Heat Transfer in Fluidized bed

A fluidized bed is a state of a two-phase mixture of particulate solid material and fluid, which is widely used in many modern technologies for efficient implementation of various physical and chemical processes. Fluidized beds have been used in technological processes such as: cracking and reforming of hydrocarbons (oil), carbonization and gasification of coal, ore roasting, Fischer-Tropsch synthesis, polyethylene manufacturing, limestone calcining, aluminum anhydride production, granulation, vinyl-chloride production, combustion of waste, nuclear fuel preparation, combustion of solid, liquid and gaseous fuels, drying, adsorption, cooling, heating, freezing, conveying, storing and thermal treating of various particulate solid materials.

The term "fluidized bed" is unavoidably connected to the term "particulate solid material". Particulate materials are mechanical mixtures of multitude of solid particles. Natural particulate materials originate from many long-term natural processes: heating, cooling, thermal dilatation, coliding, crushing, chopping up, atmospheric changes, river erosion and erosion caused by sea waves. Many technological processes also produce particulate solid material: grinding, chopping up, milling, evaporation, crystallization, spraying and drying. Particulate materials can also be of organic (plant) origin: fruits and seeds.

Particulate materials most commonly consist of solid particles with a range of shape and size. The majority of inorganic particulate solid materials found in nature have an extremely wide range of particle sizes. Such materials are called poly disperse materials. By certain technological processes, it is possible to produce particles with practically the same shape and size. Organic particulate materials found in nature (fruits and seeds) consist of particles of similar shape and size. Such materials are called mono disperse materials.

The geometrical, physical and aerodynamical properties of particulate solid materials all affect the onset of fluidization, and the characteristics, behavior and the main parameters of fluidized beds. The most important solid properties are:

- particle density (not taking porosity into account),
- skeletal (true) density,
- bulk density—mass per unit volume of fixed bed,
- porosity (or void fraction) of the fixed bed—ratio of volume of space between the particles and the volume of the fixed bed,
- mean equivalent particle diameter—particle characteristic dimension,
- particle shape,
- particle size distribution—probability distribution of particle distribution due to their size,
- free fall (or terminal) velocity—velocity of falling particle at which gravitational, Archimedes and drag forces are in equilibrium.

The various states of solid particle-fluid two-phase mixtures differ from each other by the following characteristics:

- the solid particles can be stagnant, floating or moving chaotically,
- the solid particles movement can be in a preferred direction or chaotic—one phase or both can be in movement,
- the flow direction can be vertical or horizontal,
- the fluid phase can be in cocurrent or countercurrent flow,
- the movement of the solid material can be free or limited by some kind of mechanical device (a perforated plate, for example),
the density or concentration of the mixture may differ greatly from one state to another.

Possible solid particle fluid mixture states are: fixed bed, stationary fluidized bed, fluidized bed with particle feeding at the bottom and overflow at the free surface of the bed, or vice versa, vertical conveying in the dense bed, low density vertical and horizontal conveying, downward particle movement in the dense bed with cocurrent fluid flow, and low density conveying downwards. Special cases of the above states are the moving bed and spouted bed. Transition boundaries between these states of solid material-fluid mixture are defined by the well-known Zenz diagram.

The fluidized state occurs when a fixed bed of the particulate material is penetrated in the vertical direction with fluid at sufficient velocity to break up the bed. In a fixed bed, the particles are immobile, leaning on one another at numerous contact points and applying forces to one another. Gravity forces—particle weight and the weight of the whole bed—are spread in all directions through the particle contact points. When the critical velocity (minimum fluidization velocity) is reached, the solid particles start floating, moving chaotically and colliding. Mutual contacts between the particles are of short duration and the forces between them are weak; the particulate solid material is then in the fluidized state. In the fluidized state, particles are in constant, chaotic movement, and their mean particle distance grows with increasing fluid velocity causing the bed height to rise. The pressure drop in the fluid phase across the bed is constant and equal to the bed weight over unit surface of the bed cross section. This value is reached at the minimum (incipient) fluidization velocity.

When the bed is fluidized with liquids, we have the case of the "homogenous" fluidization. Gas fluidization leads to so-called "heterogenous" fluidization. At gas velocities just above the minimum fluidization velocity, bubbles form and the fluidized bed can be treated as if it consists of two phases: bubbles, in which there are virtually no particles and a particulate (emulsion) phase, which is in a condition similar to that of the bed at the minimum fluidization velocity. Bubbles which form near the distribution plate, rise up the bed, grow and coalesce, producing bigger bubbles which sometimes break up into smaller bubbles. On the bed surface, bubbles eruptively burst, ejecting the particles far from the bed surface. Such bubble behavior makes particle circulation in the bed very intensive. Behind the bubble, in its trail, particles move upwards. Around the bubbles and between them, and especially near the walls, particles move downwards. Bubble movement thus promotes intensive gas and particle axial mixing in the fluidized bed.

The chaotic movement of the particles in the fluidized bed is the main reason for the fact that the various fluidized bed characteristics are similar to those of liquids, which is why this state of two-phase fluid-solid mixture got its name. The free surface of the fluidized bed is horizontal, but of irregular shape due to the bubbles bursting; however it makes a clear, distinctive boundary between the bed of high concentration and the space above it (freeboard), in which particle concentration decreases exponentially. Bodies of greater density sink in the fluidized bed, and those of lower density float or chaotically move near the surface. In the fluidized state, particulate solid material flows out through the openings of the vessel. Just as in the liquids, mixing of two particulate materials is intensive and homogenous. Heat transfer is also intensive, maintaining a homogenous temperature field during the heating or cooling processes or when the heat is generated by fuel combustion in the bed. Fluidized beds obey the laws of hydrostatics.
As the fluidization velocity increases, large bubbles break up into several smaller ones. When the break-up process overcomes the coalescence of the bubbles, oscillations of the pressure drop become smaller. This is the moment when turbulent regime occurs, with no big bubbles in the bed. In the particulate phase of the bed, which is becoming more homogenous, smaller voids exist in the form of the channels and jets, and particles form clusters. Neither the gaseous nor the emulsion phases can be said to be continuous. Mixing of particles becomes more intensive, and the interaction of phases is stronger. The free surface of the bed is very irregular and not clearly outlined. A lot of particles and clusters are being carried off the bed surface and then fall in to the bed again. The maximum velocity of the turbulent regime is the so-called "transport velocity," at which the fast fluidization regime occurs. At velocities above the transport velocity, particles are carried out of the system by the fluid and the bed can only be maintained by feeding new particulate material into it.

At velocities higher than transport velocity, depending on the flow rate of the solid particles returning to the bed, fast fluidization with higher or lower concentration occurs. In the fast fluidization regime, particles move upwards in clusters through the middle of the bed cross section. Near the walls, particles move downward. In this regime, particle mixing is even more intensive in both axial and radial directions. Particle concentration in the freeboard decreases exponentially in the upward direction.

All mentioned regimes of fluidization as well as the two boundary states—fixed bed and pneumatic conveying—have found their use in various devices and technological processes. Solid fuel (coal) combustion is the obvious example. Boilers with grates use fixed beds, fluidized bed combustion boilers use bubbling fluidized beds or turbulent regime (in this case with fly ash recirculation), circulating fluidized bed boilers use the fast fluidization regime and pulverized coal combustion boilers work in the pneumatic conveying regime.

For each particular fluidized bed and fluidization conditions, a maximum height exists, above which only particles whose free fall velocity is less than the gas velocity, can be found. In the case of a mono disperse material, above this height the particle concentration is zero. This height is called TDH—Transport Disengaging Height.

**Heat Transfer in Fluidized Beds**

Heat transfer in the fluidized bed is, apart from the particle and gas mixing, the most important process contributing to the intensity of the physical and chemical processes. In fact, several different processes can be distinguished: particle-gas heat transfer, heat transfer between different points in the bed, heat transfer between the fluidized bed particles and the larger particles floating in the bed and the heat transfer to the submerged surfaces in contact with the bed. All of these heat transfer processes are very intensive in fluidized beds.

In the case of uniform fluidization, the temperature difference between points in the bed does not exceed 2-5°C, with mean bed temperatures of several hundred, even 1000°C. Gas temperature, when leaving the bed, is practically the same as the particle temperature. These facts tell us of the great capability of the solid particles to exchange heat with the fluidizing gas. Intensive heat transfer is, first of all, a consequence of the large specific heat transfer surface (3000 to 45000 m²/m³), although heat transfer coefficients to the particles in the bed are relatively small, 6-25 W/m²°C. The large heat capacity of the solid particles also makes the temperature difference between gas and particles small. Gas temperature follows the particle temperature.

Gas to particle heat transfer coefficients can be calculated from the Gelperin and Einstein relation:
Despite the small values of the gas-to-particle heat transfer coefficient, even at a short distance from the distribution plate, the gas and particles temperature are practically equal. Five to ten particle diameters from the distribution plate, the temperature difference between gas and particles has decreased around 100 times. The temperature of gas in the bubbles also very quickly becomes equal to the particle temperature. Some ten millimeters from the plate is enough for this equalization to occur. If, in an inert fluidized bed, there are active particles (usually larger ones) which chemically react with the fluidizing gas, releasing heat (as in the solid fuel combustion), very complex processes of heat and mass transfer between these particles and the bed take place. At the beginning, these larger particles heat up in the contact with the inert bed material. Simultaneously, evaporation and devolatilization take place. These processes depend on the intensity of heat transfer between the bed as a whole and these particles. When chemical reactions between gas and particles begin (combustion of the char), particle temperature is higher and the reverse process of heat exchange between active particles and fluidized bed takes place. The combustion process is limited by the mass transfer process, i.e., the diffusion of the reacting gas to the surface of the active particle. The mechanisms of mass transfer towards the active particles are molecular diffusion and the convective transport, while inert bed material disrupt these processes merely by being there. Because larger active particles mainly inhabit the emulsion phase, mass transfer intensity increases with the increase of the size of inert bed material (i.e., with $v_{mf}$) and decreases with increase of the active particle diameter.

One of the most recent relations for calculating mass transfer coefficient $\beta$ is that of La Nauze and Jang:

$$Sh = \frac{\beta D_p}{D_g} = 2 + 0.5 \left(\frac{Re}{\varepsilon}\right)^{0.5} \left(Sc\right)^{0.33}$$

who proposed two mass transfer mechanisms: "packets" (clusters) of particles carry fresh gas from the bulk bed towards the active particle, the movement of these packets is controlled by the bubble flow; the other mechanism is classical convective mass transfer by gas which percolates through the emulsion phase with a velocity equal to $v_{mf}$.

Heat transfer between the active particle and the fluidized bed is controlled by three mechanisms: gas convection, particle convection and radiation. Depending on the active particle size and temperature, the mechanisms mentioned above do not have the same contribution to the overall heat transfer. These processes are also involved in the heat transfer between the bed and the immersed surfaces. Heat transfer by radiation becomes significant only when temperature differences exceed 400-500°C. For active particle size less or equal to the inert material particle size, the main transfer process is convective heat transfer; for larger particles, heat transfer due to the collision and contact with the fluidized bed particles may be important. Heat transfer coefficients $\alpha_p$ for active particles or immersed surfaces have a maximum for optimal fluidization velocity.

For active particle size close to the inert material particle size, relations (1) and (2) can be used. For larger active particles, Agarwall's relation:
When the fluidization velocity increases from $v_{mf}$ to the optimal value, heat transfer coefficients for the surfaces in contact with the fluidized bed also increase, due to the increase of heat transfer by particle contacts. For velocities greater than the optimal, the main contribution to the heat transfer is the gas convection because of the decrease of particle concentration, i.e., the increase of the bed porosity. Optimum velocity can be calculated from the Todes relation:

$$Re_{opt} = \frac{A_x}{18 \cdot 5.22 \cdot \rho_p^{0.8} \cdot \lambda_g^{0.5}}.$$

The factor with the greatest influence on the heat transfer, apart from the fluidization velocity, is the particle size. Particle size influences the change of the relative contribution of various mechanisms in the overall heat transfer. In the fluidized bed with small ($< 0.1$ mm) particles, convection by particles account for 90% of the overall heat transfer, while in the beds of large particles ($> 1$ mm) only 20% of the heat transfer is done by particle convection. Particle heat capacity is also important for the amount of heat transferred by particle convection. The maximum heat transfer coefficient is often calculated from the Zabrodski relation:

$$\alpha_{max} = 35 \cdot 8 \cdot \rho_p^{0.25} \cdot \lambda_g^{0.5} \cdot \rho_t^{0.26}.$$

In the literature, numerous relationships can be found for calculating the heat transfer to immersed surfaces of different shape: vessel walls, single horizontal or vertical pipe, tube bundles with smooth and finned tubes in in-line or staggered arrangement. Parameters that influence the heat transfer to these surfaces are: height and dimensions of the bed, bubble size, tube diameter, arrangement and position of tubes, tube distance, quality and shape of the surface. Existing relationships for calculating the heat transfer coefficient do not include all these parameters and for that reason, experimental data is greatly scattered and the accuracy of the formulas proposed is in the range up to ±50%.

References