Bed Voidage and Heat Transfer in Non-Newtonian Liquid-Solid Fluidized Bed

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ABSTRACT : *The presence of particles in liquid-solid fluidized beds enhances the bed heat transfer, because the movement of the particles leads to an increased turbulence in the system. Moreover, the violent movement of the particles has a positive effect on fouling of the heat transfer surface. The aim of this investigation was to perform systematic measurements of bed voidage and heat transfer coefficient for solid-liquid fluidization in a cylindrical tube and to study the effect of process parameters such as particle size and density, flow velocity, and liquid viscosity on these subjects. A large number of experiments were performed using different cylindrical and spherical particles fluidized in aqueous CMC solution with different concentrations. Using the experimental results, a new correlation for predicting heat transfer coefficient in non-Newtonian liquid-solid fluidized bed heat exchanger was introduced.*

KEY WORDS : *Bed voidage, Heat transfer, Non-Newtonian, Fluidized bed*.

INTRODUCTION

The application of solid/liquid fluidized bed systems within the chemical process industries shows a significant growth in recent years. There has been a considerable interest in application of solid-liquid fluidized bed heat exchangers in various process industries [1-5]. In fact the solid particles stir the thermal boundary layer and increase the heat transfer coefficient up to eight times higher than that of a single phase forced convection [6]. In addition when severe fouling is expected, any deposits that may form on the heat transfer surfaces are immediately removed by the abrasive action of the particles [5]. Fluidization largely depends on the characteristics of the solid particles, primary size, density, thermal conductivity and shape [7].

Several workers [3,5,6,8] have measured heat transfer coefficients from a heated surface of liquid-fluidized beds. However, the published results on heat transfer to solid-liquid fluidized beds did not produce a generally applicable correlation for the prediction of heat transfer coefficients and bed voidage. Accurate prediction of bed voidage is essential for the calculation of heat transfer coefficient in solid - liquid fluidized bed systems.

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Jamialahmadi et al. [9] have presented the available correlations for the prediction of the heat transfer coefficient in solid-liquid fluidized beds in details. An experimental investigation on heat transfer was made by them using water and a variety of solid particles. Moreover Jamialahmadi et al. [10] have made a comparison between the pervious reported measured and predicted optimum heat transfer coefficients. They concluded that even though individual investigators have been reasonably successful in correlating their own results, the variation between the predictions of the various correlations and the experimental data is quite considerable. The reason for this discrepancy could be the complex nature of fluidization and the effect of a number of independent parameters on the heat transfer coefficient. Moreover, the use of dissimilar particles or bed geometries give rise to different hydrodynamic characteristics of the fluidized bed. The previous workers used water and Newtonian liquid in their experimental investigations.

The aim of the present work was to study heat transfer from a vertical tube using both spherical and cylindrical particles suspended in aqueous CMC solution as a non-Newtonian system. The effect of operating parameters such as liquid flow velocity, particle size, particle density and heat flux on heat transfer have been investigated.

TEST RIG

In the apparatus used in this work, which is shown in Fig. 1, the liquid flows in a closed loop consisting of temperature controlled storage tank, pump and test sections. The flow velocity of the liquid was measured with calibrated electromagnetic flow meters. The fluid temperature in the fluidized test section was measured with thermocouples appropriately located in the pipes. The fluid temperature was measured before and after the parallel annular test section with thermocouples located in mixing chambers. The pressure inside the test rig could be adjusted by connecting the supply tank to pressurized air. The complete rig was made from stainless steel.

The fluidized bed test section shown in Fig. 2 was designed as an externally heated pipe. The thermocoax heating wire was placed into thread around the pipe and embedded by high temperature soldering tin to ensure good contact with the pipe wall. The dimensions of the fluidized bed test section are: inside diameter of pipe, 23.8 mm; length of heating wire, 3850 mm; length of cold ends of the wire, 160 mm, length of heat section, 160 mm.

The cross-section area of the fluidized test section expands above the heated section to decrease the flow velocity and restrict particle carry-over. The local wall temperature of the heated pipe is measured using four thermocouples, which are located close below the heat transfer surface. The ratio between the distance of the thermocouples from the heat transfer surface and the thermal conductivity of the pipe material (s/λ_w) was determined by calibration measurements using the Wilson plot technique [9]. The heat transfer surface temperature, the heat flux and the thermocouple temperature can be calculated using this ratio:

$$T_w = T_{th} - q\,(s/\lambda_w) \tag{1}$$

The same rig is used by the previous workers [9] in order to predict heat transfer using solid particles in pure water.

The liquid used in the present investigation was aqueous carboxymethyl cellulose (CMC) solution. CMC polymers, non-Newtonian liquid, are probably the most common solution which are used routinely both to control fluid loss and to increase viscosity. Three different sizes of cylindrical metal particles and also two different sizes of spherical particles have been used in the present study. Flow velocity and heat flux were varied while the bulk temperature was kept constant. All measurements were taken after the system had reached steady state conditions.

HEAT TRANSFER MODEL

Theoretical models for heat transfer in fluidized systems are generally based on the concept that, the particles stir the fluid near the heat transfer surface causing erosion of the laminar sublayer which performs the major resistance to heat transfer. Also the solid particles transfer heat by convection. Based on the previous work, the following heat transfer model is developed assoming that the heat resistance of the bed is negligible [9]. This assumption is valid if the difference between particle and fluid density be high enough to produce superficial Reynolds numbers in the turbulent region.

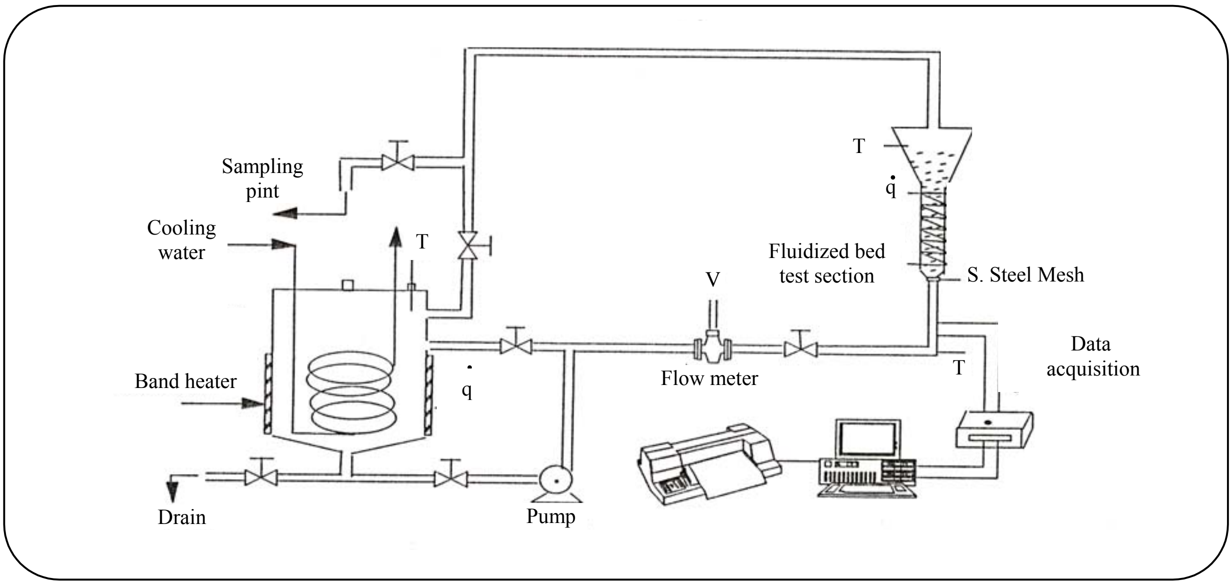

Fig. 1: Scheme of apparatus

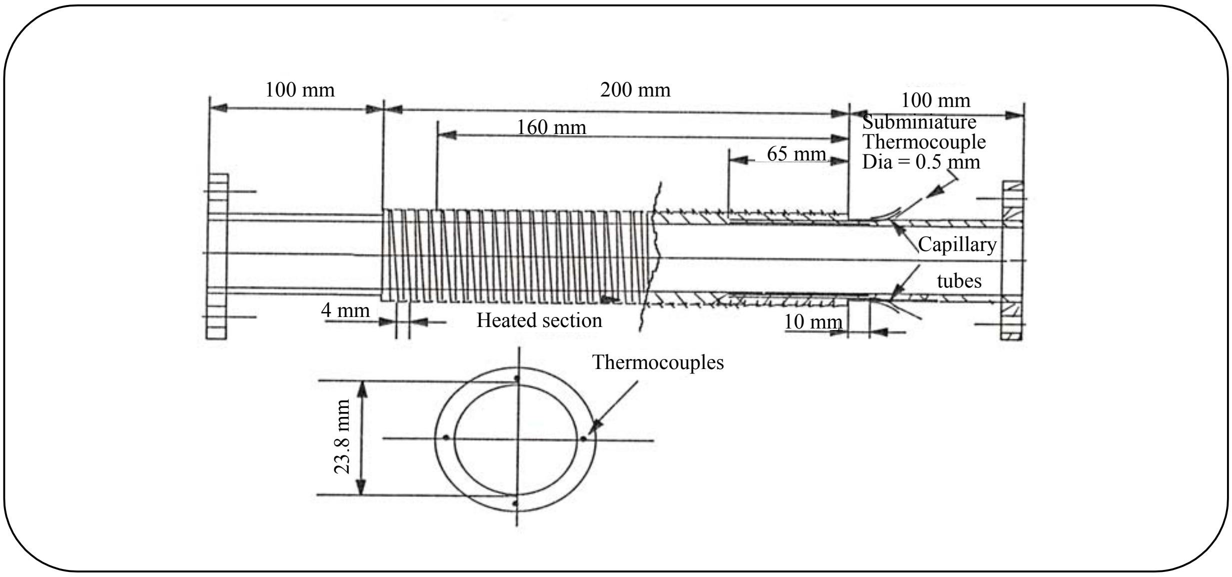

Fig. 2: Schematic of fluidized bed test section

The following equations may be written for the heat transfer mechanisms considered in this model;

$$q\ A = \alpha\ A\ \Delta T \quad (2)$$

$$q_c\ A_c = \alpha_c\ A_c\ \Delta T \quad (3)$$

$$q_p\ A_p = \alpha_p\ A_p\ \Delta T \quad (4)$$

$$A = A_c + A_p \quad (5)$$

A is the total heat transfer surface which is divided into two zones; A_p is the surface area affected by particles, and A_c is the remaining heat transfer area.

$$q\ A = q_c\ A_c + q_p\ A_p \quad (6)$$

Combining equations (5) and (6) to eliminate A_c yields,

$$A_p / A = (q - q_c) / (q_p - q_c) = (\alpha - \alpha_c) / (\alpha_p - \alpha_c) \quad (7)$$

For the fluidized bed heat transfer coefficient, α, equation (7) yields;

$$\alpha = \alpha_c + (A_p / A)(\alpha_p - \alpha_c) \quad (8)$$

The local forced convective heat transfer coefficient, α_c, can be calculated from the Gnielinski correlation [11], which has been modified to apply for local conditions [9]. The heat transfer coefficient for the particle-controlled area can be obtained from the following equation (9);

$$\alpha_p = \{(2 / \pi^{0.5})(\lambda_f \rho_f C_{p,f})^{0.5} + K (\lambda_p \rho_p C_{p,p})^{0.5}\}(f^{\,0.5}) \qquad (9)$$

In the above equation, K is a constant, which takes the area of contact between the particles and the heat transfer surface into account. In comparison with experimental data, the constant K has been reported to be 0.0705 for spherical particles and 0.141 for cylindrical particles [9]. Also f in equation (9) which is the frequency of the collision of particles with the heat transfer surface can be calculated by analogy to the kinetic theory of gases [9].

In this work, using results obtained from a large number of experimentals, a correlation was obtained for the estimation of A_p/A ratio.

An important parameters for characterization of fluidized beds is the bed porosity, which is defined as follows [9],

$$\varepsilon = 1 - V_p/V_T = 1 - 4m_p/\pi D_p \rho_p D^2 \qquad (10)$$

For a given number of particles, only the bed height has to be measured to determine the voidage.

RESULTS AND DISCUSSION

In the experimental procedure of this work, flow velocity and heat flux were varied while the bulk temperature was kept constant. All measurements were taken after the system had reached steady state condition. Accurate prediction of the bed voidage is necessary for the prediction of the state of the bed aggregation and consequently the heat transfer coefficients in fluidized bed heat exchangers.

The superficial velocity required to maintain a constant bed voidage is calculated from measured volumetric flow rate using an orificemeter. In fact, the velocity at the point of incipient fluidization is the superficial velocity based on the cross section of the empty column. The superficial velocity is used because it is impossible to measure the actual velocity between particles.

The bed voidage measured in this work are shown in Fig. 3 for two different sizes of spherical steel particles. Results obtained for the bed voidage versus the superficial liquid velocities at different CMC concentrations are shown in Fig. 4 using lead spherical particles and in Fig. 5 and 6 using two different sizes of carbon steel spherical particles. The bed voidage results are also shown in Fig. 7 using aluminum cylindrical particles, in Fig. 8 using stainless steel cylindrical particles and in Fig. 9 using brass cylindrical particles.

The general shape of the bed voidage versus liquid velocity curve is characterized by a gradual increase in voidage followed by a sharp increase and a subsequent gradual increase towards an asymptotic value of one. The previous workers [9,12] observed the same trend. Jamialahmadi et al.[9] using different particle sizes have concluded that for a given liquid velocity, the bed voidage is significantly decreased when the behavior of the fluidized bed is changed from particulate-aggregate transition mode to aggregate fluidization, while during aggregate fluidization which is the case of this work in Fig. 3, the bed voidage is only slightly affected by changing the particle size.

The effect of liquid viscosity on the bed voidage using different aqueous CMC concentrations in the above figures is investigated. In general for a given liquid velocity and a particular particle, the bed voidage is increased with an increase in liquid viscosity. These results are important, as no sufficient data is available in the literatures for such a non-Newtonian solid-liquid fluidized bed system.

Fig. 10 shows the variation of the fluidized bed heat transfer coefficient with bed porosity for two different steel particle sizes. A sharp raise in heat transfer coefficient accompanies a change from static bed to fluidized bed. The turbulent motion of the liquid causes the particles to move within the fluid bulk, and to/from the heat transfer surface. If the bed porosity is increased further, the heat transfer coefficient increases and reaches a maximum value. Then, the heat transfer coefficient stabilizes, gradually declining towards the heat transfer coefficient for the empty tube. Finally, when all the particles are taken out of the test section, all curves converge into a single line for empty tube. The reduction in heat transfer coefficient in the fluidized regime is due to the higher bed voidage when the probability of particle-wall contact and the state of aggregation in the bed decrease.

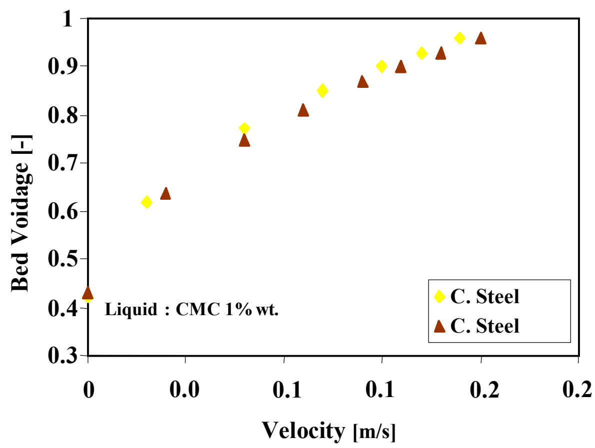

Fig. 3: Effect of velocity on the bed voidage using two different particle sizes

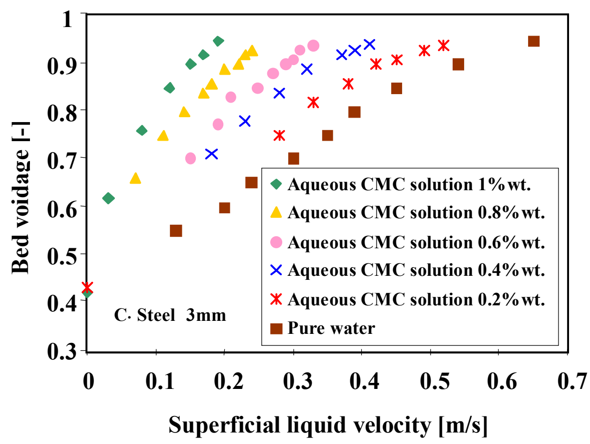

Fig. 6: Effect of different CMC concentrations on bed voidage using c.steel 3mm particles

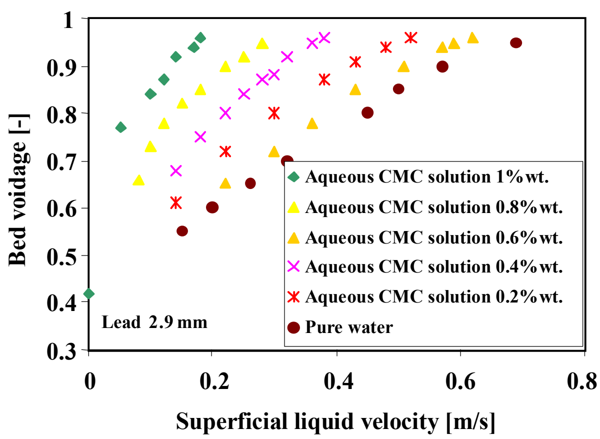

Fig. 4: Effect of different CMC concentrations on bed voidage using lead particles

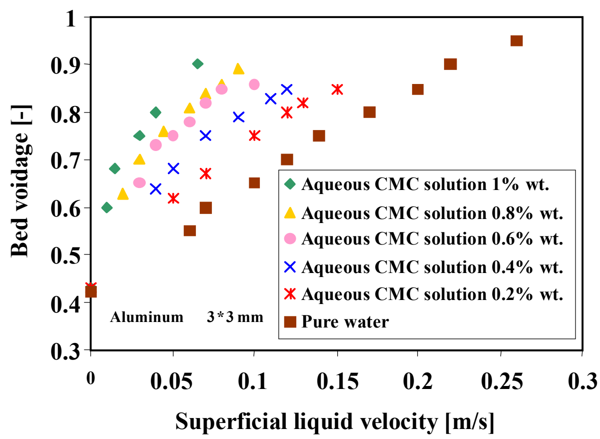

*Fig. 7: Effect of different CMC concentration on bed voidage using aluminum 3*3mm particles*

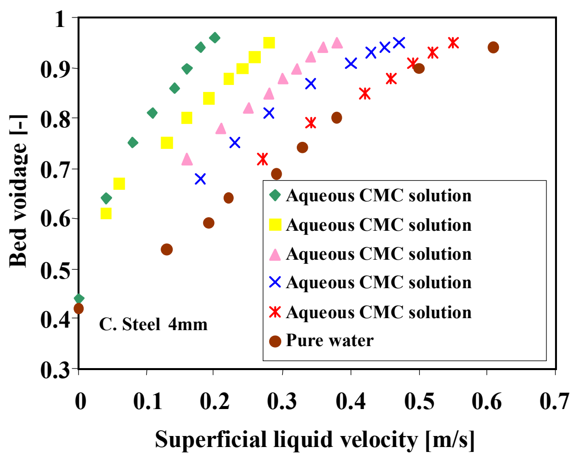

Fig. 5: Effect of different CMC concentrations on bed voidage using c.steel 4mm particles

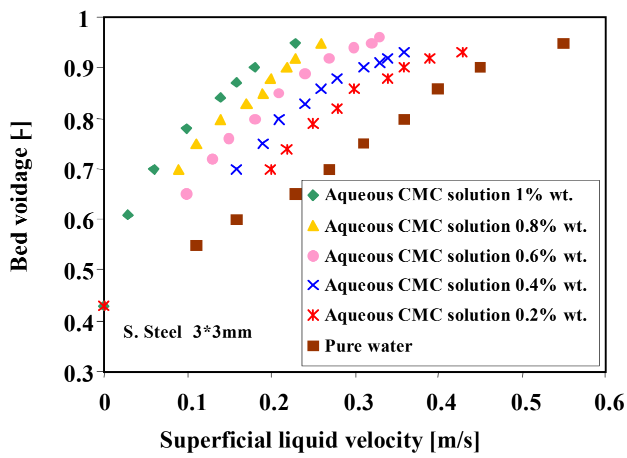

*Fig. 8: Effect of different CMC concentrations on bed voidage using s.steel 3*3mm particles*

The results show that the heat transfer coefficient, at any porosity, increases with an increase in particle size. All previous workers except one, using Newtonian liquid, also reported that the heat transfer coefficient increases significantly with increasing particle size as emphasised by Jamialahmadi et al. [9].

Fig. 11 shows variation of the heat transfer coefficient with heat flux for two different velocities. The heat transfer coefficient is almost independent of the heat flux while it increases strongly with the liquid velocity.

Therefore from the experimental results, following correlation is developed in this work for the prediction of A_p/A to be used in equation (8) for estimation of heat transfer coefficient in non-Newtonian liquid-solid fluidized bed systems;

$$A_P/A = 3.35(d_P/D_h)^{1.33}(\varepsilon-\varepsilon_{SB})^{0.353}(1-\varepsilon)^{0.25}Ar^{0.18} \quad (11)$$

ε is bed voidage and ε_{SB} is packed bed porosity. Ar is Archimedes number, which is related to the physical properties of liquid and particles as follows,

$$Ar = g\, d_p^3\,(\rho_s - \rho_l)/\nu_l^2\,\rho_l \quad (12)$$

CONCLUSIONS

In this investigation, systematic measurements of bed voidage and heat transfer coefficient for non-Newtonian liquid-solid fluidization in a cylindrical tube were performed in order to study the effect of process parameters such as particle size and density, flow velocity and liquid viscosity on these subjects. A large number of experiments were performed using different cylindrical and spherical particles fluidized in aqueous CMC solution with different concentrations. Significant increases in heat transfer coefficient were observed due to presence of the suspended solid particles. Heat transfer also increases as particle size and density increase. Using the experimental data a correlation is developed for predicting heat transfer coefficient in solid non-Newtonian liquid fluidized bed. Further work is needed to modify this correlation using different experimental apparutus and different non-Newtonian liquids.

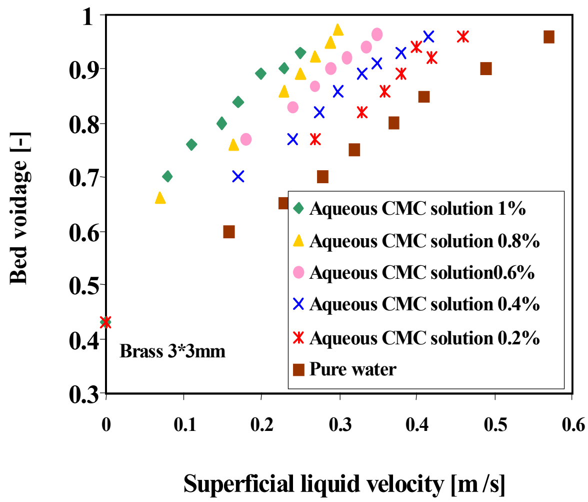

*Fig. 9: Effect of different CMC concentration on bed voidage using brass 3*3mm particles*

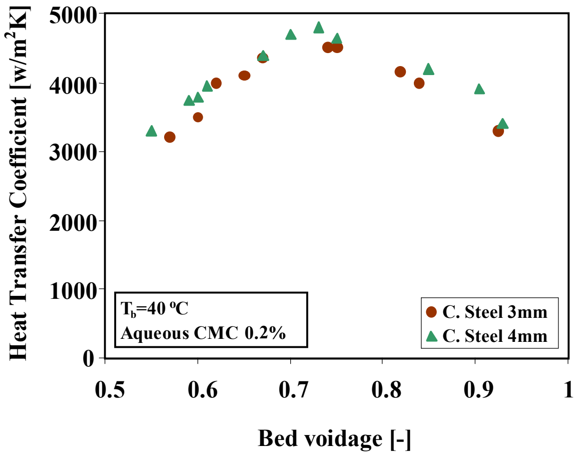

Fig. 10: Variation of heat transfer coefficient with bed voidage

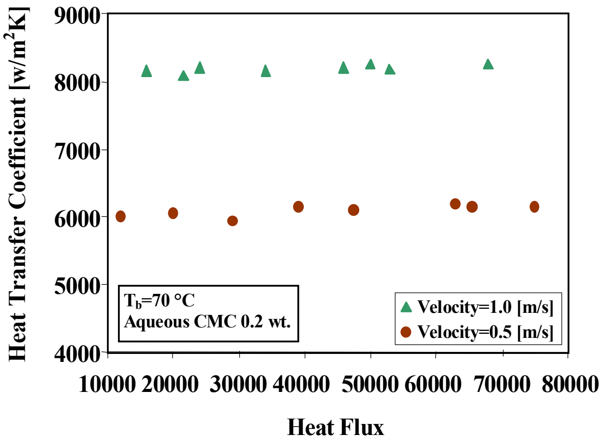

Fig. 11: Variation of heat transfer coefficient with heat flux

Nomenclature

A	Heat transfer surface area, m^2
C	Specific heat capacity, J/kg.K
d	Particle diameter, m
D	Fluidized bed diameter, m
f	Collision frequency, s^{-1}
g	Acceleration due to gravity, m^2/s
m	Mass, kg
q	Heat flux, W/m^2
s	Distance between thermocouple location and heat transfer surface, m
T	Temperature, K
V	Volume, m^3
α	Heat transfer coefficient, W/m^2 K
ε	Voidage
λ	Thermal conductivity, W/m.K
ν	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3

Subscripts

b	Bulk
c	Forced convection
f	Fluid
l	Liquid
p	Particle
SB	Packed bed
s	Solid
t	Total
th	Thermocouple
w	Wall

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