA
TUBE READING cm
5
10
15
20
25
30
14XA
AIR FLOW RATE LITRE/MINUTE