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Heat Transfer Coefficients in Air-Solid Fluidized Bed Using Vertical Heating Element

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HIGHLIGHTS

- Local heat transfer coefficient in fluidized bed increases with increasing superficial gas velocity and higher for smaller particle sizes
- The heat transfer coefficient is increased with increasing the voidage between particles
- Higher velocities and higher heating power can further enhance the heat transfer coefficient
- A mathematical correlation was developed depending on the experimental data with the aid of Using LABFIT software, showing a 5% deviation
- Smaller particles increase the turbulence within the fluid, enhancing the convective heat transfer

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ABSTRACT

In various chemical industrial applications such as hydrocracking, drying, and Fischer-Tropsch, the utilization of fluidized bed systems is prevalent. Efficient heat transfer is crucial for maintaining stable temperatures and ensuring product quality in industrial processes. Gas-solid fluidized beds, which involve gas circulation through a bed of solid particles, offer a means to achieve efficient heat exchange. However, factors such as particle size, gas velocity, and heating methods can influence the effectiveness of these systems. To investigate the impact of internal heating on heat transfer in gas-solid fluidized beds, an experimental study was conducted using glass beads of 200 and 600 µm. A Perspex fluidization column with an inner diameter of 10 cm and a total height of 2 m was packed with these beads. The experiments were performed under superficial gas velocities ranging from 0.1 to 0.5 m/s. Highly responsive sensors were employed to measure temperatures and calculate the heat transfer coefficient. Additionally, the position of the heating element and local heat transfer coefficients at different gas velocities were examined. The experimental results were compared to a mathematical model developed to simulate laboratory findings. The total heat transfer coefficient was evaluated in a gas-solid fluidized bed at different bed temperatures. Furthermore, a comparison was made between the experimental results and the model to validate the practical application, while the practical results were also compared with previous studies.

1. Introduction

Fluidized beds play a crucial role in industrial applications related to heat transfer, such as heating applications and reactors. These beds provide several advantages, including improved heat transfer rates, uniform temperature distribution, and rapid reaction rates. Fluidized beds possess scalability and flexibility, allowing them to meet diverse process requirements. They also facilitate efficient heat recovery, leading to reduced energy consumption. Furthermore, fluidized beds effectively handle particulate solids. Collectively, fluidized beds enhance process efficiency, elevate product quality, and contribute to decreasing energy expenses in industries like chemical, petrochemical, and energy production [1,2].

The minimum fluidization velocity u_{mf} is the gas velocity at which the fixed bed state changes to a fluidized state. Excess gas will create bubbles or channels in the bed at flow rates higher than the minimum fluidization velocity. The bed particles' movement will also become more vigorous [3,4]. Bubbled fluidization describes the bed's state at this point, varying gas

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velocities, the degree of fluidization shifts to another state [5]. Heat transfer between the solid and fluid phases is facilitated by the high mixing of bed particles and the large contact area between bed particles and fluidizing gas per unit bed volume [6-8].

Hou et al. [9], investigated heat transfer characteristics of different powders in gas fluidization using a combined approach of discrete element method and computational fluid dynamics. The results confirmed that the convective heat transfer was dominant, and radiative heat transfer becomes important when the bed temperature is high. However, conductive heat transfer becomes noticeable depending on the flow regimes and material properties [9]. Under optimal conditions, the heat transfer rate in fluidized systems is quite efficient. Heat transfer rates in fluidized beds are significantly higher at constant gas flow rates than those in empty tubes or fixed beds.

Another work reported that particle–particle and particle–surface collisional heat transfers might play a significant role in fluidized bed systems under certain conditions. Therefore, because of the intensive motion of particles in the turbulent fluidized regime, it appears to be of interest to model and investigate heat transfer processes induced by particle–particle and particle–surface collisions [5]. Since fluidized systems can keep the bed at a uniform temperature even while enormous amounts of heat are absorbed inside the system, they are ideal for chemical processes where precise temperature regulation is essential [10,11]. Depending on the size of the fluidizing column, they can supply or remove significant amounts of heat. As long as the gas flow sufficiently mixes the bed, the bed's temperature is relatively consistent, both axially and radially [12]. The area at which heat is transferred from the bed to a heat-exchanging wall surface is an important consideration. These interactions are particle-particle, fluid-particle, particle-wall, and gas-wall heat exchanges [13]. In this way, heat can be transported to the wall from particles in the bed near the wall using conduction, convection, and radiation. Maintaining a relatively constant temperature difference between the bed and wall by the fluidizing state, which brings new bed particles to replace those that have cooled down. The bed-to-wall heat transfer coefficient has been the subject of numerous research and correlations to discover the most relevant process parameters [14,15].

The work investigates the effect of internal heating on heat transfer coefficient in gas-solid fluidized beds. This is achieved through an experimental study using glass beads of different sizes packed in a fluidization column. The study aims to determine the impact of factors such as particle size, gas velocity, and heating power on the effectiveness of heat transfer in the fluidized bed system. Additionally, the study aims to compare the experimental results with a mathematical correlation model derived from the results and compare it with the previous correlation model to validate the results of the research.

2. Experimental work

The glass beads used in the experiment were provided by OTS Chinese company. The composition of the glass beads consists of various components, including SiO_2, Na_2O, CaO, MgTiO, Al_2O_3, K_2O, SO_3, and Fe_2O_3. The mass fraction for these components and the general properties were found after characterizing the glass beads, and the results are provided in Tables 1 and 2.

Table 1: The percentage of the various components in the glass beads

Component	Value%
SiO_2	72.00 - 73.00
Na_2O	13.30 - 14.30
CaO	7.20 - 9.20
MgTiO	3.50 - 4.00
Al_2O_3	0.80 - 2.00
K_2O	0.20 - 0.60
SO_3	0.20 - 0.30

Table 2: Properties of the glass bed

Typical physical properties	
Grain shape	Round
Melting point	1200°C
Solid density	2.60 g/cm^3
Bulk density	1.6 g/cm^3
Voidge	0.45

A gas-solid fluidized bed column was installed to study heat transfer of the immersed heater inside the bed material . Glass beads with 200 and 600μm in diameter were used. A bed height of 30 cm is used to fill a Perspex fluidizing column supported on a perforated plate, which also acts as an air distributor. The inner diameter of the column was 10 cm, and the height was 2 m. An electrical heater (D=20 mm, L=300 mm) with a power capacity of 600 W was installed vertically immersed in the glass beads. The experimental heat transfer coefficient in a gas-solid fluidized bed system was calculated under different variable conditions such as heater power (50, 75,100,125 Watts), particle size (200 , and 600 μm), and gas velocity (0.1-0.5 m/s) . The schematic diagram and photograph of the experiment setup are illustrated in Figure 1 and Figure 2, respectively. The design of the gas distributor (perforated plate, triangle pitch) was made by applying the orifice theory (Kunii, 1991) with the following details: The number of orifices is 52, and the orifice diameter is 2 mm. The free area in the distributor plate is 1.7%, and the distance between the center of the hole is 13 mm.

Seven thermocouples (Type K) were used after calibration in the experimental setup. The first thermocouple was installed in the inlet section 2 to the fluidized bed column at (10 cm) under the distributor to measure the inlet gas temperature. The second thermocouple was installed 10 cm above the distributor to measure the bed temperature, and the other five sensors were located upward above the second one, 10 cm apart between them. A digital manometer (provided by Hti-Xintai company) was used to measure the pressure difference from the pressure ports along the column. The pressure ports and the seven temperature sensor locations are shown in Figure 1.

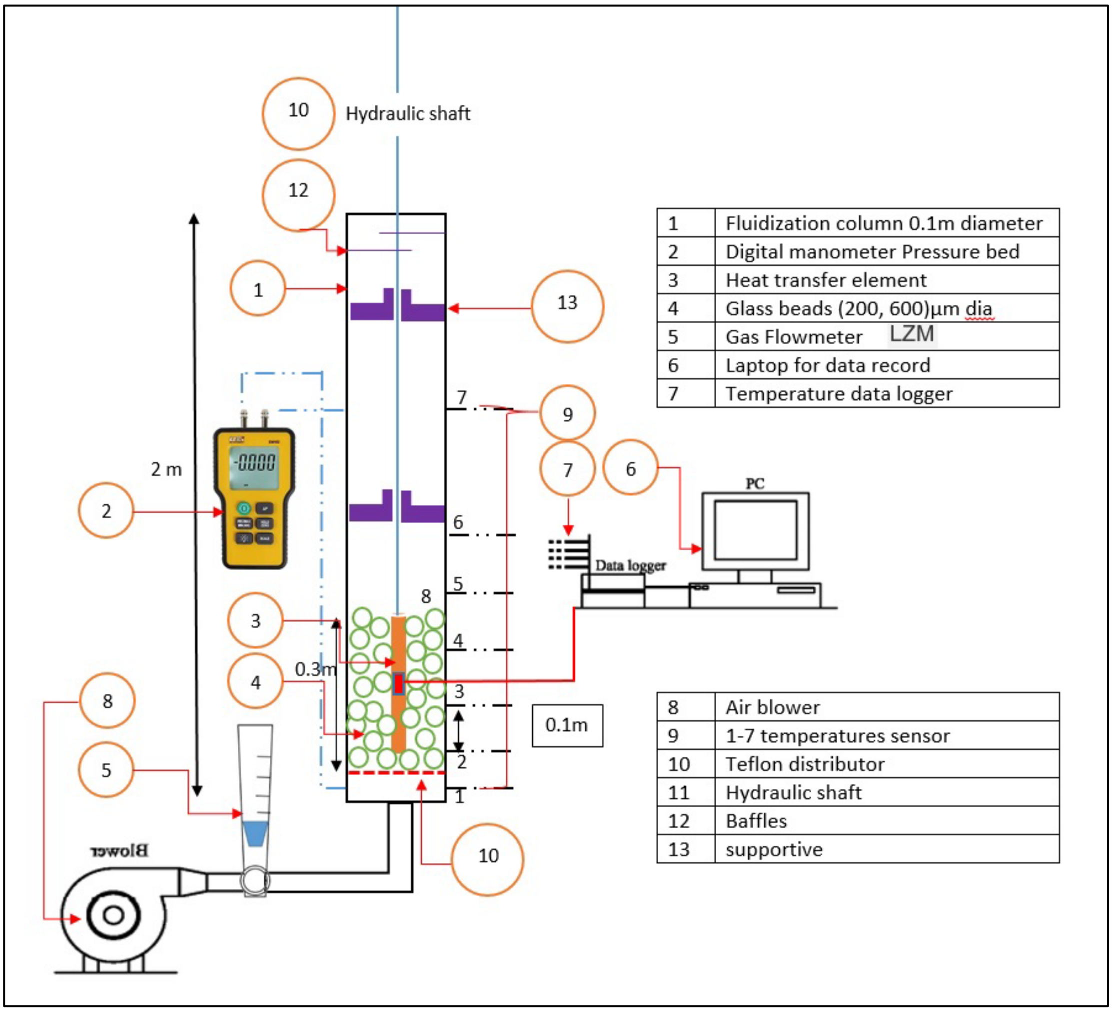

Figure 1: Schematic Diagram of the Experimental Apparatus

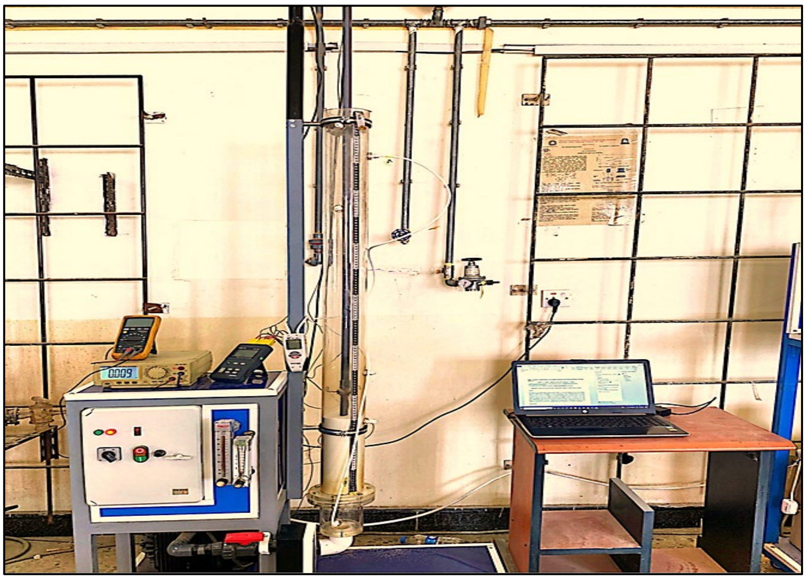

Figure 2: Experimental setup image

3. Results and Discussion

3.1 Minimum Fluidization Velocity (u_{mf})

The minimum fluidized velocity is perhaps the most important parameter in classifying fluidized bed behavior. Minimum fluidizing velocity was found experimentally by measuring the pressure drop (ΔP) versus superficial gas velocity (u) as shown in Figure 3. From Figure 3, of (ΔP) vs. (u), the minimum fluidizing velocity (u_mf) by the intersection of the variable and constant pressure line the results are shown in Figures 3 and 4 for different particle diameters.

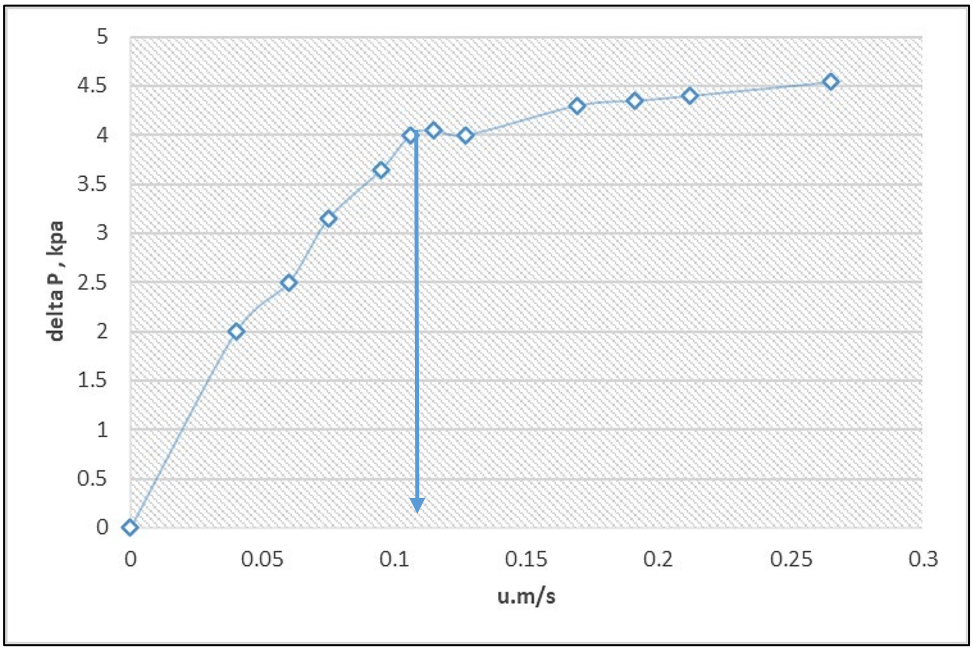

Figure 3: Relationship between superficial velocity and pressure drop for 200 µm particle diameter

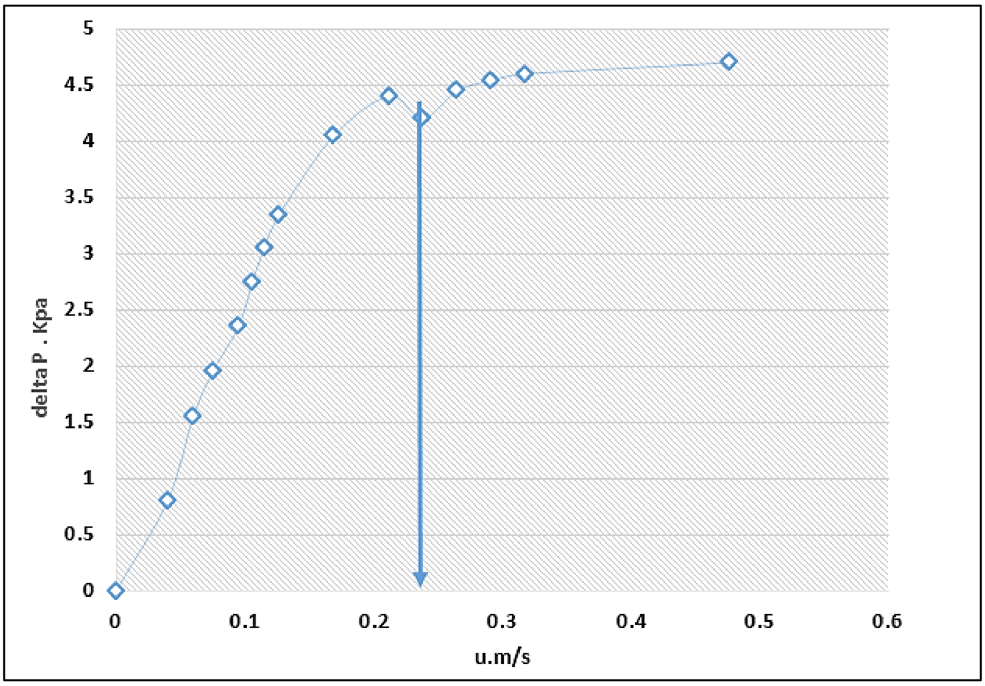

Figure 4: Relationship between superficial gas velocity and pressure drop for 600 µm particle diameter

The Numerical values of minimum fluidizing velocity are presented in Table 3.

Table 3: Numerical values of the minimum fluidizing velocity

Particles diameter	$u_{mf}\ (\frac{m}{s})$
200 µm	0.123
600 µm	0.212

3.2 Effect of Velocity on Heat Transfer Coefficient.

The heat transfer coefficient was calculated using the newton law of cooling Equation 1 on the heating element immersed on the glass beads.

$$h = \frac{q}{A.\Delta T} = \frac{V.I}{A.(T_s - T_b)} \quad (1)$$

where q : is the heat transfer rate provided by the electrical heater by changing the voltage (v) and current (I), A: is the area of the heating element, ΔT: is the temperature difference between the surface temperature (T_s) and the average bed temperature (T_b)

T_s was measured by a highly sensitive thermocouple on the surface of the heating element. While T_b was measured at different locations inside the fluidization column using sensors distributed along the fluidized bed.

The results of the calculated heat transfer coefficient at different particle sizes are shown in Figure 5. At constant velocity, the heat transfer coefficient for 200 µm particle size was higher than the heat transfer coefficient for 600 µm particle size. Increasing the air velocity from 0.2 to 0.5 causes a significant rapid rise in the heat transfer coefficient by more than 60%. Thus, the heat transfer coefficient increases rapidly over a narrow velocity range ($u_o > u_{mf}$).

When the velocity of the fluidized bed increases, more air is introduced to the solid particles, which raises their enthalpy [15]. Because fewer particles are dispersed throughout the bed as flow velocity increases, the heat transfer coefficient decreases.

Figure 5 indicates that the heat transfer coefficient (HTC) increases with increasing superficial gas velocity and is generally higher for smaller particle sizes (200 µm) compared to larger ones (600 µm). Smaller particles provide a larger surface area per unit volume, which enhances heat transfer. The benefits of using smaller particles and higher velocities are more significant at certain operating conditions, were higher mixing rates in the bed cases more frequent collection and more turbelance which alow for higher heat transfer rate by convection and conduction in generial [16,17].

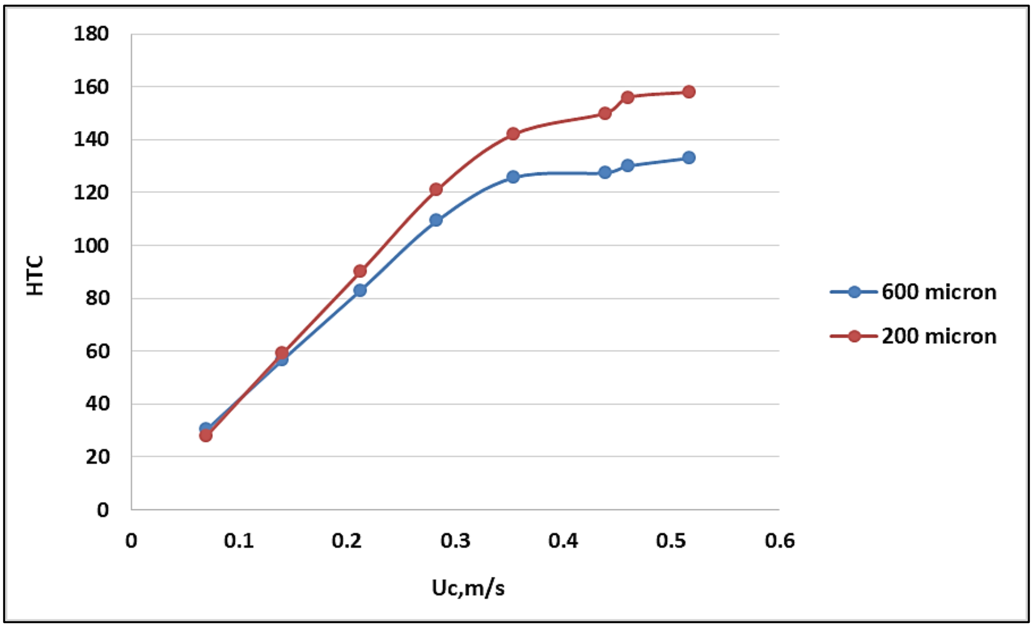

Figure 5: Heat transfer coefficient as a function of superficial velocity for different particles' diameter

3.3 Effect of Voidage on Heat Transfer Coefficient

The effect of voidage on the heat transfer coefficient was studied due to the varying behavior of the voidage with gas velocity, particle size, and particle shape. The bed voidage ϵ is computed from the pressure drop ΔP across bed height H by using Equation 2 :

$$\epsilon = 1 - \frac{\Delta P}{H(\rho_s - \rho_g)\mathrm{g}}. \quad (2)$$

The results of the calculated void fraction from Equation 2 were shown in Figures 6 and 7 for 200 and 600 µm particle size, respectively. The results show that with increasing the voidage between particles, the heat transfer coefficient increased. This occurs due to the increase in heat transfer rate by convection through the voids between the glass beads. As a result of the increase in gas velocity, the glass beads will be in a state of divergence, allowing heat transfer by convection in all parts of the fluidized bed. The void fraction at larger particle size gives a higher heat transfer coefficient from Figures 6 and 7, heat transfer cofficent at 600 µm was higher than that at 200 µm for the same void space .While the void fraction is changed by increaseing the velosity after fluidizing , the change in the size of the particle also effect the spaced between the particle and thus the voide fraction [18,19].

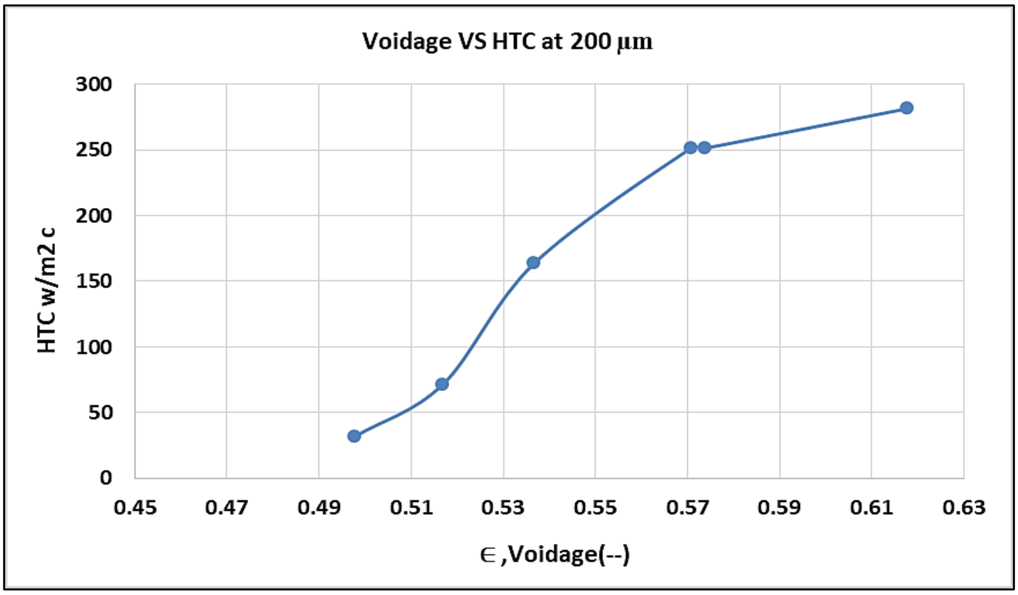

Figure 6: Heat transfer coefficient as a function of Voidage at 200µm particle diameters

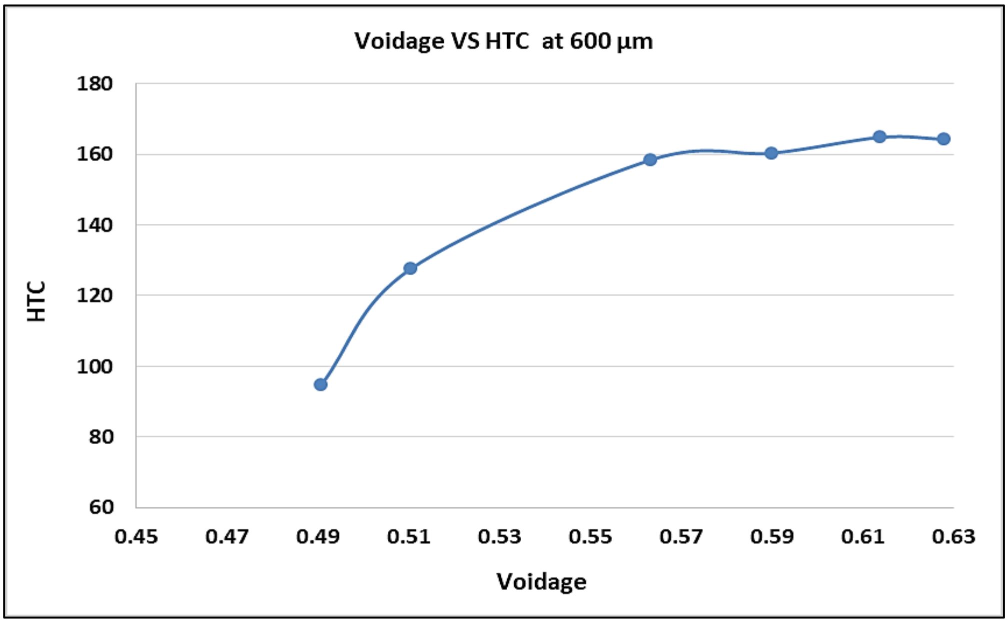

Figure 7: Heat transfer coefficient as a function of voidage for 600 µm particle diameters

3.4 Effect of Heating Power

The effect of heating power on the heat transfer coefficient was shown using a 3D graph in Figure 8. At a velocity of 0.106 m/s and a heating power of 50W, the heat transfer coefficient increased from 40.68 to 42.07 W/m^2.s . At the same velocity but with a heating power of 125w, the heat transfer coefficient increased from 57.17 to 66.18 W/m^2.s, which is a more significant increase. Moreover, at a higher velocity of 0.26 m/s, the heat transfer coefficient increased from 121.46 to 180.23 W/m^2.s at a heating power of 50w, and it increased from 336.36 to 390.28 W/m^2.s at a heating power of 125w. These results show that higher velocities and higher heating power s can further enhance the heat transfer coefficient, indicating that fluidized bed heating can be an effective heat transfer process in industrial settings. These results indicate that fluidized bed heating can significantly enhance the heat transfer coefficient, and this enhancement is more significant at higher velocities. The findings suggest that fluidized bed heating can be an effective process for heat transfer in industrial settings, particularly when higher velocities are used.

The findings show that higher heat flux values correspond to higher heating power values since raising the heater's output raises the temperature of the gas. Any temperature increase causes the thermal conductivity of fluidizing air to increase. The heat transfer coefficient for the 125W was the highest Due to a decrease in the resistance to heat flow, this increase leads to an increase in the heat transfer coefficient [20].

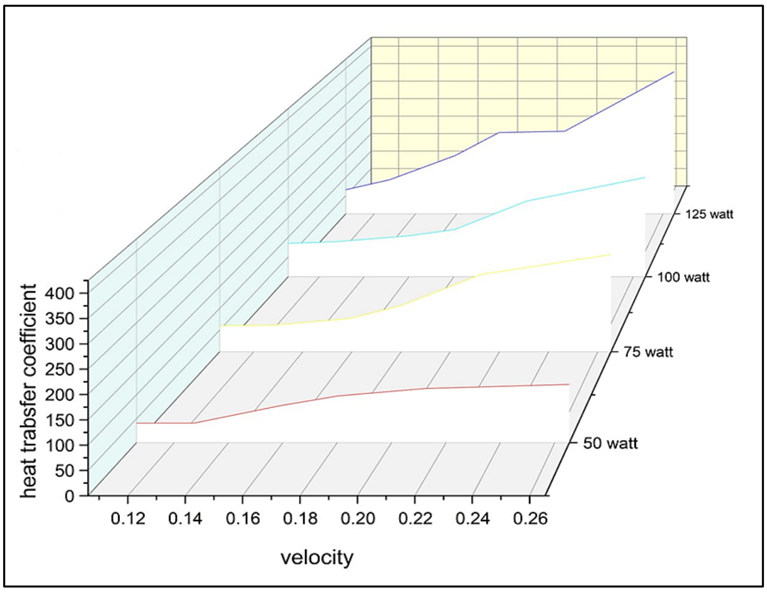

Figure 8: Effect of heating power on heat transfer coefficient

3.5 Correlation Developed

In many cases, the reported data conflicted with one another either due to different measurement techniques, especially of temperature, or due to differences in fluid dynamical conditions in the bed. There is no complete theory that can predict heat transfer data for fluidized beds, although several theories correlate with published data.

Thus, the experimental data was collected and then correlated. The general heat transfer coefficient model that based on the nusselte number is shown in Equation 3, where the general model lacks the value of the constants.

Observing the relationship published by previous researchers for heat transfer in the fluidized bed. Most forms of correlation in the from $Nu = f(Re, \mathrm{Pr})$ so that assume the following:

- Steady-state operating condition.
- Neglected Heat loss by conduction.
- Neglected Heat loss by radiation.

$$Nu = aRe^{b}.\mathrm{Pr}^{c} \qquad (3)$$

LabFit is a versatile data analysis and curve fitting software used in scientific research and laboratory settings. It enables users to model and analyze experimental data using various mathematical functions and statistical models. Key features include data fitting, regression analysis, data transformation, statistical analysis, visualization, and import/export capabilities. LabFit is applicable in various fields, such as chemistry, biology, physics, and engineering, helping researchers process, model, and interpret experimental data more effectively. Using LABFIT software to apply the experimental data. The assumed model or correlation parameters were a=23,b=0.467,c=3.242. The developed correlation after substituting the constant in Equation 3 will be presented as Equation 4:

$$Nu = 23Re^{0.467}\ \mathrm{Pr}^{3.242} \qquad (4)$$

3.6 Comparative Conditions

In the literature on heat transfer in fluidized beds, there are many correlations in the. orm $N_u = f(R_e, P_r)$, Table 4 shows the correlations of different research.

Figures 9 and 10 clearly show a clear comparison between developed correlation and different literature correlation. From these figures, it can be noted that Ranz and Marshall model (1952) and later published by Poós and Viktor [12] is the closest one to the experimental data. Figure 9 also demonstrate a 5% diffrance in accuracy between the experimental data and the developed correlation while Figure 10 shows a higher error between the develop model and the published correlation.

Table 4: Heat transfer coefficient correlation

Conditions	Correlations	Ref.
100<Re<1000	$Nu=2+1.8*Re^{0.5}Pr^{0.33}$	[12]
	$Nu_p = 0.0268\ (Re_p)^{1.26}\ (Pr)^{0.48} \left(\frac{K_s}{K_g}\right)^{-0.0375} \left(\frac{1-e}{e}\right)^{-0.173}$ (4)	[7]
0<Re<500	$=(8.35-7.4e)*(1-0.11*Re^{0.2}*Pr^{0.33})+(3.92-7.67e+3.96e^2)*Re^{0.7}*Pr^{0.33}$	[13]
250<Re<700	$Nu=23*Re^{0.46743}Pr^{3.242}$	

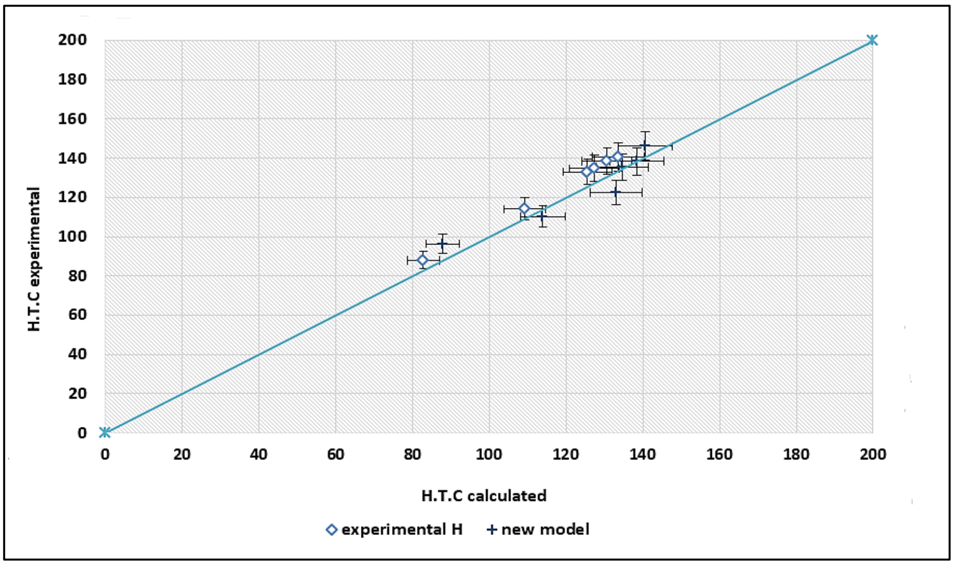

Figure 9: The comparison between experimental data and correlation data

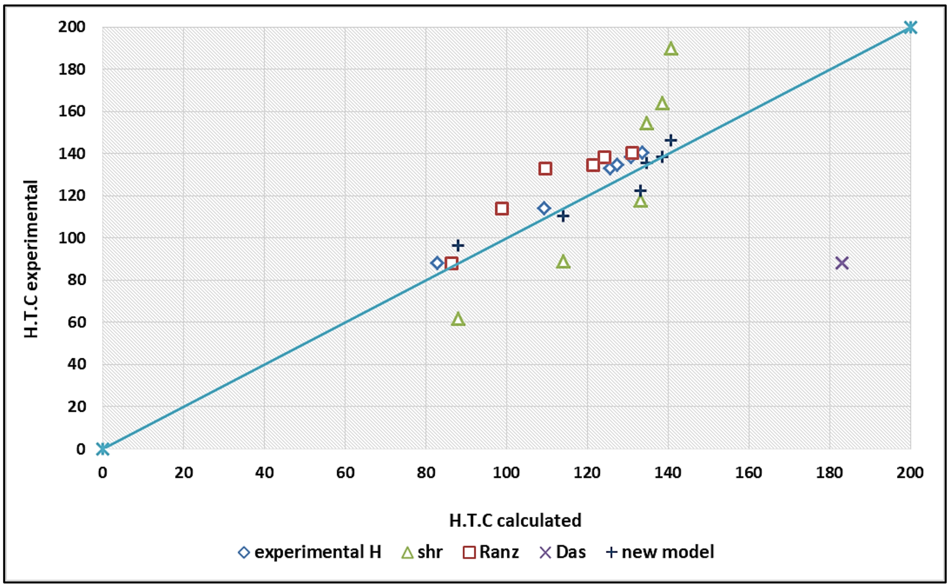

Figure 10: Show the comparison between experimental data and correlated data

Based on the provided data in Figure 11, a relationship between the Reynolds number (Re) and the heat transfer coefficient. By comparing the different estimation methods (Shr, RAns, and Das) with the experimental values of the heat transfer coefficient.

From Figure 10, it is found that at a low Reynolds number, the calculated value is in very good agreement with the value obtained from the empirical relation [21]. However, at a higher Reynolds number, the numerical heat transfer coefficient deviates from the empirical results. The maximum variation between them at the highest Reynolds number is ~600 $W/m^2.K$.

Figure 12 illustrates the dependence of heat transfer coefficients on particle size. Smaller particles with high velocities produce better heating effects than larger particles with higher heat transfer coefficients [22]. In a fluidized bed, as shown in Figure 12, smaller particles generally lead to a higher heat transfer coefficient, primarily due to increased surface area, improved fluidization, and enhanced convective heat transfer (As the solid particles are more uniformly dispersed in the fluid, the convective heat transfer mechanism becomes more effective). Smaller particles increase the turbulence within the fluid, enhancing the convective heat transfer, solid particles are suspended in a gas medium, creating a highly dynamic environment that enhances heat transfer [22].

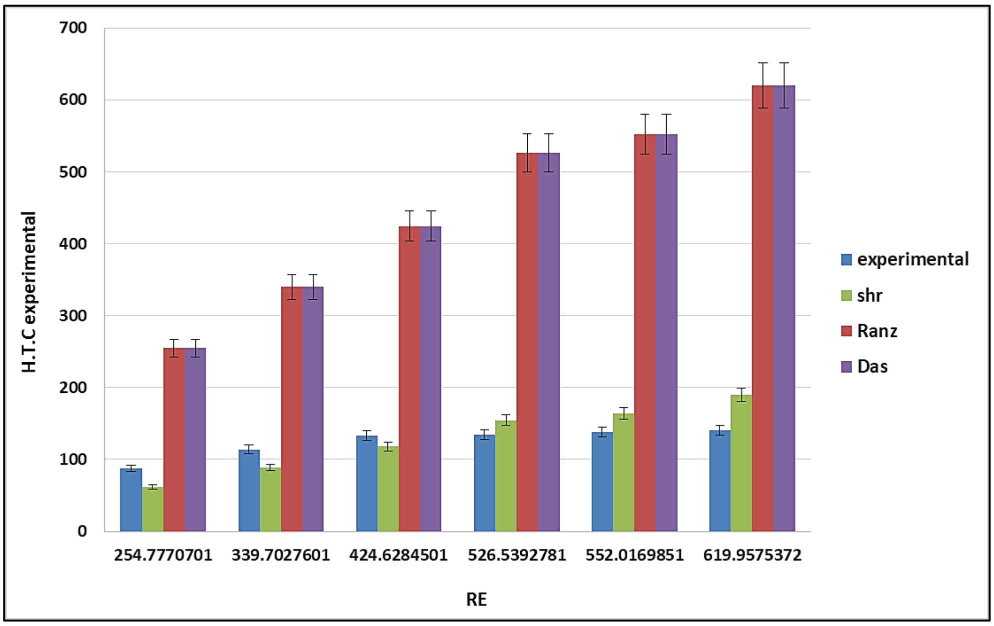

Figure 11: A comparison of the present work correlation with Re

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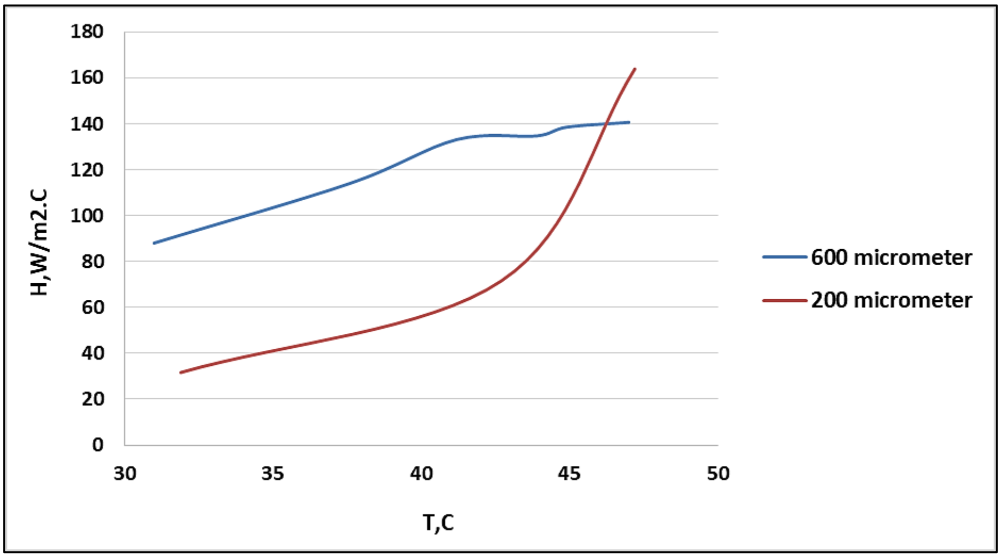

Figure 12: Effect of bed temp. on the heat transfer coefficient at different particle diameter

4. Conclusion

To investigate the impact of internal heating on heat transfer in gas-solid fluidized beds, an experimental study was conducted using glass beads of 200 and 600 µm. The total heat transfer coefficient was evaluated in a gas-solid fluidized bed at different bed temperatures. The heat transfer coefficient exhibits an increasing value with the rise in surface gas velocity. Comparisons between experimental heat transfer coefficients and modeled the heat transfer coefficients demonstrate excellent agreement, with differences of less than 5% observed. However, setting the gas velocity (Ug) to 0.2 leads to variations in the fitting for smaller values of heat transfer coefficients. From literature correlation, The correlation of Ranz is closer to developed model.

Nomenclature

Symbol	Definition	Unit
a_s	Surface area of single particle	m^2
d_c	Column diameter	m
d_b	Bed diameter	m
d_p	Particle diameter	m
g	Acceleration of gravity	m/s^2
h_o	Packed bed height	m

hmf	Bed height at minimum fluidization	m
h_p	Gas to particle heat transfer coefficient	$W/m^2.K$
T_B	Average bulk of the gas temperature	K
T_b	Average bed temperature	K
Ts	Heater surface temperature	K
T_i	Inlet gas temperature	K
T_o	Outlet gas temperature	K
umf	Minimum fluidized bed	m/s
k_g	Gas thermal conductivity	W/m.K
k_s	Solid thermal conductivity	W/m.K
W_s	Weight of glass beads	Kg
e	Void friction	-
pr	Prandtl number	-
Re	Reynold number	-
φ	Opening area percentage	-
umf	Minimum fluidized velocity	m/s
ρ	density	m^3/kg
V	voltage	volt
I	Current	Amber
q	power	w/m^2k
A	area	m^2

Author contributions

Conceptualization, F. Faraj. J. Ali and S. Najim; methodology, F. Faraj and J. Ali; software, F. Faraj; validation, F. Faraj. J. Ali and S. Najim; formal analysis, S. Najim; investigation, F. Faraj; resources, F. Faraj; data curation, F. Faraj and J. Ali; writing—original draft preparation, F. Faraj and J. Ali; Writing—review and editing, J. Ali; Visualization, J. Ali; supervision, S. Najim; project administration, F. Faraj and J. Ali. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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