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Review

The Impact of Particle Size in Fluidized Bed on Heat Transfer Behavior: A Review

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Abstract

This review paper explores the significance of fluidized bed heat exchangers in various industrial applications. By delving into the operation of fluidized beds as multiphase flow systems, the aim is to enhance their capabilities and efficiency. Key parameters such as minimum fluidization velocity and local gas holdup are crucial for characterizing the hydrodynamic behavior of materials within fluidized beds. Fluidization, achieved by passing atmospheric air through particulate solids, imparts fluid-like properties to the bed. Fluidized beds serve as reactors where this phenomenon takes place, offering several advantages in industrial processes, including high rates of heat and mass transfer, low pressure drops, and uniform temperature distribution. In future work, a focus on understanding and optimizing the fluidization process will contribute to further advancements in the performance of fluidized bed heat exchangers.

Keywords: fluidized bed, heat transfer, heat exchanger, thermal conductivity, siliceous sand, particle size

Nomenclature

c_e	heat capacity for emulsion phase [kJ/kgK]
c_g	heat capacity for gas phase [kJ/kgK]
c_s	specific heat capacity for solid phase [kJ/kgK]
d^*	dimensionless particle diameter [-]
d_p	mean bed particle diameter [mm]
d_t	cylinder/tube diameter [mm]
e_b	bed emissivity [-]
e_p	particle emissivity [-]
g	acceleration due to gravity [m^2/s]
k_e	emulsion thermal conductivity [W/m°C]
k_g	thermal conductivity of gas phase [W/mK]
k_s	thermal conductivity of solid phase [W/m°C]
ε_e	voidage of emulsion phase [-]
ε_{mf}	voidage of main fluid [-]
φ_b	bed porosity [-]
ρ_e	density of emulsion phase [kg/m^3]
ρ_s	density of solid phase [kg/m^3]

1. Introduction

Fluidized bed heat exchangers play a crucial role in numerous industrial applications. Enhancing our understanding of the operations of a fluidized bed as a multiphase flow system can significantly improve its capabilities and overall efficiency. The minimum fluidization velocity and local gas holdup are key parameters used to characterize the hydrodynamic behavior of materials within the fluidized bed. Fluidization, defined as the process of conferring fluid-like properties to a bed of particulate solids by passing atmospheric air through the material, is a fundamental phenomenon. Fluidized beds function as reactors where the fluidization of particulate solids occurs, serving as essential assets in various industrial processes. These beds offer several advantages, including high rates of heat and mass transfer, low pressure drops, and uniform temperature distribution (Rasouli et al., 2005). Hou et al. (2016) research investigates the impact of material properties and tube array settings on gas-solid flow and heat transfer in fluidized beds with tubes, using a combination of computational fluid dynamics (CFD), discrete element method (DEM), and heat transfer models. The study revealed significant differences in gas-solid flow between cohesive and non-cohesive powders, emphasizing the dominance of conductive heat transfer for small cohesive particles and convective heat transfer for large non-cohesive particles. The research also explored the complex effects of material properties and gas velocity on the uniformity of particle velocity and temperature fields. Additionally, the study examined the influence of tube array settings, uncovering intricate gas-solid flow and heat transfer characteristics. The findings aim to provide insights for optimizing the operation and design of fluidized systems with tubes.

In response to these challenges, there is a growing interest in the adsorption process utilizing solid sorbents as an alternative to the energy-intensive aqueous amine scrubbing technologies (Samanta et al., 2012). A continuous temperature swing adsorption process (Pröll et al., 2016; Schöny et al., 2016) for CO_2 separation emerges as a promising alternative. Gas-solid fluidized bed reactors, known for their excellent mixing properties, create practically isothermal conditions, ensuring high rates of heat and mass transfer between gas and solids. Their suitability for large-scale plants, efficient heat transfer rates between immersed objects and the fluidized bed, and the capability for continuous, automatically controlled operation make them an attractive option (Kunii & Levenspiel, 1991).

Moreover, the unique characteristics of gas-solid fluidized bed reactors, including a liquid-like solids flow, enable their versatile application in various physical and chemical processes such as combustion (Cui et al., 2020), gasification (Arena, 2013; Blaszczuk et al., 2018), heat recovery (Cai et al., 2019; Li et al., 2020), coating (Sjösten et al., 2004; Foroughi-Dahr et al., 2017), drying (Das et al., 2020), and temperature swing adsorption (Wormsbecker et al., 2009). Extensive studies continue to be conducted on gas-solid fluidized bed reactors to enhance our understanding of their operation (Wormsbecker et al., 2009) and applications (Dietrich et al., 2018; Zerobin & Pröll, 2020).

Kim et al. (2003) conducted a study on heat transfer and bubble characteristics within a fluidized bed featuring an immersed horizontal tube bundle. Their findings demonstrated that the average heat transfer coefficient exhibits an initial increase with ascending gas velocity, reaching a peak value before subsequently decreasing. In a related investigation, Al-Busoul and Abu-Ein (2003) explored the heat transfer characteristics around a horizontally heated tube immersed in a fluidized bed. Their results indicated an inverse proportionality between the local heat transfer coefficient and the solid particle diameter within the range of 108–856 μm.

Chen and Pei (1985) proposed a heat transfer model for the interaction between fluidized beds and immersed surfaces. The model, developed on the basis of the two-phase boundary layer and surface renewal theory, yielded a correlation for predicting the maximum heat transfer coefficient.

Devaru and Kolar (1995) reported that the performance of a tube bundle in a fluidized bed heat exchanger is contingent upon various factors. These factors include fluidization parameters such as fluidizing gas velocity, bed particle diameter, and static bed height; bundle characteristics like tube orientation, size, pitch, and location; and tube surface characteristics encompassing smooth or finned surfaces, fin height, fin pitch, fin thickness, material, and fin type.

Nag and Moral (1990) delved into the impact of rectangular fins on heat transfer within circulating fluidized beds. Their findings indicated that the utilization of fins led to a decrease in the heat transfer coefficient. Subsequently, Nag et al. (1995) formulated a mathematical model to predict heat transfer from finned surfaces in a circulating fluidized bed. Their summarization of results revealed several key trends: an augmentation in suspension density correlated with an increase in bed-to-wall heat transfer, the incorporation of fins resulted in a decrease in the heat transfer coefficient, and an escalation in the number of fins was associated with a reduction in the heat transfer coefficient.

2. Experimental procedures

The experimental setup includes a range of apparatuses essential for studying the impact of sand particle size on a fluidized bed heat exchanger. These comprise the fluidized bed heat exchanger itself, sand particles with varying sizes, temperature sensors, pressure gauges, flow meters, and the heat transfer fluid.

The experimental procedure used by Rasouli et al. (2005) involves several key steps to ensure a systematic and reliable study. Firstly, the fluidized bed is prepared by filling it with sand particles of the chosen size. Subsequently, the system is initialized, stabilizing it with the heat transfer fluid at a specified temperature and flow rate. Data collection is then initiated, systematically varying the particle size during the experiment. To ensure consistency, experiments are repeated for each particle size. The literature data available in Table 1. Safety measures are implemented throughout the experiment, and thorough documentation of all relevant parameters and observations is conducted.

Continuous monitoring of temperature, pressure, and flow rate is crucial throughout each experiment to gather comprehensive data. Post-experiment, data analysis is performed using appropriate software tools such as Excel. Regular calibration of instruments is emphasized to maintain the accuracy and reliability of the collected data.

It is important to note that this methodology and experimental setup can be tailored based on specific requirements and available resources. Ethical considerations and adherence to safety protocols remain paramount throughout the experimental process as shown in Fig. 1.

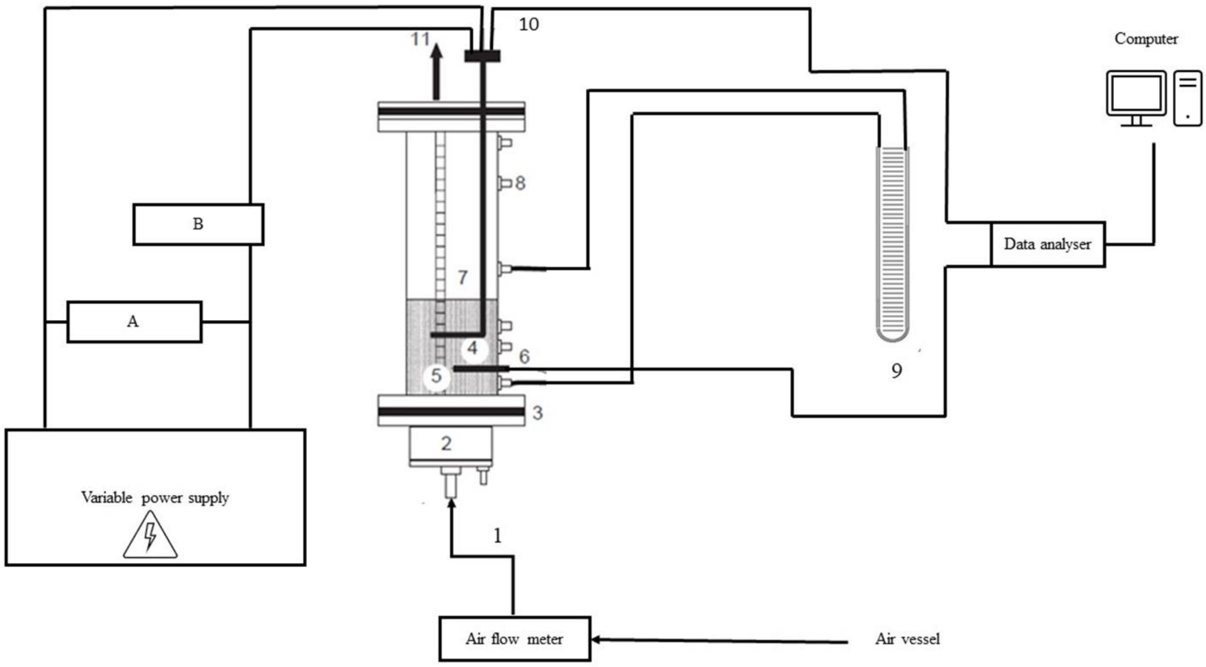

Fig. 1. Schematic diagram of the experimental set-up: (1) air inlet, (2) air distribution chamber, (3) distributor plate, (4) horizontal tube, (5) scaling for bed height measurement, (6) thermocouple for bed temperature, (7) hollow tube, (8) pressure taps, (9) pressure difference measurement device, (10) test probe thermocouple and (11) exhaust air openings, prepared on the basis of (Rasouli et al., 2005).

Table 1. Experimental conditions.

Equipment type	Particle diameter, mm	Reference
vertical	136	Ozkaynak and Chen (1980)
horizontal	256, 340, 568	Pence et al. (1994)
horizontal	240	Kim et al. (2003)
horizontal	219, 232, 246, 365, 444	Blaszczuk et al. (2018)
vertical	120, 320, 650	Baskakov et al. (1973)

Blaszczuk and Jagodzik (2021) scrutinized the energy exchange process between a dense fluidized bed and a submerged horizontal tube bundle within a commercial external heat exchanger (EHE). Conducting eight performance tests in a fluidized bed heat exchange chamber with specific dimensions, the authors developed a mechanistic model to predict the average heat transfer coefficient. This model factors in the geometric structure of the tube bundle and the location of the heat transfer surface, revealing that superficial gas velocity and suspension density significantly impact the average heat transfer coefficient, with bed particle size playing a comparatively minor role. Empirical correlations were proposed to predict heat transfer data due to the insufficiency of existing literature data for industrial fluidized bed heat exchangers, the details in Table 2. The research identified optimal conditions for heat transfer based on evaluated operating conditions, and the developed mechanistic heat transfer model was validated against experimental data obtained in the study.

Table 2. The correlations used to determine physical properties of emulsion.

Item	Equation	Reference
Emulsion heat capacity, c_e	$c_e = c_s(1-\varepsilon_e) + \varepsilon_e c_g$	Yusuf et al. (2005)
Emulsion thermal conductivity, k_e	$k_e = \varepsilon_e k_g + (1-\varepsilon_e) k_s \left[\frac{1}{\varphi_b\left(\frac{k_s}{k_g}\right) + \frac{2}{3}}\right]$	Kunii and Levenspiel (1991)
Emulsion (packet) density, ρ_e	$\rho_e = \rho_s(1-\varepsilon_e)$	Ozkaynak and Chen (1980)
Voidage of emulsion phase, ε_e	$\varepsilon_e = 1 - \frac{(1-\varepsilon_{mf})\left[0.7293 + 0.5139\frac{dp}{dt}\right]}{1+\frac{dp}{dt}}$	Saxena (1989)

Andersson's (1996) study involved measuring local heat transfer values to membrane walls in a circulating fluidized bed (CFB) boiler, utilizing silica sand of three different sizes with mean diameters of 0.22, 0.34, and 0.44 mm. Altering the sand size from 0.44 to 0.22 mm under constant fluidization velocity resulted in a substantial increase in particle concentration and, consequently, enhanced heat transfer. Despite variations in bed particle size, the average heat transfer coefficient across the membrane wall remained insensitive at a given cross-sectional average bulk density. The lateral distribution of heat flow to the crest, side of the tube, and fin was found to be independent of particle size under similar bulk densities, achieved by maintaining a constant ratio of fluidization velocity to the terminal velocity of a single average size particle. The study demonstrated the feasibility of estimating the vertical distribution of the heat transfer coefficient in the CFB furnace with an accuracy of +20% using a straightforward semi-empirical method. Papadikis et al. (2010) research was focused on modeling the fluid-particle interaction and examining the influence of varying heat transfer conditions on biomass pyrolysis within a 150 g/h fluidized bed reactor. Two distinct biomass particle sizes (350 µm and 550 µm in diameter) are introduced into the fluidized bed, leading to different heat transfer conditions. The 350 µm particle, smaller than the sand particles in the reactor (440 µm), experiences conductive heat transfer, while biomass-sand contacts for the larger 550 µm particle are deemed significant. The study utilizes the Eulerian approach to model the sand's bubbling behavior as a continuum. Biomass reaction kinetics are represented by a two-stage, semi-global model accounting for secondary reactions. Particle motion within the reactor is computed using drag laws dependent on the local volume fraction of each phase. The simulations employ FLUENT 6.2 as the modeling framework, with the entire pyrolysis model integrated as a User Defined Function (UDF). Ngoh and Lim (2016) investigated the fluidization and heat transfer behaviors in a bubbling fluidized bed using Computational Fluid Dynamics (CFD). Their simulations explored various operating conditions with different particle sizes and inlet gas superficial velocities. Analysis of solid volume fraction, solid temperature, air temperature, solid velocity vectors, and air velocity vectors revealed symmetrical and non-uniform solid volume fraction profiles during the initial phase of fluidization. Bubbles generated in this phase increased with higher inlet air superficial velocities and smaller particle sizes. The coupled analysis of solid volume fraction and temperature profiles highlighted the significance of both conductive and convective heat transfer between phases. The results indicated that the heat transfer rate from air to particles depended on interfacial surface area, influenced by voidage within the bed. Optimal operating conditions for efficient heat transfer were suggested, while over-fluidization led to poor heat transfer due to channeling, and under-fluidization resulted in suboptimal convective heat transfer compensated by increased conductive particle-to-particle heat transfer. In experimental study by Błaszczuk et al. (2018), a supercritical circulating fluidized bed combustor was employed to investigate the impact of bed particle size on the bed-to-wall heat transfer coefficient. The bed comprised particles with Sauter mean diameters of 0.219, 0.246, and 0.411 mm. Operating parameters, such as superficial gas velocity, circulation rate of solids, secondary air fraction, and pressure drop, were varied within the ranges of 3.13 to 5.11 m/s, 23.7 to 26.2 kg/m^{2}s, 0.33, and 7500 to 8440 Pa, respectively. Experimental variables included bed temperature, suspension density, and parameters of the cluster renewal approach along the furnace height. The study utilized the cluster renewal approach to predict the bed-to-wall heat transfer coefficient, and a simple semi-empirical method was introduced to estimate the overall heat transfer coefficient based on particle size and suspension density. Computational results were compared with experimental data, providing valuable insights.

3. Heat transfer characteristics

Berkache et al. (2022) investigated the behavior of a boundary layer type viscous flow with thermal effects. The study involves experimental and numerical analyses of the flow in a three-dimensional field with uniform infinite velocity, focusing on an adiabatic wall with heat input. The experiments took place in the Thermal Laboratory (LET) of the Prime Institute of Poitiers in France. The experimental work utilized a wind tunnel to create a turbulent boundary layer on the surface of a flat plate covered with epoxy resin. The flat plate was heated to 80°C using an HP 6012A power supply system that provided circulating heat flux through the Joule effect.

The numerical results highlight a distinct variation in the evolution of the thermal boundary layer at three different wall temperatures. This suggests that temperature plays a significant role in influencing the behavior of the boundary layer in viscous flow. The findings contribute to a better understanding of the thermal effects on turbulent boundary layers in three-dimensional fields, providing valuable insights for related applications or further research in fluid dynamics.

The study conducted by Qader et al. (2023) investigated forced convection heat transfer in a horizontally heated circular pipe with constant heat flux. The researchers created a porous medium within the pipe using stainless-steel balls of 1 and 3 mm diameters, resulting in porosities of 0.3690 and 0.3912, respectively. The Reynolds numbers ranged from 3,200 to 6,500 based on the pipe diameter, and the heat flux rates were set at 6,250 and 12,500 W m^{-2}. The simulation was performed using ANSYS Fluent on a stainless-steel pipe with a diameter of 51.4 mm, thickness of 5 mm, and length of 304 mm. The results indicated an increase in turbulence and the formation of eddies within the system. The analysis revealed higher convective heat transfer coefficients, pressure drops, and Nusselt numbers with an increase in Reynolds number. Additionally, the Nusselt number increased with the diameter of the stainless-steel balls (1–3 mm). An increase in porosity by 6% led to an 84.4% reduction in pressure drop. The Nusselt number increased by 46.7% (Reynolds 3,200–6,500) and 4.36% (heat flux $6{,}250^{-12}$, 500 W m^{-2}). These findings provide insights into the impact of porous media and various parameters on heat transfer characteristics in horizontally heated pipes. Miri et al. (2023) focused on the magnetohydrodynamic laminar forced convection of nanoliquid within a rectangular channel featuring an extended surface, a moving top wall, and three cylindrical blocks. The study utilized the Lattice Boltzmann method to numerically analyze the governing equations. The researchers validated their numerical code using published results, demonstrating good agreement.

The investigation explores the effects of several parameters, including Reynolds number ($50 \leq Re \leq 200$), Hartmann number ($0 \leq Ha \leq 50$), nanoparticles volume fraction ($0 \leq \varphi \leq 4\%$), and Eckert number ($0.25 \leq Ec \leq 1$). The numerical solution reveals that both local and average Nusselt numbers improve with increasing Reynolds number, Eckert number, and nanoparticles volume fraction. However, the Nusselt numbers decrease as the Hartmann number is increased. Notably, the study finds that viscous dissipation has a more pronounced impact on heat transfer rate and entropy generation in the presence of a magnetic field.

An interesting observation is that the addition of 4% nanoparticles enhances the local Nusselt number by approximately 7%. These findings contribute valuable insights into the complex interplay of various parameters in the magnetohydrodynamic forced convection of nanoliquids, offering potential applications in optimizing heat transfer processes. Mohammed et al. (2023) focused on the utilization of flat-plate solar collectors (FPSCs), considered as effective and environmentally friendly heating systems. FPSCs are commonly employed to convert solar radiation into usable heat for various thermal applications. The study emphasizes the use of nano-fluids in FPSCs as a beneficial technique to enhance their performance.

Nano-fluids, defined as colloidal suspensions containing nano-sized particles with diameters smaller than 100 nm, are explored for their potential to improve the thermo-physical features of FPSCs. These nanoparticles contribute to enhancing the thermal conductivity and convective heat transfer of liquids when mixed with the base fluid.

The article provides a comprehensive review of scientific advancements in the field of nano-fluids applied to flat-plate solar collectors. Previous research is discussed, highlighting successful applications of nano-fluids to enhance the efficiency of FPSCs. However, the study acknowledges that nano-fluids may have higher pressure drops compared to conventional liquids, and their pressure drops, along with pumping power, increase as the volume flow rate rises. Key aspects covered in the article include the concept of nano-fluids, various forms of nanoparticles, methods for preparing nano-fluids, and their thermo-physical properties. The conclusion offers observations and suggestions regarding the usage of nano-fluids in flat-plate solar collectors. Overall, the article serves as a valuable summary of research studies in this area, providing insights that may prove beneficial for future experimental studies in the field of improving solar collector efficiency using nano-fluids.

Mu et al. (2020) conducted a numerical simulation study to investigate the combined thermal behavior and hydrodynamics of a pseudo-2D fluidized bed using computational fluid dynamics–discrete element method (CFD-DEM). The simulation incorporated a constant heat source to mimic the effects of heterogeneous exothermic reactions. The research analyzed the impacts of superficial gas velocity, bed height, and heat source distribution by examining averaged volume fraction, temperature distributions, and velocity profiles. The findings highlighted significant influences of both gas superficial velocity and bed aspect ratio on fluidization behavior and temperature distributions.

Park et al. (2020) investigated the thermal performance of a directly-irradiated fluidized bed gas heater for solar thermal heating. Focusing on the impact of SiC particle size on heat transfer characteristics, experiments were conducted in a 50 mm-ID by 100 mm high solar fluidized bed gas heater. The outlet gas temperatures exhibited a maximum value with increasing gas velocity, influenced by particle motion due to bubble behavior. Heat absorption from the receiver increased with gas velocity, reaching maximum values of 18 W for fine SiC and 23 W for coarse SiC. The thermal efficiency of the receiver improved with higher gas velocity but was affected by the content of finer particles. The maximum thermal efficiency was 14% for fine SiC and 20% for coarse SiC within the experimental range. Design considerations were proposed for enhancing the system's thermal efficiency.

4. Conclusions

In conclusion, the collection of research articles discussed here presents a comprehensive exploration of heat transfer characteristics in fluidized beds, particularly emphasizing the influence of bed particle size on heat transfer coefficients. Silica sand, recognized for its favorable fluidizing properties, plays a crucial role in fluidized bed systems. The study emphasizes that the overall heat transfer coefficient exhibits an upward trend with increasing velocity. Conversely, larger particle sizes demonstrate a decrease in the heat transfer coefficient. Furthermore, the impact of varying particle sizes on pressure drop reveals a significant correlation: as particle size increases, the pressure drop also increases. Notably, smaller particle sizes result in lower pressure drop values, leading to enhanced particle collection in the fluidized bed compared to larger particles. These findings underscore the intricate relationship between particle size, heat transfer, and pressure drop in fluidized beds, offering valuable insights for optimizing the performance of fluidized bed heat exchangers. Future work may involve refining fluidization processes and exploring particle size distributions to further enhance the efficiency of fluidized bed systems.

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Wpływ Wielkości Cząstek w Złożu Fluidalnym na Przenoszenia Ciepła: Przegląd

Streszczenie

W artykule przedstawiono przegląd literatury dotyczący znaczenia wymienników ciepła ze złożem fluidalnym w różnych zastosowaniach przemysłowych. Zwiększenie możliwości i wydajności złóż fluidalnych jest celem badań tych wielofazowych systemów przepływowych. Kluczowe parametry, takie jak minimalna prędkość fluidyzacji i lokalne zatrzymywanie gazu, mają kluczowe znaczenie dla scharakteryzowania zachowania hydrodynamicznego materiałów w złożach fluidalnych. Fluidyzacja, osiągnięta poprzez przepuszczanie powietrza atmosferycznego przez cząstki stałe, nadaje złożu właściwości zbliżone do płynu. Złoża fluidalne służą jako reaktory, w których zachodzi zjawisko fluidyzacji, oferując szereg korzyści w procesach przemysłowych, w tym wysokie szybkości wymiany ciepła i masy, niskie spadki ciśnienia i równomierny rozkład temperatury. W przyszłych pracach skupienie się na zrozumieniu i optymalizacji procesu fluidyzacji przyczyni się do dalszego postępu w wydajności wymienników ciepła ze złożem fluidalnym.

Słowa kluczowe: złoże fluidalne, wymiana ciepła, wymiennik ciepła, przewodność cieplna, piasek krzemionkowy, wielkość cząstek