Fluidized bed heat exchange capacity of Alumina, coal-char and bio-char solids

F Mushtaq¹, I Ullah¹, I Khan¹, S K Sami¹, W Alam¹, M Sadiq¹, Z Tariq¹ and A Jaan¹

¹Faculty of Engineering and Architecture, Department of Chemical Engineering, Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Airport Road, Baleli, Quetta, Balochistan, Pakistan.

²National Engineering Research, Center of Chemical Fertilizer Catalyst, College of Chemical Engineering, Fuzhou University, Fuzhou, PR China.

Email. faisal.mushtaq@buitms.edu.pk

Abstract. Fluidized bed heat exchanger (FBHx) units have significant applications in various industrial processes. Heat transfer coefficient, pressure drop and superficial gas velocity are the most salient parameters used to characterize the behavior of solid particles in FBHx. This research identifies the pressure drop and surface heat transfer coefficient of Alumina, coal-char and bio-char solids in FBHx. The pressure drop and heat transfer coefficient were estimated at fixed bed height of 6cm by maintaining air flow rate of 8-100 Liters per minute (LPM). Digital temperature sensors are used to measure the bed temperature, air inlet temperature, and heater surface temperature. The results of this study suggest that the effects on pressure drop and surface heat transfer coefficient in FBHx are influenced by bed materials. Among the tested materials, pressure drop and heat transfer coefficient were found of order Alumina>coal-char>bio-char.

Keywords. Fluidized bed heat exchanger, pressure drop, superficial gas velocity, surface heat transfer coefficient, carbon solids.

1. Introduction

Fluidization bed units share the characteristics flow of fluid, where gas or liquid moved through bed of solid particles. A fluid like behavior is attained when the force exerted by the liquid or gas on solid particles in the direction of force and buoyant forces minimizes the downward gravitational forces acting on solid particles. Owning to the corresponding motion, fluidization of the solids can be achieved using gas or liquid phase. Fluidized beds are frequently used as reactors where the gas or liquid is contacted with suspended solids usually used as a catalyst [1-3]. Fluidized bed reactors (FBR) are considered valuable source in industrial applications because they offer high rate of mass transfer and less pressure drop [4]. In addition, FBR presents high rate of mixing and capacity to operate in continuous phase [5]. Fluidized bed heat exchange (FBHx) units offers much complicated heat and mass transport mechanism, where the heat carried by the gas or liquid is used to exchange heat to free flowing solid to raise the solids temperature to desired conditions, and later the reaction carried out at the surface of solids eventually transport mass back [6, 7]. FBHx can be categorized into four classes; i) catalytic gas reactor, where the reactants and products are in the gas phase, and the reaction takes places on the solid surface, either the reactant gases are brought to or solids are pre-heated and maintained to desired temperature ii) reaction gases which utilizes solids as a source of heat energy to
bring the desired reaction conditions, where the reactants and the products are in the gas phase but solids used as heat carrier source iii) gas-solid combination, where the reactants and products are in the gas and solid phase iv) fluidization with no chemical reaction, where the product gases are dried over solid surface [8].

Gas-solids fluidization regimes follows the sequence stationary bed> bubbling bed> slugging bed> turbulent bed > fast moving bed> pneumatic conveying bed, where stationary bed regime refer to minimum fluidization velocity ($U_{mf}$) that does not tends to move the solid bed. However, with the increase in superficial gas velocity ($U_g$), the system approaches bubbling bed regime, where the bubbles initiate mixing of solids [8]. $U_{mf}$ is considered as one of the most significant property when describing the fluidization behavior in FBHx [9]. Several methods described in literature are used to estimate $U_{mf}$ in fluidized bed by; i) heat transfer method, ii) pressure drop method and iii) voidage method. In first method, wall heat transfer coefficient is estimated with the increase in gas velocity and the point is noted where heat transfer coefficient increase significantly [8, 10]. This method of finding $U_{mf}$ is quite costly and requires developed experimental setup [11], where heat transfer data are estimated by maintaining steady state conditions. In the second method, pressure drop over the bed and $U_g$ are plotted and point of alteration between stationary and bubbling bed regime are indentified. In third method, $U_{mf}$ is identified when the free space inside the bed begin to increase the bed extension as the $U_g$ increases. Although voidage method is most generally used, however it is difficult to position out the point where bed extension actually begins. In general, $U_{mf}$ mainly depends on physico-chemical properties of solids, liquid and gas phase and bed geometry [10].

Fluidization of bio-char and coal-char solids produced from various industrial applications provides a prospect to develop and utilize by-product carbon rich solids. Several researcher have found widespread applications of bio-char and coal-char as a source of carbon material, such as metallurgical and mineral processing [12], biomass valorization [13], bio-solid handling [14], soil decontamination [15], carbon catalyzed gas-phase reactions [16]. Among these, gas-phase reactions catalyzed over carbon in FBHx are gaining importance over the recent decade [17-20]. The key concerns of using carbon in FBHx are non-uniform nature and variation in density associated with carbons, such as bio-char and coal-char solids which offers complex multiphase system. The effects of significant properties on FBHx capacity needs to be investigated for improved system performance and design. The primary aim of this study is to investigate the effect of air flow rate on pressure drop, $U_{mf}$ and surface heat transfer coefficient of Alumina, bio-char and coal-char solids.

2. Materials and Methods

The coal samples in the form of lumps were collected from the Machh Bolan Mine Company located at Quetta, Pakistan. Sawdust waste biomass samples were collected from local carpenter shop. The coal and sawdust samples of 3 kg were kept in air tight plastic bags and labeled for further processing. The coal and sawdust samples were subjected to combustion at temperature of 550°C and 350°C, respectively for char production. The maximum combustion temperature of coal and sawdust were selected and based on the studies [21, 22]. The coal-char and bio-char samples were sieved to obtain uniform particle of 14 and 20 mesh size, respectively and were used without physico-chemical modification. Granular fused Alumina (white Aluminum Oxide) type V of density 3770 kg/m³ and 80 grit size (average particle size 177 µm) and pour density of approximately 1620 kg/m³ was used as a reference material. SOLTEQ® fluidization and fluid bed heat transfer Unit (Model: HE 162) apparatus was used as shown in Figure 1.

The unit comprised of glass cylinder was carefully loaded with 1.25 kg of tested sample and leveled. The glass chamber is coupled with air distributor chamber that supports the bed material at the bottom. The air distributor chamber provided was designed to keep uniform airflow distribution with minimal pressure drop. The air passes through the bed material and vent to atmosphere through an air filter at the top. The bed temperature was measured by thermocouple labeled as T1. Compressed air was supplied through filter and pressure regulator assembly and airflow rotameters equipped with low flow rate (V) 6-50 liters per minutes (LPM) and high flow 40-440 LPM through air flow control
valves before entering the distribution chamber. The compressed air temperature was measured with thermocouple (T2). Variable transformer provided with electrical heater power of 250 W and surface area of 22.8 cm² was used to control input heater power (Q). The heating element fitted with thermocouple was used to determine the heater surface temperature (labeled as T3). The pressure drop across the bed at various levels was measured by liquid filled manometer upto 300mm H₂O pressure drop. For excessive pressure in chamber, the chamber is fitted with pressure relief valve.

Figure 1. Schematic Diagram of Fluidization and Fluid Bed Heat Exchanger (Model: HE 162) used in this study.

The pressure drop across the bed Δp was measured and is equal to the effective weight of the bed per unit area.

\[ \Delta p = \frac{M}{\rho_p \cdot S_b} \cdot \left( \rho_p - \rho_f \right) \cdot g \]  

(1)

Where mass M of particles of density ρp charged in the bed of cross-sectional area Sb fluidized by a fluid of density ρf and g gravitational acceleration.

The \( U_{mf} \) under ambient conditions was measured by charging 1.25 kg of particles into the chamber to form a bed. Initially, the bed is vigorously fluidized for 1-2 minutes to breakdown particle interlocking. The pressure drop under these conditions was found decreasing as the fluidizing gas velocity was reduced. Several step measurements of the pressure drop across the bed as function of reducing fluidizing gas velocity were noted. The results were plotted as of bed pressure drop and superficial gas velocity. The \( U_{mf} \) is derived from the velocity profile, where the intersection between the raising and smoothing of the profile identified. It was expected that the pressure drop tends to have value equal to or less than (because of bed column particle-wall interaction) bed weight per unit area. However, the increase in \( U_{mf} \) linearly increases the pressure drop across the bed until the bed approaches fluidization, a condition where gas flow through bed is considered laminar.

The surface heat transfer coefficient is calculated using Equation 2.

\[ h = \frac{Q}{A_h \cdot \Delta T_m} \]  

(2)

Where Q is the heater power in W in W/m².K, \( A_h \) is surface area of the heater in m² and \( \Delta T_m \) is the mean temperature difference in K and calculated from

\[ \Delta T_m = \Delta T_1 - \Delta T_2 \]  

(3)

Where \( \Delta T_1 \) is the temperature difference between heater surface (T3) and air inlet (T2) and \( \Delta T_2 \) is the temperature difference between heater surface (T3) and bed material (T1).

The following are the details of calculations:

For superficial gas velocity
a. Material= Al₂O₃, mean particle diameter=dₒ=177 μm (80 grit), particle density= ρₚ=3770 kg/m³, mass of the particles=m=1.25 kg, Air flow through bed, Vₕ=(V/60)x(T₁/T₂) and superficial gas velocity , Uₕ=Vₕ/(1000 x A), where, cross sectional area of the bed= A=0.008659 m²

b. Material= Coal-char, mean particle diameter=dₒ=1410 μm (14 mesh), particle density= ρₚ=0.0009 kg/m³, mass of the particles=m=1.25 kg, Air flow through bed, Vₕ=(V/60)x(T₁/T₂) and superficial gas velocity , Uₕ=Vₕ/(1000 x A), where, cross sectional area of the bed= A=0.008659 m²

For surface heat transfer coefficient

a. Material= Al₂O₃, mean particle diameter=dₒ=177 μm (80 grit), particle density= ρₚ=3770 kg/m³, mass of the particles=m=1.25 kg, Air flow through bed, Vₕ=(V/60)x(T₁/T₂) and superficial gas velocity , Uₕ=Vₕ/(1000 x A), where, cross sectional area of the bed= A=0.008659 m², surface heat transfer coefficient=h= Q/A x ΔT₂ and ΔT₁= T₁ – T₂ and Aₕ= surface heat transfer area of heater=0.00228 m²

b. Material= Coal-char, mean particle diameter=dₒ=1410 μm (14 mesh), particle density= ρₚ=0.0009 kg/m³, mass of the particles=m=1.25 kg, Air flow through bed, Vₕ=(V/60)x(T₁/T₂) and superficial gas velocity , Uₕ=Vₕ/(1000 x A), where, cross sectional area of the bed= A=0.008659 m², surface heat transfer coefficient=h= Q/A x ΔT₂ and ΔT₁= T₁ – T₂ and Aₕ= surface heat transfer area of heater=0.00228 m²
c. Material= Bio-char, mean particle diameter=dₒ=841 μm (20 mesh), particle density= ρₚ=0.0003 kg/m³, mass of the particles=m=1.25 kg, Air flow through bed, Vₕ=(V/60)x(T₁/T₂) and superficial gas velocity , Uₕ=Vₕ/(1000 x A), where, cross sectional area of the bed= A=0.008659 m², surface heat transfer coefficient=h= Q/A x ΔT₂ and ΔT₁= T₁ – T₂ and Aₕ= surface heat transfer area of heater=0.00228 m²

3. Results and Discussion

3.1. Effects of change in bed height, bed pressure drop and upward air flow velocity of Al₂O₃ granular bed

The results of change in bed height, pressure drop with increasing and decreasing air flow rate is given in Table 1 and Table 2 and redrawn as Figure 2 and Figure 3 as a function of superficial gas velocity, bed height and pressure drop. As can be observed from Table 1 and 2 that pressure drop is directly proportional to the superficial gas velocity. At low air flow rate, drastic increase in pressure drop can be related to lesser penetration of air within the bed material. However, pressure drop was observed fairly constant during later stages of fluidization. This is mainly due to the fact that particles are kept separated ensuing higher free space and increase in viadage. The Uₘd calculated of 0.04 m/s at 97 mm of H₂O/mm of bed height from Figure 3.

| Air flow rate (LPM) | T₁(K) | T₂(K) | H (mm) | Vₕ (L/s) | Uₕ (m/s) | ΔP/bed height (mm of H₂O/mm) |
|---------------------|-------|-------|--------|----------|----------|-----------------------------|
| 8                   | 307.5 | 306.5 | 60     | 0.13     | 0.015    | 55.3                        |
| 12                  | 309.3 | 306.5 | 61     | 0.20     | 0.023    | 76.4                        |
| 16                  | 309.1 | 306.4 | 69     | 0.27     | 0.031    | 102.8                       |
| 20                  | 309.6 | 306.5 | 73     | 0.34     | 0.039    | 124.7                       |
| 24                  | 311.6 | 306.5 | 81     | 0.41     | 0.047    | 96.6                        |
| 30                  | 313.9 | 306.4 | 85     | 0.51     | 0.059    | 97.4                        |
| 40                  | 310.7 | 307.6 | 89     | 0.67     | 0.078    | 99.7                        |
| 60                  | 310.4 | 306.6 | 93     | 1.01     | 0.117    | 101.6                       |
| 80                  | 311.2 | 306.7 | 97     | 1.35     | 0.156    | 104.8                       |
| 100                 | 311.3 | 307  | 115    | 1.69     | 0.195    | 108.6                       |
Table 2. Effects of bed height, pressure drop and air flow velocity of Al₂O₃ bed with decreasing air flow rate.

| Air flow rate (LPM) | T₁(K) | T₂(K) | H (mm) | V₅ (L/s) | U₉ (m/s) | ΔP/bed height (mm of H₂O/mm) |
|---------------------|-------|-------|--------|----------|----------|----------------------------|
| 100                 | 316.6 | 299.5 | 80     | 1.76     | 0.20     | 111.4                      |
| 80                  | 315.4 | 299.2 | 73     | 1.41     | 0.16     | 106.6                      |
| 60                  | 315.9 | 298.6 | 70     | 1.06     | 0.12     | 103.8                      |
| 40                  | 306.5 | 298.1 | 68     | 0.69     | 0.08     | 101.2                      |
| 30                  | 304.2 | 297.8 | 65     | 0.51     | 0.06     | 100.5                      |
| 24                  | 296.9 | 297.3 | 62     | 0.40     | 0.05     | 99.8                       |
| 20                  | 296.3 | 296.9 | 60     | 0.33     | 0.04     | 95.2                       |
| 16                  | 296.1 | 296.2 | 59     | 0.27     | 0.03     | 80.2                       |
| 12                  | 295.9 | 295.7 | 59     | 0.20     | 0.02     | 58.5                       |
| 8                   | 295.4 | 295.4 | 59     | 0.13     | 0.02     | 41.8                       |

3.2. Effects of change in bed height, bed pressure drop and upward air flow velocity of coal-char bed

The results of change in bed height, pressure drop with increasing and decreasing air flow rate is given in Table 3 and 4 and redrawn as Figure 4 and Figure 5 as a function of superficial gas velocity, bed height and pressure drop. As can be observed from Table 3 and 4, pressure drop increases with increase in superficial gas velocity at low to moderate air flow rate, which can be related to lesser penetration of air within the compacted bed material. However, once the bed is fluidized, pressure drop was observed fairly constant. The U₉mf determined was equal to 0.116 m/s from Figure 5. The maximum pressure drop with coal-char bed was observed 33.12 mm of H₂O/mm of bed height, where Al₂O₃ bed of the same mass produced 111.4 mm of H₂O/mm of bed height. U₉mf was estimated at 0.116 m/s at 21.5 mm of H₂O/mm of bed height pressure drop. This difference can be correlated to large difference is density.

Figure 2. Effects of superficial gas flow on pressure drop and bed height of Al₂O₃ with increasing air flow rate
Figure 3. Effects of superficial gas flow on pressure drop and bed height of Al₂O₃ with decreasing air flow rate

Table 3. Effects of change in bed height, pressure drop of coal-char bed with increasing air flow rate.

| Air flow rate (LPM) | T₁ (K) | T₂ (K) | H (mm) | Vₛ (L/s) | Uₙ (m/s) | ∆P/bed height (mm of H₂O/mm) |
|---------------------|--------|--------|--------|----------|----------|----------------------------|
| 8                   | 307.5  | 306.5  | 60     | 0.13     | 0.015    | 7.62                       |
| 12                  | 309.3  | 306.5  | 61     | 0.20     | 0.023    | 25.4                       |
| 16                  | 309.1  | 306.4  | 69     | 0.26     | 0.031    | 32.02                      |
| 20                  | 309.6  | 306.5  | 73     | 0.33     | 0.038    | 30.48                      |
| 24                  | 311.6  | 306.5  | 81     | 0.39     | 0.045    | 31.00                      |
| 30                  | 313.9  | 306.4  | 85     | 0.49     | 0.056    | 38.1                       |
| 40                  | 310.7  | 307.6  | 89     | 0.66     | 0.076    | 33.12                      |
| 60                  | 310.4  | 306.6  | 93     | 0.99     | 0.114    | 33.02                      |
| 80                  | 311.2  | 306.7  | 97     | 1.31     | 0.152    | 22.94                      |
| 100                 | 311.3  | 307    | 115    | 1.64     | 0.190    | 27.94                      |

Table 4. Effects of change in bed height, pressure drop of coal-char bed with decreasing air flow rate.

| Air flow rate (LPM) | T₁ (K) | T₂ (K) | H (mm) | Vₛ (L/s) | Uₙ (m/s) | ∆P/bed height (mm of H₂O/mm) |
|---------------------|--------|--------|--------|----------|----------|----------------------------|
| 100                 | 311.3  | 307    | 115    | 1.89019  | 0.218    | 27.94                      |
| 80                  | 311.2  | 306.7  | 100    | 1.64257  | 0.190    | 22.94                      |
| 60                  | 311.2  | 306.6  | 93     | 1.52709  | 0.176    | 33.02                      |
| 40                  | 310.7  | 307.6  | 87     | 1.43553  | 0.166    | 33.12                      |
| 30                  | 313.9  | 306.4  | 84     | 1.36655  | 0.158    | 38.1                       |
| 24                  | 311.6  | 306.5  | 81     | 1.3279   | 0.153    | 25.86                      |
| 20                  | 309.6  | 306.5  | 73     | 1.20448  | 0.139    | 30.48                      |
| 16                  | 309.1  | 306.4  | 70     | 1.15648  | 0.134    | 32.02                      |
| 12                  | 309.3  | 306.5  | 62     | 1.02398  | 0.118    | 25.4                       |
| 8                   | 307.5  | 306.5  | 60     | 0.99675  | 0.115    | 7.62                       |
3.3. Effects of heater power, superficial gas velocity on surface heat transfer coefficient of $\text{Al}_2\text{O}_3$, coal-char and bio-char bed

The results of change in heater power and superficial gas velocity on surface heat transfer coefficient of $\text{Al}_2\text{O}_3$, coal-char and bio-char are presented in Table 5, Table 6 and Table 7, respectively and compared in Figure 6. It can be observed that increase in heater power and superficial gas velocity increases the surface heat transfer coefficient with all the tested material. The highest $h$ was observed with $\text{Al}_2\text{O}_3$ of 717.70 W/m$^2$.K and lowest with bio-char of 43.76 W/m$^2$.K. Among the tested material, the surface heat transfer coefficient were observed of order $\text{Al}_2\text{O}_3 >$coal-char$> $bio-char. This difference can be mainly correlated to the difference is physico-chemical properties of the material. The heat exchange capacity in fluidized system of metals and carbon based material can be influenced greatly where the bed is fluidized.
Table 5. Effects of heater power and superficial gas velocity on surface heat transfer coefficient of Al2O3

| Height of heater (mm) | Height of T1 Probe (mm) | Air flow rate (LPM) | T1(K) | T2(K) | T3(K) | Heater power Q (W) | Vb (L/s) | Superficial gas Velocity Ug (m/s) | Surface heat transfer coefficient h (W/m².K) |
|----------------------|-------------------------|---------------------|-------|-------|-------|-------------------|---------|----------------------------------|------------------------------------------|
| 40                   | 40                      | 8                   | 326.4 | 307.3 | 356.2 | 4.3               | 0.142   | 0.016                           | 19.100                                   |
| 40                   | 40                      | 12                  | 325.7 | 307.1 | 356.4 | 4.6               | 0.212   | 0.024                           | 18.600                                   |
| 40                   | 40                      | 16                  | 324.4 | 306.3 | 356.2 | 4.9               | 0.282   | 0.033                           | 18.100                                   |
| 40                   | 40                      | 20                  | 323.2 | 306.5 | 356.7 | 5.5               | 0.351   | 0.041                           | 16.700                                   |
| 40                   | 40                      | 26                  | 323   | 307   | 356.8 | 5.7               | 0.456   | 0.053                           | 16.000                                   |
| 40                   | 40                      | 30                  | 321.6 | 306.4 | 357   | 6.3               | 0.525   | 0.061                           | 15.200                                   |
| 40                   | 40                      | 40                  | 318.3 | 306.3 | 356.9 | 7.5               | 0.693   | 0.080                           | 12.000                                   |
| 40                   | 40                      | 60                  | 316.5 | 306.5 | 357   | 9.2               | 1.033   | 0.119                           | 10.000                                   |
| 40                   | 40                      | 80                  | 316.7 | 306.4 | 358.5 | 11.6              | 1.378   | 0.159                           | 10.300                                   |
| 40                   | 40                      | 100                 | 314.2 | 306.5 | 358.3 | 12.6              | 1.709   | 0.197                           | 7.700                                    |

Table 6. Effects of heater power and superficial gas velocity on surface heat transfer coefficient of coal-char

| Height of heater (mm) | Height of T1 Probe (mm) | Air flow rate (LPM) | T1(K) | T2(K) | T3(K) | Heater power Q (W) | Vb (L/s) | Superficial gas Velocity Ug (m/s) | Surface heat transfer coefficient h (W/m².K) |
|----------------------|-------------------------|---------------------|-------|-------|-------|-------------------|---------|----------------------------------|------------------------------------------|
| 40                   | 40                      | 8                   | 340.9 | 305.5 | 329.8 | 4.3               | 0.149   | 0.017                           | 35.4                                    |
| 40                   | 40                      | 12                  | 339.6 | 305.3 | 330   | 4.6               | 0.222   | 0.026                           | 34.3                                    |
| 40                   | 40                      | 16                  | 338.2 | 304.5 | 329.8 | 4.9               | 0.296   | 0.034                           | 33.7                                    |
| 40                   | 40                      | 20                  | 338   | 304.7 | 330.3 | 5.5               | 0.370   | 0.043                           | 33.3                                    |
| 40                   | 40                      | 26                  | 337.8 | 305.2 | 330.4 | 5.7               | 0.480   | 0.055                           | 32.6                                    |
| 40                   | 40                      | 30                  | 335.4 | 304.6 | 330.6 | 6.3               | 0.551   | 0.064                           | 30.8                                    |
| 40                   | 40                      | 40                  | 334.1 | 304.5 | 329.5 | 7.5               | 0.731   | 0.084                           | 29.6                                    |
| 40                   | 40                      | 60                  | 331.3 | 304.7 | 330.6 | 9.2               | 1.087   | 0.126                           | 26.5                                    |
| 40                   | 40                      | 80                  | 330.5 | 304.6 | 334.1 | 11.6              | 1.447   | 0.167                           | 25.9                                    |
| 40                   | 40                      | 100                 | 330   | 306.7 | 333.9 | 12.6              | 1.793   | 0.207                           | 23.3                                    |

Table 7. Effects of heater power and superficial gas velocity on surface heat transfer coefficient of bio-char

| Height of heater (mm) | Height of T1 Probe (mm) | Air flow rate (LPM) | T1(K) | T2(K) | T3(K) | Heater power Q (W) | Vb (L/s) | Superficial gas Velocity Ug (m/s) | Surface heat transfer coefficient h (W/m².K) |
|----------------------|-------------------------|---------------------|-------|-------|-------|-------------------|---------|----------------------------------|------------------------------------------|
| 40                   | 40                      | 8                   | 340.9 | 305.5 | 329.8 | 4.3               | 0.149   | 0.017                           | 35.4                                    |
| 40                   | 40                      | 12                  | 339.6 | 305.3 | 330   | 4.6               | 0.222   | 0.026                           | 34.3                                    |
| 40                   | 40                      | 16                  | 338.2 | 304.5 | 329.8 | 4.9               | 0.296   | 0.034                           | 33.7                                    |
| 40                   | 40                      | 20                  | 338   | 304.7 | 330.3 | 5.5               | 0.370   | 0.043                           | 33.3                                    |
| 40                   | 40                      | 26                  | 337.8 | 305.2 | 330.4 | 5.7               | 0.480   | 0.055                           | 32.6                                    |
| 40                   | 40                      | 30                  | 335.4 | 304.6 | 330.6 | 6.3               | 0.551   | 0.064                           | 30.8                                    |
| 40                   | 40                      | 40                  | 334.1 | 304.5 | 329.5 | 7.5               | 0.731   | 0.084                           | 29.6                                    |
| 40                   | 40                      | 60                  | 331.3 | 304.7 | 330.6 | 9.2               | 1.087   | 0.126                           | 26.5                                    |
| 40                   | 40                      | 80                  | 330.5 | 304.6 | 334.1 | 11.6              | 1.447   | 0.167                           | 25.9                                    |
| 40                   | 40                      | 100                 | 330   | 306.7 | 333.9 | 12.6              | 1.793   | 0.207                           | 23.3                                    |
4. Conclusion
This study investigated the effects of change in bed height, bed pressure drop and upward air flow velocity on superficial gas velocity and fluidization behavior. Further, the effect of superficial gas velocity on surface heat transfer coefficient of Alumina, coal-char and bio-char were tested. The results of this study suggests that pressure drop increases with increase in superficial gas velocity at low to moderate air flow rate, which can be correlated to lesser penetration of air within the compacted bed material. However, once the bed is fluidized, pressure drop was observed fairly constant which is mainly due to the increase in free voidage space. In addition, increase in heater power and superficial gas velocity increases the surface heat transfer coefficient with all the tested material. Among the material tested, the surface heat transfer coefficient were observed of order \( \text{Al}_2\text{O}_3 > \text{coal-char} > \text{bio-char} \). The intermediate heat exchange properties of coal-char suggests potential application as slow raise in bed solid temperature and controls over final process temperature when tested as catalyst in bench scale fluidized bed reactor.

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