IJCPE
Iraqi Journal of Chemical and Petroleum Engineering

Iraqi Journal of Chemical and Petroleum Engineering
Vol.10 No.3 (September 2009) 1- 8
ISSN: 1997-4884

University of Baghdad
College of Engineering

Prediction of Effective Bed Thermal Conductivity and Heat Transfer Coefficient in Fluidized Beds

Majid I. Abdul-Wahab* and Suha A. Mohammed

**Chemical Engineering Department - College of Engineering - University of Baghdad – Iraq*

Abstract

Experimental study of heat transfer coefficients in air-liquid-solid fluidized beds were carried out by measuring the heat rate and the overall temperature differences across the heater at different operating conditions. The experiments were carried out in Q.V.F. glass column of 0.22 m inside diameter and 2.25 m height with an axially mounted cylindrical heater of 0.0367 m diameter and 0.5 m height. The fluidizing media were water as a continuous phase and air as a dispersed phase. Low density (Ploymethyl-methacrylate, 3.17 mm size) and high density (Glass beads, 2.31 mm size) particles were used as solid phase. The bed temperature profiles were measured axially and radially in the bed for different positions. Thermocouples were connected to an interface system and these measurements were monitored by computer on line. Theoretical analysis has been carried out to solve the differential equation governing heat transfer in the gas-liquid-solid fluidized system with its boundary conditions. Finite difference technique was used as a suitable numerical method to find the solution. By applying the temperature profiles found experimentally in solved equation, effective thermal conductivity values were found.

***Keywords*:** Fluidized beds, gas-liquid-solid, heat transfer, effective thermal conductivity.

Introduction

Gas-liquid-solid fluidization is defined as an operation in which a bed of solid particles is suspended in gas and liquid medium due to the net drag force of the gas and liquid flowing opposite to the gravitational or buoyancy force on the particles. The liquid stream forms the continuous phase, while the gas stream forms the dispersed phase. Such an operation generates considerable intimate contact among the gas, liquid and solid particles in the systems and provides substantial advantages for applications in physical, chemical or biochemical processing involving gas, liquid and solid phases (Muroyama and Fan, 1985). Three-phase fluidized beds have been extensively adopted in many industrial processes. The high heat transfer rate is recognized as one of the main characteristics for the wide application of three-phase fluidization. The hydrodynamics, heat and mass transfer of the beds have been carried out using systems of high-density particles (1700-2600 kg/m3). These particles are employed in hydrotreating and hydrocracking of petroleum products. The development of the advanced biological fluidized reactors which use light catalyst particles of densities range from 1050 to 1300 kg/m3 directed some of these studies towards the low-density particles fluidized beds. The studies began to project highlight upon the fundamental characteristics (hydrodynamics, heat and mass transfer) in three-phase fluidized beds containing low–density particles (Tang and Fan, 1990, Nore et al., 1992, Nore et al., 1994, Samir and Fan, 1993, 1994, Abdul Wahab, 1997, Van Zeen, 2003). The hydrodynamics are widely investigated (Shah et al., 1978 and Muroyama and Fan, 1985) by both experimental and mathematical studies. Although the heat and mass transfer are also investigated, but there is a lack in information concerning these fields.

Heat transfer studies in three-phase fluidized beds are classified into two groups. One deals with wall-to-bed heat transfer (Kato et al., 1981, Muroyama et al., 1986 and Nore et al., 1994, Zorana et al.2008), and the other with immersed heater-to-bed heat transfer (Baker et al., 1978, Khan et al., 1983 and Mogiliotou et al., 1988,Luo and Fan 2000, Muroyama et al.2001, Grace et al.2008). Although most of these studies have resulted in correlating equation for the experimental data, a few have analyzed the systems mathematically and proposed mechanism of the heat transfer. Furthermore, the immersed surface-to-bed heat transfer studies have used flate plate heaters (Khan et al., 1983 and Luo and Fan, 2000) and cylindrical shaped (Baker et al., 1978, Mogiliotou, 1988 and Muroyama et al.2001).

The present study focused on predicting the two important heat transfer parameters in the three phase fluidized beds, namely; the heat transfer coefficient and the effective thermal conductivity for the low and high density fluidized beds heated by a cylindrical immersed heater. The study aimed also to investigate the radial temperature profile at different axial positions experimentally. The effects of liquid and gas flow rates on the heat transfer parameters will be examined experimentally and the equations describing the heat transfer process will be solved numerically by a finite difference technique.

Experimental Work

The experimental work was performed using Q.V.F. glass test column of 0.22 m inside diameter and 2.25 m height. The column has a hemispherical bottom and consists of three sections; namely the working section, accumulation section and the liquid outlet header. The overall combined height of these sections was 2.25 m. The schematic diagram of the experimental equipment is shown in Fig. 1; more details can be found elsewhere (Suha, 2009).

The working section of the column (1.0 m height) was located between the distributor and the accumulation section. Five taps were used for mounting thermocouples axially. The axially taps were cemented to the column body by using an adhesive material (which has high thermal resistance) to prevent leakage. Three taps were used for mounting thermocouples in radial positions. The radial taps were located in vertical Teflon pipe and they were fixed axially with different radii, the Teflon pipe was moved in five axial positions.

The accumulation section (0.7 m height) acted as a reservoir to accumulate large quantity of fluid. The top of the accumulation section protruded into a concentrically mounted outlet header (a Perspex box of 0.25 m x 0.25 m x 0.75 m). The header thus, acted as a weir over which the liquid flowed, thereby maintaining an approximately constant head in the column. The liquid exited from the outlet header through three hoses which were provided with valves to enable varying proportions of the flow to be either returned to the feed reservoir or sent to the drain.

The liquid phase employed in all experiments is tap water. It was pumped through the column by means of a centrifugal pump. The water flow rate was regulated by means of globe valve connected at the discharge of the pump and also in the main feed line and measured with calibrated rotameter. Enough length of pipe was placed between the main feed globe valve and the rotameter to prevent any disturbance in the water flow passing through the rotameter. Furthermore, a by-pass line with valve was located at the outlet of the pump to direct any excess flow of water back to the feed vessel (Q.V.F.) spherical vessel of 0.1 m^3 capacity. Solid particles were supported on a perforated plate (like mesh) of spaced holes of 1 mm diameter which served as a continuous phase distributor.

The distributor was situated between the main column section and the entrance of the continuous phase which was introduced through a 2.54 cm pipe from liquid reservoir. Polymer (polymethyl-mthacrylate) particles of 3.17 mm average diameter and 1170 kg/m^3 density, and glass beads of 2.31 mm average diameter and 1910 kg/m^3 density were selected as packing. The heater assembly shown in Fig. 2, it was installed vertically at 0.3 m above the distributor as a heat source in the immersed heater-to-bed system consisted of a copper cylinder of 0.0366 m outside diameter and 0.5 m height. Two 0.013 m diameter by 0.3 m length, 3000 w/220 v electric heating **U** shaped elements were located in wells drilled inside the cylinder. The space between the heating elements and the cylinder was filled with Sand to give a good heat distribution and to prevent the damage of heater. Three copper-constantan thermocouples (Type-J) were imbedded in the copper cylinder to measure the surface temperature of the heater. They were positioned at the 0.15 m, 0.25 m and 0.35 m from the bottom of the heater respectively. They were positioned at different angles along the heater surface, i.e. 120^o a part. The thermocouple junctions were inserted in holes drilled in the surface and welded. Four copper rods of equal length and of cross shape were connected to the ends of the heater. This arrangement was adopted to ensure the heater at the center of the column.

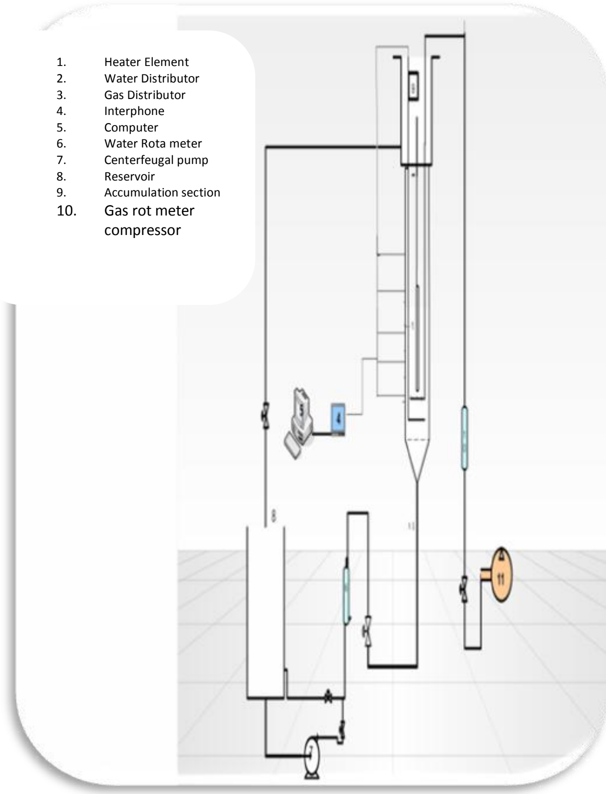

Fig. 1 Schematic diagram of the equipment

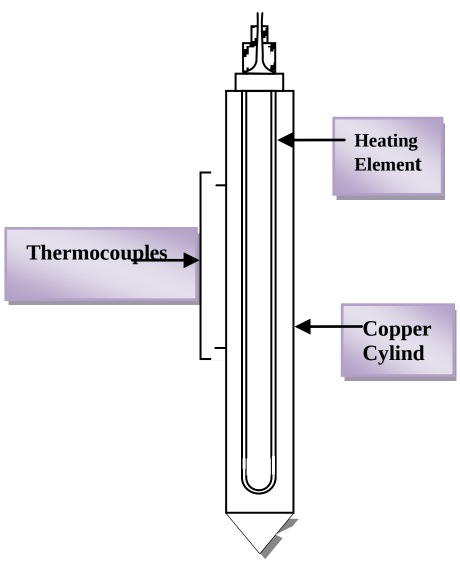

Fig. 2 The heater

Results and Discussion

Heat transfer coefficient

The heat transfer coefficient (h) between the immersed heater and the bed can be influenced by the resultant flow behavior of dispersed bubbles, fluidizing particles and the continuous medium. Thus, the effect of individual flow behavior on the heat transfer coefficient has been determined. The average heat transfer coefficient values calculated from the experimental measurement of temperature differences are plotted versus the velocity of gas for various values of liquid velocities. Figures 3-8 show these plots for different values of heat flux from the heater. It is shown clearly that the heat transfer coefficient generally increases with both liquid velocity (u_l) and gas velocity (u_g). The corresponding values of heat transfer coefficients at the same values of liquid and gas velocities show an increasing trend with the increase of heat flux from the heater. This increase in h values can be attributed to the effect of heating level on the physical properties of both gas phase and liquid phase in the bed. Figures present the experimental values of average heat transfer coefficients versus liquid velocity for various gas velocities for different heat fluxes from the heater.

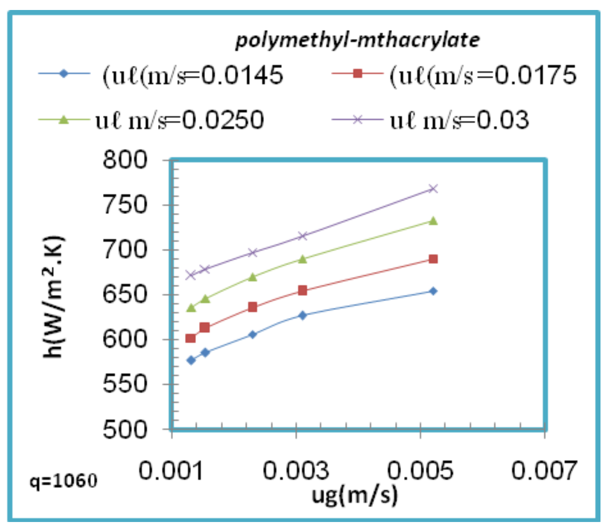

Fig. 3 h vs. u_g at different values of u_ℓ, q = 1060 W

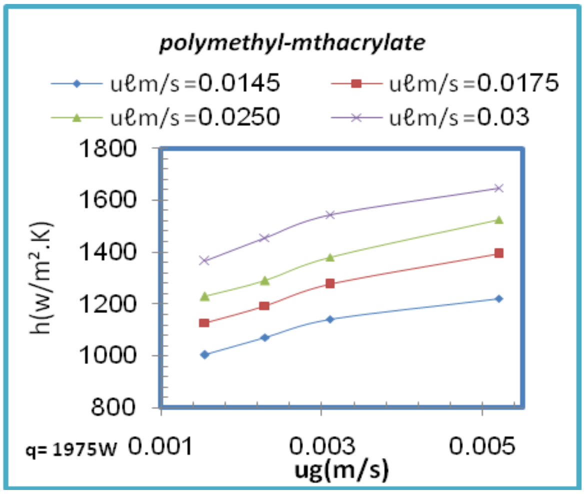

Fig. 4 h vs. u_g at different values ofu_ℓ, q = 1975 W

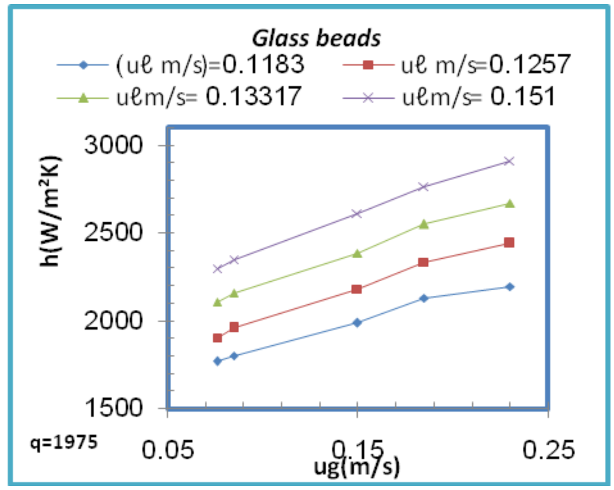

Fig.7 h vs. u_g at different values ofu_ℓ, q = 1975W

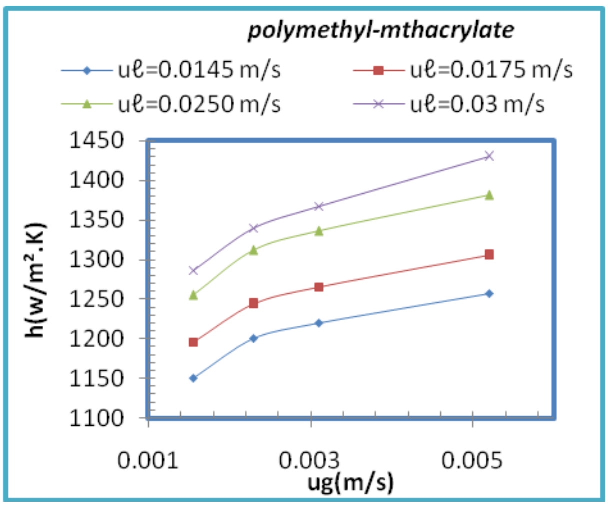

Fig. 5 h vs. u_g at different values ofu_ℓ, q = 2250W

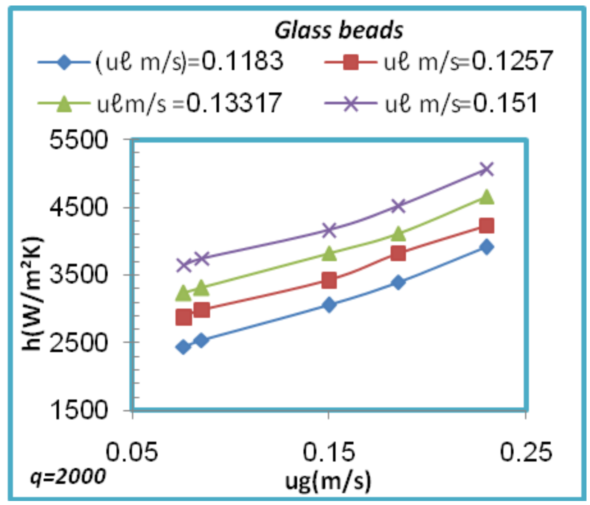

Fig. 8 h vs. u_g at different values ofu_ℓ, q = 2000 W

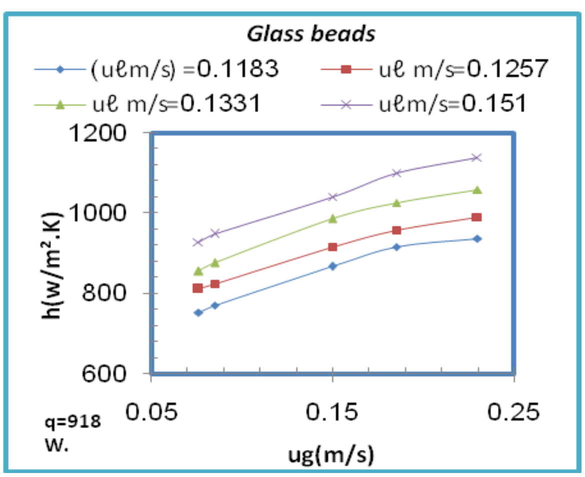

Fig. 6 h vs. u_g at different values ofu_ℓ, q = 918W

The increase of (h) can be attributed to the turbulence generated with an injection of gas flow into the liquid fluidized beds (Baker et al., 1978, Chiu and Ziegler, 1983). The effect of the generated turbulence on the heat transfer may be governed by its intensity and distribution in the bed. The initial increase of h with liquid velocity is due to the increase of turbulence, oscillatory motion of the fluidized solid particles, and fluid elements which are rapidly displaced inside the bed, generating micro-eddies of fluid. The heat transfer in the three-phase fluidized beds is mainly affected by the heat transfer coefficient near the heater surface region which is controlled by conduction through the liquid film covering the heater surface. Liquid phase velocity has a significant effect on the heat transfer coefficient in the three-phase fluidized beds with an additional effect of the gas phase velocity.

The experimental results are fitted in the following empirical correlation using linear regression technique:
For polymethyl-methacrylate particles, ρ = 1170 kg/m^3

$$Nu = 1.54(\mathrm{Re}_\ell)^{0.53}(\mathrm{Pr})^{0.36}(\mathrm{Re}_g)^{0.25} \qquad (1)$$

For Glass beads particles, ρ = 1921 kg/m^3

$$Nu = 1.07 Re_\ell^{0.4} Pr^{0.25} Re_g^{0.23} \qquad (2)$$

Temperature Profiles

Typical radial temperature profiles measured at various axial positions are shown in Figs. 9 and 10 for low and high particles density at constant gas and liquid velocity, Figs.11 and 12 at various gas velocities, and Figs.13 and 14 at various liquid velocities. In these figures the effect of gas and liquid velocities and axial positions on the radial temperate profile are shown by plotting the dimensionless temperature $(T-T_o)/(T_s-T_o)$ versus the dimensionless radial distance r/R. The radial temperature profile is relatively high at a low gas velocity in which low degree of mixing is caused by uniform fine bubbles, where the flow mode is termed "dispersed bubble flow" (Muroyama et al., 1978). On the other hand, the radial temperature profile decreases considerably at higher gas velocities at which slug flow mode dominates, where significant bed mixing occurs.

Effective radial thermal conductivity

In fluidized beds, heat can be transferred in radial direction by several mechanisms. It can be transferred through the particles by conduction and through the fluid by conduction and convection. All these heat transfer mechanisms have been assumed to occur by conduction according to an effective radial thermal conductivity (k_{er}). This is equivalent to supposing that the bed is replaced solid of thermal conductivity equal to k_{er}. Therefore the effective thermal conductivity is a property of the bed; its value depends on large number of variables, such as flow rate, particle diameter, porosity, thermal conductivities of the fluids as well as solid phase and temperature level. However, dividing k_{er} into separate contributions, each of them corresponds to mechanisms of heat transfer is not possible in the three-phase fluidized beds because of the complexity of the problem. Many correlations have been developed on this basis for gas-solid fluidized beds and the gas-solid fixed bed. However, no reliable correlation was found in the literature to estimate the value of effective thermal conductivity in the gas-liquid-solid fluidized beds. Therefore, the most logical method is to solve the differential equation that governing the heat transfer process numerically, and then by applying the experimental temperature profile in the solution, from which the effective radial thermal conductivity can be obtained.

Mathematical Model

The differential equation governing the heat transfer process in cylindrical coordinate for ga-liquid-solid fluidized beds can be written as

$$-GC_P\frac{\partial T}{\partial z} + k_{ez}\frac{\partial^2 T}{\partial z^2} + k_{er}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = 0 \qquad (3)$$

$$GC_P = G_l C_{Pl} + G_g C_{Pg} \qquad (4)$$

Where G_l and G_g are the mass velocity of the liquid phase and gas phase respectively, k_{ez} and k_{er} are the effective axial and radial thermal conductivities respectively. The boundary conditions of the problem are

$$B.C.1 \quad z = 0 \quad -k_{ez}\frac{\partial T}{\partial z} = GC_P(T_o - T) \qquad (5a)$$

$$B.C.2 \quad z = L \quad \frac{\partial T}{\partial z} = 0 \qquad (5b)$$

$$B.C.3 \quad \text{at heater surface} \quad k_{ez}\frac{\partial T}{\partial z} = q^* \quad \text{and } k_{er}\frac{\partial T}{\partial r} = q^* \qquad (5c)$$

$$B.C.4 \quad r = R \quad \frac{\partial T}{\partial r} = 0 \qquad (5d)$$

Equation 3 with its boundary conditions (Eqs. 5a-5d) was solved numerically using Matlab technique to find the theoretical axial and radial temperature distribution in the bed. The theoretical and experimental profiles were matched in order to find the values of effective radial thermal conductivity that satisfied the solution. Figs. 15 and 16 show the variation of the effective radial thermal conductivity with the gas velocity for a given particle density at different liquid velocities on log-log scale. Figs. 17 and 18 show the variation of the effective thermal conductivity with the liquid velocity at different gas velocities. The effective radial thermal conductivity is well correlated in terms of dimensionless groups. For glass beads:

$$\frac{k_{er}}{k_l} = 1.5\,\mathrm{Re}_l^{0.35}\,\mathrm{Re}_g^{0.27} \qquad (6)$$

For polymethyl-methacrylate particles:

$$\frac{k_{er}}{k_l} = 2.4\,\mathrm{Re}_l^{0.8}\,\mathrm{Re}_g^{0.07} \qquad (7)$$

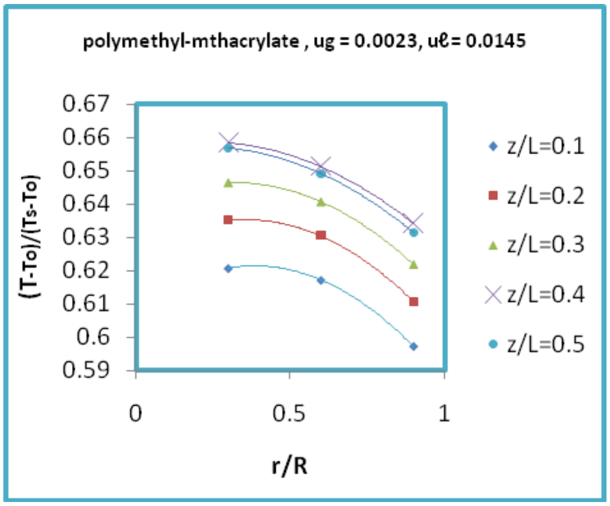

Fig. 9 Radial Temp. Profile for PM Particles

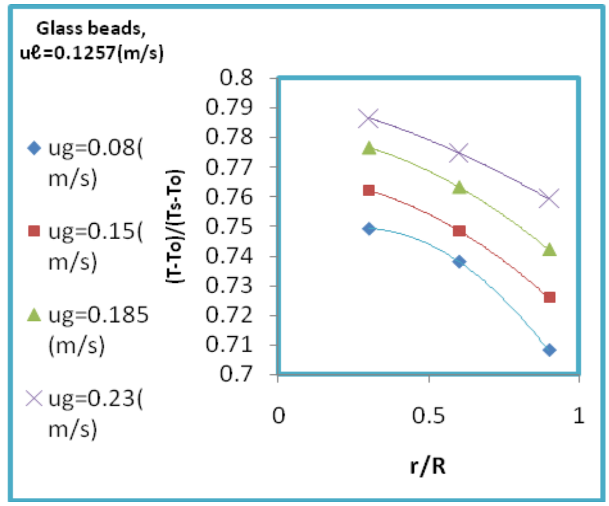

Fig. 12 Radial Temperature for Glass Beads

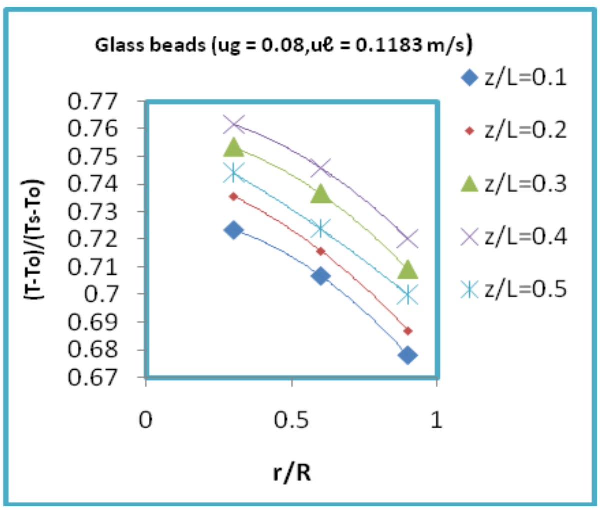

Fig. 10 Radial Temp. Profile for Glass beads

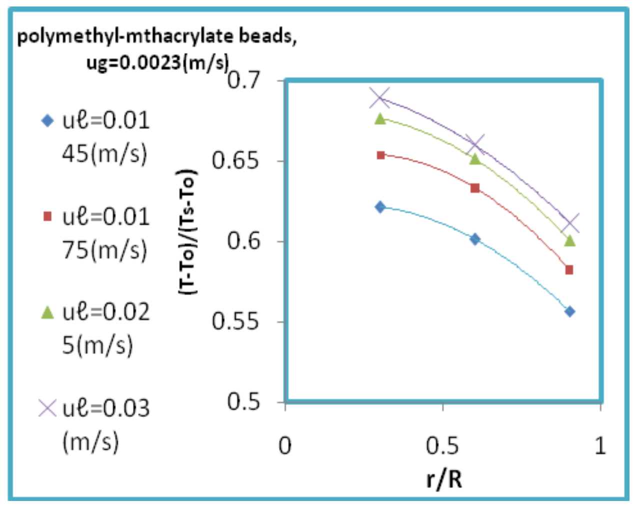

Fig. 13 Radial Temp. profile for PM Particles

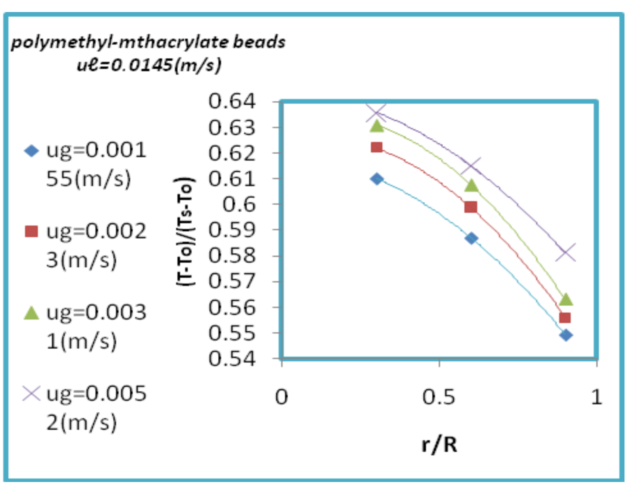

Fig. 11 Radial Temp. Profile for PM Particles

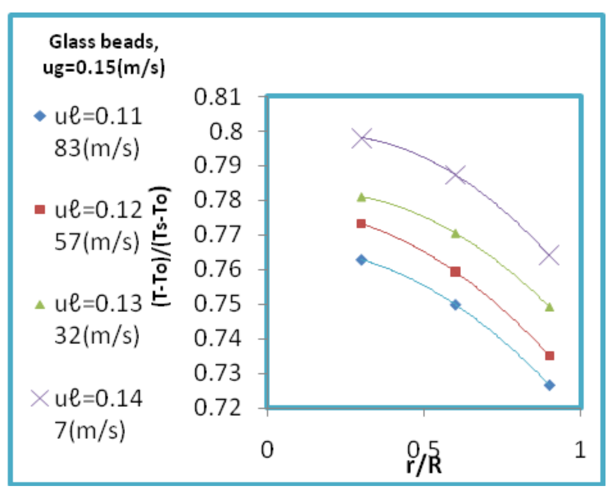

Fig. 14 Radial Temp. Profile for Glass Beads

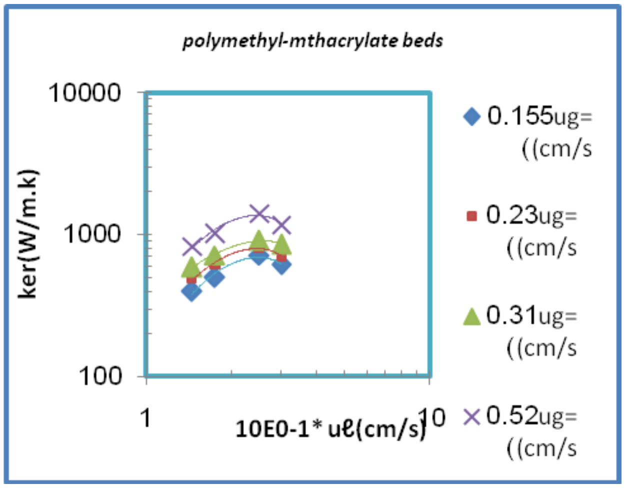

Fig. 15 K_{er} vs. u_g at different values of u_ℓ

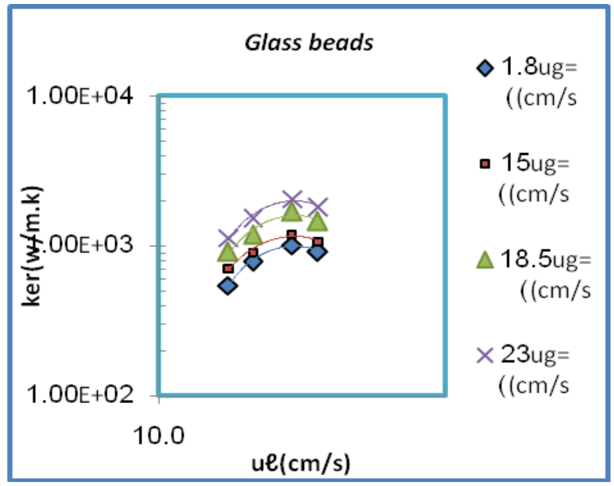

Fig. 18 K_{er} Vs. u_ℓ at different values u_g

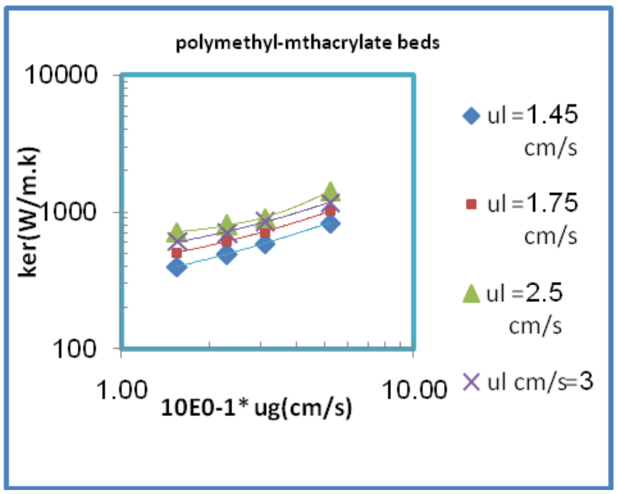

Fig.16 K_{er} Vs. u_ℓ at different values of u_g

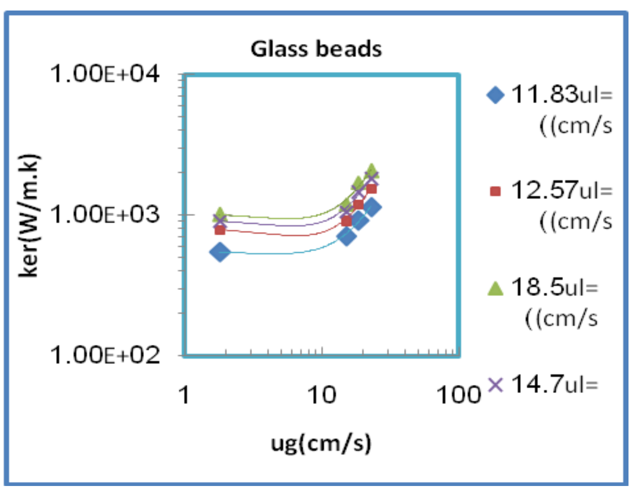

Fig. 17 K_{er} Vs. u_g at different values of u_ℓ

Conclusions

1. The temperature profiles in the gas-liquid-solid fluidized beds are found to be significant, indicating the presence of considerable resistance in the core of the bed in series with the resistance at the heater surface.
2. The effective radial thermal conductivity increases with the increase in liquid velocity. In three-phase fluidized beds it depends on the bubble flow modes, in the coalesced bubble flow regime the effective radial thermal conductivity increases significantly with increasing gas velocity especially at low liquid velocities, while in the dispersed bubble flow regime it is little affected by the introduction of the gas phase.
3. The heat transfer coefficients and effective radial thermal conductivities are increasing functions of the density of the particles.

References

1. Abdul-Wahab, M.I., (1997) "Hydrodynamics and Temperature Distribution in Low Density Particles Fluidized Beds Using The Finite Element Technique", Ph.D. Thesis, University of Baghdad.

2. Baker, C.G.J., Armstrong, E.R., and Bergougnon, M.A. (1978), "Heat Transfer in Three-Phase Fluidized Beds", Powder Technology, 21, 195-204.

3. Chiu,T.M. and Ziegler, E.N.,(1983), "Heat Transfer in Three-phase Fluidized Beds" AichE, 29,677-685.

4. Grace, J.R. and Stefanova, A.,"Heat Transfer From Immersed Vertical Tube in a Fluidized bed of group A Particles near the Transition to the turbulent fluidization flow regime" International Journal of Heat and Mass Transfer, (2008).

5. Kato, Y., Uchida, K., Kago, T. and Morooka, S., (1981), "Liquid Holdup and Heat Transfer Coefficient between Bed and Wall in Liquid-Solid and Gas-Liquid-Solid Fluidized Beds", Powder Technology, 28, 173-179.

6. Khan A.R. and Richardson, J.F., "Heat Transfer From Plane Surface to Liquids and to liquid-Solid Fluidized Beds",1983.

7. Magiliotou, M., Chem, Y.M. and Fan, L.S., (1988), "Bed-Immersed Object Heat Transfer in a Three-Phase Fluidized Bed", AIChE. J., 37, 1101-1106.

8. Muroyama, K. and Fan, L.S., (1985), "Fundamentals of Gas-Liquid-Solid Fluidization", AIChE J., 31, No.1, 1-34.

9. Muroyama, K., Fukuma, M. and Yasunishi, A., (1986), "Wall-to Bed Heat Transfer in Liquid-Solid and Gas-Liquid-Solid Fluidized Beds", Part II: Gas-Liquid-Solid Fluidized Beds, Can. J. Chem. Eng., 64, 409-418.

10. Muroyama K, Okumichi S, Goto Y, Yamamoto Y, Saito S, (2001), "Heat Transfer From Immersed Vertical Cylinders in Gas-Liquid and Gas-liquid-Solid Fluidized Beds", Chemical Engineering and Technology, Vol. 24, Issue 8.

11. Nore, O., Briens, C., Margaritis, A. and Wild, G. (1992), "Hydrodynamics Gas-Liquid Mass Transfer and Particle-Fluidized Bed for Biochemical Process Applications", Chem. Eng Sci., 47, 3573-3580.

12. Nore, O., Briens, C., Margaritis, A. and Wild, G. (1994), "Wall-to-Bed Heat Transfer in Three-Phase Fluidized Beds of Low Density Particles",Can. J.Chem.Eng.,72,546-550.

13. Samir Kumar, K. Kusakabe and L. -S. Fan (1993), "Heat Transfer in Three-Phase Fluidized beds Containing Low-Density Particles", Chemical Engineering Science, Vol. 48, Issue 13.

14. Shah, Y.T., Stiegel, G.J, and Sharma, M.M.,"Backmixing in Gas-Liquid Reactors", AIChE J., 1978.

15. Suha, A. Mohammed, " Prediction of Effective Bed Thermal Conductivity and Heat Transfer Coefficient in Fluidized Beds", M.Sc. Dissertation, Baghdad University (2009).

16. Tang, W.T. and Fan, L.S., "Hydrodynamics of A Three-Phase Fluidised Bed containing Low-Density Particles" AIChE, 1989.

17. Van Zeen, (2003), "Hydrodynamics of a Liquid-Liquid-Solid Fluidized Bed Bioreactor",Ph.D. Thesis Wageningen University, the Netherlands

18. Zorana, A., and Radmila, G., "Wall-to-bed Heat Transfer in Vertical Hydraulic transport and in Particulate fluidized Beds" International Journal of Heat and Mass Transfer, Volume 51, Issues 25-26, December 2008, Pages 5942-5948.