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The Effect Of Pulsed Flow On The Heat Transfer Coefficient Of A Vertical Tube Suspended In A Fast Fluidized Bed

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THE EFFECT OF PULSED FLOW ON THE HEAT TRANSFER COEFFICIENT OF A VERTICAL TUBE SUSPENDED IN A FAST FLUIDIZED BED

by

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This thesis, submitted by Tyler Jon Curran in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Tyler Curran

April 1st, 2016

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

Figure Page

LIST OF TABLES

Table Page

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NOMENCLATURE

1- ε = Solids fraction present in a given volume

A = Dimensional characteristic of an office plate

A_{fb} = Area of the fast bed

A_{htr} = Area of the heater surface

A_{sp} = Area of the stand pipe

C_d = Orifice discharge coefficient

D_{fb} = Diameter of the fast bed

d_{orf} = Orifice diameter

D_{pipe} = Pipe diameter at the orifice plate

dP_{orf} = The pressure drop across the orifice

dP_{pt} = Differential pressure between the pressure taps

d_{pr} = Diameter of the heater probe

g = Acceleration due to gravity

K_e = Thermal conductivity of the emulsion

G_s = Solids Recirculation Rate

h = Average convective heat transfer coefficient

Ht = Length of the heater probe

I = Current supplied to the heater

L_{pt} = Length between the pressure taps

$\dot{m}$ = Mass flow rate of air through the orifice

M_2 = Term specific to the pressure tap location

P_{atm} = Standard absolute atmospheric pressure

P_{fb} = Static pressure in the fast bed

q_{htr} = Power supplied to the heater

Re_D = Reynolds Number in the pipe upstream of the orifice

T_{fb} = The temperature of the fast bed near the heater

T_{htr} = The heater surface temperature

T_{orf} = Air temperature at orifice plate

U_o = Superficial velocity in the fast bed

V = Voltage supplied to the heater

Y1 = Expansion factor

β = Ratio of the orifice diameter to pipe diameter

$\Delta d_{sp}/\Delta t$ = Time rate change of differential pressure across the stand pipe

ε = Voidage, the fraction of volume occupied by the gas phase

ρ_g = Density of air in the fast bed

ρ_{orf} = Density of air in the orifice

ρ_s = Density of the solid particle

ρ_{sus} = Density of solids and gas emulsion

μ_e = viscosity of the emulsion

ABSTRACT

An experimental study was conducted to determine the effects of pulsing the fluidizing air on the heat transfer of a small vertical cylindrical heater suspended along the axis of a 101.9 mm diameter fast bed. Spherical aluminum metal power with a density of 2700 kg/m^3 and dp_{50} of 107 μm was used in this investigation. Experiments were first conducted without pulsing the air supply. Solids fractions were observed as high as .0154 with superficial velocities from 1.98 m/s to 4.04 m/s and recirculation rates up to 27.6 kg/m^2 s. The maximum heat transfer observed was 74.1 W/m^2 K at a solids fraction of .0152 and solids recirculation rate of 25.3 kg/m^2 s and at a superficial velocity of 2.80 m/s. Heat transfer was found to increase with increasing solids fractions and solids recirculation rates and decreasing velocity. A diaphragm valve was used to pulse the air supplied at regular periodic frequencies up to 12 Hz. Pulsed operation increased the observed heat transfer for frequencies between 1 and 2 Hz. A maximum increase of 32.7% in heat transfer was observed at 1.5 Hz. High pressure drops across the distributor plate were found to negate the effect of pulsation on heat transfer. A correlation was prosed to estimate heat transfer for non-pulsed tests based on suspension density. A correction factor was developed to predict pulsed flow results for cases with low pressure drop across the distributor plate.

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Introduction

Fluidized beds are systems where a fluid is used to suspend or transport solids particles. The working fluid may be either a liquid or a gas. Fluidization of solid particles refers to the fluid like nature of the solids when suspended in flowing gas. When a static column of particles is supplied with sufficient flow of evenly distributed gas from the bottom, the solids will become suspended in the gas and the emulsion that results behaves much like a fluid. The behavior of a fluidized system depends on the properties of the solid particles, such as density, size, shape, and their resistance to fracture and breaking apart. Density and size are important because in addition to gravity, the particles displace the fluid and are subject to Archimedes principle of buoyancy as well as the effects of hydrodynamic drag. The shape of the solid also plays an important role in the hydrodynamic drag imposed by the gas passing over the particle, as well as how the particles react with each other in motion. The shape of a solid particle is referred to as sphericity; how close the solid particle is to a true sphere in shape. Particles that break up, and become smaller as they are fluidized are called friable, and this is generally not desirable in a fluidized system. Solid particles have been classified by their behavior in fluidized system into four categories, as proposed by Geldart (1973). These particle groups help predict the behavior of the solids in various states of fluidization. Figure 1 shows the various regimes of fluidization that solids undergo as the amount of fluidizing gas is increased. A static column of particle is referred to as a fixed bed, and gas can slowly percolate through the void space between the solids but the solids remain stationary. As the velocity of gas is increased the drag forces on the solid particles also increases. With sufficient velocity this drag force becomes strong enough to overcome the weight of the solids and the solids become suspended in the gas. The velocity supplied at the point this transition occurs is called the minimum fluidization velocity and is a unique parameter to the type of solid particle being used.

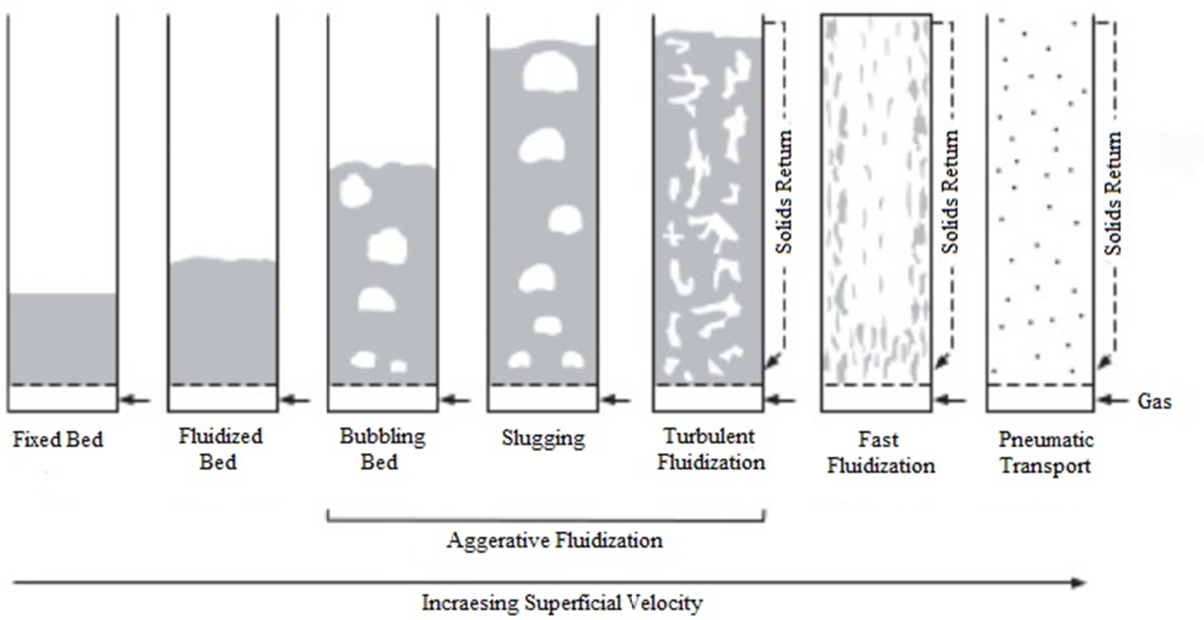

Figure 1. Various Flow Regimes of A Fluidized Bed Grace, (1986).

As velocity is increased further the gas will begin to form visible bubbles inside the emulsion, and the fluid bed is now in the bubbling bed regime. Increasing the velocity further will result in larger and larger bubbles and more vigorous motion of the emulsion.

The bubbles will begin to coalesce to grow in size as they travel up through the fluidized column. When the bubbles become large enough to cover the diameter of the column, the bed transitions into the slugging regime where alternating pockets of gas lift slugs of the emulsion up the column. Increasing the velocity past this point produces turbulence in the emulsion and the bed now enters the turbulent regime.

Solid particles can be carried by gas out of the bed entirely by the process of attrition. This process is dependent on another unique property of the solid particle; its terminal velocity. The terminal velocity is maximum speed a particle will reach in a free fall in the fluidizing gas. If the gas velocity increased beyond the terminal velocity particles will be carried out of the column by the fluidizing gas. Circulating fluid bed systems separate the particles from the gas and return them though a stand pipe or down comer to bottom of the fast bed.

As the velocity of fluidizing gas is further increased beyond the turbulent bubbling regime the bed enters the fast fluidization regime. An important characteristic of fast fluidized beds is the distribution of the solid particles in the column from bottom to top. The fraction of space occupied by solids, referred to as the solids fraction, is much higher near the bottom of the column where the recirculated solids enter the fast bed. The solids fraction decreases significantly as the height above the bottom of the bed increases. This distribution of solids along the height of the bed is dependent on the properties of the solid particles, the amount of solid particles present and the velocity of the fluidizing gas. As velocity increases further the solids fraction continues to decrease and the distribution becomes nearly uniform from bottom to top. At this point the bed is operating in the pneumatic transport regime.

Another important characteristic of fast fluidized beds is that the flow of solids is not uniform; in fact it is far from it. Solids in a fast fluidized rise with the fluidizing gas, and also fall against it. Solids often flow back down the fast bed column near the boundary layer of the outer wall. Falling groups of solids are often referred to as “strands”. Much like the distribution along the height of a fast bed, solids are also not uniformly distributed across the width of the bed. Figure 2 shows the distribution and motion of solids across as fast bed as described by Wirth (1994).

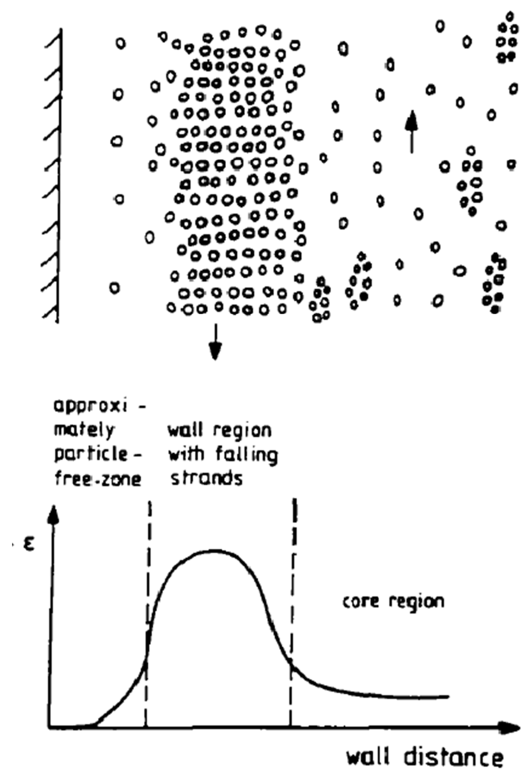

Figure 2. Profile of Solids Across the Diameter of a Fast Bed, Wirth (1994).

The fraction of solids is highest just inside of the boundary layer of the wall where they are moving down the column, and lower near the center where they are rising. As groups of solids come in contact with a surface they can transfer heat, either by direct contact or by conduction through gas boundary layer. These groups of solids are often referred to as "packets" or "clusters" and are important to understand in order to predict the heat transfer that will occur between a surface and the emulsion in the fast bed. The heat transfer within a fast bed occurs through a combination of gas convection and solids convection. The amount of heat transferred to or from the solids clusters depends on size of the cluster, the fraction of solids in the cluster and the time it is in contact with the heat transfer surface. Contact time is quite difficult to predict and therefore the study of heat transfer within a fast bed is largely an empirical science. Empirical correlations developed by experimentation are very specific to the geometry and hydrodynamics of the system they are developed from and are often limited in the operational range they cover.

Heat transfer is an important area of study in fluidized systems to improve efficiencies and reduce capital costs. The heat transfer in a fast fluidized system is highly dependent on the orientation and shape of the heat transfer surfaces as well the operating parameters of the bed, and the properties of the gas and solid particles. New research is constantly being performed to study these parameters and their effect on heat transfer. Of particular interest to this study is the effect of inducing constant frequency flow oscillations in the fast bed on the heat transfer coefficient of a suspended vertical tube.

Literature Review

A significant amount of literature has been published on the topic of heat transfer in fast fluidized beds; the following is a review of the most relevant studies found in literature. Additional research is summarized in Table 1.

Wirth (1994) studied heat transfer at ambient temperatures and pressures from atmospheric to 50 bar in a small circulating fluidized bed. Heat transfer was measured at four locations along the height of the fast bed and at one location in the downcomer. The heat transfer surfaces were hollow cylinders of varying lengths. Solid particles used were; bronze, glass, quartz, and polystyrene with diameters from 65 micron to 827 micron and Archimedes numbers from 837 to 21980. A series of experiments were carried out measuring the heat transfer observed with different materials. Results showed that the length of the heat transfer probe affected the measurement of heat transfer, and that a probe of at least 0.5 m was need to minimize the effect of the developing thermal boundary layer on the heat transfer measurements. It was also determined that the thermal properties of the particles themselves had no influence on heat transfer at ambient temperatures. For particles with small Archimedes numbers the heat transfer was mainly caused by heat conduction in the gas due to Stokes type of flow around the particle. For particles of higher Archimedes number the heat transfer was mainly due to the gas convective component. A correlation of the Nusselt number to the solids fraction present near the heat transfer surface and the Reynolds number of the strands falling near the wall was developed to predict heat transfer across a broad range of Archimedes numbers.

Kolar and Sundaresan (2000) studied the heat transfer of a vertically oriented cylindrical heater in the fast bed riser of a circulating fluid bed at ambient pressure and temperatures circulating uniformly sized silica sand. The tube was instrumented with thermocouples to measure the surface temperature heated with hot water. The tube could be moved axially up and down the fast bed as velocities and solids recirculation rates were varied. They tested four vertical locations from 20% to 70% of the fast bed height. They found that heat transfer varied inversely with height above the distributor plate and that increasing velocity decreased observed heat transfer, and increasing the recirculation rate increased heat transfer at all heights tested. They also observed that heat transfer varied with changes in height above the bed even in cases when suspension density and velocity were equal indicating that changes in the hydrodynamics of the gas solids emulsion as height in the fast bed played a role in the heat transfer observed. They also found that gas convection accounted for 30% to 80% of the overall heat transfer coefficient. They were able to derive a correlation between the Nusselt number and Reynold's number of the particle and the height in the fast bed to predict the average heat transfer coefficient within ± 5%.

Sundaresan and Kolar (2013) studied the heat transfer of a vertically oriented cylindrical heater in a circulating fluid bed at ambient pressure and temperatures. Uniformly sized silica sand was used as the bed material. They tested heated tubes of 4 different lengths from 0.6 m to 2.5 m. The tubes were heated with hot water and moved axially up and down the fast bed, they tested four vertical locations from 10% to 45% of the fast bed height. They found the position of heater had a strong effect and that heat transfer varied inversely with height above the distributor plate. Increasing velocity decreased observed heat transfer, and increasing the recirculation rate increased heat transfer at each height tested. They calculated the average heat transfer coefficient, and found it was reduced as the heater length increased. They developed a dimensional correlation between the local suspension density, particle diameter, height, and length of the heater to the heat transfer coefficient that fit their experimental data. Using other experimental data from literature with similar experimental conditions they derived a non-dimensional relationship between the Nusselt number and Reynolds number of the emulsion including a factor accounting for the heater length and height in the fast bed. The relationship they developed was shown to predict the heat transfer coefficient within a range of ± 30% from experimental results.

Table 1. Summary of Literature Reviewed for Heat Transfer In a Fast Fluidized Bed

Ref.	Date	dfb (m)	Hb (m)	Bed Material dp (mm)	Uo (m/s)	T (K)	Pr (bar)	Gs (kg/m^{2}s)	1-E (--)	HT device	Orientation	dt (mm)	Ht (m)	Hd (m)	r/R	h (w/m^2*k)
Mickley et al	1949	0.07	1.3	40 - 450	0 - 2.5	320 - 510	1		.02 - .2	Heated Tube	Vertical	12	0.88	0.2	0.017	50-400
Kaing et al.	1975	0.1	3.66	53	0.5-4.9		1		.013-.029	Heated Tube	Vertical	19	0.06	0.56-3.15	0	45 - 230
Fraley et al.	1983	.08	1.28	37	2.8	294- 304	1		.0045-.18	Heated Cylinder		95	.15		.67-.8	240-770
Wu et al	1989	.152 x .152	7.32	227,299	6.5-9.3	61 -1150	1		0-.0265	Cooled Tube	Vertical	12.7	1.22	4.27, 4.57	1, 0 - 0.92	50 - 190
Basu	1990	0.101	5.5	87, 130, 227		303- 313	1		.03-.30	Heat Flux Probe	Vertical	25		2.1	1	50 - 350
Bi et al.	1991	0.186	8	48	2.5-6.0	298- 313	1	20 - 150	.01-.15	Heated Tube	Vertical	10	.04-.34	3	0-1	60 - 420
Zheng et al.	1991	0.112	2.5	140	2.6-5.8	cold	1	5 - 20		Heated Tube	Vertical	10	3.7	2.8	1	65 - 100
Liu et al	1991	.2 x .3	6		5 - 7		1	8.1		Heated Tube	Horizontal	25	0.2	1.48		146 -170
Couturier et al	1993	3.96 x 3.96	23		6.4		1			Heated Tube	Horizontal	25.4	0.305			200 - 350

Table 1. Cont.

Ref.	Date	dfb (m)	Hb (m)	Bed Material dp (μm)	Uo (m/s)	T (K)	Pr (bar)	Gs (kg/m^{2}s)	1-E (--)	HT device	Orientation	dt (mm)	Ht (m)	Hd (m)	r/R	h (w/m^2*k)
Cheng et al	1993	.2 x .2	4		4 - 6		1	11.15		Heated Tube	Horizontal	24.5	0.2	2.4		109 - 140
K. E. Wirth	1994	.19	10	58.5, to 827					.001 - .10	Heated Tube	Vertical	200	.5	2.58 – 10.17		20-200
Ahn and Han	1995	0.05	2.5	147, 280, 540	2.5 -6.0	cold	1	20 - 100		Heated Tube	Vertical	4.75	0.9	1.8		40-80
Mincic et al	1997	0.12	5	150	2.5-4.4	cold	1			Heated Tube	Vertical			.8-3.6	0	62 - 321
Reddy and Nag	1997	.102 x .102	5.25		4.2 - 7.3		1	5 - 30		Heat Tube	Horizontal	22.5	0.102	4.3		200 - 235
Ma and Zhu	2000	0.1	15.1	67	3.5 - 10	cold	1	50-200		Tube	Vertical	6.4	0.038	0.72 - 12.3		100-250
Kolar and Sundaresan	2002	0.1 x .1	5.5	363	4.5 - 7.3	343- 353	1	21 - 72		Heated Tube	Vertical	69	0.6	.97 - 4.0		58 -101
Zhang et al	2013	0.05	2.5	74 - 79	10 - 20	293		25-200		Heated Wall			0.1	1.2	1	60-180
Brems et al	2013	0.05	2.5	75	9.8 - 19.7	293		30-450		Heated Wall			0.1	1.2	1	60 - 350
Sundaresan and Kolar	2013	.1 x .1	5.5	363, 256	4.5 - 7.3	343 - 353	1	21 - 72		Heated Tube	Vertical	0.096	.5 - 2.5	1 - 5.3	0	70 - 100

The purpose of the present study was to determine the effect of pulsing the gas supplied to a fast bed on the heat transfer coefficient of internal surfaces. To the best of this author's knowledge, no works have been published exploring the effect of a periodic frequency on heat transfer in a fast fluidized bed. There have, however, been studies published exploring this effect in bubbling beds and fixed beds. The following is a brief review of some relevant literature published in this area. Additional research is presented in Table 2.

Pence and Beasley (2002) used a small bubbling bed with a square cross-section and two horizontal tubes with heaters and thermocouples to measure heat transfer in a bed of glass beads. The bed was fluidized through a distributor plate continuously and a reciprocating piston in a cylinder was used to generate periodic pressure waves. The piston/cylinder assembly was located above the disengager section outside of the bed; a pipe connected to the cylinder ran vertically though the center of the bed to a point just above the distributor plate. The piston was driven from a flywheel that was adjustable for stoke length and speed to generate various pulse frequencies and amplitudes. A steady secondary air flow was also supplied to the pulsing cylinder. Results showed that adding steady secondary flow and pulsed secondary flow increased heat transfer. Pulsed secondary flow at a frequency of 5 Hz increased heat transfer by 12% and pulsed flows at 5 HZ with additional steady secondary flow increased heat transfer by 60%. Higher frequencies did not produce a noticeable increase in heat transfer.

Zhang and Koksal (2006) used an electric solenoid valve driven with a periodic signal from a function generator to pulse a small diameter bubbling bed from 1 Hz to 10 Hz.

They used glass beads classified as Geldart group A solids, and silica sand classified as group B solids for their experiments with bed heights of 16 cm and 14.7 cm respectively. A cylindrical heater was suspended in the bed horizontally and the surface temperature recorded using embedded thermocouples. Experiments were conducted for each particle type and varied U_o at pulsing frequencies from 0 to 10 hz to observe the effects on heat transfer in the bubbling bed. Results at frequencies of 7 Hz and 10 Hz showed significant increases of 17% to 33 % in heat transfer for the group B particles compared to continuous flow. For group A particles an increase in heat transfer was observed during pulsation for U_o/U_{mf} of less than 1.5. However, at U_o beyond this point the increase in heat transfer due to pulsed flow became negligible. In the fixed bed regime frequencies of 1 Hz produced heat transfer 2 to 3 times higher than in continuous flow tests.

Table 2. Summary of Literature On Heat Transfer In Pulsed-Fluidized Bubbling and Fixed Beds.

Ref.	Date	dia (m)	dt (m)	Material/dp (mm)	Pulsation Method	f (Hz)	Uo/Umf
Bokum and Zabrodskii	1968	0.056	0.005	Sand 180 - 815	Solenoid Valve	.5 - 2.0	
Kobayashi et al	1970	0.102	0.032	Glass Beads 73 - 580	Solenoid Valve	.67 - 2.0	.3 - 9
Nishimura et al	2002	0.095	0.043	Glass Beads 90, 340	Electric Control Valve	.2 - 1.0	.5 - 4.5
Pence and Beasly	2002	.305 x .305	0.038	Glass Beads 345	Reciprocating Piston	5 - 30	1.1 - 2.7
Zhang and Koksal	2006	0.17	0.0127	Glass Beads 37, 60, 162 Sand 160, 240, 700	Solenoid Valve	1 - 10	.4 - 60

CHAPTER II

EXPERIMENTAL SETUP

Introduction

The heat transfer study was performed by immersing an electrically heated vertical tube in fast bed section of a circulating fluidized bed as shown in Figure 3. There are six primary components of this system: Fast Bed, Stand Pipe, Heater Probe, Pulsing Valve, Bed Material, and the Instrumentation and Data Acquisition system. Solid particles are fluidized with compressed air in the stand pipe and flow through a cross-over pipe into the bottom of the fast bed. More air is supplied by a blower to the bottom of the fast bed and the particles are entrained and carried upwards. The pulsing valve is used to impart periodic frequencies into the fast bed air supply. The heater probe is suspended inside the fast bed to measure the heat transfer in that environment. After the particles reach the top of the fast bed they flow through two cyclones that separate the particles from the gas and recirculate them back to the stand pipe. The air is vented back to the atmosphere.

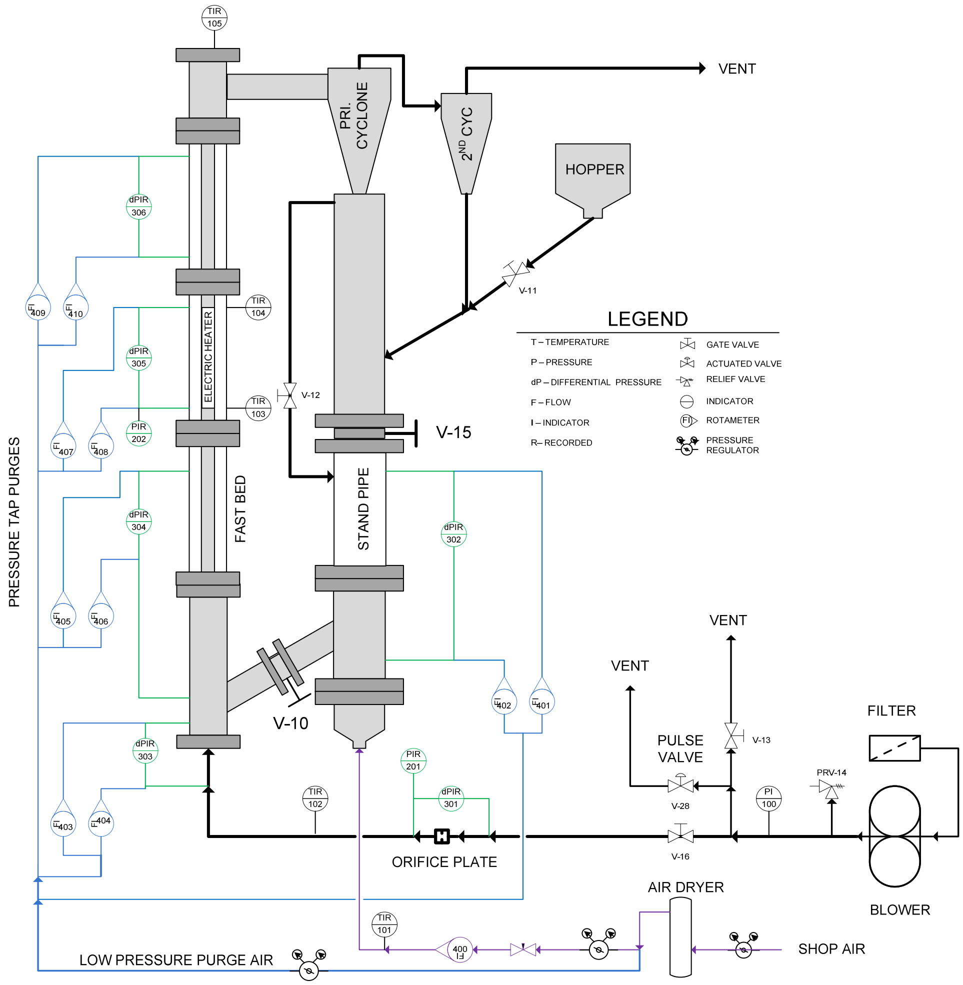

Figure 3. Circulating Fluidized Bed.

Fast Bed

The fast bed is a circular column 2.8 m high and 102 mm in diameter comprised of steel and clear acrylic sections connected together with bolted flanges. These sections were specially manufactured to provide a smooth continuous surface inside the fast bed. The distributor plate is supported within the bottom flange of fast the bed. It is comprised of two perforated plates with a piece of multi-layer mesh screen between them.

The perforations are a series of 18 machined holes 8 mm in diameter arranged in two concentric rings equally spaced apart. The inner ring is comprised of 6 holes, the outer ring contains 12. The center of the top plate has a 19 mm recess to locate the support rod for the electric heater. The solids cross-over pipe is 52 mm in diameter and enters the fast bed 25 mm above the distributor plate.

Air is supplied to the fast bed by a fixed displacement roots blower. The blower runs at constant speed and air flow is controlled using a bypass valve and supply valve. A pressure relief is installed between the blower and the bypass valve to prevent damage form high pressure. The blower is rated for a maximum of 1 bar gauge pressure and a maximum flow of .028 m^3/s. After the valve assembly, air flows through a 1980 mm long pipe section 102 mm in diameter to an orifice plate mounted between two flanged sections. A new orifice plate was fabricated for this study with a diameter of 25.40 mm, a sharp leading edge and a chamfered trailing edge. The pressure taps are installed in the pipe on each side of the orifice plate, the upstream tap is located 102 mm before the plate, and the downstream tap is 51 mm after the plate.

The fast bed column contains a number of ports for thermocouples, pressure taps, and support rods to hold the electric heater. Pressure tap ports are provided on both sides of the distributor plate while the lower fast bed has two ports spaced 890 mm apart with the lower port located 102 mm above the distributor plate. The middle bed has two pressure taps spaced 410 mm apart with the lower tap located 1.5 mm above the distributor plate, the upper bed has taps spaced 410 mm apart with the upper tap located 180 mm from the top of the bed. One thermocouple port is located downstream of the orifice plate, two ports in the middle section of the fast bed just above and below the electric heater, and one at the top of the fast bed.

Stand Pipe

The stand pipe, circular column 152 mm in diameter and 1.1 m tall, is comprised of steel and clear acrylic sections connected together with bolted flanges. The distributor plate is installed in the lower flange of the stand pipe and is of similar construction to the fast bed. Compressed air is supplied to fluidize particles in the stand pipe and is controlled with a manual flow meter. A butterfly valve is installed above the acrylic column with a 610 mm long disengager section between the valve and the cyclones. A 38 mm diameter bypass pipe connects the stand pipe to the top of disengager section to allow fluidizing gas to leave the system when the butterfly valve is closed. Solid particles are separated from the fluidizing air in two cyclones located adjacent to the top of the fast bed; the solid particles flow down from the bottom of the cyclones through the dis-engager and collect in the stand pipe. A 52 mm diameter crossover pipe located 250 mm above the distributor plate in the stand pipe carries solids over to the fast bed. A gate valve is used to control the flow of solids. Two pressure taps spaced 895 mm apart are used to measure the differential pressure in the standpipe above the distributor plate.

Electric Heater

A vertical cylindrical electric heater was used to measure heat transfer in the fast bed. A cartridge heater was press fit into a 19 mm diameter brass sleeve with a length of 292 mm.

The heater was supported from the top and bottom by thin walled brass tubing of the same diameter. The support tubes were captured between the distributor plate and the top flange of the fast bed. The tubing also served as conduit for electrical and thermocouple wires connected to the heater. Machined 50 mm long nylon bushings were used as insulators to minimize heat conduction between the heater and support tubes. The heater was installed along the axis of the fast bed with the center of the heater located 1.7 m above the distributor plate. The heater and support tubes are held in position by a series of support rods along the length of the fast bed. Figure 4 shows the locations of 4 thermocouples used to measure the surface temperature of the heat transfer tube. The outside of the brass sleeve has 4 channels milled into surface. Type K thermocouples were imbedded into the channels with ceramic cement and surface was sanded and polished smooth.

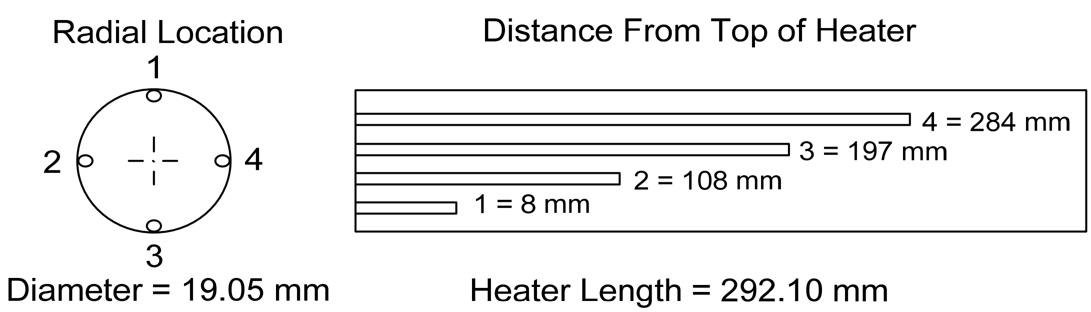

Figure 4. Electric Heater Assembly.

The heater was powered with a high accuracy Allegiant DC 6754A power supply. The heater was not designed for high temperature use; maximum operating temperature cannot exceed 100°C. The resistance of the heater at operating temperatures was found to be 7.4 Ohms. A ground wire was soldered to the inside of the brass sleeve and connected to the steel frame of the circulating fluid bed to prevent static discharges from damaging the data acquisition system.

Pulsing Valve

An electrically actuated diaphragm valve was installed between the blower and the fast bed to pulse the air supply with varying frequencies. An ASCO model 8353G002 fast acting pilot operated diaphragm valve with 52 mm threaded inlet and outlet connections was selected and purchased for this study. The valve uses a light weight diaphragm held against a sealing surface with a spring located inside a small pressure chamber. The pressure remains equal on both sides of the diaphragm and since the pressure chamber area of the diagram is larger than upstream port area a net force results sealing the diaphragm against the upstream port and preventing flow through the valve. An electronic solenoid valve located on the pressure chamber rapidly vents the pressure chamber and upstream pressure lifts the diaphragm and allows flow through valve. When the solenoid valve closes the chamber pressure begins to equalize and the spring helps to seat the diaphragm and stop flow through the valve.

A power supply was connected to a solid state relay with the output of the relay connected to the valve solenoid. An Exact Electronics model 628 pulse function generator was used to trigger the relay using a direct current square wave. The frequency and the pulse width of the square wave signal could be controlled to produce flow pulses of varying duration and frequency in the fast bed. The pulsing valve was installed as shown in Figure 5. When the pulsing valve was actuated a significant portion of the air flow was diverted through the valve and vented to atmosphere while a small amount of flow still continues to the fast bed. When the pulsing valve closes, air flow was returned to previous levels.

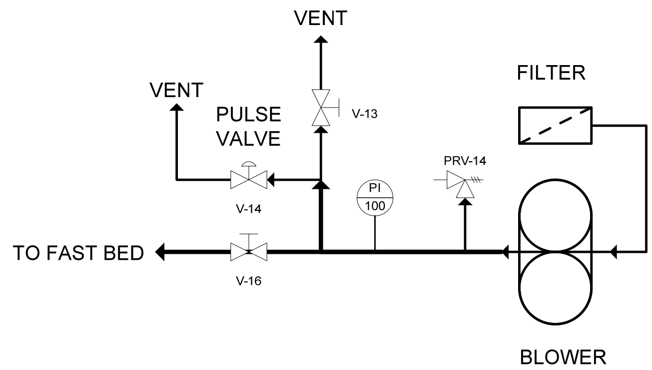

Figure 5. Pulsing Valve As Installed In 1st Configuration

To increase the amplitude of the pulse, the valve assembly was reconfigured as shown in Figure 6. In the second configuration the pulsing valve was operated in a normally open mode. The supply valve, V-16, was closed diverting all flow to the fast bed flowed through the pulsing valve. The solid state relay was triggered with a constant voltage to keep the pulsing valve open, and polarity of the pulse function generator was reversed so the square wave signal would close the pulsing valve. The operation of the pulsing valve was similar to configuration 1, however, since all flow to the fast bed passed through the pulsing valve the flow was momentarily stopped when the valve closed. Pressure is built up rapidly when the pulsing is closed, this limits the pulse duration to avoid over pressuring the blower and venting the relief valve. This configuration did provide more abrupt flow pulses to the fast bed; however pulse duration was limited due to the pressure limits of the blower.

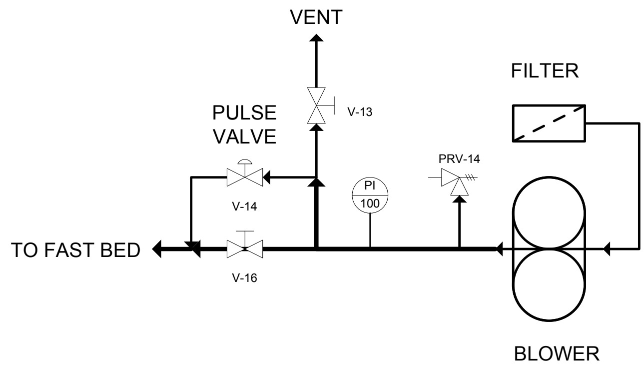

Figure 6. Pulsing Valve As Installed In 2nd Configuration.

Bed Material

The selection of a new fluid bed material was of particular importance to this study. Previous work on this fluidized bed system utilized steel shot with a dp_{50} of 345µm. This material proved too heavy and the particle size too large for the blower to adequately transport through the fast bed section, resulting in very small solids fractions in the heat transfer area.. The use of sand was also problematic as the acrylic columns used in the standpipe and the fast bed produced a significant static charge that can damage instrumentation. Aluminum metal powder was chosen because of its uniform size, good sphericity, electrical conductivity, and low friability in a fluidized system. Valmet H-95, a spherical, atomized, aluminum powder was procured for this study. The aluminum metal has a particle density of 2700 kg/m^3 and bulk density of the powder was determined to be 1500 kg/m^3. A sieve test showed the powder has a dp_{50} of 107µm and an average size of 104µm. Approximately 2% of the powder was fines with a size of less than 63µm. The results of sieve test are presented in Appendix B. Minimum fluidization velocity was found to be approximately .058 m/s. The experiments to determine the minimum fluidizing velocity are described in Appendix C.

Instrumentation and Data Acquisition

The existing instrumentation on the circulating fluid bed was removed and replaced with new components for this study. Pressure transducers used to measure static and differential pressures were selected with the appropriate range. Differential pressure transducers used for the orifice plate and fast bed had either digital or analog displays to aid in system operation. Very high accuracy was required for the differential pressure measurement at the middle of the fast bed, a Yokogawa EJA110E transducer with a display was used because of its small range and very high accuracy. The Yokogawa unit uses proprietary communications software, this instrument had to be configured and the calibration verified by the instrument shop at Energy and Environmental Research Center. The specifications of the instruments used, their locations, and signal connections can be seen in Table 3.

Table 3. Instrumentation List.

Type	Number	Range	Accuracy	Manufacturer	Part Number	Signal	Module	Channel	Type	Location and Use
PIR	201	0 - 10 PSIG*	0.25% of span*	Dwyer*	673-4*	4-20mA	2	1	AI	Orifice Plate static pressure
PIR	202	0 - 5 PSIG	0.25% of span	Dwyer	673-3	4-20mA	2	7	AI	Fast bed static pressure
dPIR	301	0 - 20 inWC	0.5% of span	Dwyer	605-20	4-20mA	2	3	AI	Orifice plate differential pressure
dPIR	302	0 - 200 inWC	0.25% of span	Dwyer	616-7	4-20mA	2	2	AI	Stand pipe differential pressure
dPIR	303	0 - 200 inWC	0.25% of span	Dwyer	616-7	4-20mA	2	4	AI	Distributor plate differential Pressure
dPIR	304	0 - 20 inWC	0.5% of span	Dwyer	605-20	4-20mA	2	0	AI	Lower fast bed differential pressure
dPIR	305	0 - 10 inWC	0.055% of span	Yokogawa	EJA110E	4-20mA	2	5	AI	Middle fast bed differential pressure
dPIR	306	0 - 10 inWC	0.5% of span	Dwyer	605-10	4-20mA	2	6	AI	Upper fast bed differential pressure
TIR	101	-200 to 1250 °C	0.75% of reading	Omega	KQSS-166U-12	TC	1	0	TC	Stand pipe air temperature
TIR	102	-200 to 1250 °C	0.75% of reading	Omega	KQSS-166U-12	TC	1	1	TC	Orifice plate air temperature
TIR	103	-200 to 1250 °C	0.75% of reading	Omega	KQSS-166U-12	TC	1	2	TC	Middle fast bed temperature
TIR	104	-200 to 1250 °C	0.75% of reading	Omega	KQSS-166U-12	TC	1	3	TC	Middle fast bed temperature
TIR	105	-200 to 1250 °C	0.75% of reading	Omega	KQSS-166U-12	TC	1	4	TC	Top of fast bed temperature
TIR	Probe 1	-200 to 1250 °C	0.75% of reading	Omega	SA1-K-72-SC	TC	3	0	TC	Heater Probe Temperature
TIR	Probe 2	-200 to 1250 °C	0.75% of reading	Omega	SA1-K-72-SC	TC	3	1	TC	Heater Probe Temperature
TIR	Probe 3	-200 to 1250 °C	0.75% of reading	Omega	SA1-K-72-SC	TC	3	2	TC	Heater Probe Temperature
TIR	Probe 4	-200 to 1250 °C	0.75% of reading	Omega	SA1-K-72-SC	TC	3	3	TC	Heater Probe Temperature
FI	400	0 to 36 SCFH	5% of span	Omega	N/A	N/A	N/A	N/A	N/A	Stand pipe air flow
FI	401 - 412	.2 -2.0 SCFH	5% of span	Dwyer	RMA-3-SSV	N/A	N/A	N/A	N/A	Pressure tap purge flow

* PIR 201 failed during testing and was replaced with a Rosemount 2088G S 22 transducer. Range = 0 – 30 PSIG, Accuracy = 0.2% of span

To prevent solids from plugging the pressure taps a continuous purge was used to keep the lines clear. The purge flow rates were very low and did not affect the pressure measurements, care was taken to balance purges on each side of the differential pressure transducers. To ensure accurate results, the zero and span for each transducer was verified regularly throughout testing.

A National Instruments Field Point FP-1000 modular data acquisition system was configured with three data acquisition modules to record signals from the instrumentation. An eight channel analog input module and two 8 channel thermocouple modules were used. The National Instruments Field Point System communicated with a desktop computer using an RS-232 protocol. The data was logged to the computer with a 5 second sampling rate and could be exported to spread sheet for post processing and data reduction.

National Instruments LabVIEW version 10 was used to develop the software program to communicate with the data acquisition system. A Virtual Instrument or VI program was developed to view the instruments in real time during operation. A calculation was also performed in real time to provide an estimate of the velocity in the fast bed. This information was used for guidance while operating the fluid bed system. Actual results were calculated during post processing. A screen capture of the VI program during testing can be seen in Figure 7.

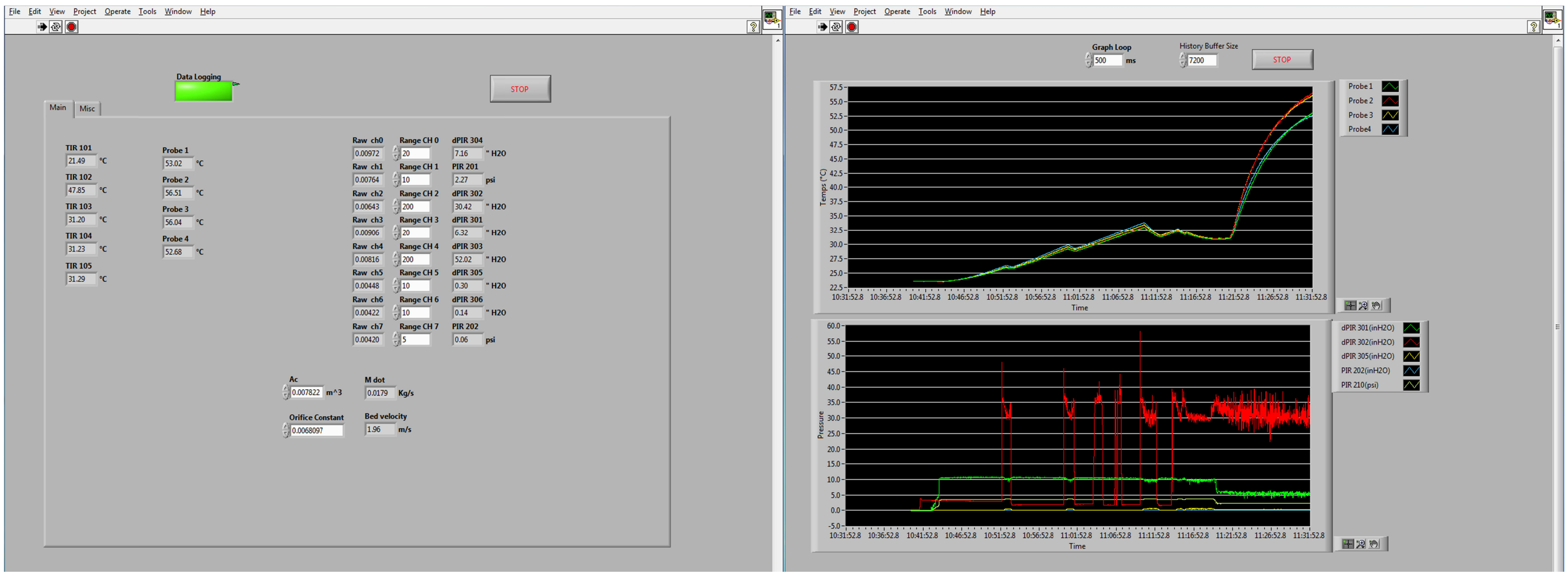

Figure 7. A Screen Capture of the National Instruments Program for the Fluid Bed System

CHAPTER III

EXPERIMENTAL PROCEDURES

Equipment Preparation and Startup

A visual inspection of the system was made prior to start-up. Each pressure tap and purge line was checked for plugs. The data acquisition system was turned on and the signal connections were verified. Communication with the software on the computer was verified. Each pressure transducer was checked for proper zero readings and the thermocouples were checked for agreement with each other. The range setting in the software was checked for each instrument. The thermocouples in the fast bed were inspected to ensure they were in the proper location. Data logging was started with a new file name and the data sampling frequency was set to five seconds. The solids level was checked in the stand pipe and new material added if needed. The hopper valve, V-11, and solids flow valve, V-10, were closed. The shop air supply was turned on and the first regulator set to provide 50 PSIG to the air dryer vessel. The air dryer was initially used, but it was determined its thermal cycling upset the fast bed temperatures. It was only used as an air reservoir in subsequent testing. The small purge regulator was turned on and purge flows were started to the pressure taps. The rotameters for each pressure tap were adjusted to 1.0 SCFH and the zero reading of each transducer was re-checked. The supply valve, V-16, was closed and the bypass valve, V-13, was opened fully and then the blower was started.

The supply valve was opened and then the bypass closed down until the desired velocity was achieved in the fast bed. The air supply regulator to the stand pipe was slowly adjusted until flow was visible on rotameter FI-400. Flow was increased slowly until the solids in the stand pipe were fluidized; flow was increased further to 100 standard liters per minute. The solids flow valve was opened slowly to send solids to the fast bed. The flow rate was-adjusted as the solids inventory increased in the fast bed to maintain the desired test conditions. If a heat transfer test was being conducted, the heater power supply was turned on and the proper voltage and current setting were verified.

Experimental Testing

It was necessary to run the circulating fluid bed system for several hours after start up to allow the system to warm up and temperatures to stabilize. Since the heat transfer measurement is dependent on the temperature difference between the heater surface and the fast bed temperatures, the system had to be as close to true thermal equilibrium as possible to provide useable results. A copy of the testing schedule was provided to the building facilities staff to ensure the ventilation system for the laboratory would operate at constant conditions. The air conditioning system was used during the summer months to control humidly and maintain consistent temperatures in the laboratory.

The experiments were divided into multiple tests each with different operating conditions. Ideally the order of these tests would be randomized to prevent confounding results, however, due to the slow thermal response time of the system, tests were conducted by varying velocity values from lowest to highest, or highest to lowest. Increasing velocity

27

increased the pressure behind the distributor plate and the blower generated more heat. Other parameters such as solids recirculation rate, solids fraction at the midpoint of the fast bed, and pulsing valve settings were performed in random order when possible. Single tests were maintained for a minimum of 20 minutes at constant settings before changing conditions or measuring the recirculation rate. Temperature trends were monitored to ensure they were not trending up or down more than 1°C during a test period. If upsets in solids recirculation or system temperature occurred during a test, the run time was extended to ensure 20 minutes of steady state data. Error analysis indicated this was sufficient amount of data to provide results with accepted measurement error. Measurement error is discussed in the Uncertainty Analysis in Appendix E.

Recirculation rate measurements were conducted by closing the butterfly valve, V-15, for short periods of time and recording the change in differential pressure of the stand pipe. With the butterfly valve closed the solids level dropped in the stand pipe, resulting in a decrease in the flow of solids to the fast bed. To ensure the recirculation rate measurement was accurate, the butterfly valve was closed for no more than 20 to 30 seconds. Recirculation rate measurements also affected the solids fraction in the heat transfer zone of the fast bed, and would upset temperatures. Therefore, measurements for recirculation rates were performed only before or after a heat transfer test was conducted. Three measurements were taken for each condition to ensure they were consistent.

System Shutdown

After an experiment was completed, the solids flow valve was closed and the velocity increased to the fast bed to blow the remaining material over to the stand pipe. The stand pipe air was shut off to defluidize the solid material. The bypass valve, V-13, was opened fully and the supply valve, V-16, was closed to stop air flow to the fast bed. The blower was allowed to cool briefly and then shut down. The pressure transducers were re-checked for proper zero readings and the purge lines checked for solids. The purge air was tuned off and the coalescing filters drained on the compressed air supply lines. Data logging was stopped and the data acquisition system turned off.

Data Reduction

Data recorded during the experiments were reviewed and separated by test condition. Trends for each test condition were reviewed to ensure they were representative of steady state operation. Values were averaged for each test condition and tabulated by experiment. Because of the noise inherent in pressure signals observed in fluidized systems, the range of values for each test average was calculated and presented in the following form:

$$Average\ Value\ \pm Range$$

Where the range is defined by Equation 4.1.

$$Range = \frac{(Max\ Value - Min\ Value)}{2} \tag{4.1}$$

This method provides a good indication of the noise and oscillations present in the system during operation. The range should not be confused with experimental error, a discussion on error can be found in Appendix E.

The air supplied by the blower to the fast bed is measured with an orifice plate where the mass flow rate can be determined using Equations 4.2 to 4.5. These equations are valid for a sharp-edge orifice with the upstream pressure tap located 1 pipe diameter from the plate and the downstream pressure tap located 1/2 pipe diameter from the plate.

$$\dot{m} = \frac{\pi}{4} Y_1 \, C_d \, {d_{orf}}^2 \sqrt{\frac{2 \, \rho_{orf} \, dP_{orf}}{(1-\beta^4)}} \qquad (4.2)$$

$$Y_1 = 1 - (.41 + .35\,\beta^4) \frac{dP_{orf}}{1.4\,(P_{atm} + P_{orf})} \qquad (4.3)$$

$$\rho_{orf} = \frac{P_{orf} + P_{atm}}{T_{orf}\, R} \qquad (4.4)$$

$$\beta = \frac{d_{orf}}{D_{pipe}} \qquad (4.5)$$

where
$\dot{m}$ = Mass flow rate of air through the orifice
Y_1 = Expansion factor
C_d = Orifice discharge coefficient
d_{orf} = Orifice diameter
ρ_{orf} = Density of air in the orifice
dP_{orf} = The pressure drop across the orifice
β = Ratio of the orifice diameter to pipe diameter
P_{atm} = Standard absolute atmospheric pressure
T_{orf} = Air temperature at orifice plate

D_{pipe} = Pipe diameter at the orifice plate
R = Ideal gas constant of Air

The discharge coefficient is found through an iterative method using the Equations 4.6 to 4.13. An initial guess of the mass flow rate is required to calculate the Reynolds number. The orifice plate equation was verified over the range of differential pressures expected. The superficial velocity in the fast bed can then be determined from the mass flow rate.

$$C_d = .5961 + .0261\,\beta^2 - .216\,\beta^4 + .00521\left(\frac{10^6\beta}{R_{e_D}}\right) + (.0188 + .0063\,A)\beta^{3.5}\left(\frac{10^6\beta}{R_{e_D}}\right)^{.3} + (.043 + .080\,e^{-10} - .123\,e^{-7})(1 - .011\,A)\left(\frac{\beta^4}{1-\beta^4}\right) - .031(M_2 - .8{M_2}^{1.1})\beta^{1.3} \quad (4.6)$$

$$R_{e_D} = \frac{4\,\dot{m}}{\pi\,\mu\,D_{pipe}} \quad (4.7)$$

$$\mu = \left[153900 + 6522\,T_{orf} - 3.591\,{T_{orf}}^2 + .001368\,{T_{orf}}^3 - .001368\,{T_{orf}}^4\right]10^{-11}\,\frac{kg}{m\,s} \quad (4.8)$$

$$A = \left(\frac{19000\,\beta}{R_{e_D}}\right)^{.8} \quad (4.9)$$

$$M_2 = \frac{.94}{1-\beta} \quad (4.10)$$

where R_{eD} = Reynolds Number in the pipe upstream of the orifice
A = Dimensional characteristic
M_2 = Term specific to the pressure tap locations

$$U_o = \frac{\dot{m}}{\rho_g A_{fb}} \tag{4.11}$$

$$\rho_g = \frac{P_{fb} + P_{atm}}{T_{fb}\, 286.987 \frac{J}{kg\ K}} \tag{4.12}$$

$$A_{fb} = \frac{\pi}{4}\left({D_{fb}}^2 - {d_{pr}}^2\right) \tag{4.13}$$

where U_o = Superficial velocity in the fast bed
ρ_g = Density of air in the fast bed
P_{fb} = Static pressure in the fast bed
T_{fb} = Temperature in the fast bed
A_{fb} = Area of the fast bed
D_{fb} = Diameter of the fast bed
d_{pr} = Diameter of the heater probe

The solids fraction at various locations in the fast bed can be determined measuring the pressure drop across a known height difference in the bed since the pressure head is caused by the weight of the emulsion. The fraction of solids in the emulsion is directly related to the pressure difference between two points as given by equation 4.14. Since the density of air is very small compared to the solid particle it is often ignored.

$$(1 - \varepsilon) = \frac{dP_{pt}}{g\, L_{pt}\, \rho_s} \tag{4.14}$$

where ε = Voidage, the fraction of volume occupied by the gas phase
dP_{pt} = Differential pressure between the pressure taps
g = Acceleration due to gravity
L_{pt} = Length between the pressure taps
ρ_s = Density of the solid particle

The recirculation rate is the average mass flux, or solids mass flow rate per unit area in the circulating fluid bed. The recirculation rate can be measured by closing the butterfly valve and recording the change in differential pressure across the stand pipe over a short time period. The change in pressure head is directly related to the change in weight of the solids in the standpipe given by Equation 4.15.

$$G_s = \frac{A_{sp}}{g\,A_{fb}}\left(\frac{\Delta dP_{sp}}{\Delta t}\right) \tag{4.15}$$

where
G_s = Solids Recirculation Rate
A_{sp} = Area of the stand pipe
A_{fb} = Area of the fast bed
g = Acceleration due to gravity
$\Delta d_{sp}/\Delta t$ = Time rate change of differential pressure across the stand pipe

The differential pressure readings recorded during the time the butterfly valve was closed were plotted in a spread sheet and the slope of the line provided the $\Delta d_{sp}/\Delta t$ term in Equation 4.15. Due to the noise in the differential pressure signals from the stand pipe this measurement is only an estimate, but was accurate enough for the purposes of this study. Three measurements were taken and the average was reported for each test condition. At least one measurement was taken before and after each test to ensure the recirculation rate had remained constant during the test period.

The total heat transfer between the heater probe and the fast bed is the sum of particle convection, gas convection and radiation. The contribution from radiation is unimportant in this study because of the relatively low temperature difference between the probe and the fast bed. In addition the effect of radiation is further reduced by the shielding effect caused by the particles in the emulsion. Conduction losses are also not a significant component of the total heat transfer as the heater was insulated from its support rod, and the rod itself was made of thin walled tubing. The average heat transfer coefficient due to particle convection and gas convection in the fast bed can be found using Newton's law of cooling.

$$h = \frac{q_{htr}}{A_{htr}(T_{htr} - T_{fb})} \tag{4.16}$$

where
h = Average convective heat transfer coefficient
q_{htr} = Power supplied to the heater
A_{htr} = Area of the heater surface
T_{htr} = The heater surface temperature
T_{fb} = The temperature of the fast bed near the heater

The average temperature of the four thermocouples installed on the heater surface was used as the heater surface temperature value, and the fast bed temperature was the average of two thermocouples in the fast bed near the heater. One thermocouple was just below the heater and the other just above. The heater power was calculated from Equation 4.17 with readings taken from the direct current power supply.

$$q_{htr} = V\ I \tag{4.17}$$

where
q_{htr} = Power supplied to the heater
V = Voltage supplied to the heater
I = Current supplied to the heater

The preceding calculations were performed on data obtained from each experiment. Sample calculations are provided in Appendix D.

CHAPTER IV

RESULTS

Summary of Experiments

The experimental work in this study was performed over a 12 month period and is comprised of 36 experiments with 148 individual test conditions conducted over 258 hours of system operation. The first experiment was a shakedown run for the instrumentation and data acquisition system. The new instrumentation was wired into the National Instrument's system and trending and data logging were checked for functionality. An equation to calculate the mass flow rate at the orifice plate and the average superficial velocity in the fast bed was added to the program. Experiments 2 thorough 5 were conducted to determine the minimum fluidization velocity of the aluminum powder. A discussion of these experiments can be found in Appendix C.

A summary of Experiments 6 through 35 and the operating parameters investigated can be seen in Table 4. Experiments 7 through 17 were conducted without using the pulsing valve to study the operational capability of the circulating fluid bed using the new material. Experiments 18 to 27 were conducted with the pulsing valve installed in the first configuration, and the remaining tests with the valve installed in the second configuration as shown Figures 5 and 6 in Chapter II. The experimental results are tabulated in Appendix A.

Table 4. Summary of experimental parameters.

Exp.	No. of tests	Uo	(1- ε)	Gs	Freq.	valve %	Variable Ranges						
6	1	V	V	~	0	0	1.5 m/s	< Uo <	4.5 m/s		0.0025	< (1-ε) <	0.0045
7	2	C	V	~	0	0	0	< (1-ε) <	0.0053		Uo = 3 m/s		Gs = 10 kg/m^2 s
8	2	C	V	~	0	0	0.0079	< (1-ε) <	0.0125		Uo = 3 m/s		Gs = 15 kg/m^2 s
10	2	C	V	~	0	0	.0048	< (1-ε) <	.0067		Uo = 3 m/s		
11	5	C	V	~	0	0	0.0048	< (1-ε) <	0.0118		Uo = 3 m/s		
12	5	C	V	~	0	0	0	< (1-ε) <	0.0136		Uo = 3 m/s		
13	6	V	~	C	0	0	2.0 m/s	< Uo <	4.0 m/s		Gs = 10 and 24 kg/m^2 s		
14	4	V	~	C	0	0	2.0 m/s	< Uo <	3.5 m/s		Gs = 10 kg/m^2 s		
15	5	V	~	C	0	0	2.5 m/s	< Uo <	3.5 m/s		Gs = 16 kg/m^2 s		
16	4	V	~	C	0	0	2.0 m/s	< Uo <	3.5 m/s		Gs = 5kg/m^2 s		
17	6	V	0	0	0	0	2.0 m/s	< Uo <	4.0 m/s		(1-ε) = 0		
18	3	C	C	C	V	V	Gs = 5 kg/m^2 s		(1-ε) = .0045		Uo = N/A		f = 0.2, 2.0 Hz
19	3	C	C	C	V	V	Gs = 21 kg/m^2 s		(1-ε) = .0100		Uo = 3.0 m/s		f = 0.2, 2.0 Hz
20	7	C	C	C	V	V	Gs = 15 kg/m^2 s		(1-ε) = .0110		Uo = 2.5 m/s		f = 2, 4, 6, 8, 10, 12 Hz
21	4	C	C	C	V	V	Gs = 23 kg/m^2 s		(1-ε) = .0140		Uo = 2.8 m/s		f =1.5, 3, 4.5 Hz
22	7	C	C	C	V	V	Gs = 23 kg/m^2 s		(1-ε) = .0145		Uo = 2.8 m/s		f = 0.6, 1.1, 2.1, 2.5 Hz
23	6	C	C	C	C	V	Uo = 2.9 m/s		(1-ε) = .0150	6%	< Valve <	42%	f = 0.6 Hz
24	5	C	C	C	C	V	Uo = 2.8 m/s		(1-ε) = .0140	35%	< Valve <	65%	f = 1.1 Hz
25	7	C	C	C	C	V	Uo = 2.9 m/s		(1-ε) = .0145	25%	< Valve <	55%	f = 1.6, 1.1 Hz
26	5	C	C	C	C	V	Uo = 2.9 m/s		(1-ε) = .0145	15%	< Valve <	35%	f = 2.1 Hz
27	6	C	C	C	V	C	Uo = 2.8 m/s		(1-ε) = .0140		Valve = 50%		f = 0.8, 1.3, 1.9, 2.5, 2.8 Hz
28	8	C	C	C	V	C	Uo = 2.8 m/s		(1-ε) = .0135		Valve = 50%		f = 1.1, 1.6, 2.1, 2.6, 3.1 Hz
29	5	C	C	C	V	C	Uo = 2.6 m/s		(1-ε) = .0140		Valve = 50%		f = 1.1, 1.6, 2.1, 2.6 Hz
30	7	C	C	C	V	C	Uo = 2.8 m/s		(1-ε) = .0140		Valve = 50%		f = 0.8, 1.0, 1.5, 2, 2.5, 3 Hz
31	5	C	C	C	V	C	Uo = 2.8 m/s		(1-ε) = .0135		Valve = 50%		f = 1.2, 1.5, 1.8, 2.1 Hz
32	5	C	C	C	V	C	Uo = 2.5 m/s		(1-ε) = .0135		Valve = 50%		f = 1.2, 1.4, 1.8, 2.2 Hz
33	6	C	C	~	C	C	Uo = 2.6 m/s		(1-ε) = .0135		Valve = 50%		f = 1.3 Hz
34	6	V	C	~	C	C	2.4 m/s	< Uo <	3.2 m/s		Valve = 50%		f = 1.5 Hz
35	6	C	C	~	C	C	Uo = 2.6 m/s		(1-ε) = .0135		Valve = 50%		f = 1.5Hz
36	6	C	C	C	V	C	Uo = 2.6 m/s		(1-ε) = .0135		Valve = 50%		f = 2.5,3, 4, 5, 6 Hz

C = Constant V = Variable of primary Interest ~ = Varies based on other factors

The purpose of Experiment 6 was to test the ability of the CFCFB to circulate solids. The heated probe was installed but was not heated during this experiment. Twenty kg of spherical aluminum was loaded into the stand pipe and fluidized with compressed air. The blower supplied air to the fast bed with $U_o \approx 2.0$ m/s. It was determined in post processing that the solids fraction in the midpoint was between .0052 and .0088 with stabile operation and no plugging occurred in the pressure taps. The data acquisition system faulted and was restarted during the run. Only 10 minutes of useful data was collected two short steady state periods were observed and no recirculation rate measurements were taken. Several solids leaks became apparent during the test and their locations were noted for repairs.

Effect of Solids Loading on Heat Transfer

Experiments 7 through 12 were conducted at constant velocity with varying solids fractions. U_o was maintained near 3.0 m/s and solids flow varied by adjusting the solids flow valve to change the solids fractions at the midpoint of the fast bed. The average heat transfer coefficient and solids recirculation rates were determined for each of the test conditions.

Experiment 7 consisted of four steady state test conditions. U_0 varied between 3.01 m/s and 3.05 m/s and the highest solids fractions obtained was .0053. The first test was performed with no solids flow into the fast bed. Solids recirculated for the second test with a solids fraction of .0053 and a recirculation rate of 10.2 kg/m^2 s. The resulting heat transfer measured was 48.9 W/m^2 K. During the experiment the National Instruments data acquisition system became unstable and had to be restarted several times. The last two test conditions were cut short and the resulting data was not useable. Experiment 8 was performed several hours after experiment 7 had been completed (in an attempt to find the cause of data acquisition system disruptions). The system was started and solids recirculated, the data acquisition system was running but the data was not recorded. Various connections to thermocouples and transducers were disconnected and reconnected to determine the source of the problem. It was determined that the nylon insulator on each end of the heater in the fast bed insulated it from the rest of the CFCFB. This caused static charges generated in the fast bed to discharge into the data acquisition system through the thermocouple wires. The heater probe was removed and a ground wire was soldered onto the inside of the brass heater case. The data acquisition system was disconnected from the building electrical ground and the frame of CFCFB, the blower inlet pipe, and the ground wire for the heater case were all connected to the building's electrical ground. These modifications alleviated the problem in future testing on the CFCFB.

The purpose of experiment 9 was to verify the electrical modifications to the data acquisition system. The system was started up and solids circulated with no electrical disruptions observed. Solids flow was stopped and the blower shut down. To observe any effect of the modifications to the heater, the power supply was set to low power setting for approximately 5 hours while the data acquisition system continued to log data. It was determined that the variation of 4°C between thermocouples when the heater was running was acceptable and the added ground wire did not affect the temperature profile of the heated probe.

Experiment 10 repeated similar conditions from experiment 7 to investigate the repeatability of the CFCFB operation and verify if the static discharge problem of the previous experiments had affected the probe temperature measurements. For both tests U_0 was observed at 2.98 m/s, solids fractions of .0048 and .0067, and recirculation rates of 8.0 kg/m^2 s and 14.5 kg/m^2 s. Average heat transfer coefficient was determined to be 45.1 W/m^2 K for test A and 50.1 W/m^2 K for test B. It was noted that during this experiment the large air dryer used for the stand pipe and purge air caused small temperature swings in the CFCFB.

The goal of the experiment 11 was to continue the testing conducted in experiment 10 by increasing the solids fractions to higher levels. The target U_0 varied between 2.93 m/s and 2.98 m/s and the solids fraction was varied between .0052 and .0118. Recirculation rates were observed between 13.1 kg/m^2 s and 23.3 kg/m^2 s, heat transfer coefficients from 45.3 W/m^2 K and 67.5 W/m^2 K. For experiment 11 the large air dryer was not used, eliminating the thermal cycling observed in previous tests. Two moisture separators in the main airline were sufficient to remove any water in the compressed air lines. A small pressure regulator was installed upstream of the air dryer, the dryer was used as an air reservoir to eliminate pressure swings caused by the main air compressor.

The goal of experiment 12 was to determine the highest attainable solids fraction at the midpoint of the bed and conduct heat transfer measurements.. Five kg of aluminum powder was added to the stand pipe to increase the solids height, this increased the static pressure at the bottom of the stand pipe when fluidized and helped increase solids flow into the fast bed.U_0 was varied from 2.82 m/s to 3.02 m/s and solids fractions were observed up to .0136. Test A indicated a solids fraction of .0117 with the solids recirculation valve fully open. An additional 5 kg of aluminum was added to the stand pipe and the system allowed to reach thermal equilibrium. Velocity was reduced to 2.83 m/s for test B which increased the solids fraction to .0136 and resulted in a maximum heat transfer of 71.1 $W/m^2 K$. Further reduction in velocity did not increase the solid fraction at the midpoint of the fast bed. Velocity was increased slightly for tests C and D to 2.93 m/s and solids fractions were .0066 and .0049. Recirculation rates ranged from 0 to 23.4 $kg/m^2 s$ for experiment 12.

The combined valid results from experiments 7 through 12 can be seen in Figures 8 and 9. These experiments were near constant velocity with U_o varying from 2.83 m/s to 3.05 m/s. The highest heat transfer coefficient was found at 71.1 $W/m^2 K$ at the maximum solids fraction of .0136. Figure 8 shows the average solids fraction present near the heat transfer surface has a strong influence on the heat transfer.

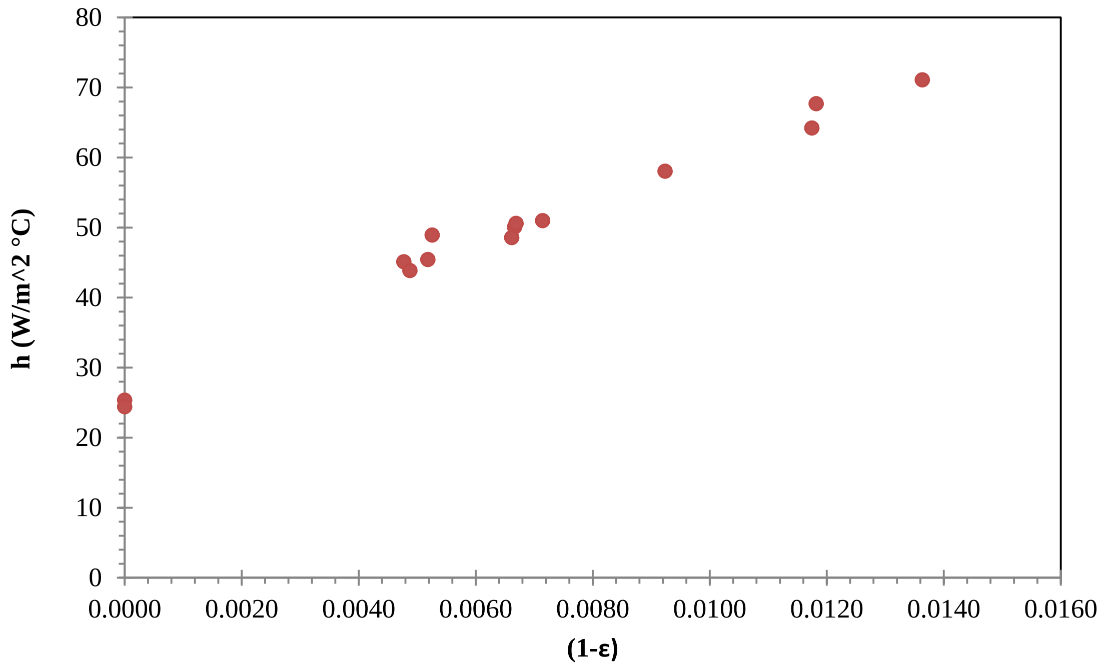

Figure 8. Solids Fraction vs. the Average Heat Transfer Coefficient for $U_o \approx 3$ m/s

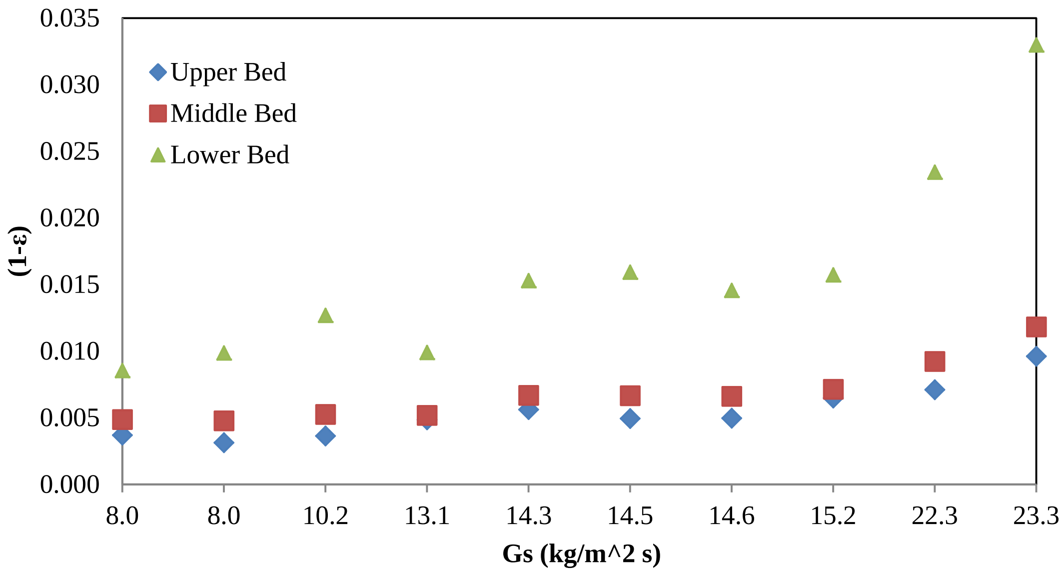

Figure 9. Solids Fractions in the Upper, Middle, and Lower Fast Bed locations for each recirculation rate observed at $U_o \approx 3$ m/s.

Figure 9 shows the solids profile of the fast bed for each recirculation rate observed in experiments 7 through 12. Once the solids flow valve is completely open the pressure difference between the stand pipe and bottom of the fast bed becomes the controlling factor of solids recirculation rates. Adding material to increase the height of the stand pipe increased the flow of solids to the fast bed. It was also noted that for a constant setting of the solids flow valve decreasing U_o increased the solids inventory in the lower portion of the fast bed, reducing U_o below 2 m/s resulted in slugging and excessive differential pressures in the fast bed. The maximum solids fraction was achieved near 2.8 m/s.

Operational Range of the Fast Bed

The next series of experiments was performed to determine operational range of circulating fluid bed. Experiments were performed at constant recirculation rates and velocities were varied to find the minimum and maximum U_o that can be achieved at a given recirculation rate. Heat transfer was measured to continue to build on data from the previous tests. $h_{f=0} / h_f$

In experiment 13 recirculation rates of 10 kg/m^2 s and 24 kg/m^2 s were maintained with velocity ranging from 2 m/s to 4 m/s. The lower recirculation rates of tests A, B, and C resulted in solids fractions that varied from .0045 to .0048 and for the higher recirculation rates in tests D and E the solids fraction was between 0.0085 and 0.0096. U_o was increased in steps for each test condition from 2.00 m/s and 3.99 m/s, the solids valve was adjusted to increase the recirculation rate and then U_o was decreased back to 2.01 m/s. It was determined in post processing that tests 13 C and 13 F were not in thermal equilibrium and the heat transfer data was not used for those tests. Heat transfer coefficients were observed between 43.2 W/m^2 K and 53.9W/m^2 K after excluding tests C and F.

Experiment 14 measured the heat transfer at constant solids recirculation rate of 10 kg/m^2 s and varied U_o from 2.0 m/s to 3.5 m/s. There was some difficulty in maintaining constant recirculation rates from one test condition to another. Several recirculation tests were performed and the data was analyzed immediately to calculate the recirculation rate. The solids flow valve was adjusted and recirculation tests repeated. Two consecutive readings needed to be taken before the test condition would begin, and one afterwards to verify rates remained constant. This process was time consuming and only 4 test conditions were achieved in 7 hours of operation.   Recirculation rates varied between 10.2 kg/m^2 s and 10.6 kg/m^2 s and velocities were achieved between 1.98 m/s to 3.52 m/s. Operation was not stable for velocities below 2 m/s. Solids fractions at the midpoint of the fast bed were observed between.0042 and .0076 with corresponding heat transfer coefficients between 42.9W/m^2 K and 54.4 W/m^2 K.

Experiment 15 was a continuation of experiment 14, measuring heat transfer at constant recirculation rate of 15 kg/m^2 s and varying U_o from 2.0 m/s to 3.5 m/s. Prior to the start of testing, 5 kg of aluminum bed material was added to the stand pipe. Recirculation rates were observed between 15.9kg/m^2 s and 16.1 kg/m^2/s for all tests with the exception of test B, post processing showed the actual recirculation rate was 14.0 kg/m^2 s. Recirculation rate tests were performed before and after each test condition. Two consecutive readings needed to be taken before the test condition would begin, and one afterwards to verify rates were constant. It was determined that for U_0 less than 2.4 m/s the recirculation rate could not be maintained. Five tests were performed actual velocities observed were between 2.48 m/s and 3.49 m/s with solids fractions from .0066 to .0100 and heat transfer coefficients found between 46.9 W/m^2 K and 58.34 W/m^2 K. At this recirculation rate lower velocities resulted in higher heat transfer, and increasing velocities reduced heat transfer.

Experiment 16 was a further continuation of experiments 14 and 15, recirculation rates were to be held constant at 5 kg/m^2 s and U_o varied from 2.0 m/s to 3.5 m/s. Recirculation rates observed varied between 5.1 kg/m^2 s and 5.5 kg/m^2 s and U_o was varied from 2.02 m/s to 3.52 m/s. Solids fractions were observed between .0029 and .0047. Four tests were performed in experiment 16, with heat transfer coefficients found between 38.8 W/m^2 K and 42.6 W/m^2 K. Similar to experiment 15, lower velocities produced higher heat transfer at constant solids recirculation rates.

The goal of experiment 17 was to measure heat transfer without any solids present with U_o varying from 2.0 m/s to 4.0 m/s. The solids recirculation valve was left closed and the stand pipe was not fluidized for the air blown heat transfer tests. The heat transfer without solids present in forced convention is significantly lower compared to equivalent conditions with a small solids fraction present. To prevent damage to the heater in the fast bed, the power was cut roughly in half to 12.56 W for the test conditions where no solids were present. Five tests were conducted with velocities observed from 2.04 m/s to 4.04 m/s with heat transfer coefficients found between 20.8 W/m^2 K and 31.6 W/m^2 K. In these tests with air only, heat transfer increased as velocity increased. Relationships available for turbulent flow in an annular pipe suggest the same relationship between velocity and heat transfer. As the Reynolds number is increased heat transfer will increase as well.

The following figures comparing the results of experiments 13 through 17 show the operational range achievable with the circulating fluid bed system. Figure 10 shows the heat transfer coefficient measured for a given solids recirculation rate at range of velocities from 2.0 m/s to 4.0 m/s. Reducing U_o while maintain the same recirculation rate resulted in increases heat transfer and increasing the recirculation rate at a constant velocity would also increase heat transfer. This relationship suggests that maximum heat transfer can be achieved by circulating the most material possible at the lowest stable velocity.

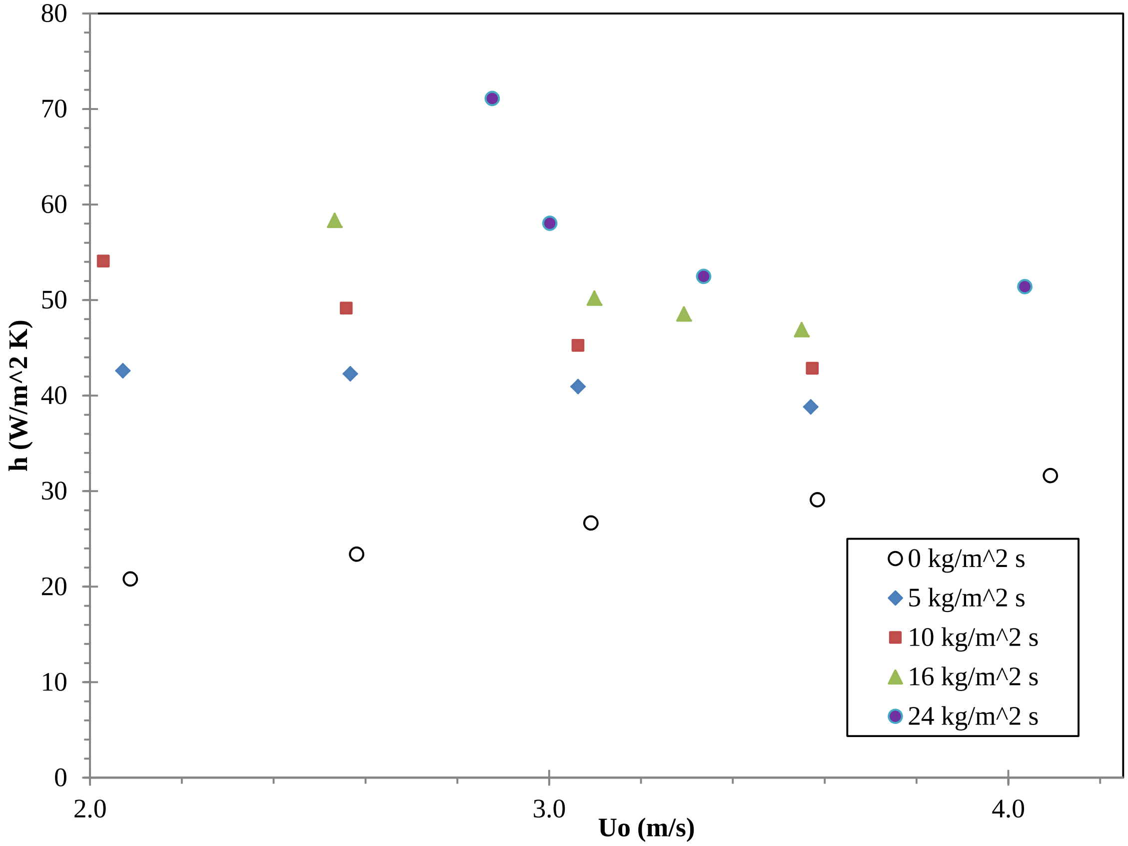

Figure 10. The Effect of Velocity and Solids Recirculation On the Heat Transfer Coefficient.

Reducing velocity would decrease heat transfer as it was not possible to maintain the solids recirculation rate below 2.8 m/s, increasing velocity would also reduce heat transfer as the recirculation rate was limited by solids cross over pipe.

Figure 11 shows the relationship observed between the solids fraction and heat transfer at different velocities. The heat transfer coefficient is strongly influenced by the average solids fraction present, however, the effect of velocity changes are small for a given solids fraction. When no solids were present, velocity had a more significant effect on heat transfer.

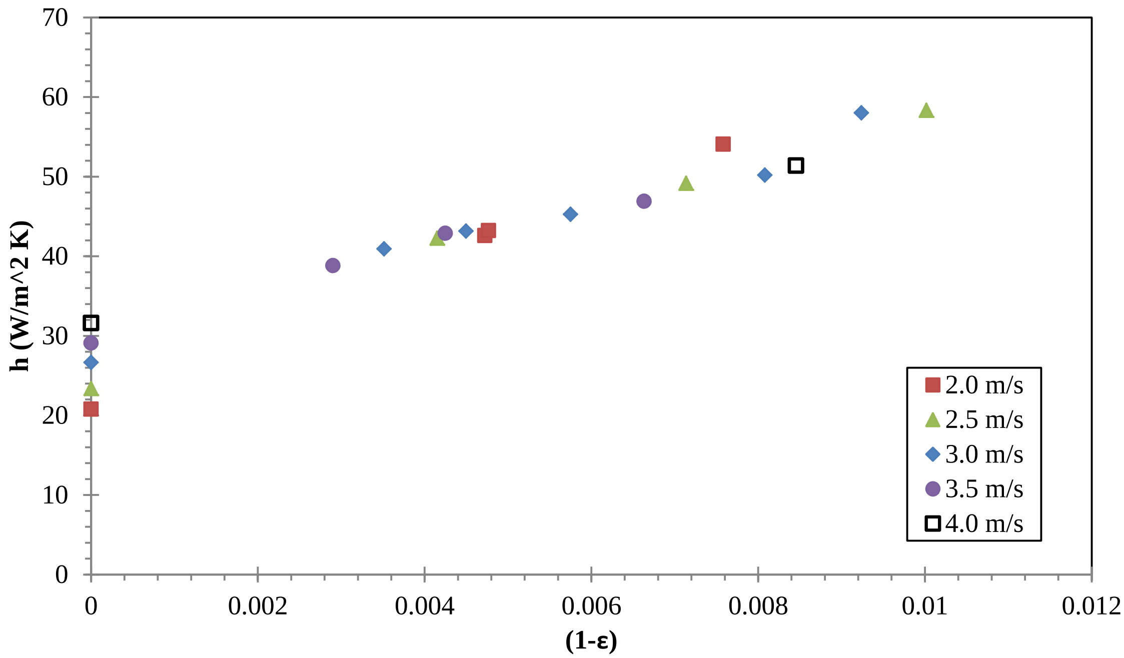

Figure 11. Solids Fraction vs. the Average Heat Transfer Coefficient for Experiments 13 to 17

It is possible to observe the effect of velocity by comparing the heat transfer coefficients found with fluidized solids to the air only tests at the same velocities. This comparison can be seen in Figure 12. The term h_{ave} / h_{conv} is found by dividing the average heat transfer coefficient by the coefficient for the gas only test at the same velocity. The results of this comparison show that solids become more influential on the heat transfer as the average velocity is lowered.

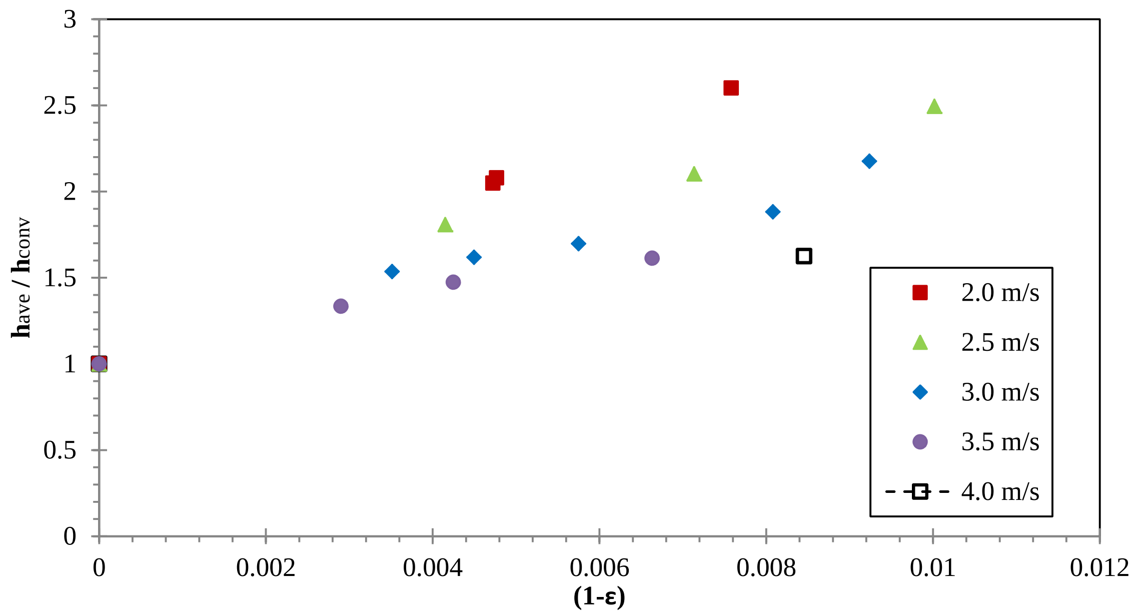

Figure 12. The Ratio of Heat Transfer With Fluidized Solids to Heat Transfer With Air Only

The solids fractions at the top, middle, and bottom of the fast bed were compared for each recirculation rate over the range of velocities tested. Figure 13 shows the solids distribution for a recirculation rate 5 $kg/m^2 s$ with velocity from 2.0 m/s to 3.5 m/s. At 3.0 m/s, the solids distribution is almost uniform indicating that the fast bed is operating in the pneumatic transport regime beyond this point. Similar results were observed for a recirculation rate of 10 $kg/m^2 s$ as seen in Figure 14. Velocities above 3 m/s produce a near uniform solids distribution indicating pneumatic transport.

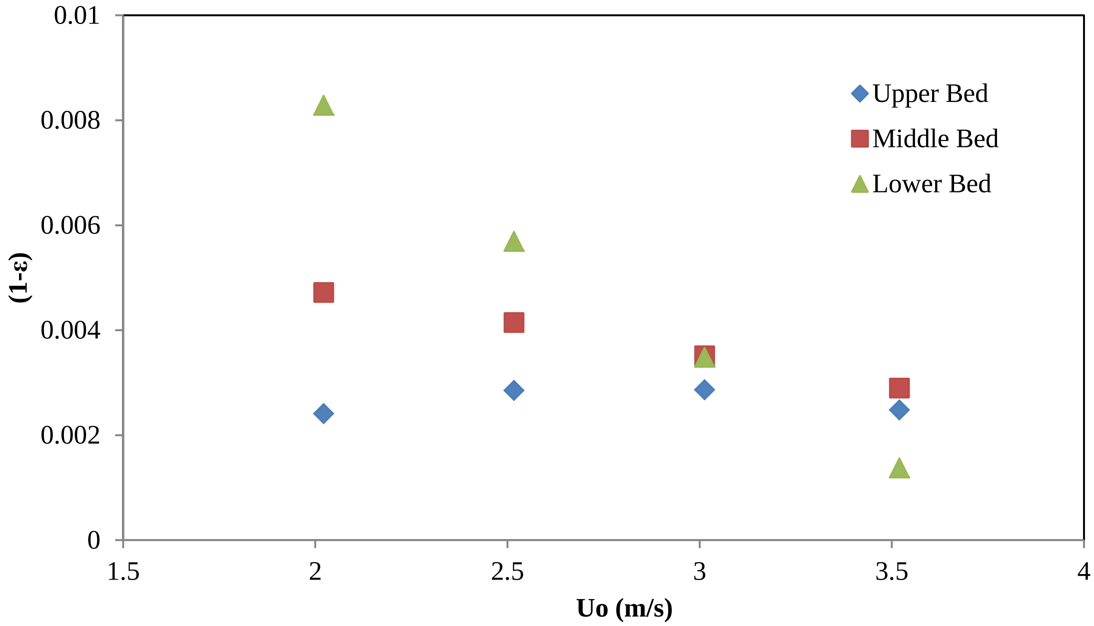

Figure 13. Variation of Solids Distribution in The Fast Bed for Gs ≈ 5 kg/m^2 s.

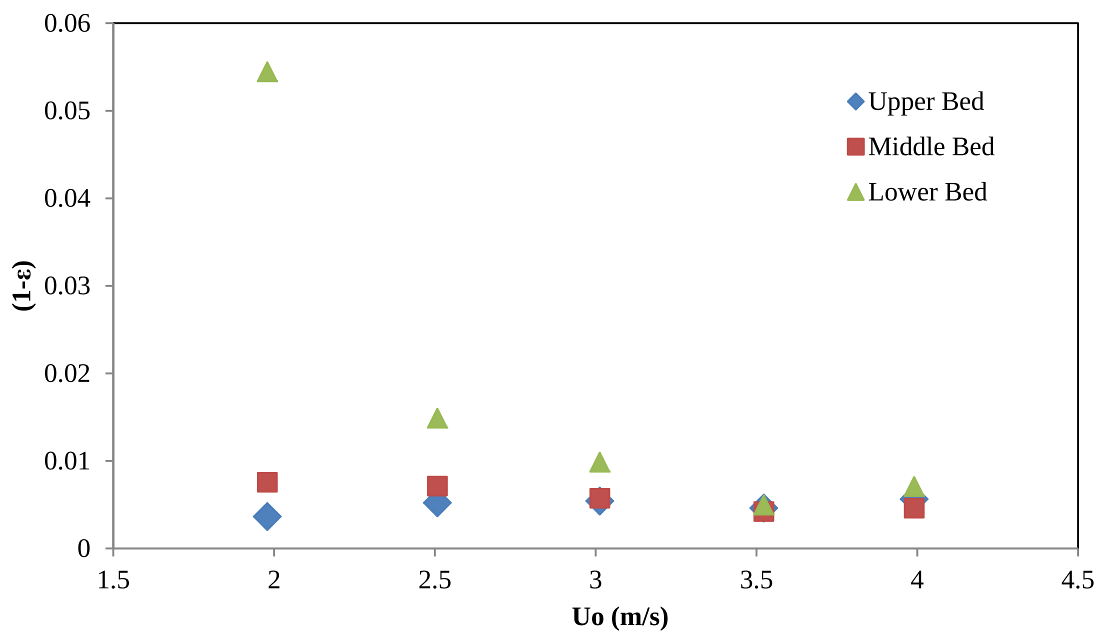

Figure 14. Variation of Solids Distribution In the Fast Bed for Gs ≈ 10 kg/m^2 s.

Figure 15 shows the solids distribution for 16 $kg/m^2\,s$ and U_o from 2.5 to 3.5 m/s. A test was not conducted at 4 m/s but previous results suggest this would be in the transport regime. Attempts with U_o = 2 m/s were not successful, indicating that the fast bed was transition to a slugging or turbulent regime below 2.5 m/s.

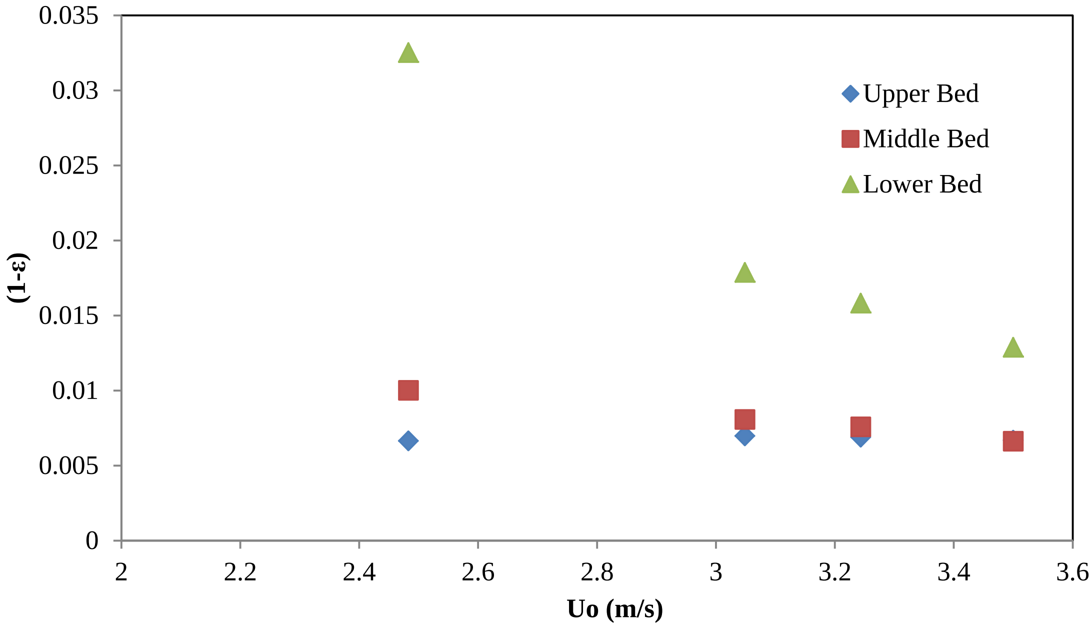

Figure 15. Variation of Solids Distribution At 3 Locations In the Fast Bed for Gs ≈ 16 kg/m^2

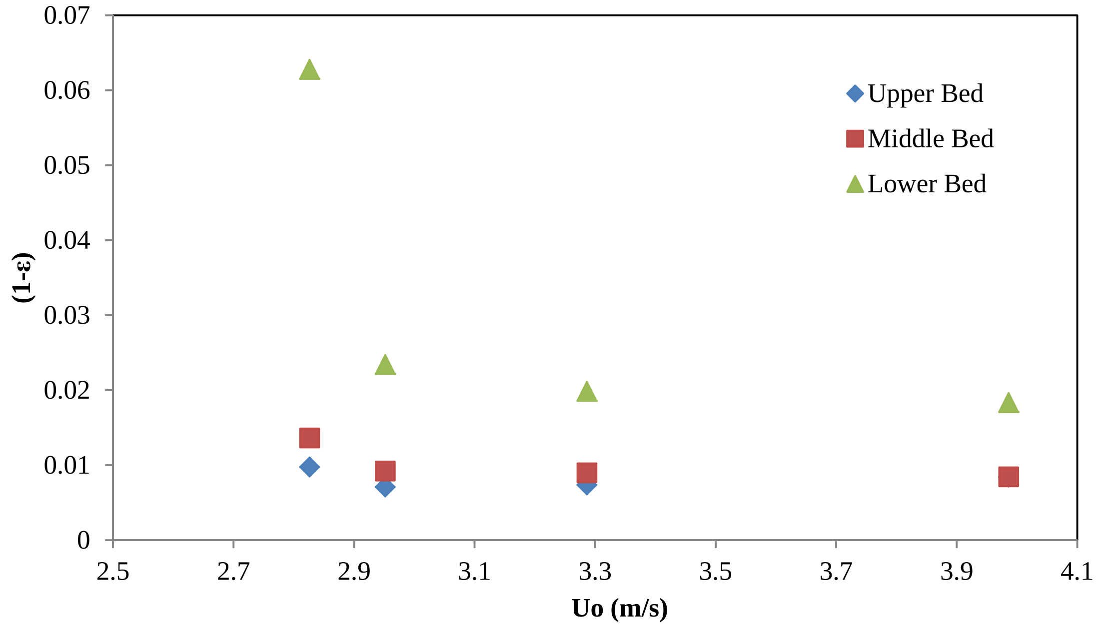

Figure 16.Variation of Solids Distribution At 3 Locations In the Fast Bed for Gs ≈ 24kg/m^{2}s.

Similar results can be seen in Figure 16 for a recirculation rate of 24 kg/m^2 s and velocities between 2.8 m/s and 4.0 m/s. Attempts to run below 2.5 m/s resulted in unstable operation. Maximum heat transfer was observed at 2.8 m/s with a recirculation rate of 23.3 kg/m^2 s.

Effect of Pulsed Air Supply on Heat Transfer

Following experiment 17, the fluid bed system was modified for pulsating operation. A solenoid powered diaphragm valve was installed downstream of the blower (see Figure 5 in CHAPER II) and connected to a power supply and digital function generator. After an initial shake down of the pulsing valve, experiment 18 was performed to explore the effects of pulsing air supply to the fast bed on the heat transfer from the probe. The initial pulsing test was done at U_o = 3.0 m/s at 0.5% solids fraction to compare with data from previous experiments. The first test condition was performed with the valve off, and two further tests were conducted with the pulsing valve operating at 0.2 Hz and 2.0 Hz with pulse widths of 200 ms and 50 ms respectively. Solids recirculation rates were observed at 5.6 kg/m^2 s for the first non-pulsed test and 5.8 kg/m^2/s for the second test with the pulse valve operating. Solids fractions were between .0043 and .0047. Little effect was observed in the heat transfer coefficients, coefficients were observed from 42.5 W/m^2 K to 43.0 W/m^2 K. After the completion of the third test, the static pressure transducer at the orifice plate (PIR 201) was discovered to be malfunctioning. This ended experiment 18 as the system was shut down to troubleshoot the problem. When reviewing the data from this experiment it was observed that PIR 201 was reporting erroneous pressure readings for the duration of experiment 18. It was determined that the transducer was damaged at some point during shake down testing of the pulsing valve. It was replaced with another transducer with a higher pressure range of 0 to 30 psig. The erroneous pressure readings from the faulty transducer affected the velocity calculations for experiment 18. It is unclear what the actual velocities were during experiment 18, and if they were constant from one test condition to another. However it was apparent that no significant changes in heat transfer were observed between the pulsed and non-pulsed tests.

Experiment 19 was a repeat of experiment 18 with higher solids fractions. The target for U_o was 3.0 m/s and a solids fraction of .0100. Three tests were performed with the first test done without the pulsing valve operating, the second and third test with pulsation. After the first test was completed, the pulsing valve was started at a frequency of 0.2 Hz and a pulse width of 200 ms. The vent valve, V-13, was adjusted to maintain the same average U_0 with the pulsing valve operating. There was some difficulty in estimating the velocity with the oscillation in the orifice plate pressures. The third test condition was performed with the pulsing valve operating at 2.0 Hz and 50 ms pulse width. U_o ranged from 3.03 m/s for the non-pulsed test and 2.94 to 2.72 m/s for the pulsed tests. Solids fractions increased from .0099 in the non-pulsed test to .0114 at 2 Hz. Heat transfer increased from 55.2 W/m^2 K to 61.2 W/m^2 K at 2 Hz, little change was observed at 0.2 Hz. Solids fractions remained relatively constant from 20.2 kg/m^2 s to 21.0 kg/m^2 s. It was not possible to determine if the lower velocity was responsible for the increased heat transfer observed at 2 hz. Better estimation of velocity was needed to ensure more uniform result in future testing.

The goal of experiment 20 was to determine the maximum frequency that could be obtained while maintaining otherwise constant conditions in the circulating fluid bed system. The target U_o was 2.5 m/s and recirculation rates was maintained at 15 kg/m^2 s. The first test was run without the pulsing valve operating to establish a baseline heat transfer measurement. Starting with the second test the pulsing valve was turned on and cycled at 2 Hz with a pulse width of 50 ms. The frequency of the pulsing valve were increased by 2 Hz for each condition until it became impossible to maintain velocity and recirculation rates. Heat transfer measurements were taken to determine if there were any correlations between frequency and the average heat transfer coefficient. As frequency increased the vent valve V-13 had to be adjusted to maintain U_o. Prior to test condition E, the pulsing valve was set at 8 HZ with a pulse width of 50 ms. Observation of the analog gauge PIR 201 indicating the differential orifice pressure showed that U_o was decreasing and no further adjustment of V-13 was possible. In order to maintain a constant U_o the pulse width was reduced to 40 ms. This was also the case with tests F and G, the pulse width was reduced to maintain U_o as frequency increased. Overall U_0 was maintained between 2.4 m/s and 2.6 m/s and recirculation rates from 15.3 kg/m^2 s to 16.4 kg/m^2 s. Heat transfer coefficients were found from 60.5 W/m^2 K to 62.4 W/m^2 K although the heat transfer was slightly elevated for all pulsed operation tests from 2 Hz to 12 Hz, the effect was too small and within the uncertainty of heat transfer measurement.

The purpose of experiment 21 was to observe the effect of pulsing the fast bed air at the highest solids fractions achievable. An additional 10 kg of aluminum powder was added to the stand pipe prior to the run and all tests were performed with solids flow valve completely open. One non-pulsed test and three pulsed flow tests were performed with frequencies of 1.5 Hz, 3 Hz, and 4.5 Hz respectively. Pulse widths for tests C and D were reduced from the 30% duty cycle target in order to maintain U_o at the higher pulse frequencies. Solids fractions observed were between .0136 and .0152 while U_o varied from 2.79 m/s to 3.00 m/s and recirculation rates from 23.1 kg/m^2 s to 25.3 kg/m^2 s. Heat transfer coefficients increased from 74.5 W/m^2 K in the non-pulsed test to 81.2 W/m^2 K in the pulsed tests with the maximum occurring at 1.5 Hz. This increase of 9.1 % was outside the range of uncertainty with a slightly higher velocity and similar solids fraction compared to the non-pulsed test.

Experiment 22 was designed to study heat transfer higher solids fractions and pulsing frequencies between 0.5 Hz to 2.5 Hz. Seven test conditions were performed in this experiment. The first test was conducted without the pulsing valve operating and the next 5 tests were conducted at frequencies from 0.6 Hz to 2.5 Hz in a randomized order and the last test condition was run with the pulsing valve off. Solids fractions .0137 to .0152 were observed and U_0 from 2.8 m/s to 2.9 m/s. Heat transfer coefficients ranged from 69.8 W/m^2 K to 78.2 W/m^2 K and recirculation rates from 21.30 kg/m^2 s to 27.58 kg/m^2 s. The highest heat transfer occurred at 1.1 Hz.

Figure 17 shows the results for experiments 21 and 22. The heat transfer coefficients were observed for frequencies from 0 Hz to 4.5 Hz with U_o nearly constant from 2.8 m/s to 3.0 m/s. All tests performed with the pulsing valve had higher heat transfer than the non-pulsed tests, significant increases were observed between 0.6 Hz and 2.1 Hz with a maximum increase of 12.7% at 1.1 Hz.

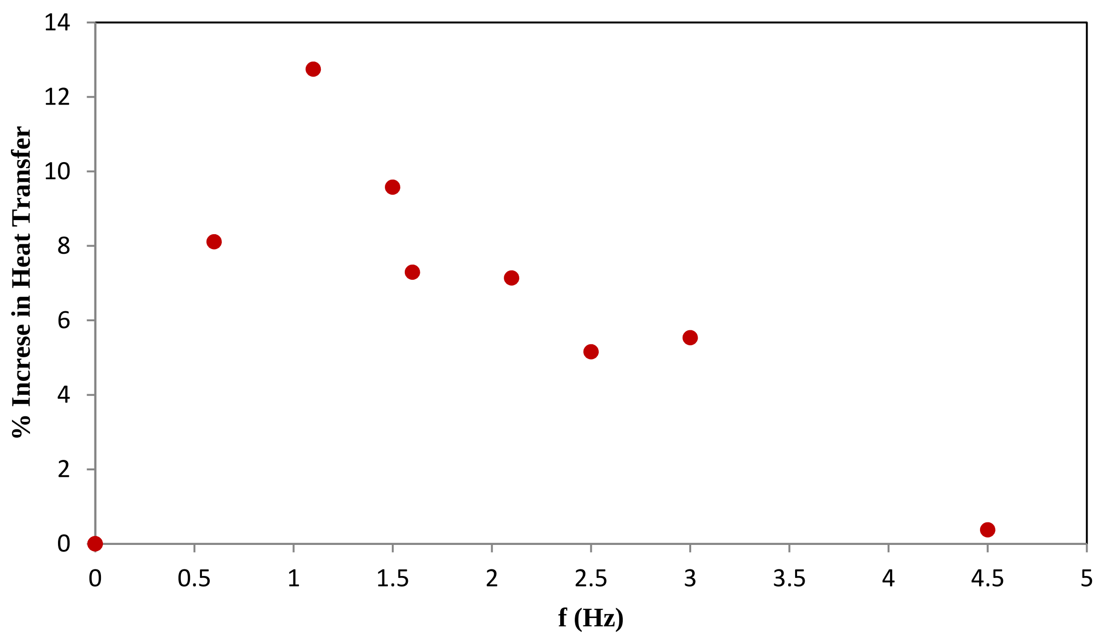

Figure 17. Percent Increase In Heat Transfer vs Frequency of Pulsation for Uo ≈ 2.8 m/s

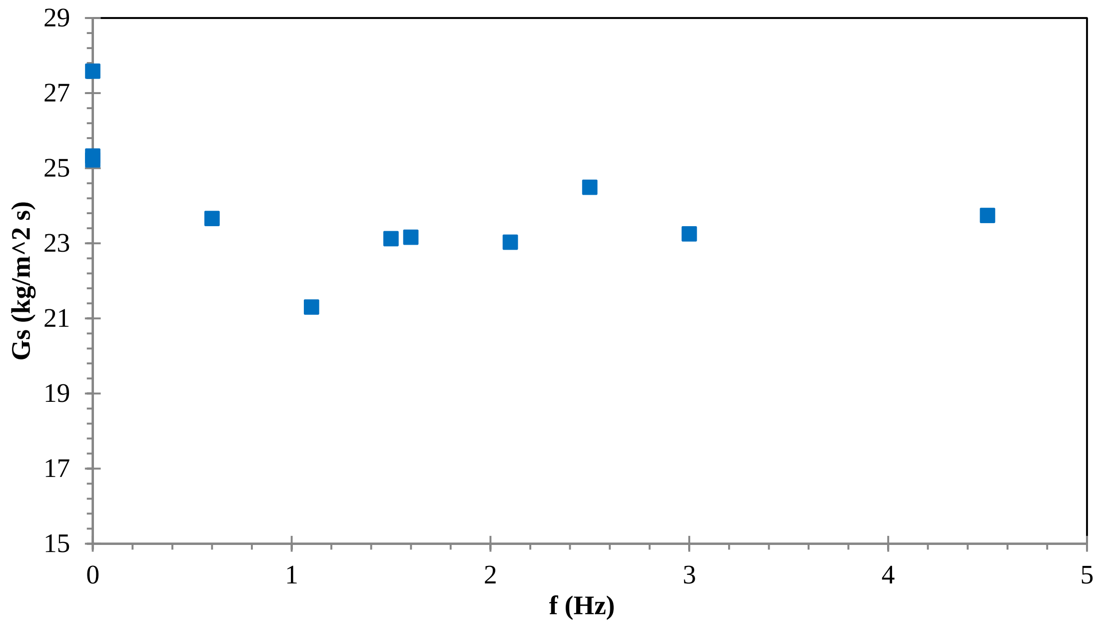

Figure 18. The Effect of Frequency On Solids Recirculation for Uo ≈ 2.8 m/s

Figure 18 above shows the recirculation rates from the same group of tests. Recirculation rates were relatively constant, with some decrease noted from .6 Hz to 4.5Hz and it should be noted that the solids flow valve was completely open for this group of tests. Figure 19 shows the solids fractions observed for this test group. The average solids fraction for the non-pulsed tests was .0148. Solids fractions for pulsed tests from 0.6 Hz to 4.5 Hz were observed between .0150 and .0132.

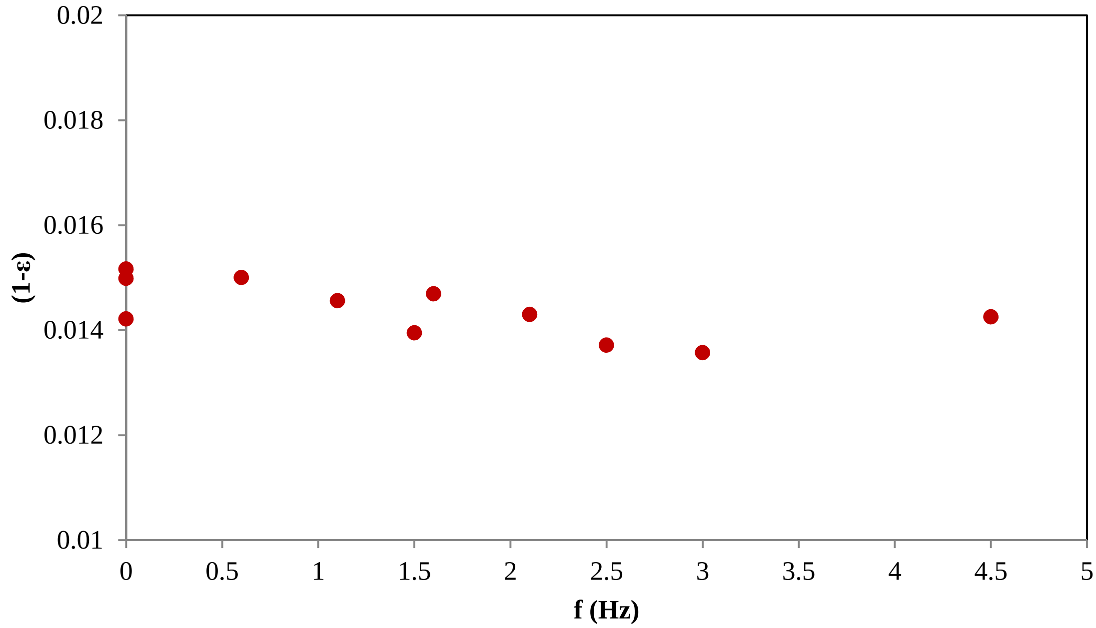

Figure 19. The Effect of Frequency On Solids Fractions for U_o ≈2.8 m/s

Effect of Pulse Duration

The purpose of experiment 23 was to investigate the effect of pulse duration on observed heat transfer at a constant frequency. The pulse width started at 100 ms and increased in 100 ms increments until the system could not be maintained at equivalent conditions. The target for U_0 was 2.8 m/s and a solids fraction at the midpoint of the fast bed at 1.5%. The first test was run with pulsing valve off and the next 5 tests were conducted with a pulsing valve operating from 100 ms to 700 ms, a duty cycle of 6% to 42% respectively. U_o ranged from 2.77 m/s to 2.92 m/s with solids fractions at the midpoint from .0148 to .0154, recirculation rates were between 20.9 kg/m^2 s and 24.9 kg/m^2 s. Heat transfer coefficients varied from 70.6 W/m^2 K to 72.7 W/m^2 K with the maximum occurring at a 42 % valve duty cycle.

Experiment 24 was a continuation of experiment 23 with a pulsing frequency of 1.1 Hz. The valve duty cycle was varied from 35 % to 65 %. U_0 was kept constant at 2.8 m/s and solids fractions at 1.5% for the duration of the experiment. The first test was performed with the pulsing valve off, and the next 4 test were conducted in random order with the pulsing valve at 1.1 Hz and pulse widths from 318 ms to 591 ms. Test E was performed at 591 ms and it was not possible to maintain U_o at pulse durations that long. U_o ranged from 2.6 m/s to 2.9 m/s with solids fractions at the midpoint from .0132 to .0153, recirculation rates were between 14.3 kg/m^2 s and 24.8 kg/m^2 s. Several of these test conditions were repeated at U_o closer to 2.8 m/s in experiment 25. Heat transfer coefficients varied from 68.9 W/m^2 K to 84.9 W/m^2 K with the maximum occurring at a 55 % valve duty cycle.

Experiment 25 was a continuation of experiment 24 with a pulsing frequency of 1.6 Hz. The valve duty cycle was varied from 25 % to 50%. U_0 was kept constant at 2.8 m/s and solids fractions at 1.5% for the duration of the experiment. The first test was performed with the pulsing valve off, and the next 4 tests were conducted in random order with the pulsing valve at 1.6 Hz and pulse widths from 156 ms to 313 ms. U_o was observed from 2.74 m/s to 2.91 m/s, this variation was less than in the previous experiment and considered acceptable. Tests E and F were performed with the pulsing valve operating at 1.1 HZ and pulse widths of 318 ms and 500 ms respectively to gain additional data at that frequency. Overall the solids fractions at the midpoint varied from .0140 to .0147, recirculation rates were between 17.8 kg/m^2 s and 24.8 kg/m^2 s. Heat transfer coefficients varied from 67.0 W/m^2 K to 74.4 W/m^2 K with the maximum occurring at a 50 % valve duty cycle. Figure 20 shows the effect of pulse width on solids distribution in the fast bed for these tests.

Increasing pulse width increased the solids fraction in the lower bed, but did not have much effect on the upper and middle locations.

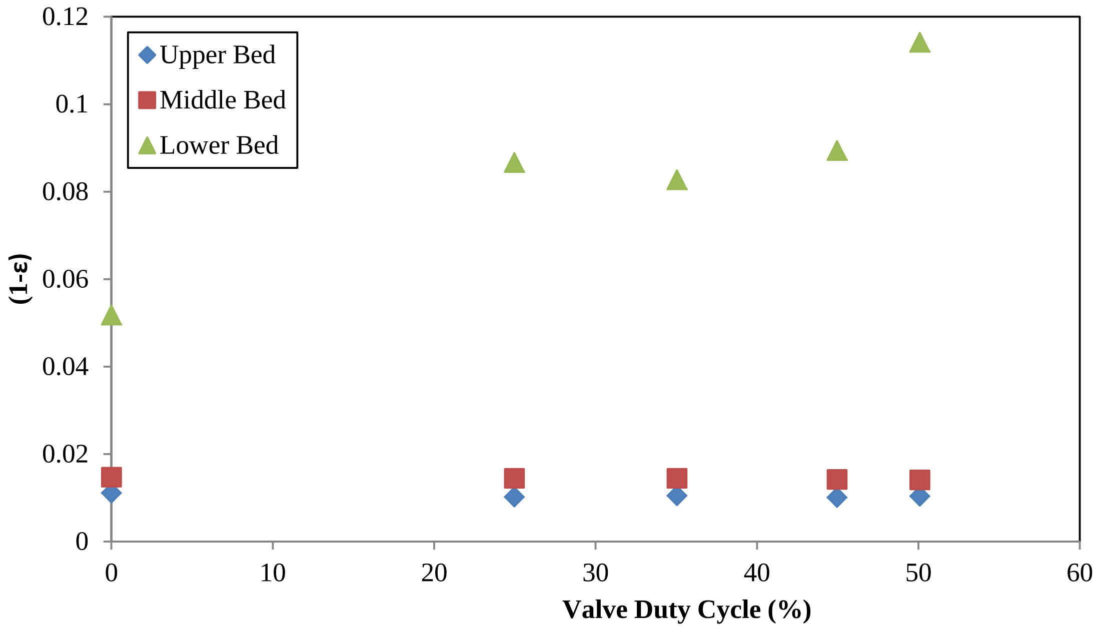

Figure 20. Variation In Solids Distribution In the Fast Bed vs Valve Duty Cycle At 1.6 Hz

Experiment 26 was a continuation of experiments 24 and 25 with a pulsing frequency of 2.1 Hz. The valve duty cycle was varied from 15 % to 35%. U_0 was kept constant at 2.8 m/s and solids fractions at a 1.5% for the duration of the experiment. The first test was performed with the pulsing valve off, and the next 4 tests were conducted in random order with the pulsing valve at 2.1 Hz and pulse widths from 71 ms to 167 ms. Higher pulse widths were attempted but it was not possible to maintain U_o. U_o was observed from 2.77 m/s to 3.01 m/s. Solids fractions at the midpoint of the fast bead were relatively constant from test to test and ranged from .0137 to .0142, recirculation rates were between 16.8 kg/m^2 s and 26.0 kg/m^2 s. Heat transfer coefficients varied from 68.5 W/m^2 K to 75.0 W/m^2 K with the maximum occurring at a 35 % valve duty cycle.

The effect of valve cycle time can be seen Figure 21. Duty cycles above 35 % show an increase in heat transfer, the maximum heat transfer occurred at 1.1 Hz and a duty cycle of 55%. Figure 22 shows the percent increase in heat transfer as duty cycle was increased. Heat transfer increased by 23% at 1.1 Hz with a duty cycle of 55%.

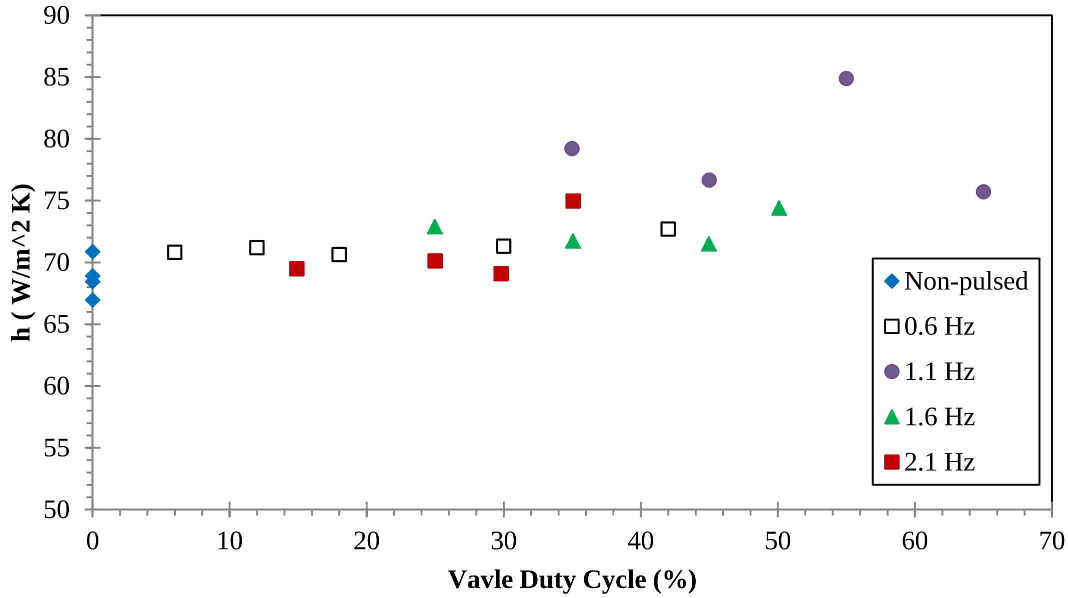

Figure 21. Average Heat Transfer Coefficient vs Valve Duty Cycle for 0.6 to 2.1 Hz.

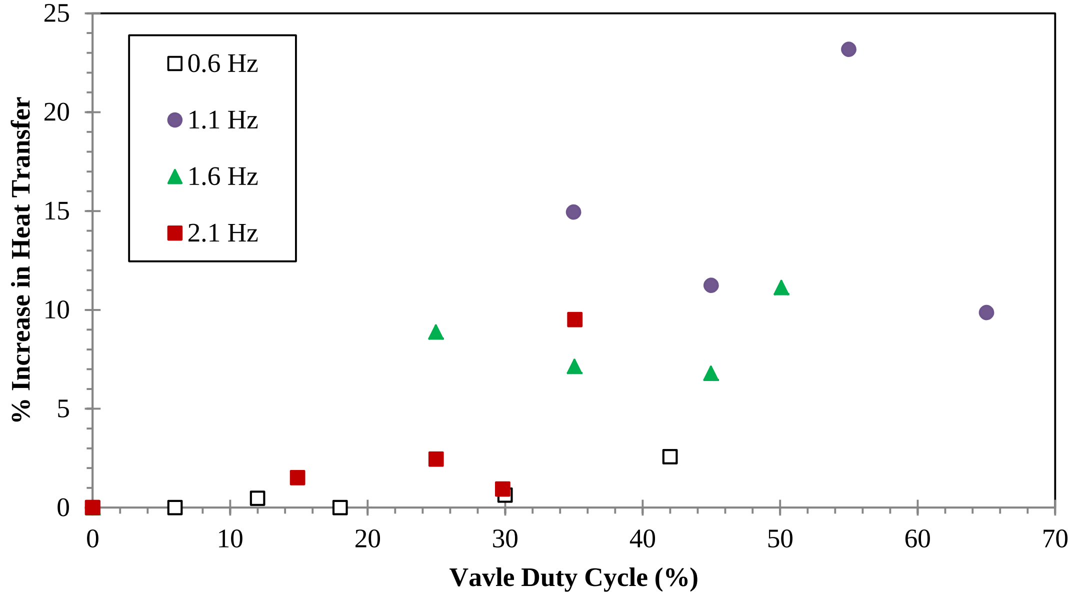

Figure 22. Percent Increase In Heat Transfer vs Valve Duty Cycle for 0.6 to 2.1 Hz.

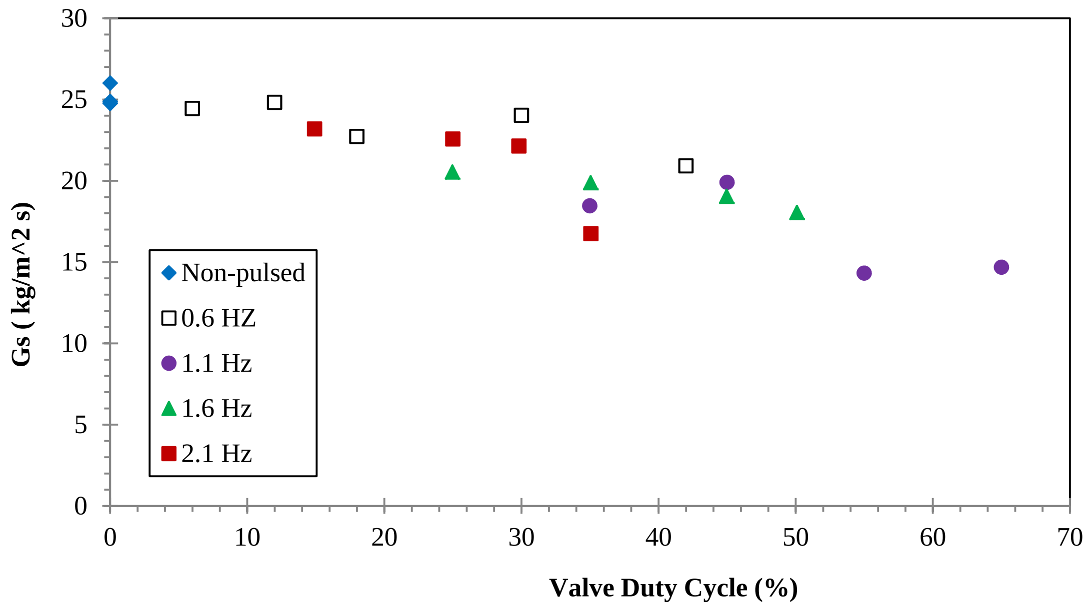

Figure 23. Solids Recirculation Rates vs Valve Duty Cycle for 0.6 to 2.1 Hz

Increasing valve cycle time also decreased recirculation rates as shown in Figure 23. There was some variation in velocity for this test series; this was the result of having to estimate the orifice plate differential pressure from an oscillating gauge during the test, after data reduction it was found that U_o varied from 2.58 m/s to 3.10 m/s. Further testing would require a more accurate real time estimate of U_o during operation to avoid this issue.

Experiment 27 was performed by pulsing the fast bed air between 1 Hz and 3 Hz with a valve duty cycle of 50% and pulse widths set accordingly. Velocity was reduced slightly to 2.7 m/s and the solids recirculation valve was fully open. The first test condition was performed with pulse valve off and the next 5 test were conducted in random order with frequencies varying from 0.8 Hz to 2.8 Hz and pulse widths from 625 ms to 179 ms respectively. U_0 remained between 2.64 m/s and 2.84 m/s while solids fractions ranged from .0137 to .0142, recirculation rates were between 17.1 kg/m^2 s and 21.4 kg/m^2 s. Heat transfer coefficients varied from 66.6 W/m^2 K to 71.0 W/m^2 K with the maximum occurring at a 1.3 Hz , this was an increase of 6.6 % over the non-pulsed test as shown in Figure 24.

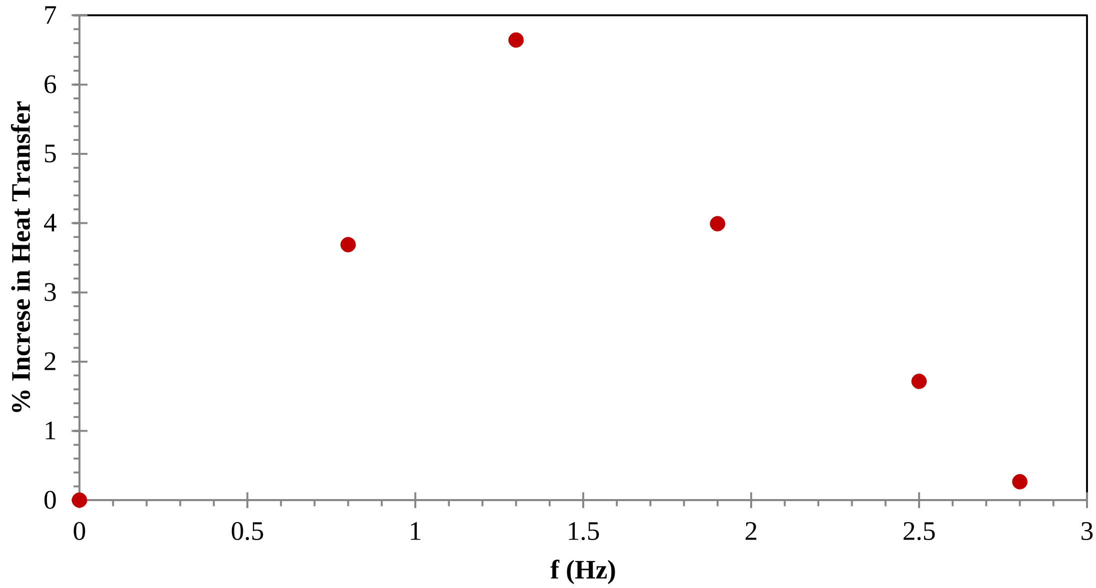

Figure 24. Percent Increase In Heat Transfer vs Frequency At 50% Valve Duty Cycle

Effect of Pulsed Air Supply on Heat Transfer for Modified Valve Configuration

Prior to experiment 28 the pulsing valve was modified. The vent side of the pulse valve was connected down stream of blocking valve V-16 using additional pipe fittings and a flexible steel line as shown in Figure 6 in CHAPTER II. The pulsing valve and controls were rewired so that the pulse valve operated in a normally open configuration. This would keep operation similar to the previous configuration and duty cycle would still represent the fraction time the valve was closed. After the new configuration was tested for proper function, experiment 28 was conducted. The purpose was to explore the effects of more abrupt pulsation from 0 Hz to 3 Hz at high solids fractions and a velocity of 2.8 m/s. The first test was performed with no pulsation and seven additional tests randomly performed with frequencies from 0 Hz to 3.1 Hz. U_o ranged from 2.56 m/s to 2.79 m/s, this variation was more than desired but the new pulsing configuration made it difficult to estimate actual velocity in the fast bed. Solid fractions were observed from .0130 to .0137. Recirculation rates were between 18.6 kg/m^2 s and 25.4 kg/m^2 s. Heat transfer coefficients varied from 63.5 W/m^2 K to 65.4 W/m^2 K. Analysis of the data produced from experiment 28 showed almost no effect of pulsation on heat transfer, further it was discovered that the pressure drop across the distributor plate in the fast bed was abnormally high and air temperatures at the orifice plate were elevated as a result of higher plenum pressures generated by the blower indicating a flow restriction. The bottom of the fast bed was disassembled and the screen in the distributor plate was found plugged with fine dust.

After the distributor plate assembly was cleaned and reinstalled experiment 29 was conducted. This series of tests were continued to explore the effect of pulsation on heat transfer in the fast bed, focusing on frequencies near 2 Hz and a valve duty cycle of 50%. The target for U_o was lowered slightly to 2.6 m/s and the solids recirculation valve was kept completely open to provide high solids fractions. The first test condition was conducted with the pulsing valve off and V-16 open, then the flow was diverted through the pulsing valve. The next four test were performed in random order at frequencies from 1.1 Hz to 2.6 Hz. U_o ranged from 2.53 m/s to 2.76 m/s and solids fractions at the midpoint ranged between .0134 and .0148. Recirculation rates were between 18.1 kg/m^2 s and 21.3 kg/m^2 s. Heat transfer coefficients varied from 63.7 W/m^2 K to 78.6 W/m^2 K with a maximum at 1.6 Hz. This was an increase of 23% over the non-pulsed test.

Figure 25 compares the heat transfer coefficients found in experiments 28 and 29. The pressure drop across the distributor plate was between 152 inWC and 162 inWC for experiments 28, after it was cleaned in experiment 29 at similar velocities the pressure drop was between 17 inWC and 27 inWC. The plugged distributor plate had dampened the effect of pulsed flow in the fast bed, after it was cleaned the heat transfer was significantly improved between 1 and 2 Hz.

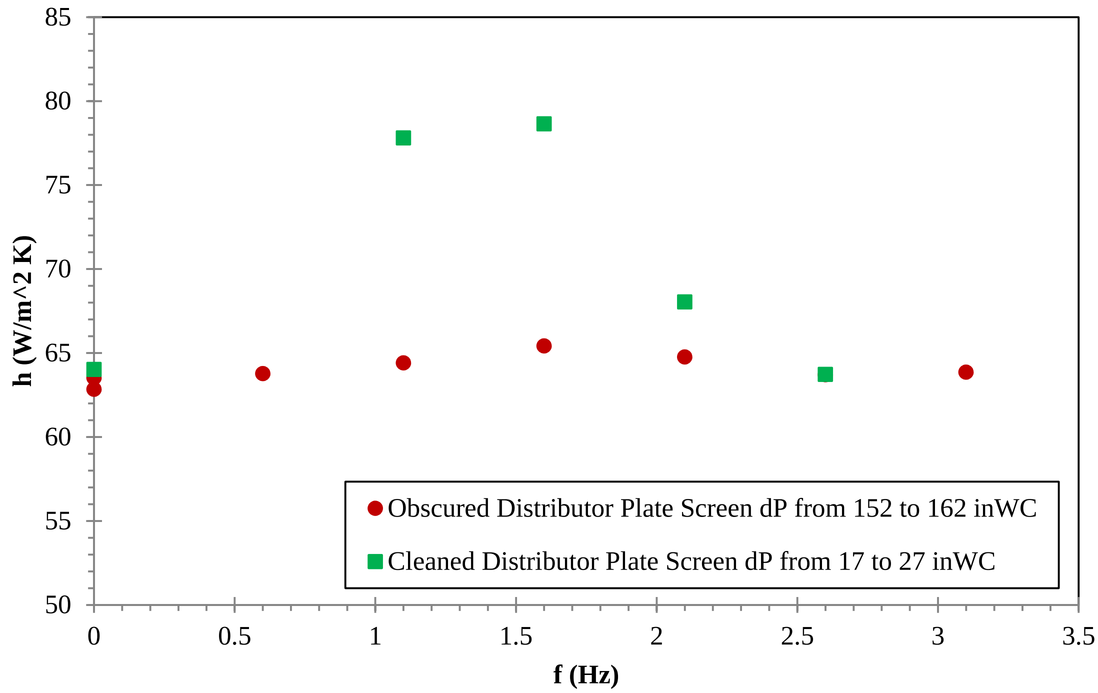

Figure 25. Effect of High Distributor Plate Pressure Drop On Pulsed-Flow Heat Transfer

The goal of experiment 30 was to continue to investigate frequencies between 1 Hz and 2.5 Hz with a pulse valve duty cycle of 50% at U_0 = 2.8 m/s and high solids fractions. The first test was performed with the pulse valve off followed by six test conditions at frequencies between 0.8 Hz and 2.5 Hz in random order. Pulse width was reduced to 350 ms for tests C and F in order to maintain U_o this corresponds to valve duty cycles of 35% and 28% respectively. U_o varied from 2.75 m/s to 2.98 m/s and solids fractions from .0133 to .0141. Recirculation rates were between 22.7 kg/m^2 s and 18.1 kg/m^2 s. Heat transfer coefficients varied from 62.1 W/m^2 K to 69.0 W/m^2 K with a maximum at 1.5 Hz. This was an increase of 23% over the non-pulsed test.

The goal of experiment 31 was to evaluate heat transfer of the probe near 2 Hz at U_o= 2.8 m/s and minimize variations in velocity and solids fraction as much as possible between test conditions. To help eliminate the variation in velocity from one test to another, the National Instruments program was used to export several minutes data for the orifice plate differential pressure measured by dPIR 301, this data was recorded at 0.5 second intervals and could be used to more accurately estimate U_o. The first test was performed with the pulse valve off followed by four test conditions at frequencies between 1.2 Hz and 2.1 Hz in random order with the valve duty cycle at 50%. U_o varied from 2.74 m/s to 2.84 m/s and solids fractions from .0132 to .0139. Recirculation rates were between 16.9 kg/m^2s and 23.3 kg/m^2s. Heat transfer coefficients varied from 62.0W/m^2 K to 68.0 W/m^2 K with a maximum at 1.2 Hz.

Experiment 32 was similar to the previous experiment with pulse frequencies near 2 Hz but U_0 reduced to 2.5 m/s The first test was performed with the pulse valve off followed by four test conditions at frequencies between 1.2 Hz and 2.2 Hz in random order. The valve duty cycle was set at 50%. U_o varied from 2.61m/s to 2.32 m/s and solids fractions from .0126 to .0139. Recirculation rates were between 10.5 kg/m^2 s and 20.2 kg/m^2 s. Heat transfer coefficients varied from 62.07W/m^2 K to 82.5 W/m^2 K with a maximum at 1.2 Hz. This was an increase of 32.9% over the non-pulsed test as shown in Figure 26.

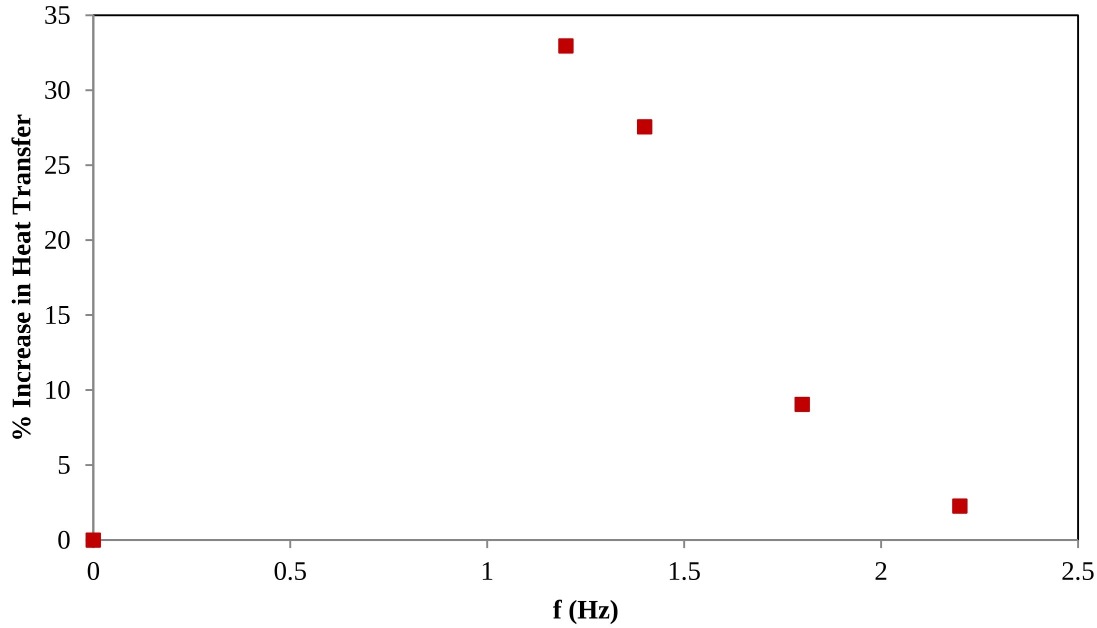

Figure 26. Percent Increase In Heat Transfer vs Frequency for $2.32 < U_o < 2.61$ m/s

Additional Pulsed Air Testing

Experiment 33 was conducted to explore the repeatability of the system, U_0 and the solids fraction at the midpoint of the fast bed would remain constant and test conditions would alternate between pulsed and non-pulsed operation. U_0 varied from 2.58 m/s to 2.67 m/s and solids fraction from .0131 to .0137. Pulsed tests were conducted at 1.3 Hz and 385 ms which gives a valve duty cycle of 50%. Six tests were performed with recirculation rates between 16.6 kg/m^2 s and 20.6 kg/m^2 s. Heat transfer coefficients varied from 62.2 W/m^2 K to 67.9 W/m^2 K with a maximum at 1.3 Hz.

In experiment 34 all tests were performed with the pulsing valve operating at 1.5 Hz and a pulse width of 333 ms. Solids fractions would be maintained constant and U_o varied from 2.4/s to 3.2m/s. Seven tests were performed with solids fractions from .0124 to .0134 and U_o observed from 2.40 m/s to 3.12 m/s. Recirculation rates were between 13.6 kg/m^2 s and 24.3 kg/m^2 s. Heat transfer coefficients varied from 58.4 W/m^2 K to 63.3 W/m^2 K with the maximum heat transfer occurring at the lowest velocity. Overall the heat transfer increases were low in comparison to previous results, it was discovered in post processing that the differential pressure across the distributor plate was high and steadily increasing over the duration of the experiment indicating it was becoming blinded off. Results from this experiment mirrored previous experiments where high a pressure drop across distributor plate had reduced the effect of pulsation on heat transfer.

Experiment 35 was conducted to explore the repeatability of the system, U_0 and the solids fraction at the midpoint of the fast bed would remain constant and test conditions would alternate between pulsed and non-pulsed operation. Prior to this experiment the bottom of the fast bed was disassembled and the distributor plate screen was cleaned and re-installed. Pulsed tests were conducted at 1.5 Hz and 333 ms, which gives a valve duty cycle of 50%. U_0 varied from 2.57 m/s to 2.77 m/s and the solids fraction from .0134to .0158. Six tests were performed with recirculation rates between 15.9 kg/m^2 s and 19.1 kg/m^2 s. Heat transfer coefficients varied from 61.2 W/m^2 K to 83.5 W/m^2.

Experiment 36 was performed to explore higher frequencies of pulsation with the pulsing valve in the second configuration. The valve was operated from 0 Hz to 6 Hz with U_o constant near 2.6 m/s. Seven tests were performed were U_0 varied from 2.57 m/s to 2.68

m/s and solids fraction from .0129 to .0137. Recirculation rates were between 22.2 kg/m^2 s and 14.7 kg/m^2 s. Heat transfer coefficients varied from 62.6 W/m^2 K to 63.5 W/m^2. Heat transfer was unaffected by pulsation over 2.5 hz, the maximum frequency obtainable in this configuration was 6 Hz and was a mechanical limitation of the pulsing valve. In the second configuration higher backpressure on the valve diaphragm made reliability a problem over 6 Hz.

Further Discussion of Combined Results

The combined results for all non-pulsed tests show a strong correlation between heat transfer coefficients and the solids fraction as shown in Figure 27. Overall solids fractions were observed from 0 to 0 .0154 with velocities from 1.98 m/s to 4.04 m/s and recirculation rates from 0 to 27.6 kg/m^2 s. The maximum heat transfer observed was 74.1 W/m^2 K at a solids fraction of .0152 and recirculation rate of 25.3 kg/m^2 s at a superficial velocity of 2.80 m/s. Figure 28 shows the correlation between the heat transfer coefficient and the solids recirculation rates.

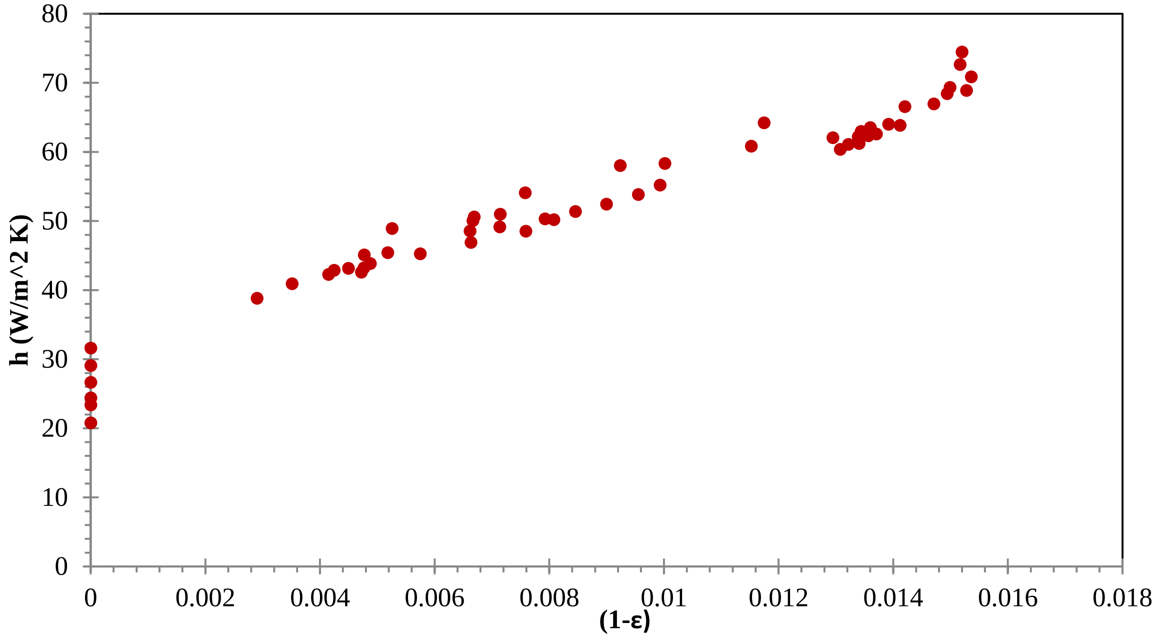

Figure 27. Average Heat Transfer Coefficient vs. Solids Fraction for All Tests Where f = 0, 2.0 m/s < U_o < 4.0 m/s, 0 < G_s < 27.6 kg/m^2 s

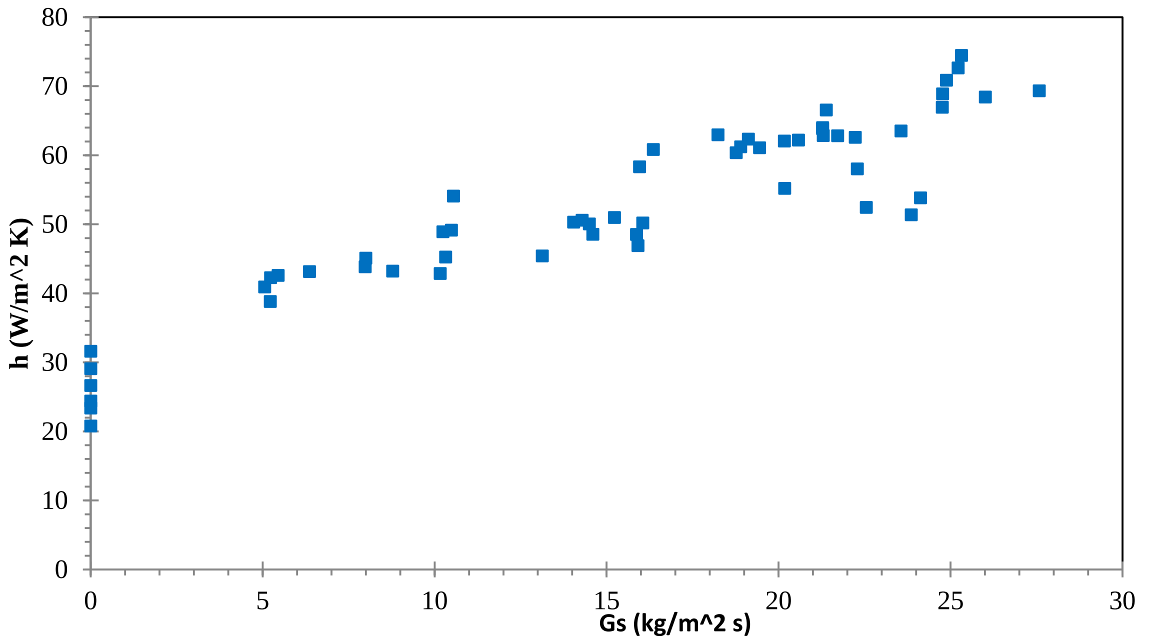

Figure 28. Average Heat Transfer Coefficients vs Solids Recirculation Rates for f = 0, 2.0 m/s < U_o < 4.0 m/s, 0 < (1-ε) < .0154

Correlations derived for heat transfer at the outer wall of a fast bed do not apply directly to this study, however these correlations proposed by Fraley (1983), Divilio and Boyd (1994), and others suggest a relationship between suspension density and heat transfer of the form shown below.

$$h = a\, {\rho_{sus}}^{b} \tag{5.1}$$

The suspension density is found by Equation 5.2

$$\rho_{sus} = \varepsilon\, \rho_g + (1 - \varepsilon)\rho_s \tag{5.2}$$

Taking the natural log of each side of Equation 5.1 and rearranging yields Equation 5.3

$$\ln(h) = \ln(a) + b\, ln(\rho_{sus}) \tag{5.3}$$

Coefficients for the non-pulsed heat transfer data were found by plotting natural log of the heat transfer coefficient versus the natural log of the suspension density as shown in Figure 29. Tests performed with no solids fractions were omitted. A line of best fit with slope, *b*, was found to be .45. The y-intercept, *ln(a)*, was found to be 2.587 which gives *a* equal to 13.3.

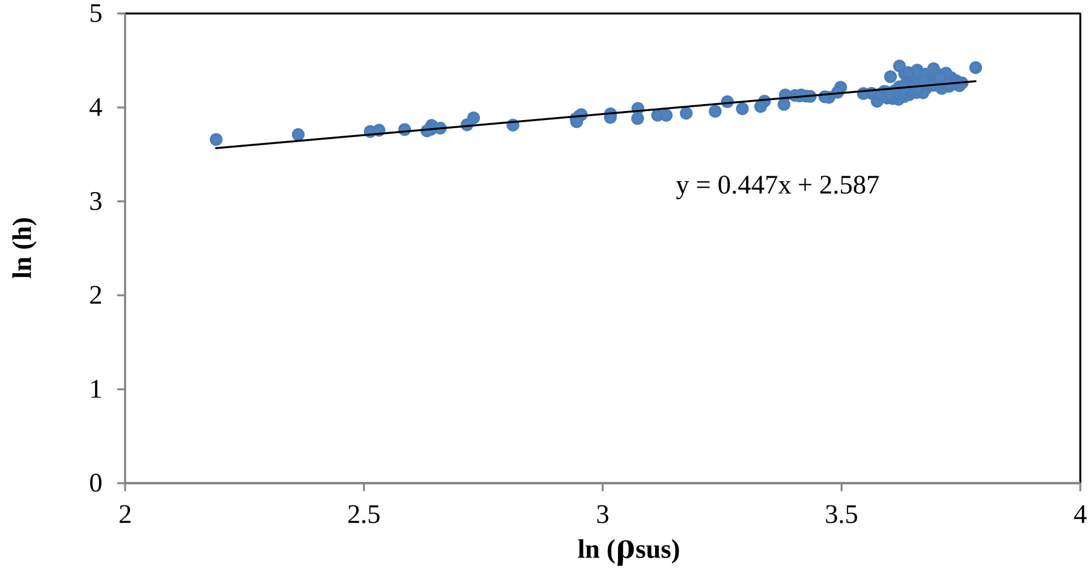

Figure 29. Log of Heat Transfer Coefficient vs Log of Suspension Density, f = 0.

Applying the coefficients *a* and *b* to Equation 5.1 gives the following correlation.

$$h = 13.3\ \rho_{sus}^{\ .45} \tag{5.4}$$

Figure 30 shows a parity plot of the experimental data and values calculated from the proposed correlation for a cylindrical heater suspended along the axis at a height of 1.7 m with Uo between 2 m/s and 4 m/s and solids fractions from .0029 to .0154. This correlation predicted within ±10% of the experimental values for non-pulsed tests. This correlation under predicts the heat transfer coefficient for pulsed flow tests with low distributor plate pressure drops.

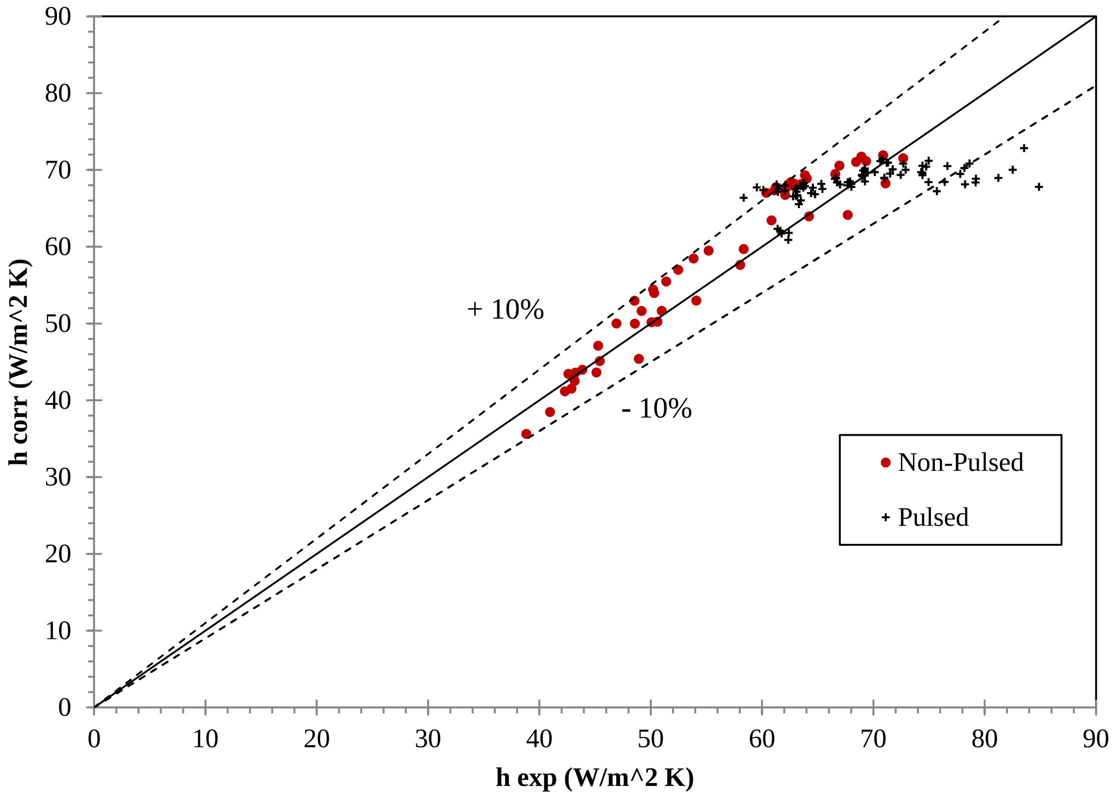

Figure 30. Parity Plot of Calculated Values (Eq. 5.4) vs Experimental Data Heat Transfer

Sundaresan and Kolar (2013) proposed a correlation for their axial heat transfer data and data from similar tests performed by Ahn and Han (1997) and Wu et al. (1989). Their correlation relates the Reynolds number of the emulsion to the Nusselt number of an annular pipe and predicted results within ±30% for emulsion Reynolds numbers between 9.7 x10^4 and 1.7 x10^6 and $H_t/(D_b\text{-}d_{htr})$ between 6.6 and 27.7.

$$\frac{h(D_b - d_{htr})}{Ke} = 32.282\left[\frac{Uo(D_b - d_{htr})\rho e}{\mu e}\right]^{.195}\left[\frac{H_t}{D_b - d_{htr}}\right]^{-.348} \qquad (5.5)$$

where U_o = Superficial velocity in the fast bed
h= Average heat transfer coefficient
K_e = Thermal conductivity of the emulsion

μe = viscosity of the emulsion
Ht = Length of the heater probe
D_b = Diameter of the fast bed
d_{htr} = Diameter of the heater probe

To estimate the properties of the solids emulsion they also used the relationship proposed by Wirth and Seiter (1991) to determine the voidage in the core of a fast bed along the axis.

$$\varepsilon_{axis} = 1 - 0.8(1 - \varepsilon) \tag{5.6}$$

Calculated values of heat transfer coefficients from Equation 5.5 were compared to experimental results as shown Figure 31. This correlation over predicts for most of the data from this study. The ratio of heater diameter to annular diameter in the present investigation is outside of the allowable range for the correlation proposed by Sundaresan and Kolar. The ratio $H_t/(D_b\text{-}d_{htr})$ is 3.5 for the set up in this study which is below the minimum of 6.6 recommended by the authors. In addition the heater used by Sundaresan and Kolar was supported from the top only and flow impinged directly on the bottom side of the heater. The heater used in this study is supported by rod of the same diameter from top to bottom and therefore the hydrodynamic boundary layer is significantly different. In order to compare results from this system to the correlation proposed by Sundaresan and Kolar the heater must be of smaller diameter and supported from the top only.

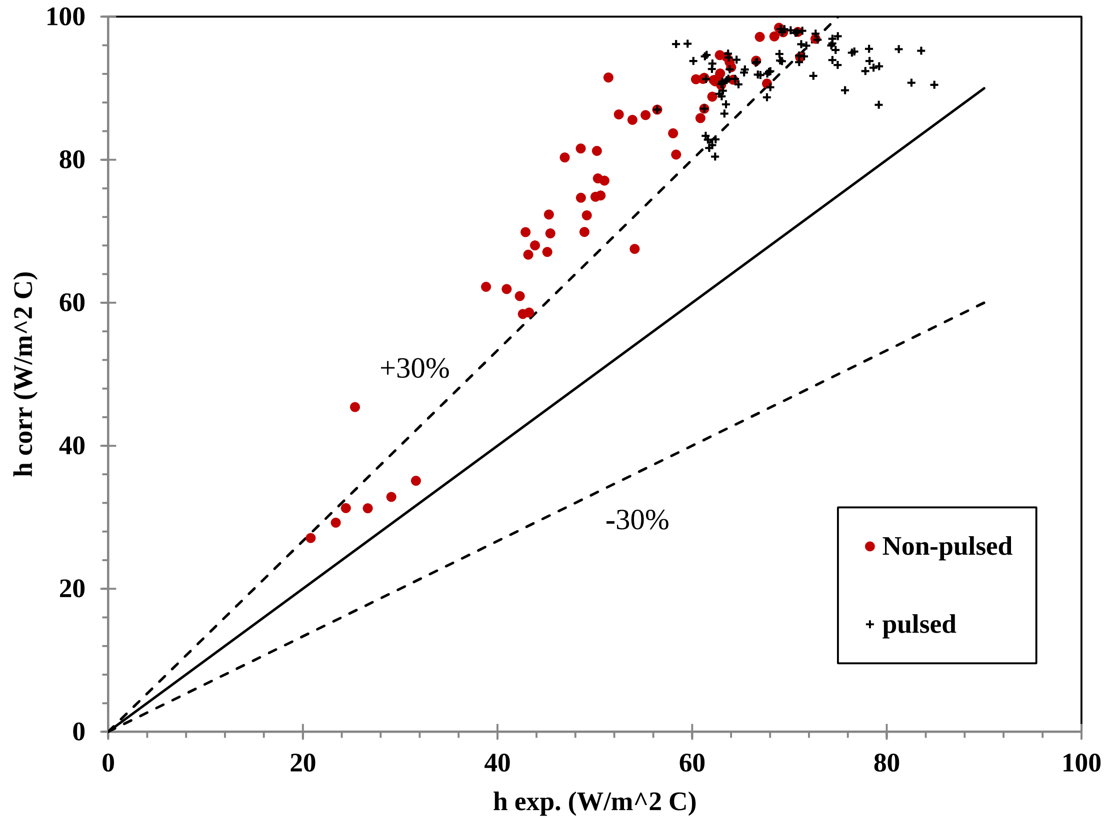

Figure 31. Parity Plot of Experimental Values vs. Eq. 5.5 Sundaresan and Kolar (2013)

Figure 32 shows the solids fraction compared to the average heat transfer coefficients for all tests performed. Pulsed flow tests did not show any significant impact of changing the pulse valve configuration. This is significant because it suggests that effective pulsed flow does not require completely stopping the flow to affect heat transfer. This would allowing some minimum fluidizing gas to pass through the distributor plate at all times.

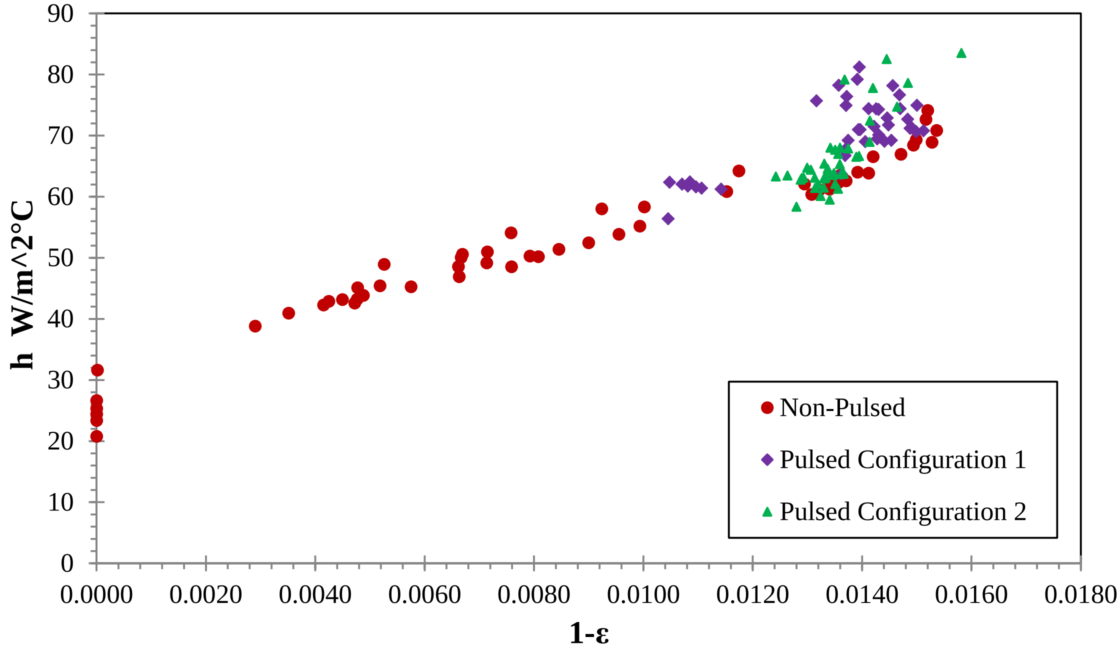

Figure 32. Average Heat Transfer Coefficient vs Solids Fraction for All Tests

Figure 33 shows the percent increase in heat transfer of the pulsed flow tests over the non-pulsed tests in each experiment. The most effective frequencies for increasing heat transfer were between 1 Hz and 2 Hz with a maximum heat transfer at 1.1 Hz for the first configuration and 1.5 Hz in the second configuration. No significant effect was found above 2.5 Hz, and the first valve configuration was able to run as fast as 12 Hz, the second configuration limited operation to 6 Hz.

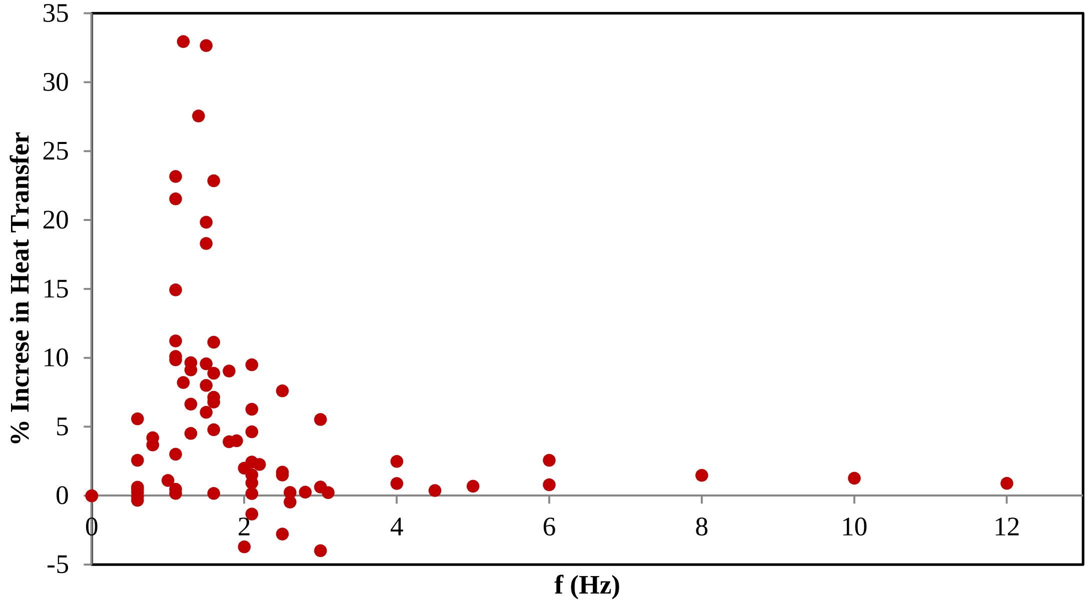

Figure 33. Percent Increase In Heat Transfer vs Frequency for All Pulsed Flow Tests.

A significant amount of variation in heat transfer can be seen in pulsed flow tests at frequencies between 1 Hz and 2 Hz. The pressure drop across the distributor plate was found to have a significant impact on the heat transfer for pulsed flow testes between 1 Hz and 2 Hz. Figure 34 shows relevant data compared from pulsed flow tests conducted between 0.6 Hz and 2.6 Hz separated into three groups based on the pressure drop across the distributor plate. The first group with an average pressure drop of 30 inWC has the largest increase in heat transfer, doubling the pressure drop across the distributor plate reduces effect of pulsation by roughly two thirds. The test conditions in this group are similar with the only exception being the distributor plate pressure drop.

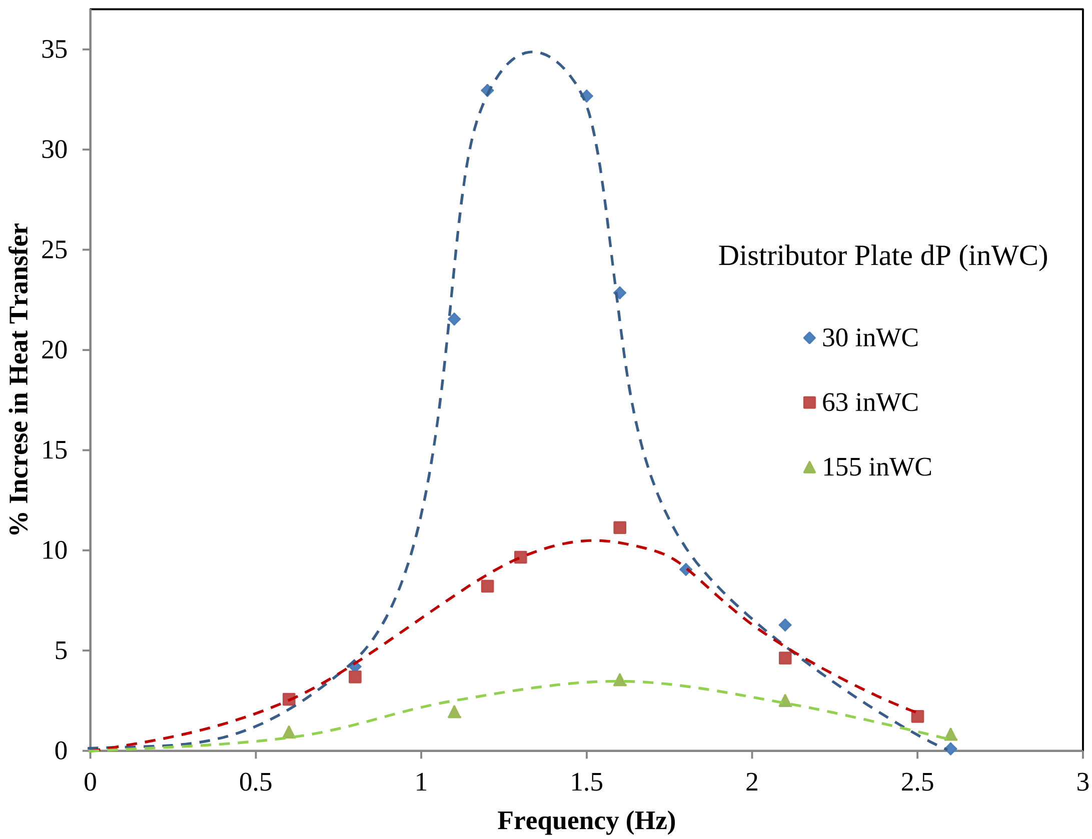

Figure 34. Effect of Distributor Plate Pressure Drop On Heat Transfer Increase Observed During Pulsed Flow Testing From 0.6 to 2.6 Hz.

The effect of distributor plate pressure drop is shown in Figure 35 for pulsed flow tests at frequencies between 1.3 and 1.6 Hz and velocities from 2.6 m/s to 2.9 m/s. The increase in heat transfer by pulsation is strongly reduced by increasing distributor plate pressures. The pressure drop was caused by the gradual buildup of dust on the mesh screen and was not a control variable. Analysis of the data from static pressure transducer for the fast bed show that high distributor plate pressure drops dampened the pressure oscillations observed.

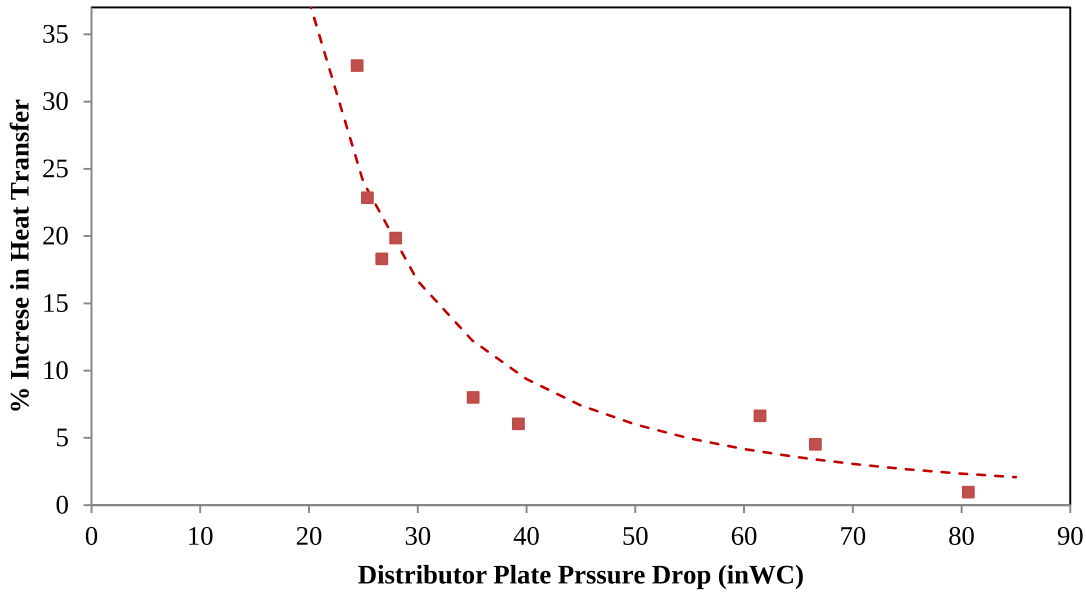

Figure 35. Heat Transfer Increase vs Pressure Drop Across The Distributor Plate for pulsed flow tests, 1.3 < f < 1.6 Hz, 2.6 < U_0 < 2.8 m/s, .013 < (1-ε) < .015

The most effective pulsed flow tests occurred between 1 and 2 Hz when the distributor plate pressure drop was less than 30 inWC. For tests performed with higher pressure drops the increase caused by pulsation was reduced significantly.

Figure 36 compares pulsed flow data for low distributor plate pressure drop of less than 30 inWC to non-pulsed tests. At the same solids fraction higher heat transfer was observed for pulsed flow compared to non-pulsed tests. The average increase observed by pulsing the air supply with frequency varying between 1 and 2 Hz was 20 % over non-pulsed tests for this group. Figure 37 shows the solids recirculation rates for this same test group. Comparing the trends from Figures 36 and 37 it can be seen that higher solids fractions are present for pulsed flow tests compared to non-pulsed flow when both flows were operating at the same recirculation rate. This observation explains explain the higher heat transfer coefficients observed in pulsed flows with lower recirculation rates since heat transfer is highly dependent on the solids fraction.

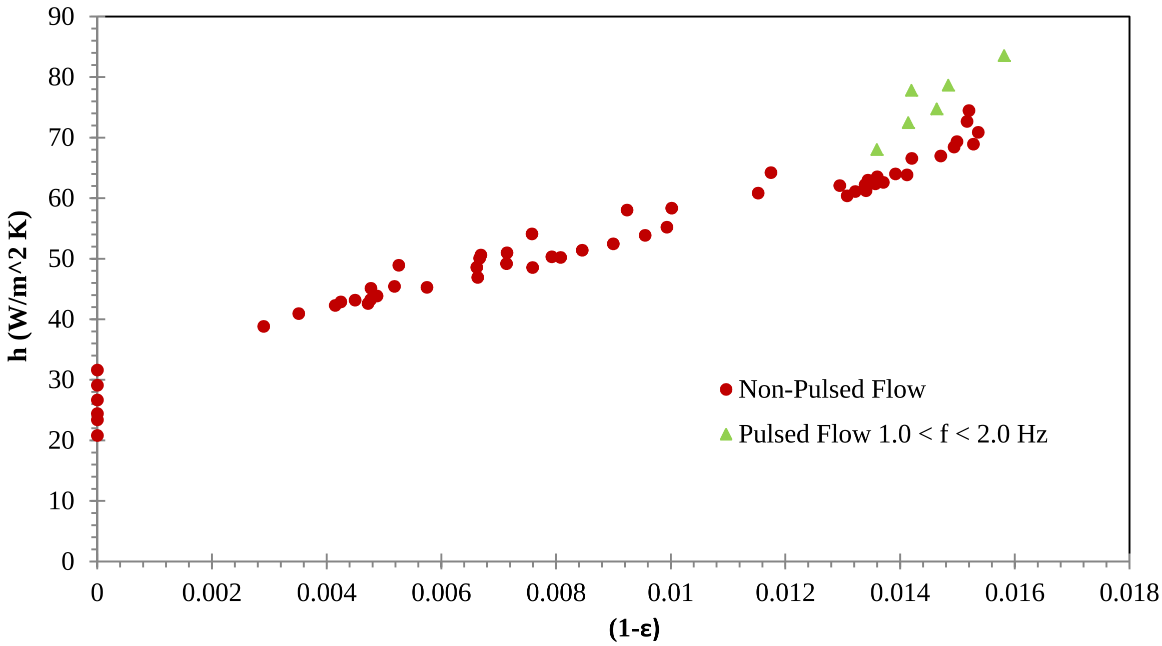

Figure 36. Heat Transfer Coefficient as a Function of Solids Fraction with Distributor Plate Pressure Drop Less Than 30 inWC.

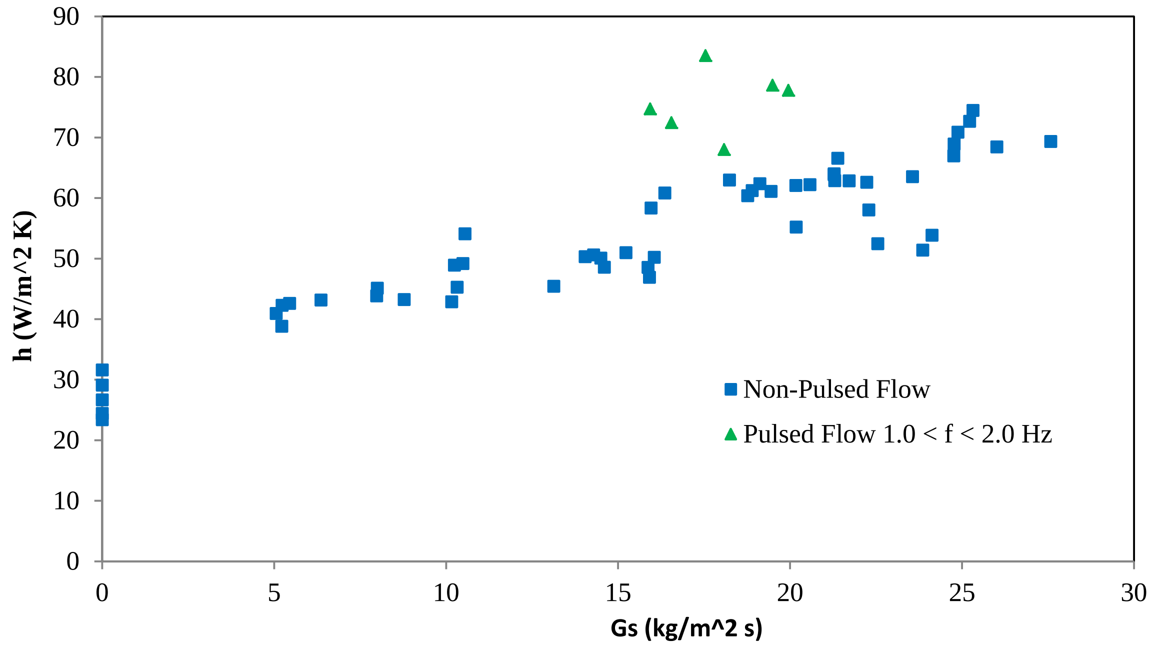

Figure 37. . Heat Transfer Coefficient As a Function of Solids Recirculation Rates With Distributor Plate Pressure Drop Less Than 30 inWC.

The increase in heat transfer coefficients caused by pulsing the flow at a frequency *f*, can be modeled using a Gaussian curve expressed by Equation 5.7. The ratio of pulsed heat transfer to non-pulsed heat transfer was plotted and the coefficients *a*, *b*, and *c* for equation 5.7 were determined to provide a fit to the curve as shown in Figure 38.

$$\frac{h_f}{h_{f=0}} = 1 + ae^{\frac{-(f-b)^2}{2c^2}} \tag{5.7}$$

where h_f = Heat transfer coefficient with pulsed flow
$h_{f=0}$ = Heat transfer coefficient with non-pulsed flow
a = Amplitude of the curve peak
f = Pulse frequency
b = Frequency at curve peak
c = Factor determining curve width

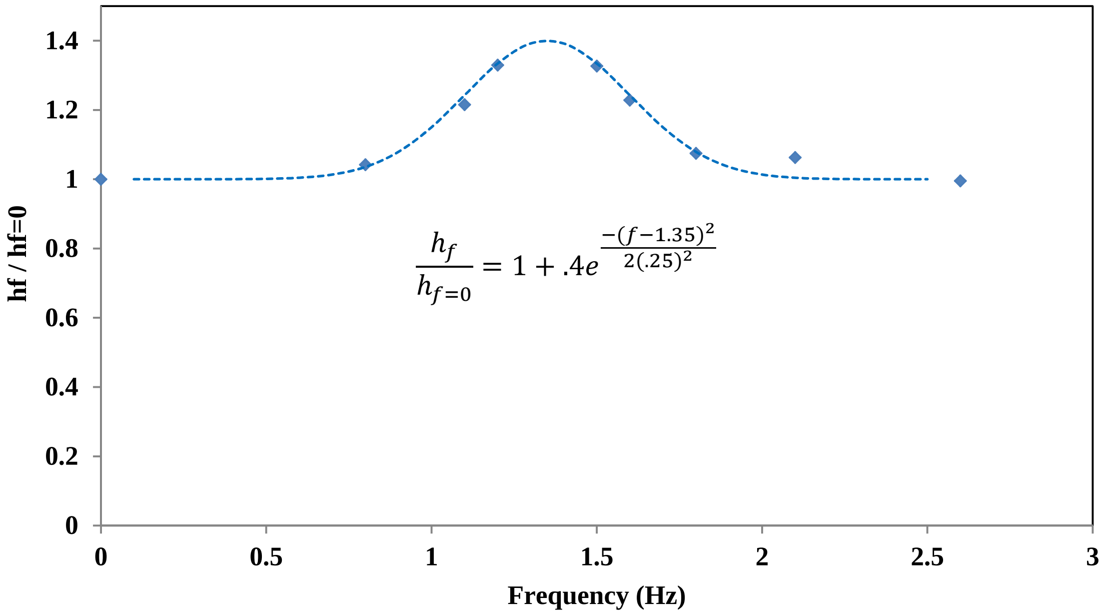

Figure 38. Equation 5.7 Fit to the Data for Distributor Plate Pressure Drop Less Than 30 inWC, a = .4, b = 1.35, c = .25

Equation 5.8 to predict the effect of pulsed flow on the heat transfer coefficient in the case of low distributor plate pressure drops as shown in figure 5.8.

$$h_f = h_{f=o} * \left(1 + .4e^{\frac{-(f-1.35)^2}{.125}}\right) \quad (5.8)$$

The proposed correlation in Equation 5.8 predicts the heat transfer for frequencies from 0 to 2.6 Hz and distributor plate pressure drops less than 35 inWC. The parity plot shown in Figure 39 shows good agreement between values calculated from Equation 5.8 and the limited experimental data available. More data is needed with constant low pressure drop across the distributor plate. To do so would require the system be modified to prevent the slow buildup on the distributor plate screen. The adverse effect of the pressure drop on the pulsed flow data was not recognized until near the end of testing, and further modifications to the system were not feasible.

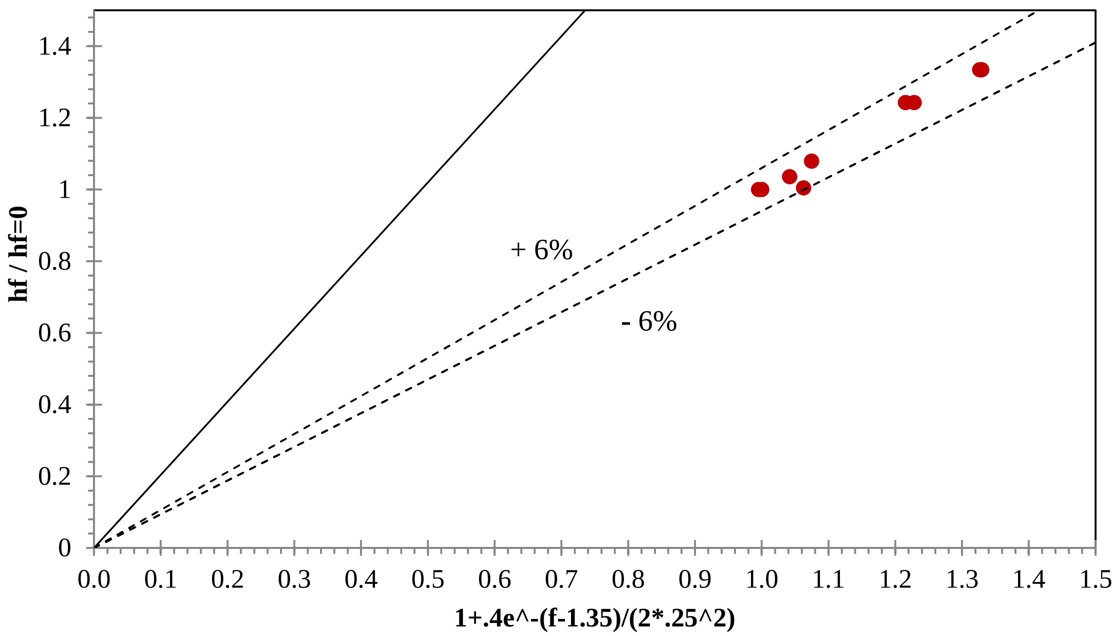

Figure 39. Parity Plot of Proposed Correlation (Eq. 5.8) Vs Experimental Data for Pulsed Flow Tests Where Distributor Plate Pressure Drop Was Less Than 30 inWC for Frequencies From 0 to 2.6 Hz

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Overall the system was able to measure heat transfer at velocities from 1.98 m/s to 4.04 m/s with solids fraction as high as .0154 and recirculation rates as high as 27.6 kg/m^2 s in normal non-pulsed operation. The highest heat transfer observed in normal operation was 74.1 W/m^2 K. Heat transfer on a cylindrical heater suspended axially in the fast bed was found to vary directly with solids fraction of the emulsion near the heater and inversely with the superficial velocity in the fast bed. Solids fractions and recirculation rates were limited by the pressure difference between the standpipe and the bottom of the fast bed limiting the range of velocities that could be achieved at higher solids fractions in the midpoint of the fast bed.

Pulsed operation had a significant impact on heat transfer from 1 Hz to 2 Hz with a maximum heat transfer coefficient found at 1.1 Hz of 84.9 W/m^2 K. Heat transfer was increased by a maximum of 32.7 % over normal operation by pulsing the fast bed at 1.5 Hz when distributor plate pressure drops were low. Pulsed flow resulted in higher solids fractions compared to non-pulsed flows with the same recirculation rate. Fine particulate built up on the distributor plate screen causing an increase in the pressure drop across the distributor plate. Pulsed flows with higher distributor plate pressure drops did not produce significant heat transfer increases. Best results for pulsed flow heat transfer were obtained when distributor plate pressure drops were less than 30 inWC.

Equation 5.4 was developed to predict heat transfer within ± 10% for non-pulsed flows with U_o from 2.0 to 4.0 m/s. and solids fractions up to .0154.

$$h = 13.3\, \rho_{sus}{}^{.45} \tag{5.4}$$

Equation 5.8 was developed to predict heat transfer for pulsed flow testing for cases with low distributor plate pressure drop. Limited data was available and further work will be needed to verify the proposed correlation.

$$h_f = h_{f=o} * \left(1 + .4e^{\frac{-(f-1.35)^2}{.125}}\right) \tag{5.8}$$

The use of 100 μm spherical aluminum powder was successful in reducing the problem caused by static discharge in the circulating fluid bed system used in this study. In addition higher solids fractions were achievable at the midpoint of the bed and problems with moisture and loss of compressed air flow were eliminated due to the lower air flow requirements to fluidize the material in the stand pipe. .

Recommendations

It is recommended the future work evaluate alternate heat transfer geometry at different orientations and locations axially and radially within the bed to further understand the overall effect of pulsed flow on heat transfer in a fast bed. Other materials such as sand and other particle sizes should also be evaluated. Wall heat transfer effects are of particular importance to further study to determine the effect of pulsed flow in large scale combustors. Further work should also involve evaluating the effects of pulsed flow on combustion, catalytic reactions, and solids elutriation in circulating systems with a fast bed.

To increase the operating range of the fluidized bed system used in this study the solids crossover should be modified with an eductor or similar device to move solids from the stand pipe into the fast bed independent of the pressure difference between the two. Additionally a data acquisition system with sufficient sampling speed should be used to resolve the pressure waves created in the fast bed. As results showed in this study the pressure drop across the distributor plate influenced pulsed flow heat transfer results and further investigations into effect of distributor plate design on pulsed flow operation should be considered. Attrition rates in the cyclones were not rigorously evaluated in this study. Future studies on this system should consider the effect of elutriation and overall solids inventory on experimental results. A bag house filter system should also be considered to fully recover any solids that attrite past the cyclones.

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APPENDIX A – TABULATED RESULTS

Experiment No.		6			6	
Test No.		A			B	
Start Date		2/5/15			2/5/15	
Data Averages Start Time		18:28:10			18:38:04	
Data Averages End Time		18:35:03			18:40:29	
Test Duration		0:06:53			0:02:25	
No. of data points averaged		80			28	
Pressures (PSIG)						
Orifice Static	1.95	±	2.32	2.40	±	0.03
Fast Bed Static	0.03	±	0.69	0.11	±	0.03
Differential Pressures (inH2O)						
Orifice	4.92	±	5.35	6.02	±	1.41
Distributor Plate	37.56	±	48.45	52.33	±	7.87
Lower Fast Bed	12.47	±	10.64	9.64	±	4.34
Middle Fast Bed	0.23	±	1.43	0.38	±	0.06
Upper Fast Bed	0.06	±	1.64	0.00	±	0.37
Stand Pipe	30.91	±	41.73	29.91	±	1.74
Temperatures (°C)						
Gas Inlet	22.57	±	11.77	24.15	±	0.37
Fast Bed 103	22.59	±	11.75	24.20	±	0.31
Fast Bed 104	22.59	±	11.77	24.16	±	0.09
Ave. Fast Bed		22.59			24.18	
Fast Bed Top	22.65	±	112.30	24.15	±	0.62
Stand Pipe Air	20.63	±	26.88	20.43	±	0.02
Probe 1	21.64	±	11.19	22.98	±	0.00
Probe 2	21.72	±	11.21	23.04	±	0.00
Probe 3	21.80	±	11.27	23.14	±	0.00
Probe 4	21.87	±	11.32	N/A	±	0.00
Ave. Probe		21.76			23.05	
Operating Parameter						
Frequency (Hz)		0			0	
Pulse Width (ms)		0			0	
Valve Duty Cycle %		0			0	
Air Density in Orifice (kg/m^3)		1.352			1.382	
Air Density in Fast Bed (kg/m^3)		1.196			1.196	
Orifice Flow (kg/s)		0.0176			0.0196	
Uo (m/s)		1.88			2.10	
Solids Fraction (1-ε)		0.0052			0.0088	
Heater Voltage (V)		0.000			0.000	
Heater Current (A)		0.000			0.000	
Power (W)		0.000			0.000	
Ave Heat Transfer Coefficient (W/m*K)		0.00			0.00	
Solids Recirculation Rate (kg/m^2*s)		N/A			N/A	

Experiment No.	7	7	8	8
Test No.	A	B	C	D
Start Date	2/16/15	2/16/15	2/16/15	2/16/15
Data Averages Start Time	11:45:30	13:00:00	14:21:34	14:52:13
Data Averages End Time	12:07:01	13:25:00	14:32:27	14:59:56
Test Duration	0:21:31	0:25:00	0:10:53	0:07:43
No. of data points averaged	254	293	127	90
Pressures (PSIG)				
Orifice Static	3.27 ± 0.01	3.52 ± 0.01	3.75 ± 0.02	3.48 ± 0.01
Fast Bed Static	0.05 ± 0.00	0.08 ± 0.03	0.16 ± 0.06	0.11 ± 0.04
Differential Pressures (inH2O)				
Orifice	10.95 ± 0.17	11.36 ± 0.60	11.23 ± 0.42	10.99 ± 0.20
Distributor Plate	87.84 ± 0.27	91.67 ± 0.73	90.68 ± 3.65	88.83 ± 0.88
Lower Fast Bed	0.00 ± 0.07	1.21 ± 0.40	3.51 ± 1.68	1.59 ± 0.46
Middle Fast Bed	0.00 ± 0.00	0.23 ± 0.04	0.54 ± 0.11	0.34 ± 0.05
Upper Fast Bed	0.00 ± 0.01	0.16 ± 0.20	0.40 ± 0.45	0.26 ± 0.19
Stand Pipe	2.16 ± 0.09	38.25 ± 6.63	33.26 ± 5.31	34.08 ± 2.51
Temperatures (°C)				
Gas Inlet	51.43 ± 0.08	39.72 ± 0.54	N/A ± 0.00	N/A ± 0.00
Fast Bed 103	48.08 ± 0.12	39.36 ± 11.66	N/A ± 0.00	N/A ± 0.00
Fast Bed 104	48.04 ± 0.20	39.42 ± 5.15	N/A ± 0.00	N/A ± 0.00
Ave. Fast Bed	48.06	39.39	N/A	N/A
Fast Bed Top	46.94 ± 0.22	39.54 ± 0.40	N/A ± 0.00	N/A ± 0.00
Stand Pipe Air	22.74 ± 0.08	21.51 ± 0.17	N/A ± 0.00	N/A ± 0.00
Probe 1	106.60 ± 0.23	69.07 ± 1.17	57.20 ± 0.30	65.25 ± 0.33
Probe 2	110.38 ± 0.23	71.65 ± 1.88	59.40 ± 0.47	67.60 ± 0.34
Probe 3	106.72 ± 0.23	70.26 ± 1.34	59.16 ± 0.33	66.60 ± 0.36
Probe 4	99.22 ± 0.22	66.10 ± 1.29	57.01 ± 0.20	63.30 ± 0.25
Ave. Probe	105.73	69.27	58.19	65.69
Operating Parameter				
Frequency (Hz)	0	0	0	0
Pulse Width (ms)	0	0	0	0
Valve Duty Cycle %	0	0	0	0
Air Density in Orifice (kg/m^3)	1.330	1.399	N/A	N/A
Air Density in Fast Bed (kg/m^3)	1.103	1.136	N/A	N/A
Orifice Flow (kg/s)	0.0260	0.0271	N/A	N/A
Uo (m/s)	3.01	3.05	N/A	N/A
Solids Fraction (1-ε)	0.0000	0.0053	0.0125	0.0079
Heater Voltage (V)	13.550	13.550	13.550	13.550
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.488	25.488	25.488	25.488
Ave Heat Transfer Coefficient (W/m*K)	25.35	48.93	N/A	N/A
Solids Recirculation Rate (kg/m^2*s)	0.00	10.24	15.15	15.64

Experiment No.		10			10	
Test No.		A			B	
Start Date		2/26/15			2/26/15	
Data Averages Start Time		16:45:01			17:20:07	
Data Averages End Time		17:07:37			17:40:42	
Test Duration		0:22:36			0:20:35	
No. of data points averaged		271			247	
Pressures (PSIG)						
Orifice Static	3.63	±	0.02	3.68	±	0.03
Fast Bed Static	0.09	±	0.03	0.11	±	0.04
Differential Pressures (inH2O)						
Orifice	11.52	±	0.20	11.42	±	0.32
Distributor Plate	96.57	±	0.78	96.05	±	1.40
Lower Fast Bed	0.94	±	0.45	1.52	±	0.81
Middle Fast Bed	0.21	±	0.02	0.29	±	0.05
Upper Fast Bed	0.14	±	0.19	0.21	±	0.80
Stand Pipe	36.27	±	5.33	35.23	±	3.54
Temperatures (°C)						
Gas Inlet	51.81	±	1.49	53.66	±	0.64
Fast Bed 103	34.60	±	1.31	36.29	±	0.65
Fast Bed 104	34.63	±	1.31	36.33	±	0.62
Ave. Fast Bed		34.62			36.31	
Fast Bed Top	34.57	±	1.35	36.35	±	0.54
Stand Pipe Air	23.58	±	3.07	31.06	±	1.88
Probe 1	66.58	±	1.51	64.55	±	0.33
Probe 2	69.95	±	1.53	67.94	±	0.54
Probe 3	68.29	±	1.54	66.88	±	0.39
Probe 4	63.24	±	1.51	62.65	±	0.34
Ave. Probe		67.02			65.51	
Operating Parameter						
Frequency (Hz)		0			0	
Pulse Width (ms)		0			0	
Valve Duty Cycle %		0			0	
Air Density in Orifice (kg/m^3)		1.354			1.351	
Air Density in Fast Bed (kg/m^3)		1.154			1.149	
Orifice Flow (kg/s)		0.0269			0.0267	
Uo (m/s)		2.98			2.98	
Solids Fraction (1-ε)		0.0048			0.0067	
Heater Voltage (V)		13.550			13.550	
Heater Current (A)		1.881			1.881	
Power (W)		25.488			25.488	
Ave Heat Transfer Coefficient (W/m*K)		45.12			50.07	
Solids Recirculation Rate (kg/m^2*s)		8.00			14.50	

Experiment No.	11	11	11	11	11
Test No.	A	B	C	D	E
Start Date	2/27/15	2/27/15	2/27/15	2/27/15	2/27/15
Data Averages Start Time	14:00:23	14:45:04	15:20:07	15:55:13	16:29:19
Data Averages End Time	14:29:00	15:04:50	15:39:55	16:18:02	16:50:55
Test Duration	0:28:37	0:19:46	0:19:48	0:22:49	0:21:36
No. of data points averaged	114	79	79	91	86
Pressures (PSIG)					
Orifice Static	3.96 ± 0.03	4.08 ± 0.02	4.06 ± 0.02	4.04 ± 0.01	4.02 ± 0.01
Fast Bed Static	0.10 ± 0.03	0.15 ± 0.05	0.13 ± 0.03	0.11 ± 0.04	0.08 ± 0.02
Differential Pressures (inH2O)					
Orifice	11.18 ± 0.21	10.86 ± 0.25	10.96 ± 0.16	11.03 ± 0.18	11.10 ± 0.15
Distributor Plate	103.08 ± 0.87	101.25 ± 1.63	103.04 ± 0.97	104.01 ± 1.03	104.92 ± 0.72
Lower Fast Bed	1.46 ± 0.47	3.14 ± 0.82	2.23 ± 0.54	1.50 ± 0.42	0.94 ± 0.35
Middle Fast Bed	0.29 ± 0.02	0.51 ± 0.07	0.40 ± 0.04	0.31 ± 0.03	0.22 ± 0.02
Upper Fast Bed	0.24 ± 0.26	0.42 ± 0.32	0.31 ± 0.25	0.28 ± 0.24	0.21 ± 0.18
Stand Pipe	34.76 ± 5.14	32.76 ± 4.70	33.75 ± 5.06	34.75 ± 3.93	35.12 ± 6.38
Temperatures (°C)					
Gas Inlet	57.21 ± 1.04	58.03 ± 0.47	59.30 ± 0.36	60.29 ± 0.47	61.31 ± 0.48
Fast Bed 103	37.74 ± 0.93	38.89 ± 0.36	40.05 ± 0.23	40.90 ± 0.34	41.61 ± 0.20
Fast Bed 104	37.73 ± 0.93	38.91 ± 0.36	40.06 ± 0.25	40.90 ± 0.33	41.57 ± 0.17
Ave. Fast Bed	37.74	38.90	40.06	40.90	41.59
Fast Bed Top	37.61 ± 0.95	38.96 ± 0.37	40.05 ± 0.23	40.81 ± 0.31	41.36 ± 0.19
Stand Pipe Air	19.29 ± 0.17	19.93 ± 0.16	20.43 ± 0.14	20.80 ± 0.09	20.93 ± 0.08
Probe 1	65.52 ± 1.15	59.18 ± 0.22	63.89 ± 0.20	68.44 ± 0.16	73.00 ± 0.45
Probe 2	69.01 ± 1.15	62.21 ± 0.42	67.21 ± 0.26	71.89 ± 0.42	76.56 ± 0.44
Probe 3	68.07 ± 1.14	61.75 ± 0.22	66.66 ± 0.22	71.03 ± 0.14	75.19 ± 0.40
Probe 4	63.90 ± 1.12	58.85 ± 0.26	63.23 ± 0.28	66.94 ± 0.12	70.33 ± 0.40
Ave. Probe	66.63	60.50	65.24	69.57	73.77
Operating Parameter					
Frequency (Hz)	0	0	0	0	0
Pulse Width (ms)	0	0	0	0	0
Valve Duty Cycle %	0	0	0	0	0
Air Density in Orifice (kg/m^3)	1.357	1.362	1.355	1.350	1.344
Air Density in Fast Bed (kg/m^3)	1.144	1.143	1.137	1.132	1.128
Orifice Flow (kg/s)	0.0265	0.0262	0.0262	0.0263	0.0263
Uo (m/s)	2.96	2.93	2.95	2.97	2.98
Solids Fraction (1-ε)	0.0067	0.0118	0.0092	0.0071	0.0052
Heater Voltage (V)	13.550	13.550	13.550	13.550	13.550
Heater Current (A)	1.881	1.881	1.881	1.881	1.881
Power (W)	25.488	25.488	25.488	25.488	25.488
Ave Heat Transfer Coefficient (W/m*K)	50.60	67.69	58.03	50.98	45.42
Solids Recirculation Rate (kg/m^2*s)	14.29	23.26	22.29	15.23	13.13

	A			B			C			D			E		
Experiment No.	12			12			12			12			12		
Test No.	A			B			C			D			E		
Start Date	3/12/15			3/12/15			3/12/15			3/12/15			3/12/15		
Data Averages Start Time	16:00:04			17:40:01			18:40:14			19:16:00			20:00:02		
Data Averages End Time	16:20:02			18:02:00			19:00:04			19:37:04			20:15:03		
Test Duration	0:19:58			0:21:59			0:19:50			0:21:04			0:15:01		
No. of data points averaged	235			255			226			247			175		
Pressures (PSIG)															
Orifice Static	4.28	±	0.02	4.11	±	0.06	3.95	±	0.02	3.95	±	0.04	3.85	±	0.01
Fast Bed Static	0.15	±	0.05	0.16	±	0.08	0.10	±	0.04	0.07	±	0.02	0.06	±	0.00
Differential Pressures (inH2O)															
Orifice	11.10	±	0.21	10.00	±	0.98	10.74	±	0.22	10.70	±	0.14	10.58	±	0.14
Distributor Plate	107.58	±	1.35	96.72	±	9.25	103.66	±	1.19	103.71	±	0.71	102.46	±	0.27
Lower Fast Bed	2.92	±	0.77	5.98	±	4.52	1.39	±	0.40	0.81	±	0.29	0.00	±	0.09
Middle Fast Bed	0.51	±	0.08	0.59	±	0.12	0.29	±	0.04	0.21	±	0.02	0.00	±	0.00
Upper Fast Bed	0.40	±	0.39	0.42	±	0.48	0.21	±	0.26	0.16	±	0.19	0.00	±	0.01
Stand Pipe	32.63	±	8.92	35.92	±	2.03	40.21	±	4.34	40.64	±	3.17	2.40	±	0.09
Temperatures (°C)															
Gas Inlet	56.68	±	0.47	56.96	±	0.54	57.25	±	0.76	59.06	±	0.98	54.91	±	0.20
Fast Bed 103	39.51	±	0.36	40.03	±	0.28	39.83	±	0.62	41.61	±	0.59	51.36	±	0.30
Fast Bed 104	39.52	±	0.36	40.05	±	0.90	39.83	±	0.59	41.57	±	0.58	51.22	±	0.30
Ave. Fast Bed	39.52			40.04			39.83			41.59			51.29		
Fast Bed Top	39.54	±	0.34	40.11	±	0.26	39.74	±	0.53	41.29	±	0.37	49.51	±	0.37
Stand Pipe Air	21.59	±	0.11	21.91	±	0.06	20.94	±	0.19	21.50	±	0.17	23.03	±	0.14
Probe 1	60.86	±	0.37	59.49	±	0.54	69.02	±	0.33	74.29	±	0.26	80.35	±	0.33
Probe 2	64.04	±	0.64	62.40	±	0.81	72.51	±	0.61	77.88	±	0.26	83.03	±	0.34
Probe 3	63.59	±	0.48	61.80	±	0.59	71.35	±	0.39	76.30	±	0.28	81.66	±	0.31
Probe 4	60.42	±	0.53	58.73	±	0.58	66.83	±	0.33	71.22	±	0.30	77.76	±	0.23
Ave. Probe	62.23			60.60			69.93			74.92			80.70		
Operating Parameter															
Frequency (Hz)	0			0			0			0			0		
Pulse Width (ms)	0			0			0			0			0		
Valve Duty Cycle %	0			0			0			0			0		
Air Density in Orifice (kg/m^3)	1.382			1.368			1.356			1.348			1.358		
Air Density in Fast Bed (kg/m^3)	1.140			1.139			1.136			1.127			1.092		
Orifice Flow (kg/s)	0.0267			0.0252			0.0260			0.0259			0.0258		
Uo (m/s)	2.99			2.83			2.93			2.93			3.02		
Solids Fraction (1-ε)	0.0117			0.0136			0.0066			0.0049			0.0000		
Heater Voltage (V)	13.520			13.550			13.550			13.550			9.500		
Heater Current (A)	1.881			1.881			1.881			1.881			1.318		
Power (W)	25.431			25.488			25.488			25.488			12.521		
Ave Heat Transfer Coefficient (W/m*K)	64.22			71.09			48.57			43.85			24.42		
Solids Recirculation Rate (kg/m^2*s)	N/A			23.38			14.60			7.98			0.00		

Experiment No.		13			13			13	
Test No.		A			B			C	
Start Date		3/23/15			3/23/15			3/23/15	
Data Averages Start Time		12:23:01			13:32:03			14:05:03	
Data Averages End Time		12:43:02			13:53:00			14:26:03	
Test Duration		0:20:01			0:20:57			0:21:00	
No. of data points averaged		236			247			249	
Pressures (PSIG)									
Orifice Static	2.08	±	0.01	4.17	±	0.02	6.80	±	0.04
Fast Bed Static	0.04	±	0.02	0.07	±	0.02	0.13	±	0.05
Differential Pressures (inH2O)									
Orifice	5.57	±	0.21	11.31	±	0.19	17.64	±	0.25
Distributor Plate	53.90	±	0.59	110.49	±	0.81	180.54	±	1.74
Lower Fast Bed	0.87	±	0.27	0.62	±	0.27	0.68	±	0.51
Middle Fast Bed	0.21	±	0.03	0.19	±	0.03	0.20	±	0.03
Upper Fast Bed	0.10	±	0.12	0.17	±	0.16	0.24	±	0.28
Stand Pipe	38.97	±	3.30	39.53	±	5.55	38.05	±	6.54
Temperatures (°C)									
Gas Inlet	48.05	±	0.45	60.68	±	0.54	75.26	±	3.81
Fast Bed 103	34.21	±	0.26	40.14	±	0.87	46.20	±	2.93
Fast Bed 104	34.28	±	0.26	40.10	±	0.84	46.14	±	2.86
Ave. Fast Bed		34.25			40.12			46.17	
Fast Bed Top	34.29	±	0.28	39.88	±	0.68	46.11	±	2.72
Stand Pipe Air	20.73	±	0.11	21.14	±	0.09	21.29	±	0.06
Probe 1	67.01	±	0.58	73.34	±	0.84	77.83	±	2.44
Probe 2	70.82	±	0.51	76.99	±	0.87	81.24	±	2.44
Probe 3	69.48	±	0.50	75.28	±	0.78	79.36	±	2.46
Probe 4	64.61	±	0.61	70.03	±	0.70	74.13	±	2.57
Ave. Probe		67.98			73.91			78.14	
Operating Parameter								Heat Transfer Data Excluded	
Frequency (Hz)		0			0			0	
Pulse Width (ms)		0			0			0	
Valve Duty Cycle %		0			0			0	
Air Density in Orifice (kg/m^3)		1.255			1.358			1.482	
Air Density in Fast Bed (kg/m^3)		1.151			1.132			1.116	
Orifice Flow (kg/s)		0.0180			0.0267			0.0348	
Uo (m/s)		2.00			3.01			3.99	
Solids Fraction (1-ε)		0.0048			0.0045			0.0046	
Heater Voltage (V)		13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		43.24			43.16			45.63	
Solids Recirculation Rate (kg/m^2*s)		9.24			9.36			10.06	

Experiment No.	13			13			13		
Test No.	D			E			F		
Start Date	3/23/15			3/23/15			3/23/15		
Data Averages Start Time	14:40:01			15:35:03			16:10:03		
Data Averages End Time	15:03:00			15:55:03			16:30:01		
Test Duration	0:22:59			0:20:00			0:19:58		
No. of data points averaged	272			236			236		
Pressures (PSIG)									
Orifice Static	6.94	±	0.03	4.23	±	0.02	2.64	±	0.12
Fast Bed Static	0.19	±	0.07	0.11	±	0.05	0.06	±	0.09
Differential Pressures (inH2O)									
Orifice	17.40	±	0.30	10.84	±	0.31	5.36	±	1.81
Distributor Plate	179.21	±	1.66	106.26	±	1.23	51.41	±	12.84
Lower Fast Bed	1.75	±	0.82	2.05	±	0.57	12.91	±	8.73
Middle Fast Bed	0.37	±	0.05	0.41	±	0.05	0.39	±	0.08
Upper Fast Bed	0.36	±	0.46	0.31	±	0.29	0.17	±	0.51
Stand Pipe	34.81	±	5.30	33.74	±	6.07	26.53	±	5.49
Temperatures (°C)									
Gas Inlet	80.24	±	0.67	63.43	±	0.87	53.44	±	1.74
Fast Bed 103	50.66	±	1.18	44.72	±	1.01	39.83	±	1.37
Fast Bed 104	50.60	±	1.15	44.72	±	0.95	39.91	±	1.35
Ave. Fast Bed	50.63			44.72			39.87		
Fast Bed Top	50.42	±	1.14	44.74	±	1.00	40.02	±	1.34
Stand Pipe Air	21.54	±	0.11	21.65	±	0.08	21.69	±	0.05
Probe 1	78.16	±	0.67	70.54	±	1.39	62.53	±	2.09
Probe 2	81.54	±	0.75	73.96	±	1.82	65.55	±	2.47
Probe 3	80.36	±	0.72	73.24	±	1.37	64.71	±	2.18
Probe 4	75.98	±	0.73	69.47	±	1.32	61.42	±	2.26
Ave. Probe	79.01			71.80			63.55		
Operating Parameter							Heat Transfer Data Excluded		
Frequency (Hz)	0			0			0		
Pulse Width (ms)	0			0			0		
Valve Duty Cycle %	0			0			0		
Air Density in Orifice (kg/m^3)	1.471			1.351			1.275		
Air Density in Fast Bed (kg/m^3)	1.105			1.119			1.133		
Orifice Flow (kg/s)	0.0344			0.0261			0.0178		
Uo (m/s)	3.99			2.98			2.01		
Solids Fraction (1-ε)	0.0085			0.0096			0.0090		
Heater Voltage (V)	13.520			13.520			13.520		
Heater Current (A)	1.881			1.881			1.881		
Power (W)	25.431			25.431			25.431		
Ave Heat Transfer Coefficient (W/m*K)	51.39			53.85			61.60		
Solids Recirculation Rate (kg/m^2*s)	23.86			24.13			9.83		

Experiment No.	14	14	14	14
Test No.	A	B	C	D
Start Date	4/27/15	4/27/15	4/27/15	4/27/15
Data Averages Start Time	11:45:03	13:30:01	15:30:04	16:25:02
Data Averages End Time	12:05:01	13:50:05	15:50:02	16:45:02
Test Duration	0:19:58	0:20:04	0:19:58	0:20:00
No. of data points averaged	236	239	239	239
Pressures (PSIG)				
Orifice Static	2.30 ± 0.08	3.01 ± 0.03	4.11 ± 0.02	5.34 ± 0.02
Fast Bed Static	0.05 ± 0.06	0.06 ± 0.03	0.08 ± 0.03	0.09 ± 0.03
Differential Pressures (inH2O)				
Orifice	5.48 ± 1.52	8.36 ± 0.19	11.24 ± 0.21	14.36 ± 0.44
Distributor Plate	51.85 ± 10.17	78.43 ± 0.87	107.82 ± 0.69	141.80 ± 1.12
Lower Fast Bed	5.18 ± 4.49	1.42 ± 0.36	0.94 ± 0.38	0.47 ± 0.33
Middle Fast Bed	0.33 ± 0.05	0.31 ± 0.03	0.25 ± 0.03	0.18 ± 0.03
Upper Fast Bed	0.16 ± 0.42	0.23 ± 0.17	0.23 ± 0.18	0.20 ± 0.24
Stand Pipe	31.12 ± 7.61	33.43 ± 3.90	31.41 ± 3.79	30.25 ± 4.39
Temperatures (°C)				
Gas Inlet	47.42 ± 0.31	52.89 ± 0.33	61.09 ± 0.31	69.17 ± 0.76
Fast Bed 103	31.73 ± 0.26	36.16 ± 0.23	42.02 ± 0.39	46.76 ± 1.00
Fast Bed 104	31.80 ± 0.28	36.23 ± 0.22	42.00 ± 0.36	46.67 ± 0.93
Ave. Fast Bed	31.77	36.19	42.01	46.71
Fast Bed Top	31.87 ± 0.26	36.19 ± 0.23	41.87 ± 0.31	46.54 ± 0.78
Stand Pipe Air	21.33 ± 0.05	21.57 ± 0.06	22.17 ± 0.06	22.33 ± 0.08
Probe 1	57.49 ± 0.26	64.84 ± 0.25	73.56 ± 0.30	80.34 ± 1.15
Probe 2	60.91 ± 0.62	68.35 ± 0.86	77.14 ± 0.28	83.92 ± 1.03
Probe 3	60.15 ± 0.40	67.31 ± 0.23	75.61 ± 0.19	82.05 ± 0.89
Probe 4	56.37 ± 0.33	62.92 ± 0.25	70.61 ± 0.16	76.61 ± 0.86
Ave. Probe	58.73	65.86	74.23	80.73
Operating Parameter				
Frequency (Hz)	0	0	0	0
Pulse Width (ms)	0	0	0	0
Valve Duty Cycle %	0	0	0	0
Air Density in Orifice (kg/m^3)	1.274	1.305	1.351	1.406
Air Density in Fast Bed (kg/m^3)	1.162	1.146	1.126	1.110
Orifice Flow (kg/s)	0.0180	0.0225	0.0265	0.0306
Uo (m/s)	1.98	2.51	3.01	3.52
Solids Fraction (1-ε)	0.0076	0.0071	0.0057	0.0042
Heater Voltage (V)	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	54.09	49.17	45.27	42.88
Solids Recirculation Rate (kg/m^2*s)	10.55	10.49	10.32	10.16

Experiment No.	15	15	15	15	15
Test No.	A	B	C	D	E
Start Date	5/25/15	5/25/15	5/25/15	5/25/15	5/25/15
Data Averages Start Time	12:30:02	13:20:03	14:15:01	15:30:03	16:10:03
Data Averages End Time	12:50:02	13:40:02	14:45:02	15:50:04	16:30:02
Test Duration	0:20:00	0:19:59	0:30:01	0:20:01	0:19:59
No. of data points averaged	234	232	353	236	239
Pressures (PSIG)					
Orifice Static	3.09 ± 0.05	3.43 ± 0.02	4.14 ± 0.02	4.59 ± 0.02	5.18 ± 0.05
Fast Bed Static	0.10 ± 0.05	0.09 ± 0.03	0.11 ± 0.04	0.11 ± 0.04	0.12 ± 0.05
Differential Pressures (inH2O)					
Orifice	8.20 ± 0.84	9.67 ± 0.20	11.56 ± 0.25	12.71 ± 0.32	14.35 ± 0.32
Distributor Plate	74.51 ± 7.54	87.66 ± 1.02	106.12 ± 1.44	118.20 ± 1.16	135.41 ± 1.57
Lower Fast Bed	3.10 ± 2.15	1.68 ± 0.46	1.70 ± 0.64	1.51 ± 0.55	1.23 ± 0.50
Middle Fast Bed	0.43 ± 0.06	0.34 ± 0.04	0.35 ± 0.06	0.33 ± 0.04	0.29 ± 0.04
Upper Fast Bed	0.29 ± 0.27	0.26 ± 0.22	0.30 ± 0.30	0.30 ± 0.29	0.29 ± 0.29
Stand Pipe	34.24 ± 2.19	37.01 ± 2.91	35.94 ± 4.35	35.22 ± 3.03	34.51 ± 4.36
Temperatures (°C)					
Gas Inlet	54.92 ± 0.20	58.03 ± 0.20	62.58 ± 0.33	65.89 ± 0.17	69.29 ± 0.92
Fast Bed 103	36.90 ± 0.53	39.47 ± 0.47	42.46 ± 0.68	44.85 ± 0.31	46.86 ± 0.70
Fast Bed 104	36.95 ± 0.54	39.49 ± 0.47	42.45 ± 0.65	44.82 ± 0.30	46.80 ± 0.65
Ave. Fast Bed	36.93	39.48	42.46	44.83	46.83
Fast Bed Top	36.99 ± 0.54	39.49 ± 0.45	42.42 ± 0.62	44.78 ± 0.30	46.69 ± 0.62
Stand Pipe Air	23.26 ± 0.03	23.40 ± 0.08	23.55 ± 0.08	23.64 ± 0.06	23.77 ± 0.05
Probe 1	60.81 ± 0.39	67.52 ± 0.31	70.66 ± 0.54	74.15 ± 0.23	77.37 ± 0.70
Probe 2	64.05 ± 0.61	70.97 ± 0.51	74.06 ± 0.76	77.55 ± 0.33	80.76 ± 0.89
Probe 3	63.28 ± 0.40	69.94 ± 0.25	72.94 ± 0.51	76.27 ± 0.17	79.29 ± 0.54
Probe 4	59.78 ± 0.47	65.72 ± 0.33	68.62 ± 0.48	71.72 ± 0.14	74.46 ± 0.51
Ave. Probe	61.98	68.53	71.57	74.92	77.97
Operating Parameter					
Frequency (Hz)	0	0	0	0	0
Pulse Width (ms)	0	0	0	0	0
Valve Duty Cycle %	0	0	0	0	0
Air Density in Orifice (kg/m^3)	1.302	1.315	1.348	1.367	1.394
Air Density in Fast Bed (kg/m^3)	1.146	1.136	1.127	1.119	1.113
Orifice Flow (kg/s)	0.0223	0.0243	0.0269	0.0284	0.0305
Uo (m/s)	2.48	2.73	3.05	3.24	3.50
Solids Fraction (1-ε)	0.0100	0.0079	0.0081	0.0076	0.0066
Heater Voltage (V)	13.550	13.550	13.550	13.500	13.540
Heater Current (A)	1.881	1.881	1.881	1.881	1.881
Power (W)	25.488	25.488	25.488	25.394	25.469
Ave Heat Transfer Coefficient (W/m*K)	58.35	50.31	50.21	48.40	46.91
Solids Recirculation Rate (kg/m^2*s)	15.96	14.04	16.05	15.87	15.91

	A			B			C			D		
Experiment No.	16			16			16			16		
Test No.	A			B			C			D		
Start Date	5/28/15			5/28/15			5/28/15			5/28/15		
Data Averages Start Time	17:05:04			18:15:58			18:55:02			19:45:02		
Data Averages End Time	17:25:06			18:33:13			19:15:04			20:05:04		
Test Duration	0:20:02			0:17:15			0:20:02			0:20:02		
No. of data points averaged	236			200			229			233		
Pressures (PSIG)												
Orifice Static	1.95	±	0.02	2.82	±	0.01	3.82	±	0.01	4.96	±	0.01
Fast Bed Static	0.04	±	0.02	0.05	±	0.01	0.06	±	0.02	0.08	±	0.02
Differential Pressures (inH2O)												
Orifice	5.80	±	0.19	8.45	±	0.25	11.43	±	0.20	14.53	±	0.33
Distributor Plate	51.29	±	0.43	74.55	±	0.44	102.01	±	0.58	133.47	±	0.66
Lower Fast Bed	0.79	±	0.20	0.54	±	0.25	0.33	±	0.26	0.13	±	0.23
Middle Fast Bed	0.20	±	0.02	0.18	±	0.03	0.15	±	0.03	0.13	±	0.03
Upper Fast Bed	0.10	±	0.09	0.12	±	0.13	0.12	±	0.12	0.11	±	0.11
Stand Pipe	33.83	±	3.48	34.32	±	5.28	34.27	±	3.29	32.94	±	3.91
Temperatures (°C)												
Gas Inlet	46.19	±	0.40	52.25	±	0.09	58.18	±	0.54	66.34	±	0.44
Fast Bed 103	31.66	±	0.37	36.62	±	0.62	40.24	±	0.65	46.13	±	1.06
Fast Bed 104	31.72	±	0.36	36.60	±	0.56	40.14	±	0.64	45.76	±	1.00
Ave. Fast Bed	31.69			36.61			40.19			45.94		
Fast Bed Top	31.65	±	0.39	36.28	±	0.48	39.65	±	0.62	45.30	±	0.92
Stand Pipe Air	21.86	±	0.09	22.19	±	0.09	22.14	±	0.08	22.18	±	0.08
Probe 1	65.24	±	0.33	70.65	±	0.98	75.65	±	1.15	83.19	±	1.20
Probe 2	68.94	±	0.48	74.29	±	1.04	79.22	±	1.15	86.91	±	1.25
Probe 3	67.44	±	0.39	72.56	±	0.96	77.18	±	1.14	84.96	±	1.21
Probe 4	62.40	±	0.42	67.21	±	0.84	71.49	±	1.07	79.21	±	1.15
Ave. Probe	66.01			71.18			75.89			83.57		
Operating Parameter												
Frequency (Hz)	0			0			0			0		
Pulse Width (ms)	0			0			0			0		
Valve Duty Cycle %	0			0			0			0		
Air Density in Orifice (kg/m^3)	1.253			1.293			1.342			1.391		
Air Density in Fast Bed (kg/m^3)	1.161			1.143			1.131			1.112		
Orifice Flow (kg/s)	0.0184			0.0225			0.0267			0.0306		
Uo (m/s)	2.02			2.52			3.01			3.52		
Solids Fraction (1-ε)	0.0047			0.0041			0.0035			0.0029		
Heater Voltage (V)	13.550			13.550			13.550			13.540		
Heater Current (A)	1.881			1.881			1.881			1.881		
Power (W)	25.488			25.488			25.488			25.469		
Ave Heat Transfer Coefficient (W/m*K)	42.60			42.29			40.95			38.82		
Solids Recirculation Rate (kg/m^2*s)	5.45			5.23			5.05			5.22		

Experiment No.	17			17			17		
Test No.	A			B			C		
Start Date	6/3/15			6/3/15			6/3/15		
Data Averages Start Time	18:05:02			18:30:02			19:00:02		
Data Averages End Time	18:20:02			18:45:02			19:15:04		
Test Duration	0:15:00			0:15:00			0:15:02		
No. of data points averaged	180			180			179		
Pressures (PSIG)									
Orifice Static	1.80	±	0.01	2.65	±	0.02	3.67	±	0.02
Fast Bed Static	0.02	±	0.00	0.04	±	0.00	0.06	±	0.00
Differential Pressures (inH2O)									
Orifice	5.70	±	0.19	8.31	±	0.16	11.18	±	0.21
Distributor Plate	49.85	±	0.29	72.55	±	0.31	99.43	±	0.31
Lower Fast Bed	-0.10	±	0.02	-0.12	±	0.04	-0.14	±	0.06
Middle Fast Bed	0.00	±	0.00	0.00	±	0.00	0.00	±	0.00
Upper Fast Bed	-0.06	±	0.01	-0.06	±	0.01	-0.06	±	0.01
Stand Pipe	2.54	±	0.07	2.48	±	0.04	2.50	±	0.05
Temperatures (°C)									
Gas Inlet	44.35	±	0.34	49.24	±	0.98	56.52	±	0.84
Fast Bed 103	37.07	±	0.40	40.88	±	0.95	47.11	±	0.96
Fast Bed 104	37.19	±	0.45	40.77	±	0.93	46.82	±	0.98
Ave. Fast Bed	37.13			40.83			46.96		
Fast Bed Top	36.00	±	0.44	39.39	±	0.92	45.19	±	0.90
Stand Pipe Air	21.39	±	0.09	21.64	±	0.11	22.00	±	0.09
Probe 1	71.33	±	0.30	71.26	±	0.33	73.54	±	1.06
Probe 2	74.25	±	0.26	74.02	±	0.33	76.19	±	1.06
Probe 3	72.82	±	0.28	72.60	±	0.39	74.94	±	1.09
Probe 4	68.70	±	0.30	68.63	±	0.48	71.24	±	1.09
Ave. Probe	71.77			71.63			73.98		
Operating Parameter									
Frequency (Hz)	0			0			0		
Pulse Width (ms)	0			0			0		
Valve Duty Cycle %	0			0			0		
Air Density in Orifice (kg/m^3)	1.248			1.293			1.338		
Air Density in Fast Bed (kg/m^3)	1.139			1.127			1.107		
Orifice Flow (kg/s)	0.0182			0.0223			0.0263		
Uo (m/s)	2.04			2.53			3.04		
Solids Fraction (1-ε)	0.0000			0.0000			0.0000		
Heater Voltage (V)	9.530			9.530			9.530		
Heater Current (A)	1.318			1.318			1.318		
Power (W)	12.561			12.561			12.561		
Ave Heat Transfer Coefficient (W/m*K)	20.79			23.39			26.66		
Solids Recirculation Rate (kg/m^2*s)	0.00			0.00			0.00		

Experiment No.	17			17			17		
Test No.	D			E			F		
Start Date	6/3/15			6/3/15			6/3/15		
Data Averages Start Time	19:30:03			19:55:02			20:28:04		
Data Averages End Time	19:45:03			20:10:04			20:48:01		
Test Duration	0:15:00			0:15:02			0:19:57		
No. of data points averaged	177			179			237		
Pressures (PSIG)									
Orifice Static	4.76	±	0.02	5.98	±	0.02	4.69	±	0.02
Fast Bed Static	0.09	±	0.00	0.12	±	0.00	0.14	±	0.05
Differential Pressures (inH2O)									
Orifice	14.06	±	0.21	17.08	±	0.31	13.27	±	0.21
Distributor Plate	128.07	±	0.31	160.32	±	0.39	120.04	±	1.38
Lower Fast Bed	-0.16	±	0.08	-0.19	±	0.09	1.89	±	0.55
Middle Fast Bed	0.00	±	0.00	0.00	±	0.00	0.39	±	0.05
Upper Fast Bed	-0.06	±	0.02	-0.05	±	0.02	0.32	±	0.44
Stand Pipe	2.43	±	0.07	2.44	±	0.13	31.38	±	4.54
Temperatures (°C)									
Gas Inlet	63.96	±	0.93	71.80	±	1.46	66.36	±	0.61
Fast Bed 103	53.59	±	1.07	60.25	±	1.56	42.25	±	0.78
Fast Bed 104	53.20	±	1.09	59.71	±	1.49	42.25	±	0.78
Ave. Fast Bed	53.40			59.98			42.25		
Fast Bed Top	51.35	±	1.09	57.60	±	1.56	42.25	±	0.76
Stand Pipe Air	22.26	±	0.09	22.48	±	0.08	21.68	±	0.14
Probe 1	77.70	±	1.31	82.26	±	1.74	69.14	±	0.51
Probe 2	80.25	±	1.32	84.75	±	1.76	72.45	±	0.96
Probe 3	79.11	±	1.34	83.71	±	1.79	71.40	±	0.50
Probe 4	75.59	±	1.37	80.34	±	1.84	67.22	±	0.53
Ave. Probe	78.16			82.76			70.05		
Operating Parameter									
Frequency (Hz)	0			0			0		
Pulse Width (ms)	0			0			0		
Valve Duty Cycle %	0			0			0		
Air Density in Orifice (kg/m^3)	1.386			1.440			1.372		
Air Density in Fast Bed (kg/m^3)	1.087			1.068			1.130		
Orifice Flow (kg/s)	0.0301			0.0338			0.0291		
Uo (m/s)	3.53			4.04			3.29		
Solids Fraction (1-ε)	0.0000			0.0000			0.0090		
Heater Voltage (V)	9.530			9.530			13.520		
Heater Current (A)	1.318			1.318			1.881		
Power (W)	12.561			12.561			25.431		
Ave Heat Transfer Coefficient (W/m*K)	29.09			31.62			52.46		
Solids Recirculation Rate (kg/m^2*s)	0.00			0.00			22.55		

Experiment No.	18	18	18
Test No.	A	B	C
Start Date	8/5/15	8/5/15	8/5/15
Data Averages Start Time	18:40:00	19:10:02	19:45:01
Data Averages End Time	19:00:02	19:30:03	20:05:04
Test Duration	0:20:02	0:20:01	0:20:03
No. of data points averaged	240	240	240
Pressures (PSIG)			
Orifice Static	10.63 ± 0.00	10.63 ± 0.00	10.63 ± 0.00
Fast Bed Static	0.04 ± 0.01	0.04 ± 0.03	0.03 ± 0.03
Differential Pressures (inH2O)			
Orifice	8.69 ± 0.17	8.25 ± 3.67	7.72 ± 3.50
Distributor Plate	69.80 ± 0.53	65.85 ± 14.14	58.62 ± 10.02
Lower Fast Bed	0.52 ± 0.26	0.60 ± 0.43	0.69 ± 0.44
Middle Fast Bed	0.19 ± 0.03	0.19 ± 0.03	0.20 ± 0.03
Upper Fast Bed	0.17 ± 0.11	0.17 ± 0.15	0.16 ± 0.22
Stand Pipe	31.37 ± 1.66	31.15 ± 1.74	30.73 ± 2.90
Temperatures (°C)			
Gas Inlet	49.89 ± 0.34	49.44 ± 0.62	47.59 ± 0.31
Fast Bed 103	34.43 ± 0.59	35.05 ± 0.25	34.56 ± 0.45
Fast Bed 104	34.40 ± 0.59	35.04 ± 0.22	34.59 ± 0.39
Ave. Fast Bed	34.41	35.04	34.58
Fast Bed Top	34.08 ± 0.58	34.80 ± 0.20	34.50 ± 0.36
Stand Pipe Air	21.24 ± 0.08	21.43 ± 0.09	21.61 ± 0.05
Probe 1	68.00 ± 0.70	68.75 ± 0.12	67.75 ± 0.42
Probe 2	71.64 ± 0.70	72.37 ± 0.31	71.39 ± 0.68
Probe 3	70.03 ± 0.67	70.82 ± 0.16	69.95 ± 0.23
Probe 4	64.81 ± 0.65	65.66 ± 0.11	64.93 ± 0.19
Ave. Probe	68.62	69.40	68.50
Operating Parameter			
Frequency (Hz)	0.0	0.2	2.0
Pulse Width (ms)	0	200	50
Valve Duty Cycle %	0.0	4.0	10.0
Air Density in Orifice (kg/m^3)	1.883	1.886	1.897
Air Density in Fast Bed (kg/m^3)	1.151	1.149	1.150
Orifice Flow (kg/s)	0.0275	0.0269	0.0261
Uo (m/s)	3.06	2.99	2.90
Solids Fraction (1-ε)	0.0043	0.0045	0.0047
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	42.64	42.45	42.99
Solids Recirculation Rate (kg/m^2*s)	5.57	5.83	N/A

Experiment No.	19	19	19
Test No.	A	B	C
Start Date	8/6/15	8/6/15	8/6/15
Data Averages Start Time	18:48:01	19:25:02	20:05:00
Data Averages End Time	19:08:02	19:45:02	20:25:03
Test Duration	0:20:01	0:20:00	0:20:03
No. of data points averaged	239	240	239
Pressures (PSIG)			
Orifice Static	3.43 ± 0.02	3.27 ± 0.80	2.71 ± 0.39
Fast Bed Static	0.13 ± 0.04	0.12 ± 0.09	0.11 ± 0.09
Differential Pressures (inH2O)			
Orifice	12.05 ± 0.26	11.35 ± 7.40	9.98 ± 6.05
Distributor Plate	88.40 ± 1.19	85.02 ± 26.05	65.30 ± 18.31
Lower Fast Bed	1.97 ± 0.53	2.04 ± 1.00	2.89 ± 1.85
Middle Fast Bed	0.43 ± 0.05	0.45 ± 0.07	0.49 ± 0.08
Upper Fast Bed	0.38 ± 0.26	0.38 ± 0.42	0.35 ± 0.47
Stand Pipe	28.44 ± 1.33	28.01 ± 1.49	25.66 ± 1.95
Temperatures (°C)			
Gas Inlet	57.31 ± 0.28	56.55 ± 1.06	52.06 ± 0.65
Fast Bed 103	38.06 ± 0.56	38.91 ± 0.19	37.28 ± 0.39
Fast Bed 104	38.06 ± 0.58	38.92 ± 0.14	37.32 ± 0.39
Ave. Fast Bed	38.06	38.91	37.30
Fast Bed Top	38.03 ± 0.54	38.90 ± 0.12	37.37 ± 0.34
Stand Pipe Air	21.86 ± 0.11	22.08 ± 0.06	22.23 ± 0.05
Probe 1	63.46 ± 0.59	63.71 ± 0.25	59.97 ± 0.67
Probe 2	66.67 ± 0.90	66.86 ± 0.72	63.00 ± 1.15
Probe 3	65.82 ± 0.59	66.10 ± 0.36	62.38 ± 0.89
Probe 4	61.97 ± 0.56	62.39 ± 0.28	59.11 ± 0.68
Ave. Probe	64.48	64.77	61.11
Operating Parameter			
Frequency (Hz)	0.0	0.2	2
Pulse Width (ms)	0	200	50
Valve Duty Cycle %	0.0	4.0	10.0
Air Density in Orifice (kg/m^3)	1.318	1.309	1.286
Air Density in Fast Bed (kg/m^3)	1.144	1.141	1.146
Orifice Flow (kg/s)	0.0271	0.0263	0.0244
Uo (m/s)	3.03	2.94	2.72
Solids Fraction (1-ε)	0.0099	0.0105	0.0114
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	55.21	56.41	61.24
Solids Recirculation Rate (kg/m^2*s)	20.18	20.72	21.00

Experiment No.	20			20			20			20		
Test No.	A			B			C			D		
Start Date	8/13/15			8/13/15			8/13/15			8/13/15		
Data Averages Start Time	18:30:00			19:10:01			19:40:01			20:20:03		
Data Averages End Time	18:50:00			19:30:00			20:00:01			20:40:02		
Test Duration	0:20:00			0:19:59			0:20:00			0:19:59		
No. of data points averaged	235			232			230			234		
Pressures (PSIG)												
Orifice Static	2.51	±	0.03	2.27	±	0.29	2.18	±	0.20	2.31	±	0.11
Fast Bed Static	0.11	±	0.04	0.09	±	0.08	0.09	±	0.10	0.10	±	0.09
Differential Pressures (inH2O)												
Orifice	9.05	±	0.53	8.19	±	5.33	7.68	±	5.76	8.52	±	4.83
Distributor Plate	61.25	±	1.96	50.04	±	18.89	46.18	±	13.79	51.89	±	16.74
Lower Fast Bed	2.66	±	0.71	5.77	±	4.13	6.98	±	7.33	5.11	±	2.67
Middle Fast Bed	0.50	±	0.07	0.46	±	0.07	0.45	±	0.08	0.47	±	0.07
Upper Fast Bed	0.36	±	0.26	0.31	±	0.64	0.32	±	0.62	0.29	±	0.52
Stand Pipe	25.05	±	1.00	22.39	±	1.77	21.74	±	2.25	22.80	±	2.16
Temperatures (°C)												
Gas Inlet	53.56	±	0.22	50.73	±	0.37	49.41	±	0.33	49.18	±	0.28
Fast Bed 103	37.53	±	0.09	36.65	±	0.22	36.03	±	0.19	35.71	±	0.08
Fast Bed 104	37.56	±	0.09	36.71	±	0.19	36.10	±	0.23	35.78	±	0.09
Ave. Fast Bed	37.55			36.68			36.06			35.74		
Fast Bed Top	37.66	±	0.08	36.79	±	0.20	36.17	±	0.19	35.85	±	0.06
Stand Pipe Air	23.35	±	0.09	23.67	±	0.11	23.94	±	0.11	24.19	±	0.05
Probe 1	60.35	±	0.25	59.03	±	0.28	58.34	±	0.30	57.92	±	0.34
Probe 2	63.38	±	0.65	62.02	±	0.70	61.34	±	0.67	60.97	±	0.51
Probe 3	62.79	±	0.39	61.42	±	0.42	60.64	±	0.42	60.38	±	0.33
Probe 4	59.55	±	0.23	58.25	±	0.40	57.48	±	0.44	57.19	±	0.39
Ave. Probe	61.52			60.18			59.45			59.11		
Operating Parameter												
Frequency (Hz)	0.0			2.0			4.0			6.0		
Pulse Width (ms)	0			50			50			50		
Valve Duty Cycle %	0.0			10.0			20.0			30.0		
Air Density in Orifice (kg/m^3)	1.265			1.258			1.257			1.268		
Air Density in Fast Bed (kg/m^3)	1.145			1.147			1.149			1.151		
Orifice Flow (kg/s)	0.0230			0.0219			0.0212			0.0224		
Uo (m/s)	2.57			2.44			2.36			2.49		
Solids Fraction (1-ε)	0.0115			0.0107			0.0105			0.0109		
Heater Voltage (V)	13.520			13.520			13.520			13.520		
Heater Current (A)	1.881			1.881			1.881			1.881		
Power (W)	25.431			25.431			25.431			25.431		
Ave Heat Transfer Coefficient (W/m*K)	60.85			62.06			62.37			62.41		
Solids Recirculation Rate (kg/m^2*s)	16.36			15.29			15.72			15.65		

Experiment No.	20	20	20
Test No.	E	F	G
Start Date	8/13/15	8/13/15	8/13/15
Data Averages Start Time	20:50:01	21:20:02	21:55:02
Data Averages End Time	21:10:02	21:40:02	22:15:03
Test Duration	0:20:01	0:20:00	0:20:01
No. of data points averaged	234	235	231
Pressures (PSIG)			
Orifice Static	2.32 ± 0.10	2.37 ± 0.08	2.38 ± 0.10
Fast Bed Static	0.10 ± 0.07	0.10 ± 0.05	0.10 ± 0.04
Differential Pressures (inH2O)			
Orifice	7.86 ± 3.82	8.28 ± 3.20	8.42 ± 3.11
Distributor Plate	52.34 ± 11.38	54.59 ± 8.64	55.98 ± 9.30
Lower Fast Bed	4.73 ± 3.10	4.08 ± 2.11	3.54 ± 2.45
Middle Fast Bed	0.47 ± 0.07	0.47 ± 0.07	0.48 ± 0.07
Upper Fast Bed	0.32 ± 0.53	0.33 ± 0.32	0.34 ± 0.34
Stand Pipe	22.74 ± 1.89	23.11 ± 1.58	23.31 ± 1.71
Temperatures (°C)			
Gas Inlet	49.11 ± 0.19	49.47 ± 0.16	49.75 ± 0.23
Fast Bed 103	35.77 ± 0.08	35.92 ± 0.08	36.10 ± 0.09
Fast Bed 104	35.83 ± 0.06	35.99 ± 0.08	36.14 ± 0.08
Ave. Fast Bed	35.80	35.96	36.12
Fast Bed Top	35.88 ± 0.05	36.04 ± 0.05	36.21 ± 0.08
Stand Pipe Air	24.31 ± 0.03	24.36 ± 0.03	24.44 ± 0.03
Probe 1	58.26 ± 0.19	58.46 ± 0.28	58.68 ± 0.25
Probe 2	61.29 ± 0.62	61.50 ± 0.50	61.73 ± 0.58
Probe 3	60.67 ± 0.37	60.90 ± 0.39	61.18 ± 0.31
Probe 4	57.45 ± 0.28	57.65 ± 0.30	57.92 ± 0.37
Ave. Probe	59.42	59.63	59.88
Operating Parameter			
Frequency (Hz)	8.0	10.0	12.0
Pulse Width (ms)	40	25	15
Valve Duty Cycle %	32.0	25.0	18.0
Air Density in Orifice (kg/m^3)	1.268	1.271	1.271
Air Density in Fast Bed (kg/m^3)	1.151	1.150	1.150
Orifice Flow (kg/s)	0.0215	0.0221	0.0223
Uo (m/s)	2.39	2.45	2.48
Solids Fraction (1-ε)	0.0108	0.0110	0.0111
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	61.75	61.62	61.40
Solids Recirculation Rate (kg/m^2*s)	15.25	15.26	15.35

Experiment No.	21	21	21	21
Test No.	A	B	C	D
Start Date	8/19/15	8/19/15	8/19/15	8/19/15
Data Averages Start Time	18:05:03	18:40:02	19:15:03	19:50:04
Data Averages End Time	18:25:02	19:00:04	19:35:01	20:10:01
Test Duration	0:19:59	0:20:02	0:19:58	0:19:57
No. of data points averaged	230	230	232	231
Pressures (PSIG)				
Orifice Static	3.42 ± 0.06	3.18 ± 1.12	3.06 ± 0.49	3.23 ± 0.24
Fast Bed Static	0.16 ± 0.09	0.16 ± 0.17	0.14 ± 0.16	0.16 ± 0.12
Differential Pressures (inH2O)				
Orifice	10.38 ± 1.53	11.39 ± 10.40	11.00 ± 8.95	12.00 ± 6.18
Distributor Plate	76.19 ± 10.10	66.54 ± 42.53	62.89 ± 27.14	70.66 ± 21.47
Lower Fast Bed	8.76 ± 8.31	12.90 ± 8.04	12.53 ± 7.75	10.04 ± 6.62
Middle Fast Bed	0.66 ± 0.11	0.60 ± 0.13	0.59 ± 0.12	0.62 ± 0.13
Upper Fast Bed	0.44 ± 0.51	0.42 ± 0.80	0.42 ± 0.80	0.45 ± 0.86
Stand Pipe	36.85 ± 2.52	34.99 ± 3.80	34.50 ± 3.26	35.46 ± 4.21
Temperatures (°C)				
Gas Inlet	55.20 ± 0.11	53.31 ± 1.20	51.29 ± 0.47	51.55 ± 0.37
Fast Bed 103	35.87 ± 0.33	35.97 ± 0.17	35.18 ± 0.22	35.00 ± 0.08
Fast Bed 104	35.92 ± 0.44	36.04 ± 0.36	35.25 ± 0.22	35.08 ± 0.08
Ave. Fast Bed	35.90	36.00	35.22	35.04
Fast Bed Top	35.97 ± 0.33	36.07 ± 0.17	35.29 ± 0.22	35.11 ± 0.06
Stand Pipe Air	20.67 ± 0.06	20.77 ± 0.05	20.87 ± 0.05	20.93 ± 0.05
Probe 1	54.69 ± 0.65	53.29 ± 0.50	53.21 ± 0.33	53.78 ± 0.36
Probe 2	57.29 ± 0.86	55.65 ± 0.76	55.65 ± 0.61	56.42 ± 0.62
Probe 3	56.42 ± 0.75	54.77 ± 0.70	54.69 ± 0.36	55.64 ± 0.51
Probe 4	53.53 ± 0.81	52.12 ± 0.51	51.89 ± 0.36	52.75 ± 0.48
Ave. Probe	55.48	53.96	53.86	54.65
Operating Parameter				
Frequency (Hz)	0.0	1.5	3.0	4.5
Pulse Width (ms)	0	200	80	35
Valve Duty Cycle %	0.0	30.0	24.0	15.8
Air Density in Orifice (kg/m^3)	1.326	1.315	1.315	1.326
Air Density in Fast Bed (kg/m^3)	1.155	1.155	1.156	1.158
Orifice Flow (kg/s)	0.0253	0.0264	0.0259	0.0272
Uo (m/s)	2.80	2.92	2.86	3.00
Solids Fraction (1-ε)	0.0152	0.0140	0.0136	0.0143
Heater Voltage (V)	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	74.47	81.23	78.23	74.40
Solids Recirculation Rate (kg/m^2*s)	25.32	23.12	23.25	23.75

Experiment No.	22	22	22	22
Test No.	A	B	C	D
Start Date	8/23/15	8/23/15	8/23/15	8/23/15
Data Averages Start Time	13:50:03	14:23:02	15:00:04	15:30:05
Data Averages End Time	14:10:01	14:43:03	15:20:04	15:50:02
Test Duration	0:19:58	0:20:01	0:20:00	0:19:57
No. of data points averaged	233	234	235	233
Pressures (PSIG)				
Orifice Static	3.32 ± 0.05	2.91 ± 0.81	3.08 ± 0.99	3.29 ± 1.10
Fast Bed Static	0.15 ± 0.08	0.15 ± 0.19	0.16 ± 0.15	0.17 ± 0.12
Differential Pressures (inH2O)				
Orifice	10.60 ± 1.41	11.77 ± 10.00	10.64 ± 10.00	10.99 ± 9.53
Distributor Plate	74.06 ± 9.87	59.17 ± 36.83	65.02 ± 35.83	70.32 ± 34.41
Lower Fast Bed	8.55 ± 6.87	12.99 ± 7.73	11.91 ± 8.22	9.69 ± 6.06
Middle Fast Bed	0.66 ± 0.11	0.59 ± 0.18	0.63 ± 0.12	0.65 ± 0.11
Upper Fast Bed	0.46 ± 0.61	0.43 ± 1.12	0.44 ± 0.73	0.51 ± 0.77
Stand Pipe	35.91 ± 2.32	33.53 ± 3.27	33.94 ± 2.75	34.68 ± 2.77
Temperatures (°C)				
Gas Inlet	54.54 ± 0.20	51.88 ± 0.82	51.52 ± 0.82	51.80 ± 1.74
Fast Bed 103	34.74 ± 0.58	34.89 ± 0.22	34.75 ± 0.09	34.97 ± 0.16
Fast Bed 104	34.80 ± 0.56	34.96 ± 0.25	34.82 ± 0.09	35.05 ± 0.25
Ave. Fast Bed	34.77	34.93	34.78	35.01
Fast Bed Top	34.83 ± 0.54	35.00 ± 0.25	34.85 ± 0.08	35.08 ± 0.12
Stand Pipe Air	20.43 ± 0.03	20.43 ± 0.03	20.49 ± 0.05	20.48 ± 0.08
Probe 1	53.87 ± 0.68	53.21 ± 0.40	52.64 ± 0.39	53.48 ± 0.34
Probe 2	56.62 ± 0.78	55.78 ± 0.70	55.14 ± 0.73	56.15 ± 0.75
Probe 3	55.91 ± 0.73	54.94 ± 0.47	54.37 ± 0.67	55.57 ± 0.62
Probe 4	52.97 ± 0.82	52.12 ± 0.48	51.61 ± 0.54	52.68 ± 0.51
Ave. Probe	54.84	54.01	53.44	54.47
Operating Parameter				
Frequency (Hz)	0.0	2.5	1.1	0.6
Pulse Width (ms)	0	100	227	417
Valve Duty Cycle %	0.0	25.0	25.0	25.0
Air Density in Orifice (kg/m^3)	1.321	1.302	1.315	1.330
Air Density in Fast Bed (kg/m^3)	1.159	1.158	1.159	1.159
Orifice Flow (kg/s)	0.0255	0.0266	0.0255	0.0260
Uo (m/s)	2.81	2.94	2.81	2.87
Solids Fraction (1-ε)	0.0152	0.0137	0.0146	0.0150
Heater Voltage (V)	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	72.66	76.41	78.18	74.97
Solids Recirculation Rate (kg/m^2*s)	25.22	22.49	21.30	23.66

Experiment No.		22			22			22	
Test No.		E			F			G	
Start Date		8/23/15			8/23/15			8/23/15	
Data Averages Start Time		16:05:00			16:40:03			17:20:00	
Data Averages End Time		16:25:01			17:00:04			17:40:03	
Test Duration		0:20:01			0:20:01			0:20:03	
No. of data points averaged		237			239			234	
Pressures (PSIG)									
Orifice Static	3.05	±	0.59	3.12	±	0.67	3.43	±	0.04
Fast Bed Static	0.16	±	0.14	0.16	±	0.15	0.17	±	0.06
Differential Pressures (inH2O)									
Orifice	11.39	±	8.92	10.91	±	9.98	11.20	±	1.41
Distributor Plate	61.97	±	29.13	66.08	±	29.98	78.62	±	9.17
Lower Fast Bed	10.69	±	6.45	9.93	±	7.55	6.43	±	4.26
Middle Fast Bed	0.62	±	0.10	0.64	±	0.13	0.65	±	0.12
Upper Fast Bed	0.46	±	0.78	0.46	±	0.73	0.49	±	0.49
Stand Pipe	33.83	±	3.10	34.00	±	2.13	35.59	±	1.86
Temperatures (°C)									
Gas Inlet	51.04	±	0.42	51.44	±	0.61	55.26	±	0.50
Fast Bed 103	34.77	±	0.08	34.87	±	0.09	36.29	±	0.39
Fast Bed 104	34.85	±	0.12	34.95	±	0.12	36.35	±	0.40
Ave. Fast Bed		34.81			34.91			36.32	
Fast Bed Top	34.87	±	0.09	34.96	±	0.09	36.38	±	0.42
Stand Pipe Air	20.59	±	0.08	20.75	±	0.05	20.77	±	0.03
Probe 1	53.53	±	0.30	53.58	±	0.36	56.21	±	0.58
Probe 2	56.17	±	0.59	56.23	±	0.59	59.02	±	1.00
Probe 3	55.46	±	0.42	55.55	±	0.51	58.34	±	0.75
Probe 4	52.60	±	0.44	52.70	±	0.50	55.33	±	0.68
Ave. Probe		54.44			54.51			57.22	
Operating Parameter									
Frequency (Hz)		2.1			1.6			0.0	
Pulse Width (ms)		143			156			0	
Valve Duty Cycle %		30.0			25.0			0.0	
Air Density in Orifice (kg/m^3)		1.315			1.318			1.326	
Air Density in Fast Bed (kg/m^3)		1.159			1.159			1.154	
Orifice Flow (kg/s)		0.0264			0.0258			0.0262	
Uo (m/s)		2.91			2.85			2.91	
Solids Fraction (1-ε)		0.0143			0.0147			0.0150	
Heater Voltage (V)		13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		74.30			74.40			69.78	
Solids Recirculation Rate (kg/m^2*s)		23.03			23.16			27.58	

Experiment No.		23			23			23	
Test No.		A			B			C	
Start Date		8/27/15			8/27/15			8/27/15	
Data Averages Start Time		17:20:02			17:59:59			18:35:01	
Data Averages End Time		17:40:04			18:20:00			18:55:00	
Test Duration		0:20:02			0:20:01			0:19:59	
No. of data points averaged		233			237			234	
Pressures (PSIG)									
Orifice Static	3.38	±	0.04	3.30	±	0.74	3.16	±	0.82
Fast Bed Static	0.16	±	0.07	0.16	±	0.11	0.16	±	0.13
Differential Pressures (inH2O)									
Orifice	10.72	±	1.71	10.94	±	8.10	10.24	±	7.50
Distributor Plate	77.14	±	12.23	74.32	±	27.95	73.44	±	29.94
Lower Fast Bed	6.80	±	4.21	7.03	±	4.24	8.29	±	7.15
Middle Fast Bed	0.66	±	0.10	0.65	±	0.10	0.64	±	0.11
Upper Fast Bed	0.52	±	0.47	0.48	±	0.56	0.46	±	0.58
Stand Pipe	34.57	±	2.28	33.86	±	3.10	33.16	±	2.10
Temperatures (°C)									
Gas Inlet	55.57	±	0.26	54.86	±	0.78	54.15	±	0.89
Fast Bed 103	35.96	±	0.50	36.87	±	0.17	36.95	±	0.06
Fast Bed 104	36.02	±	0.51	36.94	±	0.17	37.01	±	0.08
Ave. Fast Bed		35.99			36.90			36.98	
Fast Bed Top	36.05	±	0.51	36.97	±	0.14	37.06	±	0.06
Stand Pipe Air	21.21	±	0.08	21.34	±	0.05	21.57	±	0.06
Probe 1	55.50	±	0.62	56.47	±	0.30	56.40	±	0.20
Probe 2	58.32	±	0.84	59.23	±	0.62	59.15	±	0.58
Probe 3	57.70	±	0.64	58.61	±	0.44	58.60	±	0.33
Probe 4	54.77	±	0.61	55.69	±	0.45	55.72	±	0.36
Ave. Probe		56.57			57.50			57.47	
Operating Parameter									
Frequency (Hz)		0.0			0.6			0.6	
Pulse Width (ms)		0			100			200	
Valve Duty Cycle %		0.0			6.0			12.0	
Air Density in Orifice (kg/m^3)		1.321			1.318			1.310	
Air Density in Fast Bed (kg/m^3)		1.154			1.151			1.151	
Orifice Flow (kg/s)		0.0256			0.0259			0.0249	
Uo (m/s)		2.84			2.87			2.77	
Solids Fraction (1-ε)		0.0154			0.0151			0.0149	
Heater Voltage (V)		13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		70.87			70.81			71.20	
Solids Recirculation Rate (kg/m^2*s)		24.88			24.45			24.82	

Experiment No.	23	23	23
Test No.	D	E	F
Start Date	8/27/15	8/27/15	8/27/15
Data Averages Start Time	19:09:59	19:42:04	20:15:02
Data Averages End Time	19:30:02	20:02:05	20:35:03
Test Duration	0:20:03	0:20:01	0:20:01
No. of data points averaged	236	236	238
Pressures (PSIG)			
Orifice Static	3.40 ± 0.99	3.31 ± 1.16	3.34 ± 1.32
Fast Bed Static	0.17 ± 0.13	0.16 ± 0.13	0.16 ± 0.14
Differential Pressures (inH2O)			
Orifice	10.94 ± 8.87	11.27 ± 9.00	11.08 ± 9.31
Distributor Plate	71.75 ± 32.97	74.49 ± 37.77	73.21 ± 39.59
Lower Fast Bed	7.40 ± 4.76	7.98 ± 6.41	8.62 ± 7.95
Middle Fast Bed	0.65 ± 0.10	0.64 ± 0.11	0.64 ± 0.10
Upper Fast Bed	0.48 ± 0.66	0.50 ± 0.57	0.47 ± 0.64
Stand Pipe	33.53 ± 2.84	32.85 ± 2.94	32.39 ± 2.72
Temperatures (°C)			
Gas Inlet	54.66 ± 1.31	54.65 ± 1.65	54.20 ± 1.82
Fast Bed 103	37.26 ± 0.14	37.47 ± 0.11	37.42 ± 0.09
Fast Bed 104	37.34 ± 0.17	37.54 ± 0.09	37.50 ± 0.09
Ave. Fast Bed	37.30	37.51	37.46
Fast Bed Top	37.36 ± 0.16	37.56 ± 0.09	37.51 ± 0.06
Stand Pipe Air	21.74 ± 0.08	21.93 ± 0.06	22.07 ± 0.06
Probe 1	56.93 ± 0.34	56.90 ± 0.30	56.47 ± 0.37
Probe 2	59.68 ± 0.62	59.66 ± 0.75	59.17 ± 0.82
Probe 3	59.06 ± 0.39	59.09 ± 0.42	58.63 ± 0.50
Probe 4	56.13 ± 0.47	56.18 ± 0.34	55.83 ± 0.44
Ave. Probe	57.95	57.96	57.53
Operating Parameter			
Frequency (Hz)	0.6	0.6	0.6
Pulse Width (ms)	300	500	700
Valve Duty Cycle %	18.0	30.0	42.0
Air Density in Orifice (kg/m^3)	1.326	1.320	1.324
Air Density in Fast Bed (kg/m^3)	1.150	1.149	1.149
Orifice Flow (kg/s)	0.0259	0.0263	0.0261
Uo (m/s)	2.88	2.92	2.90
Solids Fraction (1-ε)	0.0150	0.0149	0.0148
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	70.63	71.31	72.69
Solids Recirculation Rate (kg/m^2*s)	22.73	24.03	20.92

Experiment No.		24			24			24			24			24	
Test No.		A			B			C			D			E	
Start Date		8/30/15			8/30/15			8/30/15			8/30/15			8/30/15	
Data Averages Start Time		15:40:02			16:20:00			16:49:59			17:24:58			18:00:00	
Data Averages End Time		15:59:53			16:40:02			17:08:19			17:45:00			18:20:01	
Test Duration		0:19:51			0:20:02			0:18:20			0:20:02			0:20:01	
No. of data points averaged		234			232			212			233			233	
Pressures (PSIG)															
Orifice Static	3.33	±	0.04	2.80	±	1.21	2.75	±	1.22	3.08	±	1.19	2.74	±	0.97
Fast Bed Static	0.16	±	0.06	0.13	±	0.15	0.11	±	0.14	0.15	±	0.18	0.13	±	0.15
Differential Pressures (inH2O)															
Orifice	11.02	±	1.27	9.86	±	10.69	9.07	±	10.15	10.02	±	9.74	9.03	±	9.89
Distributor Plate	77.03	±	7.14	56.42	±	40.42	48.49	±	46.20	65.68	±	41.64	53.79	±	40.18
Lower Fast Bed	5.95	±	3.33	13.91	±	7.80	16.53	±	7.40	9.95	±	8.18	13.85	±	7.47
Middle Fast Bed	0.66	±	0.10	0.60	±	0.16	0.58	±	0.14	0.63	±	0.13	0.57	±	0.11
Upper Fast Bed	0.51	±	0.38	0.39	±	0.82	0.37	±	0.78	0.43	±	0.70	0.35	±	0.72
Stand Pipe	34.43	±	2.69	30.53	±	3.26	29.10	±	5.56	31.77	±	2.80	30.16	±	2.92
Temperatures (°C)															
Gas Inlet	56.55	±	0.09	52.29	±	1.59	50.62	±	1.34	52.54	±	1.31	50.50	±	0.96
Fast Bed 103	37.52	±	0.30	36.67	±	0.31	35.85	±	0.28	36.02	±	0.28	35.68	±	0.22
Fast Bed 104	37.60	±	0.31	36.78	±	0.33	35.96	±	0.28	36.11	±	0.25	35.78	±	0.20
Ave. Fast Bed		37.56			36.73			35.90			36.06			35.73	
Fast Bed Top	37.66	±	0.30	36.85	±	0.33	36.03	±	0.25	36.16	±	0.26	35.85	±	0.20
Stand Pipe Air	21.17	±	0.09	21.58	±	0.11	21.87	±	0.12	22.14	±	0.09	22.32	±	0.06
Probe 1	57.66	±	0.39	54.24	±	0.45	52.27	±	0.53	54.12	±	0.70	54.13	±	0.39
Probe 2	60.49	±	0.65	56.76	±	0.53	54.69	±	0.76	56.72	±	0.96	56.71	±	0.59
Probe 3	59.86	±	0.54	56.08	±	0.48	53.92	±	0.75	56.11	±	0.98	55.95	±	0.48
Probe 4	56.89	±	0.59	53.49	±	0.39	51.46	±	0.72	53.41	±	0.76	53.19	±	0.51
Ave. Probe		58.72			55.14			53.09			55.09			55.00	
Operating Parameter															
Frequency (Hz)		0.0			1.1			1.1			1.1			1.1	
Pulse Width (ms)		0			318			500			409			591	
Valve Duty Cycle %		0.0			35.0			55.0			45.0			65.0	
Air Density in Orifice (kg/m^3)		1.314			1.291			1.294			1.311			1.294	
Air Density in Fast Bed (kg/m^3)		1.149			1.149			1.151			1.153			1.153	
Orifice Flow (kg/s)		0.0259			0.0243			0.0233			0.0247			0.0233	
Uo (m/s)		2.88			2.70			2.59			2.74			2.58	
Solids Fraction (1-ε)		0.0153			0.0139			0.0134			0.0147			0.0132	
Heater Voltage (V)		13.520			13.520			13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		68.92			79.21			84.88			76.66			75.71	
Solids Recirculation Rate (kg/m^2*s)		24.77			18.46			14.32			19.91			14.69	

Experiment No.	25			25			25		
Test No.	A			B			C		
Start Date	9/2/15			9/2/15			9/2/15		
Data Averages Start Time	17:30:02			18:09:34			18:45:01		
Data Averages End Time	17:50:03			18:30:00			19:05:02		
Test Duration	0:20:01			0:20:26			0:20:01		
No. of data points averaged	235			238			232		
Pressures (PSIG)									
Orifice Static	3.24	±	0.03	2.91	±	1.01	2.78	±	0.98
Fast Bed Static	0.16	±	0.08	0.16	±	0.15	0.15	±	0.15
Differential Pressures (inH2O)									
Orifice	11.10	±	0.82	11.41	±	10.24	10.16	±	10.24
Distributor Plate	76.00	±	6.39	63.37	±	38.65	57.90	±	42.31
Lower Fast Bed	4.93	±	2.66	8.25	±	8.47	10.86	±	8.40
Middle Fast Bed	0.64	±	0.10	0.62	±	0.10	0.61	±	0.10
Upper Fast Bed	0.48	±	0.32	0.44	±	0.76	0.45	±	0.90
Stand Pipe	33.42	±	1.74	30.98	±	2.66	29.72	±	2.68
Temperatures (°C)									
Gas Inlet	55.74	±	0.16	53.45	±	0.75	51.85	±	1.06
Fast Bed 103	37.37	±	0.33	37.10	±	0.09	36.54	±	0.20
Fast Bed 104	37.43	±	0.33	37.16	±	0.09	36.62	±	0.20
Ave. Fast Bed	37.40			37.13			36.58		
Fast Bed Top	37.47	±	0.31	37.21	±	0.08	36.67	±	0.22
Stand Pipe Air	21.82	±	0.08	22.09	±	0.09	22.35	±	0.08
Probe 1	58.11	±	0.48	56.06	±	0.36	55.15	±	0.36
Probe 2	60.96	±	0.75	58.77	±	0.59	57.83	±	0.62
Probe 3	60.35	±	0.51	58.23	±	0.42	57.23	±	0.45
Probe 4	57.32	±	0.48	55.48	±	0.34	54.52	±	0.42
Ave. Probe	59.19			57.14			56.18		
Operating Parameter									
Frequency (Hz)	0.0			1.6			1.6		
Pulse Width (ms)	0			156			313		
Valve Duty Cycle %	0.0			25.0			50.1		
Air Density in Orifice (kg/m^3)	1.310			1.295			1.292		
Air Density in Fast Bed (kg/m^3)	1.149			1.150			1.151		
Orifice Flow (kg/s)	0.0260			0.0262			0.0247		
Uo (m/s)	2.89			2.91			2.74		
Solids Fraction (1-ε)	0.0147			0.0145			0.0141		
Heater Voltage (V)	13.520			13.520			13.520		
Heater Current (A)	1.881			1.881			1.881		
Power (W)	25.431			25.431			25.431		
Ave Heat Transfer Coefficient (W/m*K)	66.95			72.90			74.41		
Solids Recirculation Rate (kg/m^2*s)	24.76			20.55			18.06		

Experiment No.	25	25	25	25
Test No.	D	E	F	G
Start Date	9/2/15	9/2/15	9/2/15	9/2/15
Data Averages Start Time	19:20:04	19:55:01	20:30:00	21:05:01
Data Averages End Time	19:40:01	20:15:04	20:50:01	21:25:04
Test Duration	0:19:57	0:20:03	0:20:01	0:20:03
No. of data points averaged	232	231	231	231
Pressures (PSIG)				
Orifice Static	2.95 ± 0.77	2.86 ± 0.80	3.09 ± 1.01	2.86 ± 0.96
Fast Bed Static	0.15 ± 0.11	0.15 ± 0.13	0.16 ± 0.12	0.14 ± 0.13
Differential Pressures (inH2O)				
Orifice	10.86 ± 9.84	10.32 ± 8.53	11.96 ± 8.50	10.11 ± 8.70
Distributor Plate	64.47 ± 31.43	61.04 ± 31.05	69.90 ± 32.36	61.19 ± 34.24
Lower Fast Bed	7.87 ± 8.77	8.51 ± 4.87	5.87 ± 4.31	8.71 ± 8.84
Middle Fast Bed	0.63 ± 0.10	0.61 ± 0.11	0.63 ± 0.12	0.60 ± 0.11
Upper Fast Bed	0.45 ± 0.65	0.44 ± 0.70	0.47 ± 0.71	0.41 ± 0.64
Stand Pipe	30.94 ± 2.45	30.31 ± 1.97	31.65 ± 2.05	29.93 ± 2.03
Temperatures (°C)				
Gas Inlet	52.54 ± 0.93	52.11 ± 1.00	53.75 ± 1.01	52.13 ± 1.62
Fast Bed 103	36.52 ± 0.12	36.48 ± 0.08	37.07 ± 0.25	36.81 ± 0.19
Fast Bed 104	36.60 ± 0.14	36.57 ± 0.08	37.13 ± 0.23	36.90 ± 0.17
Ave. Fast Bed	36.56	36.52	37.10	36.85
Fast Bed Top	36.64 ± 0.14	36.60 ± 0.08	37.17 ± 0.22	36.93 ± 0.17
Stand Pipe Air	22.54 ± 0.08	22.71 ± 0.06	22.84 ± 0.05	22.96 ± 0.03
Probe 1	55.83 ± 0.33	55.89 ± 0.37	57.05 ± 0.45	56.31 ± 0.30
Probe 2	58.55 ± 0.68	58.61 ± 0.76	59.89 ± 0.84	59.08 ± 0.61
Probe 3	58.01 ± 0.51	58.03 ± 0.42	59.34 ± 0.67	58.54 ± 0.42
Probe 4	55.19 ± 0.44	55.16 ± 0.37	56.38 ± 0.59	55.66 ± 0.42
Ave. Probe	56.90	56.92	58.17	57.40
Operating Parameter				
Frequency (Hz)	1.6	1.6	1.1	1.1
Pulse Width (ms)	219	281	318	500
Valve Duty Cycle %	35.0	45.0	35.0	55.0
Air Density in Orifice (kg/m^3)	1.301	1.297	1.307	1.297
Air Density in Fast Bed (kg/m^3)	1.152	1.152	1.150	1.150
Orifice Flow (kg/s)	0.0256	0.0249	0.0269	0.0247
Uo (m/s)	2.84	2.76	2.99	2.74
Solids Fraction (1-ε)	0.0145	0.0142	0.0145	0.0140
Heater Voltage (V)	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	71.74	71.50	69.24	70.99
Solids Recirculation Rate (kg/m^2*s)	19.89	19.05	22.55	17.78

Experiment No.	26	26	26	26	26
Test No.	A	B	C	D	E
Start Date	9/6/15	9/6/15	9/6/15	9/6/15	9/6/15
Data Averages Start Time	13:30:03	14:10:00	14:45:04	15:15:02	15:45:01
Data Averages End Time	13:50:04	14:30:03	15:05:05	15:35:03	16:05:02
Test Duration	0:20:01	0:20:03	0:20:01	0:20:01	0:20:01
No. of data points averaged	235	235	237	236	237
Pressures (PSIG)					
Orifice Static	3.24 ± 0.04	2.81 ± 0.98	3.03 ± 0.62	3.07 ± 0.80	3.12 ± 0.79
Fast Bed Static	0.15 ± 0.05	0.15 ± 0.18	0.15 ± 0.14	0.15 ± 0.15	0.16 ± 0.14
Differential Pressures (inH2O)					
Orifice	10.93 ± 1.12	10.42 ± 10.69	12.88 ± 8.28	12.62 ± 8.90	12.48 ± 9.53
Distributor Plate	74.92 ± 5.77	59.33 ± 40.35	69.41 ± 28.68	68.38 ± 34.81	71.21 ± 35.33
Lower Fast Bed	5.58 ± 2.82	11.58 ± 9.00	7.27 ± 4.20	7.09 ± 5.35	6.35 ± 4.65
Middle Fast Bed	0.65 ± 0.11	0.59 ± 0.10	0.62 ± 0.11	0.62 ± 0.11	0.62 ± 0.10
Upper Fast Bed	0.48 ± 0.46	0.42 ± 0.82	0.45 ± 0.70	0.48 ± 0.94	0.47 ± 0.85
Stand Pipe	32.93 ± 2.42	29.95 ± 3.50	31.39 ± 2.96	31.34 ± 2.66	31.61 ± 2.80
Temperatures (°C)					
Gas Inlet	55.15 ± 0.17	52.41 ± 0.87	53.56 ± 0.62	53.46 ± 1.17	53.88 ± 0.81
Fast Bed 103	36.44 ± 0.40	36.04 ± 0.12	36.48 ± 0.23	36.71 ± 0.17	37.05 ± 0.14
Fast Bed 104	36.52 ± 0.44	36.13 ± 0.14	36.54 ± 0.20	36.77 ± 0.16	37.10 ± 0.12
Ave. Fast Bed	36.48	36.08	36.51	36.74	37.08
Fast Bed Top	36.53 ± 0.45	36.16 ± 0.11	36.58 ± 0.22	36.80 ± 0.17	37.13 ± 0.14
Stand Pipe Air	21.85 ± 0.12	22.17 ± 0.09	22.47 ± 0.09	22.64 ± 0.06	22.77 ± 0.06
Probe 1	56.71 ± 0.65	54.47 ± 0.31	56.37 ± 0.33	56.44 ± 0.26	57.07 ± 0.30
Probe 2	59.57 ± 0.90	57.14 ± 0.59	59.16 ± 0.75	59.22 ± 0.64	59.87 ± 0.62
Probe 3	58.93 ± 0.61	56.61 ± 0.45	58.67 ± 0.53	58.69 ± 0.47	59.36 ± 0.42
Probe 4	55.95 ± 0.64	53.94 ± 0.40	55.80 ± 0.48	55.81 ± 0.45	56.44 ± 0.40
Ave. Probe	57.79	55.54	57.50	57.54	58.19
Operating Parameter					
Frequency (Hz)	0.0	2.1	2.1	2.1	2.1
Pulse Width (ms)	0	167	71	119	142
Valve Duty Cycle %	0.0	35.1	14.9	25.0	29.8
Air Density in Orifice (kg/m^3)	1.312	1.292	1.303	1.307	1.309
Air Density in Fast Bed (kg/m^3)	1.152	1.153	1.152	1.151	1.150
Orifice Flow (kg/s)	0.0258	0.0250	0.0279	0.0277	0.0275
Uo (m/s)	2.86	2.77	3.10	3.07	3.06
Solids Fraction (1-ε)	0.0149	0.0137	0.0143	0.0143	0.0144
Heater Voltage (V)	13.520	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	68.45	74.95	69.48	70.12	69.09
Solids Recirculation Rate (kg/m^2*s)	26.01	16.75	23.19	22.57	22.14

Experiment No.	27			27			27		
Test No.	A			B			C		
Start Date	9/13/15			9/13/15			9/13/15		
Data Averages Start Time	12:45:00			13:40:00			14:15:04		
Data Averages End Time	13:00:02			14:00:01			14:35:08		
Test Duration	0:15:02			0:20:01			0:20:04		
No. of data points averaged	175			239			239		
Pressures (PSIG)									
Orifice Static	3.15	±	0.04	2.84	±	1.01	2.85	±	0.65
Fast Bed Static	0.15	±	0.06	0.13	±	0.13	0.14	±	0.14
Differential Pressures (inH2O)									
Orifice	9.96	±	1.13	10.86	±	9.51	10.60	±	8.44
Distributor Plate	72.32	±	8.09	61.46	±	39.86	61.41	±	30.76
Lower Fast Bed	5.55	±	2.53	9.22	±	6.64	8.19	±	8.86
Middle Fast Bed	0.61	±	0.10	0.60	±	0.11	0.59	±	0.11
Upper Fast Bed	0.44	±	0.39	0.43	±	0.72	0.47	±	0.77
Stand Pipe	31.03	±	1.76	28.86	±	2.48	29.21	±	2.79
Temperatures (°C)									
Gas Inlet	54.39	±	0.14	52.48	±	1.09	52.48	±	0.50
Fast Bed 103	35.89	±	0.36	36.41	±	0.12	36.58	±	0.08
Fast Bed 104	35.93	±	0.36	36.47	±	0.09	36.65	±	0.09
Ave. Fast Bed	35.91			36.44			36.62		
Fast Bed Top	35.95	±	0.33	36.50	±	0.09	36.69	±	0.08
Stand Pipe Air	21.73	±	0.09	22.31	±	0.11	22.67	±	0.11
Probe 1	56.73	±	0.42	55.91	±	0.36	56.64	±	0.25
Probe 2	59.63	±	0.61	58.66	±	0.79	59.42	±	0.59
Probe 3	58.99	±	0.58	58.12	±	0.50	58.81	±	0.39
Probe 4	55.93	±	0.48	55.26	±	0.53	55.88	±	0.37
Ave. Probe	57.82			56.99			57.69		
Operating Parameter									
Frequency (Hz)	0.0			1.3			1.9		
Pulse Width (ms)	0			385			263		
Valve Duty Cycle %	0.0			50.1			50.0		
Air Density in Orifice (kg/m^3)	1.309			1.294			1.294		
Air Density in Fast Bed (kg/m^3)	1.154			1.151			1.150		
Orifice Flow (kg/s)	0.0246			0.0255			0.0252		
Uo (m/s)	2.72			2.84			2.80		
Solids Fraction (1-ε)	0.0142			0.0139			0.0137		
Heater Voltage (V)	13.520			13.520			13.520		
Heater Current (A)	1.881			1.881			1.881		
Power (W)	25.431			25.431			25.431		
Ave Heat Transfer Coefficient (W/m*K)	66.57			70.99			69.23		
Solids Recirculation Rate (kg/m^2*s)	21.39			17.11			20.40		

Experiment No.	27	27	27
Test No.	D	E	F
Start Date	9/13/15	9/13/15	9/13/15
Data Averages Start Time	14:44:59	15:24:59	16:00:01
Data Averages End Time	15:10:02	15:45:04	16:20:02
Test Duration	0:25:03	0:20:05	0:20:01
No. of data points averaged	295	239	238
Pressures (PSIG)			
Orifice Static	2.90 ± 0.45	3.05 ± 0.92	2.93 ± 0.33
Fast Bed Static	0.14 ± 0.11	0.14 ± 0.11	0.14 ± 0.11
Differential Pressures (inH2O)			
Orifice	9.50 ± 6.39	9.97 ± 8.15	9.33 ± 5.77
Distributor Plate	63.11 ± 24.68	68.09 ± 33.43	64.99 ± 20.38
Lower Fast Bed	7.73 ± 5.59	7.01 ± 5.38	6.75 ± 4.26
Middle Fast Bed	0.59 ± 0.08	0.61 ± 0.10	0.59 ± 0.11
Upper Fast Bed	0.41 ± 0.73	0.44 ± 0.57	0.43 ± 0.67
Stand Pipe	29.28 ± 2.79	29.43 ± 2.02	29.16 ± 2.10
Temperatures (°C)			
Gas Inlet	52.47 ± 0.45	53.51 ± 1.12	52.91 ± 0.37
Fast Bed 103	36.73 ± 0.11	37.21 ± 0.17	37.29 ± 0.08
Fast Bed 104	36.80 ± 0.09	37.28 ± 0.19	37.36 ± 0.08
Ave. Fast Bed	36.76	37.24	37.32
Fast Bed Top	36.82 ± 0.09	37.31 ± 0.19	37.39 ± 0.06
Stand Pipe Air	22.98 ± 0.12	23.26 ± 0.08	23.48 ± 0.06
Probe 1	57.22 ± 0.31	57.27 ± 0.36	58.07 ± 0.25
Probe 2	60.06 ± 0.64	60.07 ± 0.86	60.95 ± 0.67
Probe 3	59.46 ± 0.39	59.55 ± 0.58	60.34 ± 0.50
Probe 4	56.46 ± 0.37	56.61 ± 0.37	57.34 ± 0.31
Ave. Probe	58.30	58.37	59.18
Operating Parameter			
Frequency (Hz)	2.5	0.8	2.8
Pulse Width (ms)	200	625	179
Valve Duty Cycle %	50.0	50.0	50.1
Air Density in Orifice (kg/m^3)	1.298	1.305	1.298
Air Density in Fast Bed (kg/m^3)	1.150	1.148	1.148
Orifice Flow (kg/s)	0.0239	0.0246	0.0237
Uo (m/s)	2.66	2.74	2.64
Solids Fraction (1-ε)	0.0137	0.0141	0.0137
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	67.71	69.03	66.75
Solids Recirculation Rate (kg/m^2*s)	19.21	18.50	17.28

Experiment No.	28	28	28	28
Test No.	A	B	C	D
Start Date	11/1/15	11/1/15	11/1/15	11/1/15
Data Averages Start Time	12:55:01	13:45:03	14:20:04	15:09:59
Data Averages End Time	13:15:00	14:05:03	14:40:00	15:30:04
Test Duration	0:19:59	0:20:00	0:19:56	0:20:05
No. of data points averaged	238	240	238	235
Pressures (PSIG)				
Orifice Static	6.28 ± 0.02	6.18 ± 1.17	6.34 ± 0.21	6.41 ± 0.76
Fast Bed Static	0.15 ± 0.06	0.15 ± 0.07	0.15 ± 0.05	0.15 ± 0.07
Differential Pressures (inH2O)				
Orifice	8.93 ± 0.67	9.08 ± 5.79	8.79 ± 0.54	8.56 ± 6.66
Distributor Plate	158.43 ± 6.87	155.18 ± 32.99	160.57 ± 11.12	161.88 ± 33.93
Lower Fast Bed	5.12 ± 2.59	5.32 ± 4.96	4.93 ± 3.90	5.37 ± 4.97
Middle Fast Bed	0.59 ± 0.13	0.59 ± 0.09	0.59 ± 0.10	0.59 ± 0.09
Upper Fast Bed	0.44 ± 0.33	0.43 ± 0.47	0.43 ± 0.35	0.44 ± 0.47
Stand Pipe	30.91 ± 2.33	30.26 ± 2.75	30.30 ± 2.04	29.86 ± 2.39
Temperatures (°C)				
Gas Inlet	70.97 ± 0.25	70.97 ± 1.18	72.52 ± 0.40	70.52 ± 1.20
Fast Bed 103	43.06 ± 0.48	43.81 ± 0.36	44.84 ± 0.25	44.19 ± 0.31
Fast Bed 104	43.10 ± 0.45	43.84 ± 0.36	44.86 ± 0.23	44.22 ± 0.33
Ave. Fast Bed	43.08	43.83	44.85	44.20
Fast Bed Top	43.10 ± 0.45	43.85 ± 0.34	44.87 ± 0.25	44.23 ± 0.33
Stand Pipe Air	22.06 ± 0.12	22.61 ± 0.14	22.95 ± 0.09	23.30 ± 0.09
Probe 1	64.92 ± 0.62	65.60 ± 0.45	66.96 ± 0.19	65.99 ± 0.25
Probe 2	67.93 ± 0.84	68.59 ± 0.76	69.95 ± 0.61	68.96 ± 0.54
Probe 3	67.25 ± 0.76	67.94 ± 0.45	69.28 ± 0.36	68.26 ± 0.54
Probe 4	64.06 ± 0.56	64.77 ± 0.51	66.06 ± 0.44	65.10 ± 0.44
Ave. Probe	66.04	66.72	68.06	67.08
Operating Parameter				
Frequency (Hz)	0.0	2.6	0.0	2.6
Pulse Width (ms)	0	190	0	300
Valve Duty Cycle %	0.0	49.4	0.0	78.0
Air Density in Orifice (kg/m^3)	1.465	1.457	1.462	1.476
Air Density in Fast Bed (kg/m^3)	1.128	1.125	1.121	1.123
Orifice Flow (kg/s)	0.0246	0.0248	0.0244	0.0242
Uo (m/s)	2.79	2.82	2.78	2.75
Solids Fraction (1-ε)	0.0136	0.0136	0.0136	0.0137
Heater Voltage (V)	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	63.52	63.70	62.83	63.77
Solids Recirculation Rate (kg/m^2*s)	25.36	N/A	21.72	18.60

	E	F	G	H
Experiment No.	28	28	28	28
Test No.	E	F	G	H
Start Date	11/1/15	11/1/15	11/1/15	11/1/15
Data Averages Start Time	15:40:02	16:15:00	16:55:00	16:55:00
Data Averages End Time	16:00:01	16:35:02	17:15:04	17:15:04
Test Duration	0:19:59	0:20:02	0:20:04	0:20:04
No. of data points averaged	237	240	237	237
Pressures (PSIG)				
Orifice Static	6.31 ± 0.30	6.13 ± 0.76	6.20 ± 0.76	6.24 ± 0.48
Fast Bed Static	0.14 ± 0.08	0.13 ± 0.09	0.13 ± 0.08	0.13 ± 0.08
Differential Pressures (inH2O)				
Orifice	7.94 ± 5.55	8.19 ± 6.47	7.78 ± 6.25	7.47 ± 6.25
Distributor Plate	159.92 ± 21.32	152.81 ± 42.56	152.26 ± 40.00	154.77 ± 32.40
Lower Fast Bed	5.67 ± 3.40	7.60 ± 6.84	7.41 ± 5.53	7.76 ± 8.83
Middle Fast Bed	0.58 ± 0.09	0.58 ± 0.10	0.56 ± 0.10	0.56 ± 0.09
Upper Fast Bed	0.41 ± 0.53	0.40 ± 0.65	0.39 ± 0.51	0.38 ± 0.52
Stand Pipe	29.10 ± 2.52	28.04 ± 3.12	28.07 ± 2.45	27.82 ± 2.58
Temperatures (°C)				
Gas Inlet	72.71 ± 0.92	73.04 ± 0.78	72.11 ± 0.64	72.72 ± 0.54
Fast Bed 103	44.76 ± 0.30	44.85 ± 0.16	44.85 ± 0.14	44.89 ± 0.14
Fast Bed 104	44.81 ± 0.30	44.90 ± 0.12	44.89 ± 0.12	44.93 ± 0.16
Ave. Fast Bed	44.78	44.88	44.87	44.91
Fast Bed Top	44.80 ± 0.25	44.90 ± 0.11	44.89 ± 0.11	44.94 ± 0.14
Stand Pipe Air	23.49 ± 0.08	23.73 ± 0.06	23.95 ± 0.08	24.10 ± 0.08
Probe 1	66.47 ± 0.26	66.06 ± 0.30	66.41 ± 0.25	66.34 ± 0.25
Probe 2	69.46 ± 0.58	68.98 ± 0.68	69.32 ± 0.64	69.26 ± 0.65
Probe 3	68.84 ± 0.44	68.35 ± 0.37	68.70 ± 0.31	68.59 ± 0.48
Probe 4	65.73 ± 0.48	65.30 ± 0.45	65.62 ± 0.36	65.53 ± 0.47
Ave. Probe	67.63	67.17	67.51	67.43
Operating Parameter				
Frequency (Hz)	3.1	1.6	1.1	2.1
Pulse Width (ms)	200	300	300	250
Valve Duty Cycle %	62.0	48.0	33.0	52.5
Air Density in Orifice (kg/m^3)	1.459	1.446	1.454	1.454
Air Density in Fast Bed (kg/m^3)	1.121	1.120	1.120	1.120
Orifice Flow (kg/s)	0.0232	0.0234	0.0229	0.0224
Uo (m/s)	2.64	2.67	2.61	2.56
Solids Fraction (1-ε)	0.0135	0.0133	0.0131	0.0130
Heater Voltage (V)	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	63.85	65.42	64.41	64.76
Solids Recirculation Rate (kg/m^2*s)	19.08	19.78	19.12	19.30

Experiment No.	29	29	29	29	29
Test No.	A	B	C	D	E
Start Date	11/8/15	11/8/15	11/8/15	11/8/15	11/8/15
Data Averages Start Time	15:14:59	16:05:01	16:45:01	17:19:59	17:55:01
Data Averages End Time	15:35:01	16:25:03	17:05:02	17:39:01	18:15:05
Test Duration	0:20:02	0:20:02	0:20:01	0:19:02	0:20:04
No. of data points averaged	238	238	240	226	239
Pressures (PSIG)					
Orifice Static	1.32 ± 0.07	1.24 ± 0.39	1.65 ± 0.98	1.69 ± 0.80	1.48 ± 0.24
Fast Bed Static	0.14 ± 0.07	0.17 ± 0.25	0.17 ± 0.25	0.17 ± 0.27	0.15 ± 0.14
Differential Pressures (inH2O)					
Orifice	11.41 ± 3.10	9.92 ± 9.04	10.10 ± 9.75	9.38 ± 9.07	10.57 ± 6.68
Distributor Plate	22.75 ± 4.48	17.18 ± 14.02	26.90 ± 22.70	25.36 ± 19.28	27.29 ± 13.28
Lower Fast Bed	5.08 ± 2.55	5.76 ± 6.25	13.31 ± 10.43	13.30 ± 9.73	5.31 ± 4.87
Middle Fast Bed	0.60 ± 0.08	0.59 ± 0.10	0.61 ± 0.14	0.64 ± 0.12	0.58 ± 0.09
Upper Fast Bed	0.47 ± 0.50	0.46 ± 1.13	0.45 ± 1.19	0.47 ± 1.11	0.45 ± 0.85
Stand Pipe	30.68 ± 2.22	29.25 ± 3.68	27.74 ± 3.78	26.33 ± 3.47	29.03 ± 3.42
Temperatures (°C)					
Gas Inlet	44.86 ± 0.19	47.15 ± 0.68	49.56 ± 1.03	50.33 ± 0.68	49.20 ± 0.61
Fast Bed 103	31.61 ± 0.37	32.98 ± 0.28	34.08 ± 0.31	34.66 ± 0.20	35.09 ± 0.08
Fast Bed 104	31.66 ± 0.39	33.03 ± 0.30	34.14 ± 0.31	34.74 ± 0.19	35.14 ± 0.09
Ave. Fast Bed	31.63	33.01	34.11	34.70	35.11
Fast Bed Top	31.68 ± 0.39	33.05 ± 0.28	34.14 ± 0.33	34.73 ± 0.19	35.15 ± 0.08
Stand Pipe Air	20.98 ± 0.14	21.48 ± 0.11	21.91 ± 0.14	22.20 ± 0.06	22.42 ± 0.06
Probe 1	53.37 ± 0.45	53.27 ± 0.48	51.61 ± 0.90	52.24 ± 0.42	56.90 ± 0.34
Probe 2	56.32 ± 0.79	56.10 ± 0.95	54.27 ± 1.25	54.82 ± 0.67	59.86 ± 0.75
Probe 3	55.61 ± 0.54	55.66 ± 0.59	54.05 ± 1.14	54.28 ± 0.59	59.22 ± 0.39
Probe 4	52.37 ± 0.59	52.75 ± 0.58	51.52 ± 1.06	51.65 ± 0.61	56.04 ± 0.31
Ave. Probe	54.42	54.44	52.86	53.25	58.00
Operating Parameter					
Frequency (Hz)	0.0	2.1	1.1	1.6	2.6
Pulse Width (ms)	0	240	350	313	190
Valve Duty Cycle %	0.0	50.4	38.5	50.1	49.4
Air Density in Orifice (kg/m^3)	1.210	1.195	1.217	1.217	1.205
Air Density in Fast Bed (kg/m^3)	1.170	1.167	1.162	1.160	1.157
Orifice Flow (kg/s)	0.0253	0.0234	0.0239	0.0230	0.0243
Uo (m/s)	2.76	2.57	2.63	2.54	2.69
Solids Fraction (1-ε)	0.0139	0.0136	0.0142	0.0148	0.0134
Heater Voltage (V)	13.520	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	64.01	68.03	77.80	78.64	63.72
Solids Recirculation Rate (kg/m^2*s)	21.28	18.08	19.95	19.49	20.66

Experiment No.	30	30	30	30
Test No.	A	B	C	D
Start Date	11/11/15	11/11/15	11/11/15	11/11/15
Data Averages Start Time	13:40:00	14:40:04	15:15:00	15:55:00
Data Averages End Time	14:00:03	14:56:58	15:35:02	16:15:02
Test Duration	0:20:03	0:16:54	0:20:02	0:20:02
No. of data points averaged	237	199	235	238
Pressures (PSIG)				
Orifice Static	1.58 ± 0.06	1.58 ± 0.50	1.80 ± 0.76	1.77 ± 0.87
Fast Bed Static	0.14 ± 0.06	0.17 ± 0.20	0.18 ± 0.24	0.19 ± 0.27
Differential Pressures (inH2O)				
Orifice	11.21 ± 1.67	13.09 ± 9.43	12.10 ± 9.18	11.32 ± 9.90
Distributor Plate	30.41 ± 5.38	35.36 ± 18.68	37.86 ± 23.46	35.09 ± 24.81
Lower Fast Bed	4.87 ± 2.62	2.96 ± 2.91	3.82 ± 6.37	5.93 ± 10.94
Middle Fast Bed	0.61 ± 0.08	0.57 ± 0.08	0.58 ± 0.10	0.61 ± 0.10
Upper Fast Bed	0.49 ± 0.36	0.53 ± 1.10	0.51 ± 1.32	0.52 ± 1.09
Stand Pipe	31.31 ± 1.65	32.55 ± 3.77	30.86 ± 3.68	29.47 ± 4.53
Temperatures (°C)				
Gas Inlet	47.18 ± 0.20	53.08 ± 0.68	53.29 ± 0.68	55.00 ± 0.96
Fast Bed 103	33.04 ± 0.39	36.30 ± 0.45	37.07 ± 0.16	37.61 ± 0.20
Fast Bed 104	33.09 ± 0.37	36.34 ± 0.42	37.13 ± 0.19	37.67 ± 0.19
Ave. Fast Bed	33.06	36.32	37.10	37.64
Fast Bed Top	33.09 ± 0.37	36.29 ± 0.42	37.12 ± 0.19	37.66 ± 0.20
Stand Pipe Air	21.60 ± 0.08	22.03 ± 0.09	22.32 ± 0.08	22.56 ± 0.06
Probe 1	54.83 ± 0.47	58.81 ± 0.45	58.39 ± 0.45	57.48 ± 0.64
Probe 2	57.83 ± 0.56	61.98 ± 0.64	61.41 ± 0.75	60.41 ± 1.11
Probe 3	57.10 ± 0.56	61.38 ± 0.54	61.04 ± 0.53	60.07 ± 0.79
Probe 4	53.84 ± 0.51	58.00 ± 0.50	57.93 ± 0.40	57.19 ± 0.73
Ave. Probe	55.90	60.04	59.69	58.79
Operating Parameter				
Frequency (Hz)	0.0	2.0	1.0	1.5
Pulse Width (ms)	0	250	350	33
Valve Duty Cycle %	0.0	50.0	35.0	5.0
Air Density in Orifice (kg/m^3)	1.220	1.198	1.214	1.205
Air Density in Fast Bed (kg/m^3)	1.164	1.154	1.152	1.151
Orifice Flow (kg/s)	0.0252	0.0270	0.0261	0.0251
Uo (m/s)	2.77	2.99	2.90	2.79
Solids Fraction (1-ε)	0.0141	0.0133	0.0134	0.0141
Heater Voltage (V)	13.520	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	63.86	61.49	64.57	68.97
Solids Recirculation Rate (kg/m^2*s)	21.28	18.08	19.95	19.49

Experiment No.	30	30	30
Test No.	E	F	G
Start Date	11/11/15	11/11/15	11/11/15
Data Averages Start Time	16:35:05	17:09:59	17:35:00
Data Averages End Time	16:55:02	17:25:01	17:50:00
Test Duration	0:19:57	0:15:02	0:15:00
No. of data points averaged	235	176	176
Pressures (PSIG)			
Orifice Static	1.59 ± 0.17	1.82 ± 0.74	1.73 ± 0.27
Fast Bed Static	0.14 ± 0.10	0.16 ± 0.22	0.14 ± 0.13
Differential Pressures (inH2O)			
Orifice	12.06 ± 5.01	10.82 ± 8.08	11.47 ± 6.42
Distributor Plate	34.22 ± 9.66	37.05 ± 23.47	37.74 ± 13.51
Lower Fast Bed	3.35 ± 1.71	5.62 ± 10.94	3.34 ± 2.42
Middle Fast Bed	0.59 ± 0.08	0.60 ± 0.10	0.58 ± 0.10
Upper Fast Bed	0.51 ± 0.78	0.51 ± 1.20	0.51 ± 0.84
Stand Pipe	31.10 ± 3.29	28.93 ± 3.27	30.45 ± 2.94
Temperatures (°C)			
Gas Inlet	51.21 ± 0.86	50.89 ± 0.68	51.28 ± 0.37
Fast Bed 103	37.33 ± 0.34	36.64 ± 0.14	36.61 ± 0.12
Fast Bed 104	37.40 ± 0.31	36.72 ± 0.12	36.69 ± 0.09
Ave. Fast Bed	37.37	36.68	36.65
Fast Bed Top	37.42 ± 0.31	36.74 ± 0.09	36.70 ± 0.11
Stand Pipe Air	22.72 ± 0.05	22.72 ± 0.05	22.69 ± 0.05
Probe 1	60.01 ± 0.39	57.42 ± 0.50	58.96 ± 0.28
Probe 2	63.11 ± 0.67	60.24 ± 0.95	62.04 ± 0.61
Probe 3	62.44 ± 0.65	59.89 ± 0.61	61.44 ± 0.42
Probe 4	59.07 ± 0.48	56.84 ± 0.51	58.15 ± 0.33
Ave. Probe	61.16	58.60	60.15
Operating Parameter			
Frequency (Hz)	3.0	0.8	2.5
Pulse Width (ms)	167	350	200
Valve Duty Cycle %	50.1	28.0	50.0
Air Density in Orifice (kg/m^3)	1.206	1.224	1.216
Air Density in Fast Bed (kg/m^3)	1.148	1.152	1.151
Orifice Flow (kg/s)	0.0260	0.0248	0.0254
Uo (m/s)	2.89	2.75	2.83
Solids Fraction (1-ε)	0.0136	0.0139	0.0135
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	61.31	66.54	62.08
Solids Recirculation Rate (kg/m^2*s)	20.66	21.66	22.66

Experiment No.		31			31			31			31			31	
Test No.		A			B			C			D			E	
Start Date		11/15/15			11/15/15			11/15/15			11/15/15			11/15/15	
Data Averages Start Time		14:05:01			15:00:03			15:40:04			16:15:02			16:54:54	
Data Averages End Time		14:25:03			15:20:04			16:00:03			16:35:02			17:15:04	
Test Duration		0:20:02			0:20:01			0:19:59			0:20:00			0:20:10	
No. of data points averaged		238			238			238			237			238	
Pressures (PSIG)															
Orifice Static	1.81	±	0.05	1.79	±	0.57	1.88	±	0.78	1.71	±	0.42	2.28	±	1.12
Fast Bed Static	0.15	±	0.08	0.17	±	0.21	0.18	±	0.24	0.16	±	0.16	0.18	±	0.25
Differential Pressures (inH2O)															
Orifice	11.07	±	1.44	11.02	±	8.61	11.17	±	9.35	11.70	±	8.05	10.65	±	9.33
Distributor Plate	37.85	±	4.22	36.97	±	22.08	39.25	±	25.40	37.55	±	17.52	49.56	±	35.94
Lower Fast Bed	4.20	±	2.52	4.50	±	6.06	4.11	±	7.48	3.23	±	2.82	5.33	±	7.20
Middle Fast Bed	0.59	±	0.09	0.59	±	0.08	0.60	±	0.10	0.57	±	0.09	0.58	±	0.12
Upper Fast Bed	0.43	±	0.44	0.47	±	1.08	0.49	±	1.15	0.47	±	0.93	0.55	±	1.21
Stand Pipe	30.42	±	2.03	29.49	±	3.64	29.25	±	3.85	30.13	±	3.36	27.80	±	3.68
Temperatures (°C)															
Gas Inlet	45.71	±	0.26	49.66	±	1.23	52.76	±	0.96	51.55	±	0.89	56.08	±	1.45
Fast Bed 103	31.23	±	0.44	33.18	±	0.54	35.04	±	0.45	35.71	±	0.11	36.78	±	0.48
Fast Bed 104	31.30	±	0.39	33.22	±	0.53	35.09	±	0.47	35.78	±	0.12	36.85	±	0.47
Ave. Fast Bed		31.26			33.20			35.06			35.75			36.81	
Fast Bed Top	31.27	±	0.39	33.19	±	0.51	35.03	±	0.42	35.72	±	0.11	36.77	±	0.45
Stand Pipe Air	19.57	±	0.14	20.21	±	0.16	20.71	±	0.11	21.09	±	0.11	21.38	±	0.08
Probe 1	53.40	±	0.44	54.35	±	0.53	55.74	±	0.61	58.10	±	0.23	57.02	±	0.64
Probe 2	56.41	±	0.87	57.31	±	0.82	58.67	±	0.87	61.17	±	0.62	59.90	±	0.95
Probe 3	55.70	±	0.40	56.80	±	0.53	58.21	±	0.70	60.54	±	0.30	59.55	±	0.67
Probe 4	52.35	±	0.42	53.66	±	0.54	55.15	±	0.70	57.24	±	0.33	56.54	±	0.64
Ave. Probe		54.46			55.53			56.94			59.26			58.25	
Operating Parameter															
Frequency (Hz)		0.0			1.8			1.5			2.1			1.2	
Pulse Width (ms)		0			277			333			238			416	
Valve Duty Cycle %		0.0			49.9			50.0			50.0			49.9	
Air Density in Orifice (kg/m^3)		1.244			1.227			1.222			1.214			1.239	
Air Density in Fast Bed (kg/m^3)		1.171			1.166			1.160			1.155			1.153	
Orifice Flow (kg/s)		0.0253			0.0250			0.0252			0.0257			0.0247	
Uo (m/s)		2.76			2.75			2.77			2.84			2.74	
Solids Fraction (1-ε)		0.0136			0.0136			0.0139			0.0132			0.0134	
Heater Voltage (V)		13.520			13.520			13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		62.86			65.33			66.67			62.02			68.03	
Solids Recirculation Rate (kg/m^2*s)		21.30			23.31			23.02			22.06			16.92	

Experiment No.		32			32			32			32			32	
Test No.		A			B			C			D			E	
Start Date		11/22/15			11/22/15			11/22/15			11/22/15			11/22/15	
Data Averages Start Time		13:50:01			14:44:59			15:29:58			16:14:59			16:55:02	
Data Averages End Time		14:06:57			15:05:01			15:50:00			16:35:05			17:15:02	
Test Duration		0:16:56			0:20:02			0:20:02			0:20:06			0:20:00	
No. of data points averaged		198			232			230			230			229	
Pressures (PSIG)															
Orifice Static	2.20	±	0.06	2.06	±	0.55	2.61	±	1.24	2.42	±	1.14	2.25	±	0.44
Fast Bed Static	0.13	±	0.07	0.13	±	0.17	0.12	±	0.23	0.14	±	0.20	0.13	±	0.16
Differential Pressures (inH2O)															
Orifice	9.65	±	1.78	8.77	±	7.27	8.30	±	8.46	7.55	±	7.70	8.96	±	7.17
Distributor Plate	45.20	±	8.39	38.67	±	22.55	42.87	±	35.92	39.09	±	33.34	45.65	±	22.13
Lower Fast Bed	6.93	±	3.94	9.98	±	9.32	16.51	±	10.55	17.23	±	8.87	8.30	±	6.60
Middle Fast Bed	0.56	±	0.09	0.58	±	0.08	0.62	±	0.11	0.59	±	0.11	0.55	±	0.09
Upper Fast Bed	0.44	±	0.44	0.42	±	1.03	0.61	±	1.08	0.44	±	0.97	0.39	±	0.88
Stand Pipe	29.00	±	2.61	27.26	±	3.78	25.59	±	4.43	24.44	±	5.08	27.14	±	3.28
Temperatures (°C)															
Gas Inlet	46.55	±	4.20	48.31	±	0.67	53.70	±	1.39	53.90	±	0.92	52.48	±	0.72
Fast Bed 103	31.56	±	0.23	32.34	±	0.28	34.23	±	0.50	35.15	±	0.16	35.53	±	0.09
Fast Bed 104	31.59	±	0.25	32.39	±	0.26	34.26	±	0.47	35.21	±	0.14	35.56	±	0.08
Ave. Fast Bed		31.58			32.37			34.25			35.18			35.55	
Fast Bed Top	31.63	±	0.23	32.44	±	0.26	34.29	±	0.50	35.24	±	0.33	35.61	±	0.08
Stand Pipe Air	18.92	±	0.44	19.67	±	0.20	20.31	±	0.16	20.88	±	0.12	21.32	±	0.12
Probe 1	54.03	±	0.33	53.05	±	0.53	51.18	±	0.86	52.93	±	0.54	57.37	±	0.17
Probe 2	57.03	±	0.64	56.01	±	0.79	53.60	±	1.09	55.41	±	0.86	60.35	±	0.64
Probe 3	56.29	±	0.54	55.01	±	0.54	52.84	±	1.01	54.44	±	0.51	59.76	±	0.39
Probe 4	52.95	±	0.42	51.59	±	0.54	50.06	±	1.09	51.63	±	0.50	56.61	±	0.33
Ave. Probe		55.07			53.92			51.92			53.60			58.52	
Operating Parameter															
Frequency (Hz)		0.0			1.8			1.2			1.4			2.2	
Pulse Width (ms)		0			277			416			357			227	
Valve Duty Cycle %		0.0			49.9			49.9			50.0			49.9	
Air Density in Orifice (kg/m^3)		1.270			1.252			1.272			1.257			1.250	
Air Density in Fast Bed (kg/m^3)		1.169			1.166			1.158			1.156			1.153	
Orifice Flow (kg/s)		0.0238			0.0226			0.0221			0.0210			0.0228	
Uo (m/s)		2.61			2.47			2.44			2.32			2.53	
Solids Fraction (1-ε)		0.0129			0.0135			0.0144			0.0137			0.0126	
Heater Voltage (V)		13.520			13.520			13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		62.07			67.69			82.52			79.18			63.48	
Solids Recirculation Rate (kg/m^2*s)		20.17			13.49			16.62			10.47			16.80	

Experiment No.	33	33	33
Test No.	A	B	C
Start Date	11/29/15	11/29/15	11/29/15
Data Averages Start Time	14:40:01	15:35:00	16:15:00
Data Averages End Time	15:00:03	15:55:02	16:38:16
Test Duration	0:20:02	0:20:02	0:23:16
No. of data points averaged	234	238	275
Pressures (PSIG)			
Orifice Static	2.63 ± 0.07	2.59 ± 1.08	2.62 ± 0.07
Fast Bed Static	0.14 ± 0.07	0.15 ± 0.20	0.14 ± 0.06
Differential Pressures (inH2O)			
Orifice	9.55 ± 1.44	9.66 ± 8.22	9.63 ± 1.47
Distributor Plate	58.97 ± 9.16	52.97 ± 36.44	59.43 ± 6.28
Lower Fast Bed	5.41 ± 2.48	8.98 ± 10.72	4.93 ± 2.58
Middle Fast Bed	0.58 ± 0.08	0.59 ± 0.09	0.57 ± 0.10
Upper Fast Bed	0.43 ± 0.55	0.43 ± 1.13	0.43 ± 0.44
Stand Pipe	29.23 ± 2.47	27.84 ± 3.59	28.81 ± 4.28
Temperatures (°C)			
Gas Inlet	53.05 ± 0.19	57.47 ± 1.77	54.75 ± 0.89
Fast Bed 103	36.86 ± 0.30	38.26 ± 0.51	38.83 ± 0.17
Fast Bed 104	36.88 ± 0.30	38.28 ± 0.50	38.84 ± 0.17
Ave. Fast Bed	36.87	38.27	38.84
Fast Bed Top	36.91 ± 0.28	38.30 ± 0.51	38.88 ± 0.17
Stand Pipe Air	23.88 ± 0.06	24.01 ± 0.05	24.20 ± 0.03
Probe 1	59.20 ± 0.36	58.64 ± 0.50	61.60 ± 0.30
Probe 2	62.25 ± 0.48	61.46 ± 0.82	64.65 ± 0.59
Probe 3	61.55 ± 0.53	60.97 ± 0.62	63.95 ± 0.31
Probe 4	58.26 ± 0.40	57.94 ± 0.56	60.62 ± 0.37
Ave. Probe	60.31	59.75	62.70
Operating Parameter			
Frequency (Hz)	0.0	1.3	0.0
Pulse Width (ms)	0	385	0
Valve Duty Cycle %	0.0	50.1	0.0
Air Density in Orifice (kg/m^3)	1.276	1.256	1.269
Air Density in Fast Bed (kg/m^3)	1.150	1.145	1.142
Orifice Flow (kg/s)	0.0238	0.0237	0.0238
Uo (m/s)	2.64	2.65	2.66
Solids Fraction (1-ε)	0.0134	0.0137	0.0132
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	62.21	67.89	61.11
Solids Recirculation Rate (kg/m^2*s)	20.58	16.64	19.45

Experiment No.	33	33	33
Test No.	D	E	F
Start Date	11/29/15	11/29/15	11/29/15
Data Averages Start Time	17:14:21	18:05:00	18:40:01
Data Averages End Time	17:34:30	18:25:02	19:00:05
Test Duration	0:20:09	0:20:02	0:20:04
No. of data points averaged	240	237	238
Pressures (PSIG)			
Orifice Static	2.94 ± 1.20	2.93 ± 0.04	3.10 ± 1.13
Fast Bed Static	0.14 ± 0.21	0.14 ± 0.06	0.15 ± 0.17
Differential Pressures (inH2O)			
Orifice	9.28 ± 8.30	9.47 ± 0.85	8.91 ± 8.11
Distributor Plate	62.61 ± 43.30	68.93 ± 6.38	66.56 ± 38.57
Lower Fast Bed	7.52 ± 10.55	4.35 ± 3.14	5.48 ± 6.50
Middle Fast Bed	0.59 ± 0.10	0.57 ± 0.08	0.58 ± 0.08
Upper Fast Bed	0.43 ± 1.05	0.44 ± 0.34	0.49 ± 1.02
Stand Pipe	27.42 ± 2.75	28.47 ± 1.89	27.61 ± 3.04
Temperatures (°C)			
Gas Inlet	60.84 ± 2.10	57.30 ± 1.57	58.80 ± 2.60
Fast Bed 103	39.86 ± 0.51	40.44 ± 0.40	40.03 ± 0.44
Fast Bed 104	39.86 ± 0.51	40.45 ± 0.40	40.04 ± 0.44
Ave. Fast Bed	39.86	40.44	40.04
Fast Bed Top	39.89 ± 0.50	40.50 ± 0.39	40.08 ± 0.40
Stand Pipe Air	24.36 ± 0.03	24.47 ± 0.05	24.44 ± 0.06
Probe 1	60.56 ± 0.95	63.48 ± 0.36	62.01 ± 0.26
Probe 2	63.36 ± 1.31	66.57 ± 0.70	64.98 ± 0.62
Probe 3	62.80 ± 1.14	65.86 ± 0.34	64.42 ± 0.34
Probe 4	59.78 ± 1.12	62.49 ± 0.44	61.17 ± 0.39
Ave. Probe	61.63	64.60	63.14
Operating Parameter			
Frequency (Hz)	1.3	0.0	1.3
Pulse Width (ms)	385	0	385
Valve Duty Cycle %	50.1	0.0	50.1
Air Density in Orifice (kg/m^3)	1.269	1.281	1.288
Air Density in Fast Bed (kg/m^3)	1.138	1.137	1.139
Orifice Flow (kg/s)	0.0234	0.0237	0.0231
Uo (m/s)	2.62	2.67	2.59
Solids Fraction (1-ε)	0.0136	0.0131	0.0133
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	67.01	60.38	63.11
Solids Recirculation Rate (kg/m^2*s)	18.72	18.77	18.56

Experiment No.		34			34			34	
Test No.		A			B			C	
Start Date		12/2/15			12/2/15			12/2/15	
Data Averages Start Time		20:17:59			20:44:31			21:14:58	
Data Averages End Time		20:27:39			20:59:50			21:30:03	
Test Duration		0:09:40			0:15:19			0:15:05	
No. of data points averaged		111			175			172	
Pressures (PSIG)									
Orifice Static	4.66	±	1.10	4.26	±	1.07	4.18	±	0.95
Fast Bed Static	0.16	±	0.11	0.15	±	0.11	0.15	±	0.13
Differential Pressures (inH2O)									
Orifice	12.05	±	9.22	11.02	±	8.42	9.82	±	7.65
Distributor Plate	118.90	±	43.27	110.46	±	40.78	105.17	±	37.44
Lower Fast Bed	2.79	±	1.69	3.07	±	1.93	3.45	±	2.56
Middle Fast Bed	0.55	±	0.06	0.58	±	0.07	0.57	±	0.10
Upper Fast Bed	0.48	±	0.97	0.50	±	0.77	0.46	±	0.86
Stand Pipe	31.28	±	2.64	30.58	±	2.23	29.03	±	3.27
Temperatures (°C)									
Gas Inlet	72.38	±	0.82	70.40	±	1.28	66.83	±	1.25
Fast Bed 103	44.71	±	0.36	45.18	±	0.12	44.17	±	0.36
Fast Bed 104	44.66	±	0.36	45.14	±	0.12	44.16	±	0.33
Ave. Fast Bed		44.69			45.16			44.16	
Fast Bed Top	44.62	±	0.36	45.15	±	0.11	44.19	±	0.34
Stand Pipe Air	23.39	±	0.06	23.63	±	0.09	23.68	±	0.08
Probe 1	68.60	±	0.45	68.52	±	0.23	67.29	±	0.45
Probe 2	71.75	±	0.62	71.60	±	0.65	70.34	±	0.72
Probe 3	71.00	±	0.44	70.96	±	0.33	69.70	±	0.47
Probe 4	67.37	±	0.45	67.57	±	0.31	66.36	±	0.47
Ave. Probe		69.68			69.66			68.42	
Operating Parameter									
Frequency (Hz)		1.5			1.5			1.5	
Pulse Width (ms)		333			333			333	
Valve Duty Cycle %		50.0			50.0			50.0	
Air Density in Orifice (kg/m^3)		1.346			1.326			1.334	
Air Density in Fast Bed (kg/m^3)		1.123			1.120			1.124	
Orifice Flow (kg/s)		0.0274			0.0260			0.0246	
Uo (m/s)		3.12			2.97			2.80	
Solids Fraction (1-ε)		0.0128			0.0134			0.0132	
Heater Voltage (V)		13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		58.36			59.53			60.12	
Solids Recirculation Rate (kg/m^2*s)		24.27			20.51			19.25	

Experiment No.	34	34	34
Test No.	D	E	F
Start Date	12/2/15	12/2/15	12/2/15
Data Averages Start Time	21:40:02	22:15:01	22:40:03
Data Averages End Time	21:55:03	22:30:04	22:55:04
Test Duration	0:15:01	0:15:03	0:15:01
No. of data points averaged	172	172	172
Pressures (PSIG)			
Orifice Static	3.97 ± 0.87	3.70 ± 1.86	3.57 ± 0.79
Fast Bed Static	0.13 ± 0.12	0.12 ± 0.13	0.12 ± 0.10
Differential Pressures (inH2O)			
Orifice	8.67 ± 7.21	8.12 ± 6.74	7.40 ± 6.30
Distributor Plate	95.40 ± 37.56	88.47 ± 40.17	80.62 ± 36.90
Lower Fast Bed	5.82 ± 6.22	7.87 ± 9.25	8.79 ± 8.73
Middle Fast Bed	0.57 ± 0.09	0.56 ± 0.15	0.54 ± 0.08
Upper Fast Bed	0.41 ± 0.80	0.38 ± 0.74	0.36 ± 0.84
Stand Pipe	27.40 ± 2.74	26.20 ± 2.88	25.35 ± 3.62
Temperatures (°C)			
Gas Inlet	64.34 ± 1.09	61.23 ± 1.96	59.39 ± 0.90
Fast Bed 103	42.99 ± 0.30	41.43 ± 0.39	40.36 ± 0.28
Fast Bed 104	42.98 ± 0.30	41.46 ± 0.37	40.38 ± 0.30
Ave. Fast Bed	42.99	41.44	40.37
Fast Bed Top	43.02 ± 0.31	41.51 ± 0.37	40.43 ± 0.30
Stand Pipe Air	23.77 ± 0.11	23.82 ± 0.11	23.85 ± 0.08
Probe 1	65.65 ± 0.53	63.57 ± 0.56	62.32 ± 0.47
Probe 2	68.61 ± 0.76	66.49 ± 0.73	65.21 ± 0.64
Probe 3	67.94 ± 0.68	65.90 ± 0.64	64.60 ± 0.54
Probe 4	64.71 ± 0.62	62.74 ± 0.70	61.49 ± 0.51
Ave. Probe	66.73	64.67	63.41
Operating Parameter			
Frequency (Hz)	1.5	1.5	1.5
Pulse Width (ms)	333	333	333
Valve Duty Cycle %	50.0	50.0	50.0
Air Density in Orifice (kg/m^3)	1.329	1.322	1.319
Air Density in Fast Bed (kg/m^3)	1.127	1.131	1.135
Orifice Flow (kg/s)	0.0231	0.0223	0.0213
Uo (m/s)	2.62	2.52	2.40
Solids Fraction (1-ε)	0.0131	0.0129	0.0124
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	61.43	62.79	63.31
Solids Recirculation Rate (kg/m^2*s)	18.27	15.57	13.55

Experiment No.	35	35	35
Test No.	A	B	C
Start Date	12/6/15	12/6/15	12/6/15
Data Averages Start Time	15:15:02	16:10:01	16:50:00
Data Averages End Time	15:35:02	16:30:02	17:10:02
Test Duration	0:20:00	0:20:01	0:20:02
No. of data points averaged	234	234	235
Pressures (PSIG)			
Orifice Static	1.17 ± 0.09	1.61 ± 0.93	1.39 ± 0.05
Fast Bed Static	0.14 ± 0.12	0.20 ± 0.30	0.15 ± 0.08
Differential Pressures (inH2O)			
Orifice	10.49 ± 3.23	9.71 ± 10.02	10.09 ± 2.33
Distributor Plate	17.48 ± 3.98	24.42 ± 21.07	25.28 ± 5.27
Lower Fast Bed	6.61 ± 4.54	15.26 ± 10.47	5.61 ± 3.52
Middle Fast Bed	0.58 ± 0.10	0.68 ± 0.16	0.59 ± 0.08
Upper Fast Bed	0.47 ± 0.75	0.56 ± 1.14	0.46 ± 0.54
Stand Pipe	28.98 ± 2.89	27.01 ± 4.38	28.97 ± 3.09
Temperatures (°C)			
Gas Inlet	44.23 ± 0.14	49.69 ± 1.04	47.84 ± 0.54
Fast Bed 103	31.84 ± 0.34	33.90 ± 0.51	34.79 ± 0.08
Fast Bed 104	31.88 ± 0.34	33.94 ± 0.48	34.82 ± 0.34
Ave. Fast Bed	31.86	33.92	34.80
Fast Bed Top	31.92 ± 0.33	33.96 ± 0.47	34.87 ± 0.06
Stand Pipe Air	22.01 ± 0.14	22.60 ± 0.14	23.05 ± 0.11
Probe 1	53.92 ± 0.44	50.23 ± 0.58	57.14 ± 0.25
Probe 2	56.95 ± 0.58	52.83 ± 0.72	60.17 ± 0.65
Probe 3	56.28 ± 0.39	52.52 ± 0.61	59.41 ± 0.31
Probe 4	52.93 ± 0.50	49.93 ± 0.61	56.04 ± 0.36
Ave. Probe	55.02	51.38	58.19
Operating Parameter			
Frequency (Hz)	0.0	1.5	0.0
Pulse Width (ms)	0	333	0
Valve Duty Cycle %	0.0	50.0	0.0
Air Density in Orifice (kg/m^3)	1.201	1.214	1.204
Air Density in Fast Bed (kg/m^3)	1.169	1.165	1.158
Orifice Flow (kg/s)	0.0242	0.0234	0.0237
Uo (m/s)	2.64	2.57	2.62
Solids Fraction (1-ε)	0.0134	0.0158	0.0136
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	62.97	83.54	62.36
Solids Recirculation Rate (kg/m^2*s)	18.24	17.54	19.12

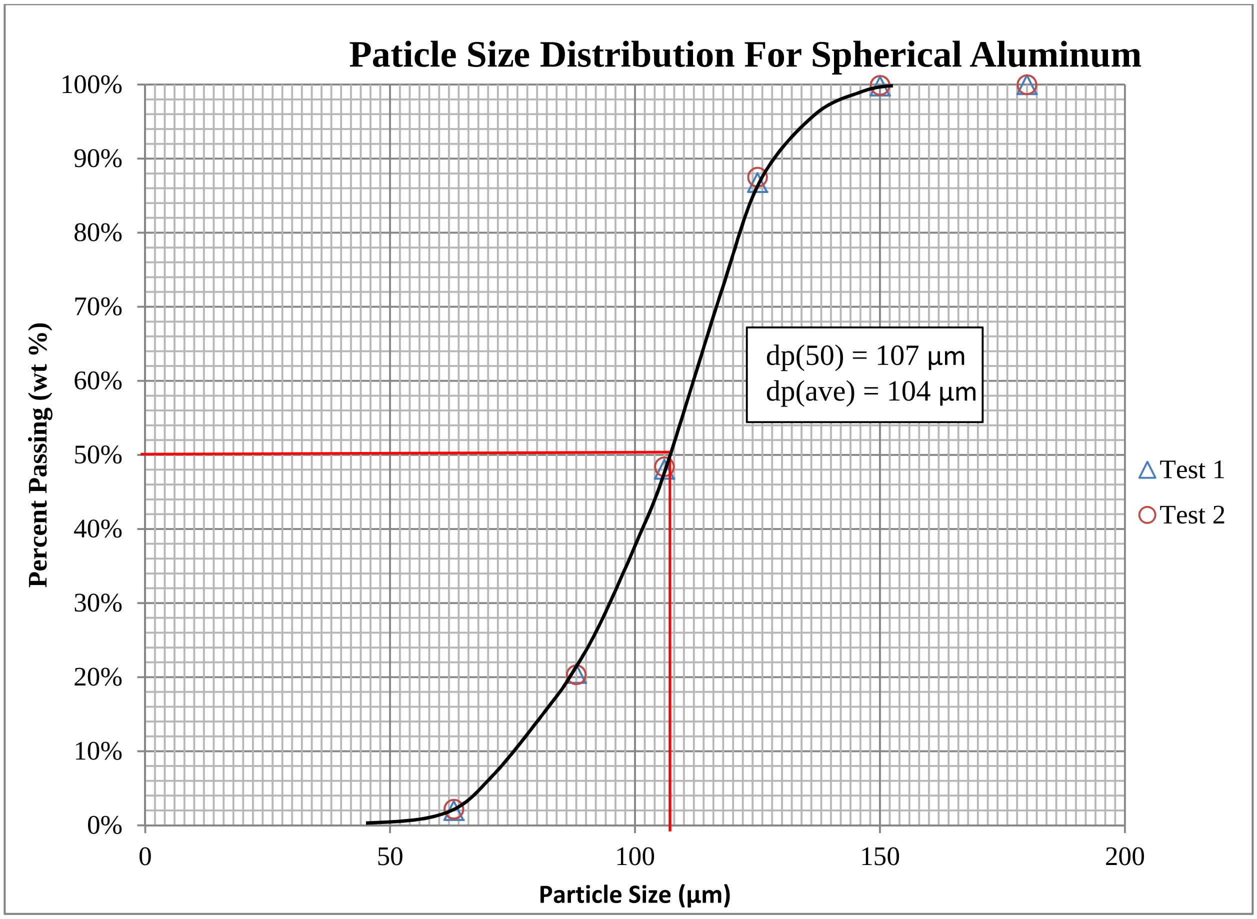
Experiment No.		35			35			35	
Test No.		D			E			F	
Start Date		12/6/15			12/6/15			12/6/15	
Data Averages Start Time		17:30:02			18:10:02			18:59:59	
Data Averages End Time		17:50:03			18:30:06			19:20:01	
Test Duration		0:20:01			0:20:04			0:20:02	
No. of data points averaged		231			231			232	
Pressures (PSIG)									
Orifice Static	1.58	±	0.84	1.41	±	0.04	1.60	±	0.77
Fast Bed Static	0.17	±	0.27	0.15	±	0.07	0.18	±	0.27
Differential Pressures (inH2O)									
Orifice	11.26	±	9.43	10.55	±	2.09	9.56	±	9.12
Distributor Plate	27.97	±	20.24	27.41	±	4.51	26.68	±	21.45
Lower Fast Bed	10.58	±	10.69	4.20	±	2.54	9.58	±	10.63
Middle Fast Bed	0.63	±	0.14	0.58	±	0.07	0.61	±	0.12
Upper Fast Bed	0.49	±	1.17	0.44	±	0.43	0.50	±	1.07
Stand Pipe	27.44	±	4.55	29.05	±	2.67	26.88	±	3.85
Temperatures (°C)									
Gas Inlet	50.21	±	1.09	48.16	±	0.50	50.68	±	1.00
Fast Bed 103	35.29	±	0.26	35.49	±	0.14	35.68	±	0.23
Fast Bed 104	35.33	±	0.23	35.52	±	0.12	35.71	±	0.25
Ave. Fast Bed		35.31			35.51			35.70	
Fast Bed Top	35.36	±	0.25	35.56	±	0.11	35.74	±	0.23
Stand Pipe Air	23.25	±	0.08	23.44	±	0.08	23.47	±	0.06
Probe 1	53.68	±	0.54	58.27	±	0.22	54.65	±	0.39
Probe 2	56.42	±	0.90	61.32	±	0.58	57.39	±	0.75
Probe 3	56.01	±	0.70	60.56	±	0.30	57.07	±	0.51
Probe 4	53.19	±	0.59	57.14	±	0.22	54.20	±	0.53
Ave. Probe		54.83			59.32			55.83	
Operating Parameter									
Frequency (Hz)		1.5			0.0			1.5	
Pulse Width (ms)		333			0			333	
Valve Duty Cycle %		50.0			0.0			50.0	
Air Density in Orifice (kg/m^3)		1.209			1.204			1.209	
Air Density in Fast Bed (kg/m^3)		1.158			1.155			1.157	
Orifice Flow (kg/s)		0.0251			0.0243			0.0232	
Uo (m/s)		2.77			2.69			2.56	
Solids Fraction (1-ε)		0.0146			0.0134			0.0141	
Heater Voltage (V)		13.520			13.520			13.520	
Heater Current (A)		1.881			1.881			1.881	
Power (W)		25.431			25.431			25.431	
Ave Heat Transfer Coefficient (W/m*K)		74.74			61.24			72.45	
Solids Recirculation Rate (kg/m^2*s)		15.93			18.90			16.55	

Experiment No.	36			36			36		
Test No.	A			B			C		
Start Date	2/15/16			2/15/16			2/15/16		
Data Averages Start Time	13:10:01			13:59:59			14:40:00		
Data Averages End Time	13:30:04			14:20:03			15:00:03		
Test Duration	0:20:03			0:20:04			0:20:03		
No. of data points averaged	232			234			235		
Pressures (PSIG)									
Orifice Static	1.44	±	0.07	1.41	±	0.34	1.39	±	0.29
Fast Bed Static	0.14	±	0.06	0.13	±	0.18	0.14	±	0.14
Differential Pressures (inH2O)									
Orifice	10.28	±	1.96	10.38	±	8.07	10.19	±	5.48
Distributor Plate	27.61	±	5.74	26.42	±	13.73	25.80	±	9.94
Lower Fast Bed	5.57	±	2.87	5.80	±	4.79	6.01	±	4.19
Middle Fast Bed	0.59	±	0.09	0.58	±	0.09	0.57	±	0.13
Upper Fast Bed	0.47	±	0.56	0.48	±	0.83	0.46	±	0.88
Stand Pipe	29.53	±	2.95	29.01	±	4.09	28.46	±	3.78
Temperatures (°C)									
Gas Inlet	47.02	±	0.17	49.41	±	0.56	49.30	±	0.30
Fast Bed 103	33.33	±	0.31	34.73	±	0.33	35.32	±	0.12
Fast Bed 104	33.37	±	0.31	34.75	±	0.31	35.34	±	0.09
Ave. Fast Bed	33.35			34.74			35.33		
Fast Bed Top	33.41	±	0.34	34.78	±	0.30	35.39	±	0.09
Stand Pipe Air	22.53	±	0.09	22.99	±	0.12	23.38	±	0.09
Probe 1	55.54	±	0.42	56.60	±	0.37	57.42	±	0.22
Probe 2	58.57	±	0.75	59.57	±	0.73	60.39	±	0.54
Probe 3	57.93	±	0.40	58.93	±	0.53	59.71	±	0.37
Probe 4	54.57	±	0.44	55.66	±	0.45	56.41	±	0.36
Ave. Probe	56.65			57.69			58.48		
Operating Parameter									
Frequency (Hz)	0.0			2.5			3.0		
Pulse Width (ms)	0			200			167		
Valve Duty Cycle %	0.0			50.0			50.1		
Air Density in Orifice (kg/m^3)	1.211			1.200			1.198		
Air Density in Fast Bed (kg/m^3)	1.163			1.157			1.155		
Orifice Flow (kg/s)	0.0240			0.0240			0.0238		
Uo (m/s)	2.64			2.66			2.63		
Solids Fraction (1-ε)	0.0137			0.0135			0.0133		
Heater Voltage (V)	13.520			13.520			13.520		
Heater Current (A)	1.881			1.881			1.881		
Power (W)	25.431			25.431			25.431		
Ave Heat Transfer Coefficient (W/m*K)	62.61			63.54			63.00		
Solids Recirculation Rate (kg/m^2*s)	22.23			17.72			19.85		

Experiment No.	36	36	36
Test No.	D	E	F
Start Date	2/15/16	2/15/16	2/15/16
Data Averages Start Time	15:24:02	16:09:59	16:40:01
Data Averages End Time	15:44:03	16:30:00	16:50:00
Test Duration	0:20:01	0:20:01	0:09:59
No. of data points averaged	235	236	118
Pressures (PSIG)			
Orifice Static	1.45 ± 0.45	1.38 ± 0.15	1.43 ± 0.22
Fast Bed Static	0.13 ± 0.13	0.12 ± 0.14	0.13 ± 0.10
Differential Pressures (inH2O)			
Orifice	10.10 ± 7.07	9.66 ± 5.86	10.53 ± 4.48
Distributor Plate	26.20 ± 12.48	24.14 ± 9.34	26.98 ± 9.41
Lower Fast Bed	8.06 ± 8.98	7.68 ± 4.79	6.06 ± 4.78
Middle Fast Bed	0.56 ± 0.14	0.56 ± 0.08	0.57 ± 0.08
Upper Fast Bed	0.40 ± 0.81	0.44 ± 0.89	0.42 ± 0.81
Stand Pipe	27.44 ± 5.17	27.01 ± 3.54	28.17 ± 4.66
Temperatures (°C)			
Gas Inlet	49.33 ± 0.62	49.38 ± 0.22	49.53 ± 0.36
Fast Bed 103	35.36 ± 0.17	35.47 ± 0.05	35.62 ± 0.09
Fast Bed 104	35.39 ± 0.12	35.50 ± 0.05	35.65 ± 0.09
Ave. Fast Bed	35.38	35.49	35.64
Fast Bed Top	35.43 ± 0.12	35.54 ± 0.06	35.68 ± 0.08
Stand Pipe Air	23.70 ± 0.09	23.91 ± 0.05	23.99 ± 0.03
Probe 1	57.38 ± 0.31	57.55 ± 0.33	57.70 ± 0.22
Probe 2	60.36 ± 0.62	60.52 ± 0.67	60.67 ± 0.42
Probe 3	59.70 ± 0.39	59.86 ± 0.34	59.97 ± 0.30
Probe 4	56.41 ± 0.40	56.57 ± 0.26	56.65 ± 0.31
Ave. Probe	58.47	58.63	58.75
Operating Parameter			
Frequency (Hz)	4.0	5.0	6.0
Pulse Width (ms)	125	100	83
Valve Duty Cycle %	50.0	50.0	49.8
Air Density in Orifice (kg/m^3)	1.203	1.198	1.201
Air Density in Fast Bed (kg/m^3)	1.154	1.153	1.154
Orifice Flow (kg/s)	0.0237	0.0232	0.0242
Uo (m/s)	2.63	2.57	2.68
Solids Fraction (1-ε)	0.0129	0.0129	0.0131
Heater Voltage (V)	13.520	13.520	13.520
Heater Current (A)	1.881	1.881	1.881
Power (W)	25.431	25.431	25.431
Ave Heat Transfer Coefficient (W/m*K)	63.17	63.04	63.11
Solids Recirculation Rate (kg/m^2*s)	14.69	15.64	16.90

APPENDIX B – MATERIAL SIZE DISTRIBUTION

Table B.1. Sieve test results for Valmet aluminum metal powder

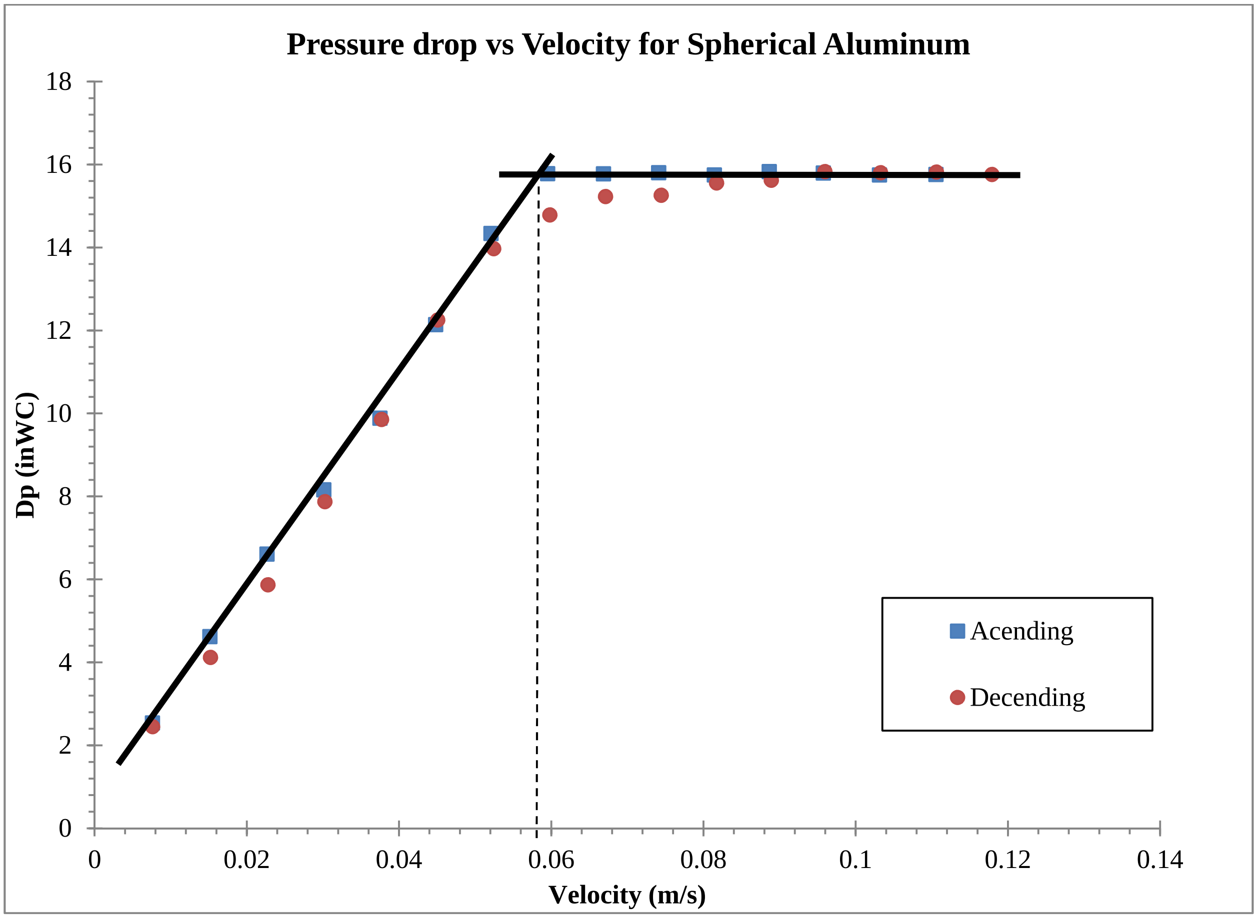


APPENDIX C – MINIMUM FLUIDIZING VELOCITY

The purpose of the experimental run number 2 was to determine the minimum fluidization velocity of the new material. The stand pipe was filled with 10 kg of spherical aluminum powder. Initial bed height was 660mm. Compressed air was controlled with an adjustable pressure regulator and measured with a variable area rotameter. The air temperature and pressure at the VA meter were recorded to correct to flow readings to standard conditions. The differential pressure across the stand pipe was also recorded. The air flow was slowly increased in .5 SCFM increments until fluidization occurred and the standpipe dp remained constant with the addition of more fluidizing air. The flows were then reduced in .5 SCFM increments all the war until the flow was completed stopped. This process was repeated four times. U_0 was calculated from the corrected VA meter flows. Standpipe dp was plotted against U_0 to determine $U_{mf.}$ It was later determined that the bed height was too high to accurately find U_{mf}. The bed height was reduced for the next fluidization tests.

Experiments 3 and 4 were conducted to determine U_{mf} for the spherical aluminum. Material was removed from the stand pipe until the bed height was no more than 3 diameters tall, initial bed height was 381mm. Fluidizing air flow was increased in .25 SCFM increments from 0 to 4 SCFM and then reduced in a similar manner back to zero. The results of test 3 and 4 were similar, however, the plot of standpipe dp against U_o was skewed at lower flow settings. It was determined the VA meter was not sufficiently accurate at lower flow rates and another VA meter with a smaller flow range was needed.

Experiment 5 was a continuation of the previous fluidization tests. A new VA meter was installed with range of 0 to 5.88 SCFM for test 5. The fluidization air was increased from 0 to 4.2 SCFM in .3 SCFM increments and reduced in a similar manner back to 0. The standpipe dp was again plotted against U_0 and U_{mf} was determined to be .058 m/s. The result of Experiment 5 can be seen in figure C.1 below.



APPENDIX D – SAMPLE CALCULATIONS

The Following calculations were performed using the equations listed in Chapter 3 and data taken from Experiment 11 test condition B.

$$\rho_{orf} = \frac{P_{orf} + P_{atm}}{T_{orf}\ 286.987 \frac{J}{kg\ K}}$$

$$\rho_{orf} = \frac{28130.60 \frac{N}{m^2} + 101325 \frac{N}{m^2}}{(331.18\ K)\ 286.987 \frac{J}{kg\ K}}$$

$$\rho_{air} = 1.362 \frac{kg}{m^3}$$

$$\mu = \left[153900 + 6522\ T_{orf} - 3.591\ {T_{orf}}^2 + .001368\ {T_{orf}}^3 - .001368\ {T_{orf}}^4\right] 10^{-11} \frac{kg}{m\ s}$$

$$\mu = [153900 + 6522(331.18) - 3.591\ (331.18)^2 + .001368\ (331.18)^3 - .000000183\ (331.18)^4]\ 10^{-11} \frac{kg}{m\ s}$$

$$\mu = .0000197 \frac{kg}{m\ s}$$

$$C_d = .5961 + .0261\ \beta^2 - .216\ \beta^4 + .00521 \left(\frac{10^6\beta}{R_{e_D}}\right) + (.0188 + .0063\ A)\beta^{3.5} \left(\frac{10^6\beta}{R_{e_D}}\right)^{.3} + (.043 + .080\ e^{-10} - .123\ e^{-7})(1 - .011\ A) \left(\frac{\beta^4}{1-\beta^4}\right) - .031(M_2 - .8{M_2}^{1.1})\beta^{1.3}$$

$$\beta = \frac{d_{orf}}{D_{pipe}}$$

$$\beta = \frac{.0254\ m}{.1016\ m}$$

$\beta = .25$

$$R_{e_D} = \frac{4\,\dot{m}}{\pi\,\mu\,D_{pipe}}$$

$$R_{e_D} = \frac{4\left(.025\,\frac{kg}{s}\right)}{\pi\,(.0000197\,\frac{kg}{m\,s})(.1016\,m)}$$

$$R_{e_D} = 15903$$

$$A = \left(\frac{19000\,\beta}{R_{e_D}}\right)^{.8}$$

$$A = \left(\frac{19000(.25)}{15903}\right)^{.8}$$

$$A = .380$$

$$M_2 = \frac{.94}{1-\beta}$$

$$M_2 = \frac{.94}{1-(.25)}$$

$$M_2 = 1.253$$

$$C_d = .5961 + .0261\,(.25)^2 - .216\,(.25)^4 + .00521\left(\frac{10^6(.25)}{15903}\right) + \left(.0188 + .0063\,(.380)\right)\beta(.25)^{3.5}\left(\frac{10^6(.25)}{15903}\right)^{.3} + (.043 + .080\,e^{-10} - .123\,e^{-7})\left(1 - .011\,(.380)\right)\left(\frac{\beta(.25)^4}{1-(.25)^4}\right) - .031((1.253) - .8(1.253)^{1.1})(.25)^{1.3}$$

$$C_d = .601$$

$$Y_1 = 1 - (.41 + .35\,\beta^4)\frac{dP_{orf}}{1.4\,(P_{atm} + P_{orf})}$$

$$Y_1 = 1 - (.41 + .35\,\beta(.25)^4)\frac{2705.1\ \frac{N}{m^2}}{1.4(101325\ \frac{N}{m^2}\ +\ 28130.6\frac{N}{m^2})}$$

$$Y_1 = .999$$

$$\dot{m} = \frac{\pi}{4}\ Y_1\ C_d\ d_{orf}{}^2\sqrt{\frac{2\ \rho_{orf}\ dP_{orf}}{(1-\beta^4)}}$$

$$\dot{m} = \frac{\pi}{4}(.999)(.601)(.0254\ m)^2\sqrt{\frac{2\left(1.36\frac{kg}{m^3}\right)\left(2705.1\ \frac{N}{m^2}\right)}{(1-\beta^4)}}$$

$$\dot{m} =\ .0262\ \frac{kg}{s}$$

$$A_{fb}\ = \frac{\pi}{4}(D_{fb}{}^2 - d_{pr}{}^2)$$

$$A_{fb} = \frac{\pi}{4}((.1016)^2 - (.01905)^2)$$

$$A_{fb}\ =\ .007822\ m^2$$

$$\rho_g\ =\ \frac{P_{fb} + P_{atm}}{T_{fb}\ 286.987\frac{J}{kg\ K}}$$

$$\rho_g\ = \frac{1034.2\ \frac{N}{m^2} + 101325\ \frac{N}{m^2}}{(312.05\ K)\ 286.987\frac{J}{kg\ K}}$$

$$\rho_g = 1.143\ \frac{kg}{m^3}$$

$$U_o\ = \frac{\dot{m}}{\rho_g A_{fb}}$$

$$U_o\ = \frac{.0262\frac{kg}{m^3}}{(1.143\ \frac{kg}{m^3})(.007822\ m^2)}$$

$$U_0\ =\ 2.93$$

$$q_{htr} = V\,I$$

$$q_{htr} = (13.550\,V)(1.881\,A)$$

$$q_{htr} = 25.488\,W$$

$$h = \frac{q_{htr}}{A_{htr}(T_{htr} - T_{fb})}$$

$$h = \frac{25.488\,W}{(.01743\,m^2)((60.50°C) - (38.90°C))}$$

$$h = 67.69\,\frac{W}{m^2 °C}$$

$$(1-\varepsilon) = \frac{dP_{pt}}{g\,L_{pt}\,\rho_s}$$

$$(1-\varepsilon) = \frac{127.0\,\frac{N}{m^2}}{9.81\,\frac{m}{s^2}\,(.4064\,m)\,(2700\,\frac{kg}{m^2})}$$

$$(1-\varepsilon) = .0118$$

$$\rho_{sus} = (1-\varepsilon)p_s + \varepsilon\,\rho_g$$

$$\rho_{sus} = (.0118)(2700\,\frac{kg}{m^3}) + (.9882)(\,1.143\frac{kg}{m^3})$$

$$\rho_{sus} = 33.0\,\frac{kg}{m^3}$$

$$G_s = \frac{A_{sp}}{g\,A_{fb}}\left(\frac{\Delta dP_{sp}}{\Delta t}\right)$$

$$G_s = \frac{.0182\,m^2}{9.81\,\frac{m}{s^2}(.0078\,m^2)}\left(92.9\frac{kg}{m\,s}\right)$$

$$G_s = 22.9\frac{kg}{m^2 s}$$

APPENDIX E – UNCERTIANTY ANALYIS

The total error of measurement is the sum of sampling error and instrument error. The instrument error is the instrument's stated accuracy for the range being measured, this information can be found in Table 3 in Chapter II. The sampling error can be found using the following equation for the standard deviation of a sample.

$$SD_{sample} = \sqrt{\frac{\sum(x_i - \bar{x})}{n-1}} \tag{D.1}$$

The error can then be estimated as the standard deviation of the mean value.

$$\%\ error = SD_{mean} = \frac{SD_{sample}}{n} \tag{D.2}$$

The sum of measurement error and instrument error for type K thermocouples was found to be near .41 °C for the heater probe and near .26 °C for the fast bed. The error for the current supplied to the heater was estimated to be .05 A and the error in the voltage was .05 V. The area of the heater is dependent on its length and diameter, these were measured with a caliper and the error in measurement is 0.4 mm. Rewriting equation 4.16 in terms of variable I, V, L, D, and T we get the following.

$$h = \frac{V * I}{\pi * D * L\,(T_{htr} - T_{fb})} \tag{D.3}$$

The law of propagation of errors gives the total uncertainty for heat transfer in the equation D.4.

$$Y_p = \frac{1}{h}\sqrt{\left(\frac{\delta}{\delta V}h\right)^2 * \Delta V^2 + \left(\frac{\delta}{\delta I}h\right)^2 * \Delta I^2 + \left(\frac{\delta}{\delta D}h\right)^2 * \Delta D^2 + \left(\frac{\delta}{\delta L}h\right)^2 * \Delta L^2 + \left(\frac{\delta}{\delta T_{htr}}h\right)^2 * \Delta T_{htr}{}^2 + \left(\frac{\delta}{\delta T_{fb}}h\right)^2 * \Delta T_{fb}{}^2} \quad \text{(D.4)}$$

Performing the differentials for each variable of interest with respect to h we get equation D.5. The delta terms are the error determined earlier.

$$Y_p = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta T_{htr}}{(T_{htr} - T_{fb})}\right)^2 + \left(\frac{\Delta T_{fb}}{(T_{htr} - T_{fb})}\right)^2} \quad \text{(D.5)}$$

The uncertainty in the calculation of the heat transfer coefficient can then be found.

$$Y_p = \sqrt{\left(\frac{.05}{13.52}\right)^2 + \left(\frac{.05}{1.881}\right)^2 + \left(\frac{.0004}{.01905}\right)^2 + \left(\frac{.0004}{.2921}\right)^2 + \left(\frac{.41}{(22)}\right)^2 + \left(\frac{.26}{(22)}\right)^2}$$

$Y_p = .041$

The experimental error in heat transfer measurement was found to be 4.1%

Another issue of concern was the accuracy of the orifice plate measurement when oscillating frequencies were imparted to the fast bed. Table D.1 shows the standard deviation for tests A and D in Experiment 29. Comparing the measurement error in the orifice plate differential pressure of the non-pulsed test to test D pulsed at 1.6 Hz using equation D.2 we get the following.

$$\%\ error\ Test\ A = SD_{mean} = \frac{1.36}{238} = .00057\ in\ WC$$

$$\%\ error\ Test\ D = SD_{mean} = \frac{10.95}{226} = .0485\ in\ WC$$

The total error is the sum of measurement error plus instrument error, the instrument error can be obtained from the data in Table 3 in Chapter II. The instrument error is 0.1 in WC. The total error then becomes.

$$Total\ error\ Test\ A = 0.1 + .00057 = .10057\ in\ WC$$

$$Total\ error\ Test\ D = 0.1 + .00485 = .10485\ in\ WC$$

Given the number of data points taken in the experiment the noise in the differential pressure measurement when the pulsing valve is active did not significantly impact the accuracy of the velocity measurement.

Table D.1 Standard deviation of measurements for Experiment 29, Tests A and D

Experiment No.		29			29	
Test No.		A			D	
Start Date		11/8/15			11/8/15	
Data Averages Start Time		15:14:59			17:19:59	
Data Averages End Time		15:35:01			17:39:01	
Test Duration		0:20:02			0:19:02	
No. of data points averaged		238			226	
Pressures (PSIG)						
Orifice Static	1.32	±	0.02	1.69	±	0.44
Fast Bed Static	0.14	±	0.02	0.17	±	0.13
Differential Pressures (inH2O)						
Orifice	11.41	±	0.70	9.38	±	5.96
Distributor Plate	22.75	±	1.36	25.36	±	10.95
Lower Fast Bed	5.08	±	0.97	13.30	±	5.95
Middle Fast Bed	0.60	±	0.03	0.64	±	0.04
Upper Fast Bed	0.47	±	0.18	0.47	±	0.52
Stand Pipe	30.68	±	0.72	26.33	±	1.28
Temperatures (°C)						
Orifice Inlet	44.86	±	0.10	50.33	±	0.28
Fast Bed 103	31.61	±	0.22	34.66	±	0.09
Fast Bed 104	31.66	±	0.22	34.74	±	0.09
Ave. Fast Bed	**31.63**	**±**	**0.31**	**34.70**	**±**	**0.13**
Fast Bed Top	31.68	±	0.22	34.73	±	0.09
Stand Pipe Air	20.98	±	0.07	22.20	±	0.04
Probe 1	53.37	±	0.27	52.24	±	0.20
Probe 2	56.32	±	0.31	54.82	±	0.28
Probe 3	55.61	±	0.28	54.28	±	0.25
Probe 4	52.37	±	0.27	51.65	±	0.21
Ave. Probe	**54.42**	**±**	**0.57**	**53.25**	**±**	**0.47**