Heat transfer in a liquid fluidized bed
by Sambasiva Rao Uppala

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Chemical Engineering
Montana State University

Abstract:
Local and average heat transfer coefficients for heat transfer from an electrically heated internal tube to a water fluidized bed were investigated. Three types of particles were used in this study. Glass spheres of 0.0185-inch average diameter, coke particles of 0.014-inch average diameter and stainless steel particles of 0.014-inch average diameter were used. A movable thermocouple was fitted inside the heated tube to measure the tube's wall temperature at any vertical height. Bulk fluid temperatures were determined with protected thermocouples placed at five locations in the bed.

Variables studied included particle size, shape, and concentration, and liquid mass velocity. Average heat transfer coefficients over the fluidized bed were correlated with an equation based on a particle mode heat transfer mechanism. Local heat transfer coefficients were estimated at five different locations.

The results of this investigation are as follows: (l) Local heat transfer coefficients show a progressive increase with mass velocity. A decrease is observed in the local heat transfer coefficient with distance from the entrance of the tube. (2) For fluidization, the average Nusselt number is correlated with an equation based on a particle mode heat transfer mechanism.

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by

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A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree

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Chemical Engineering

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Bozeman, Montana

December, 1969

ACKNOWLEDGEMENT

The author wishes to express his gratitude to Dr. William E. Genetti for his assistance and encouragement throughout the duration of the investigation, and to Dr. R. L. Nickelson, Dr. F. P. McCandless and Dr. R. E. Lund for being on his graduate committee. He would like to thank Mr. Cy Huso and Mr. Jim Tillery for their assistance in the construction of the equipment. He would also like to thank the Chemical Engineering Department at Montana State University for its financial support.

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ABSTRACT

Local and average heat transfer coefficients for heat transfer from an electrically heated internal tube to a water fluidized bed were investigated. Three types of particles were used in this study. Glass spheres of 0.0185-inch average diameter, coke particles of 0.014-inch average diameter and stainless steel particles of 0.014-inch average diameter were used. A movable thermocouple was fitted inside the heated tube to measure the tube's wall temperature at any vertical height. Bulk fluid temperatures were determined with protected thermocouples placed at five locations in the bed.

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$$Nu_p = \frac{2\phi\,(1-\varepsilon)^{-0.85}}{\left[\,1+ \frac{102}{Re_p^{\,0.43}} \left(\frac{K_\ell}{\rho_s C_s g^{0.5} D_p^{\,1.5}} \right) \left(\frac{\rho_s}{\rho_\ell}\right)^{0.8} \right]^{2}}$$

INTRODUCTION

One of the many devices developed in recent years to handle the industrial process heat transfer efficiently is the fluidized bed. Some of the devices used to decrease the resistance to heat transfer include: rough surfaces, extended surfaces, and baffled tubular heat exchangers. The phenomenon of heat transport in fluidized beds has been the subject of numerous studies in the past two decades because of the many desirable characteristics of fluidized-bed heat transfer and the increased application of fluidized-bed reactors.

Fluidization is the operation by which fine solids are transformed into a fluid-like state through contact with a gas or liquid. When fluid is passed through a bed of fine particles, there is a certain velocity when the particles are suspended in the upward flowing gas or liquid. The bed is then considered to be just fluidized and is referred to as a bed at minimum fluidization. In liquid-solid systems, an increase in flow rate above minimum fluidization usually results in a smooth, progressive expansion of the bed. A bed such as this is called a particulately fluidized bed, a homogeneously fluidized, or simply a liquid fluidized bed.

The presence of solids greatly increases the heat transfer rates from a surface to a liquid fluidized bed. This is attributed to the increased turbulance the fluidized bed offers, as well as the energy transfered by solids in contact with the surface.

This investigation is a study of local and average heat transfer rates from an electrically heated surface to the fluidized bed. Heater surface temperatures were measured by a moving thermocouple probe inside an electrically heated tube. Surface temperatures and bulk temperatures made it possible to calculate local heat transfer coefficients at different places along the tube and for different liquid flow rates and particle concentrations.

LITERATURE SURVEY

Proposed Fluidized Bed Heat Transfer Mechanisms

Several theoretical mechanisms to describe the fluidized bed heat transfer were proposed. Extensive descriptions of these are given by Leva (7), Kunii and Levenspiel (5), Genetti (2) and Zenz and Othmer (11). One of the mechanisms proposed was the particle mode heat transfer mechanism by Zieglar, Koppel and Brazelton (12). A modified particle mode heat transfer mechanism for gas fluidized beds was proposed by Genetti and Knudsen (3). The mechanism that is being applied to liquid fluidized bed heat transfer in the present investigation is similar to that presented by Genetti and Knudsen. The details and modifications of this mechanism are discussed at the end of this section.

Experimental Study of Fluidized Bed Heat Transfer

The experimental study of liquid fluidized bed heat transfer is meager compared to the work done in the case of gas fluidized bed heat transfer. The experimental studies of the latter were summarized by Leva (7), Kunii and Levenspiel (5) and Genetti (2).

The experimental study of fluidized bed heat transfer has been broken down into two categories: Particle-to-Fluid Heat Transfer and Surface-to-Fluidized-Bed Heat Transfer.

Particle-to-Fluid Heat Transfer:

In a fluidized bed the particles serve as energy carriers. The particles gain energy at the heat transfer surface and release it to the fluid phase. In particle-to-fluid heat transfer, one is interested in the rate of heat transfer from the particle to the fluid. Studies on heat transfer between solid particles and fluidizing medium are necessary mainly to elucidate the mechanism of dissipation of heat of reaction, heat of dilution, etc., in a fluidized bed, and also in fluidized bed reactor design.

Sunkoori and Kaparthi (10) fluidized heated quartz and granite particles of different sizes in a water fluidizing medium. They measured heat transfer coefficients between the particles and the fluidizing medium under unsteady state conditions. Heat transfer coefficients varying from 113 to 620 Btu/hr.ft.^{2}°F were obtained and they noticed an increase in heat transfer rates with particle diameter and mass velocity. They correlated their data with the following equation:

$$\frac{h_p D_p}{K} = 0.00391\left(\frac{D_p G}{\mu}\right)^{2.1} \qquad (1)$$

More recently Holman, Moore and Wang (4) measured particle-to-fluid heat transfer coefficients for stainless steel and lead spheres fluidized in a water medium. The spheres were heated by an induction heating field. These authors correlated the particle Nusselt numbers with the following equation:

$$Nu_p = 1.28 \times 10^{-5} (Re_p F_\varepsilon)^{2.0} Pr^{0.67} \left(\frac{D_t}{D_p}\right)^{0.5} \left(\frac{\rho_f}{\rho_s}\right)^2 \left(\frac{\mu}{\mu_o}\right)^{0.83} \qquad (2)$$

The velocity correction factor, F_ε, was used to account for variation in porosity.

Surface-to-Fluidized-Bed Heat Transfer:

Lemlich and Caldas (6) fluidized glass particles of different sizes in a liquid medium. Heat transfer rates from the external, heated wall were measured. A maximum in heat transfer coefficient was obtained for each particle size. They identified two flow regimes; below the mass velocity, corresponding to the maximum heat transfer coefficient, another above the mass velocity, also corresponding to the maximum heat transfer coefficient. They have proposed correlations for respective regimes.

For low velocity fluidization the correlation is as follows:

$$Nu_p = 0.055\ Re_p \qquad (3)$$

For high velocity fluidization the following equation was proposed:

$$j = (St)(Pr)^{2/3} = 1.4\left(\frac{D_t}{D_p}\right)^{0.79}/Re_t\varepsilon \qquad (4)$$

Richardson and Mitson (9) measured the coefficients for the transfer of heat to a liquid-solid fluidized system and they found that the presence of solids can increase the coefficients by a factor of up to five. They correlated their data with the following equation:

$$Nu = 55\ Pr^{0.4}\left(\frac{C_s}{C_\ell}\right)^{0.28}\left(\frac{\rho_\ell V_i D_p}{\mu_\ell}\right)^N \qquad (5)$$

where: $$N = 0.020\left(\frac{\rho_s}{\rho_\ell} + 3.45\right) \qquad (5a)$$

Presently proposed Heat Transfer Mechanism:

The model that is proposed here is an extension of the model proposed by Genetti and Knudsen (2,3) for gas fluidized bed heat transfer.

This model is formulated under the assumption that particles are spheres of uniform diameter. Furthermore, particles from the bulk of the fluidized bed are assumed to move adjacent to the transfer surface, while close to the surface, the particle receives energy by convection from the fluid around it. After some time the particle leaves the surface and returns to the bulk of the bed. The major portion of heat transfer is assumed to occur by this mechanism, while conductive and radiative heat transfer is negligible. Based on this mechanism, the boundary value problem is solved, and under the assumptions which are still valid for the case of liquids, the time average heat transfer rate is obtained as:

$$q_p = \frac{\pi D_p K_\ell (T_w - T_b)}{\left(1 + \frac{M\bar{\theta}}{2}\right)^2} \tag{6}$$

where: $$M = \frac{12K_\ell}{\rho_s C_s D_p^2} \quad \text{and} \tag{6a}$$

$\bar{\theta}$ = the average contact time.

In order to obtain an expression for the heat transfer flux based on the wall surface, the number of particles at the surface per unit area will have to be derived. The number of particles per unit area, γ_p, will be related to the particle fraction $(1-\varepsilon)$, and the particle diameter. A relation of the following form has been proposed:

$$\gamma_p = K_1 (1-\varepsilon)^{-0.85} f(D_p) \tag{7}$$

It is experimentally observed that the heat transfer coefficient is dependent on particle fraction in the manner assumed in Equation 7.

For a completely covered surface with hexagonal packing, γ_p and $(1-\varepsilon)$ are:

$$\gamma_p = \frac{2/\sqrt{3}}{D_p^2} \tag{8}$$

$$(1-\varepsilon) = 14/27 \tag{9}$$

therefore: $K_1 = 0.637$ and (10)

$$f(D_p) = \frac{1}{D_p^2} \tag{11}$$

By substituting Equations 10 and 11 into Equation 7, we get the following equation for γ_p:

$$\gamma_p = \frac{0.637\ (1-\varepsilon)^{-0.85}}{D_p^2} \tag{12}$$

By multiplying q_p by γ_p, we can write an equation for the heat flux from the wall surface, i.e.,

$$q = \gamma_p q_p = \frac{2.0\ (1-\varepsilon)^{-0.85}\ (T_w - T_b)}{D_p \left(1 + \frac{6K_\ell \bar{\theta}}{\rho_s C_s D_p^2}\right)^2} \tag{13}$$

The particle Nusselt number is:

$$Nu_p = \frac{2.0\ (1-\varepsilon)^{-0.85}}{\left(1 + \frac{6K_\ell \bar{\theta}}{\rho_s D_s D_p^2}\right)^2} \tag{14}$$

The average contact time would be affected by the following variables:

1. particle diameter, D_p
2. particle density, ρ_s
3. liquid density, ρ_ℓ
4. liquid viscosity, μ
5. acceleration due to gravity, g
6. mass velocity, G

With the aid of dimensional analysis the following dimensionless groups can be obtained:

$$\left(\frac{\rho_s}{\rho_\ell}\right), \qquad \left(\frac{\bar{\theta}\, g^{1/2}}{D_p^{1/2}}\right), \qquad \left(\frac{D_p G}{\mu}\right)$$

With these groups an equation of the following form for $\bar{\theta}$ is obtained:[1]

$$\bar{\theta} = C_1\left(\frac{D_p}{g}\right)^{1/2} Re_p^{e} \left(\frac{\rho_s}{\rho_\ell}\right)^{f} \tag{15}$$

The exponents in this equation have to be determined experimentally. Substituting Equation 15 in Equation 14 the following is obtained:

$$Nu_p = \frac{2.0\,(1-\varepsilon)^{-0.85}}{\left[1+ \frac{6K_\ell\, C_1}{\rho_s C_s D_p^2}\left(\frac{D_p}{g}\right)^{1/2} Re_p^{e} \left(\frac{\rho_s}{\rho_\ell}\right)^{f}\right]^2} \tag{16}$$

1. It would be expected that the average contact time, $\bar{\theta}$, would also depend on the particle fraction, $(1-\varepsilon)$, however, no such dependence was observed experimentally in the correlation obtained.

EXPERIMENTAL EQUIPMENT

The experimental equipment was designed in order to determine local and average heat transfer coefficients from an internal heat source to a liquid fluidized bed. The components of the equipment included a fluidizing unit, a pump, a power source and the measuring devices. The general set-up of the equipment is shown in Figure 1.

The Fluidizing Unit

The fluidizing unit consisted of a 2 1/2-inch I.D., two feet long, cast acrylic tube. The thickness of the tube wall was 1/8-inch. At the top and bottom it was fitted with flanges of 3/4-inch thickness. Over the top flange was fitted a rubber gasket and a circular plate made of micarta. The top plate and the top flange were tightened with bolts to ensure air-tightness. Four openings of 1/2-inch diameter were made around the tube at 1 1/2-inches from the top of the tube to serve as the outlet for the fluid. The four outlets were connected by the use of T-junctions and a single tube carried the water to the tank.

To the bottom flange affixed to the tube, another flange of the same dimensions was attached by bolts, with a gasket in-between. Between the flanges was placed a perforated circular iron plate, over which a 200 mesh wire screen was affixed. This plate held the particles in the bed. The intake piping was attached to the flange.

A 321 stainless steel tube, 3/4-inch O.D., 0.012-inch thick and 30-inches long, was fitted through the center of the bed. Electrical wire

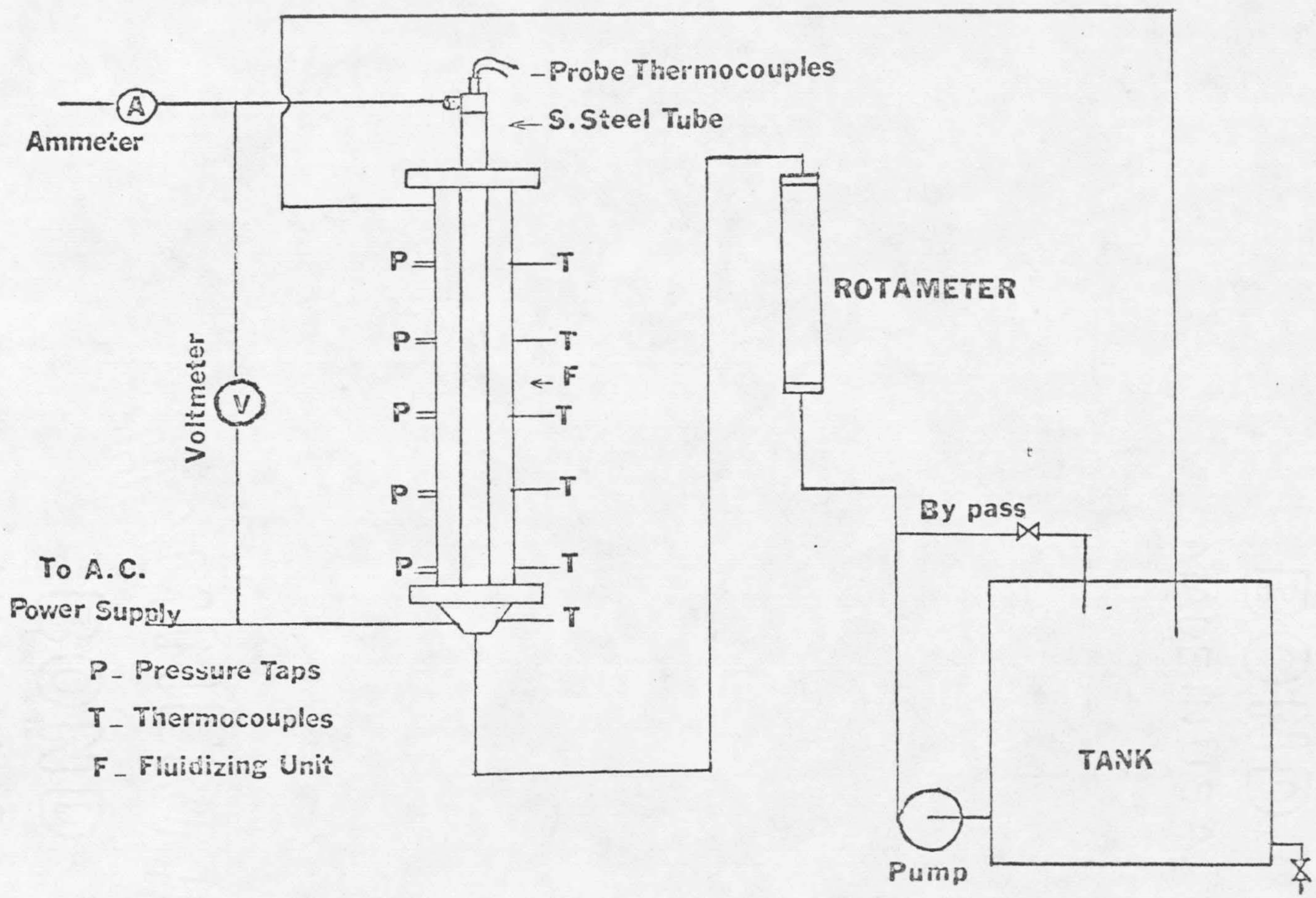

Figure 1. Diagram of equipment.

contacts were made at the top and bottom of the steel tube. A moving thermocouple probe was arranged to run through the center of the steel tube. This probe was attached to a metal rod, used to move the probe up and down. A thermocouple was placed in the fluid intake section to measure the inlet fluid temperature. Five thermocouples and thermocouple shields were mounted at 1.5, 5.5, 9.5, 13.5, and 17.5 inches from the bottom. The thermocouple shield consisted of 0.3 inch diameter, 0.3 inch high cylinder made of fine wire mesh. Five pressure taps were located at 1 1/2-inches from the bottom of the tube and every 4 inches thereafter along the length of the tube.

The stainless steel tube was the heating device. The wall temperature was measured by one moving thermocouple probe inside the heating element.

A centrifugal pump was used to pump water from the tank through the fluidized unit. A bypass was provided to control the flow rate. Water flow rate was measured by a rotameter located in the water supply line. The rotameter was calibrated. Details of this calibration are given in Appendix B.

The Alternating Current Power Supply

The alternating current power supply was made from the supply lines through a step-down transformer. The resistance in the circuit was adjusted so that the current was about 30 to 45 amperes. The emf and current were measured by an AC Voltmeter with a range from zero to five volts and an AC Ammeter with a range from zero to fifty amperes. The meters were quoted by the manufacturers to be accurate within ± 2 percent.

Measuring Devices

The pressure drop across the bed was measured by a manometer system using carbon tetrachloride fluid with a specific gravity of 1.584.

The wall temperature was measured at various positions by a thermocouple probe which moved up and down inside the tube wall. A thermocouple was embedded in each contact and was electrically insulated from the copper. Each copper contact was held in contact with the wall by a spring. A detailed description of such a probe was given by Noë and Knudsen (8).

All temperatures were measured with Iron-Constantan thermocouples. The thermocouple emf was read using a Leeds and Northrup Co. potentiometer model 0386100. Thermocouples placed in the bed were used to determine the bulk temperature of the water flowing through. All reference junctions were kept in an ice-bath at 32°F.

A switching system was used to complete the thermocouple circuits.

EXPERIMENTAL PROGRAM AND PROCEDURE

Experimental Program

The objective of this investigation was to determine local and average heat transfer coefficients for transfer of energy from an internally heated tube to water flowing through a fluidized bed at various operating conditions. The experimental program was designed to fulfill this objective.

The variables that are most likely to affect the transfer of energy from an internal surface to a fluidized bed can be catagorized into three groups: (1) properties of the fluidizing medium and fluidized particles, (2) operating conditions and (3) equipment geometry and design.

Variables under consideration in this investigation are: particle concentration or static bed height, particle distribution and liquid flow rate. Heat flux, tube wall temperature profile, and vertical bulk liquid temperature were measured in order to calculate the desired coefficients. Bed section pressure drops were measured in order to calculate particle distributions.

Water was used as the fluidizing medium. The water used was approximately at the same temperature for all runs which made it possible to keep the thermal conductivity, heat capacity, viscosity and density of the fluid constant.

Properties of the Particles

Three types of particles were used in this investigation: (1) glass spheres, manufactured by the Minnesota Mining and Manufacturing Company, of 0.0185 inch average diameter; (2) stainless steel particles, manufactured by the Hoeganaes Corporation, Riverton, N.J., of 0.014 inch average diameter; and (3) coke particles of 0.014 inch average diameter. The densities of the glass, stainless steel and coke particles are 156 lb/ft^3, 488 lb/ft^3 and 138 lb/ft^3, respectively. It can be seen from Figure 2 that the glass particles are spherical, whereas the coke and stainless steel particles are somewhat irregular in shape.

Particle Concentration and Distribution

Static bed heights of six and nine inches were investigated for the three types of particles. Data were also taken without particles in the system in order to compare with data reported in literature.

Fluid Mass Velocity

The fluid mass velocities were restricted to the low velocity region. The mass velocity ranged from 2,960 to 32,650 $lb/hr.ft.^2$ Different possible flow rates were investigated at each static bed height. The first rate was chosen near the minimum fluidizing velocity and thereafter the rate was increased.

Experimental Procedure

The following preliminary procedure was performed before each experimental run: