LIQUID TO PARTICLE HEAT TRANSFER IN FLUIDISED BEDS

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ABSTRACT

The liquid to particle heat transfer coefficient was measured in beds fluidised by water and three glycerol-water mixtures.

A literature survey revealed little agreement between the results of previous investigators of fluid to particle heat transfer. A variety of techniques was employed to measure the fluid to particle heat transfer coefficent, also, temperature data were recorded and interpreted in many ways.

In this investigation, the liquid to particle heat transfer coefficients were measured under unsteady state conditions by introducing a step change in the temperature of the inflowing liquid to beds of aluminium and alumina particles fluidised by water or three glycerol-water mixtures. The coefficients were measured by employing the technique of tagging a particle with a thermocouple which allows a direct measurement of particle temperature.

1 INTRODUCTION

Fluidised beds by their very nature make ideal heat exchangers. They possess a large heat-transfer area, a high heat exchange effectiveness, and are of a simple design which helps to keep the construction costs low. All of this enchances the benefits derived from the application of fluidised beds in heat exchange processes in the chemical industry and contributed to making the fluidised beds a technological success.

For reasons of efficiency, safety of operation and the quality of product, it is important that a thorough understanding of the heat transfer processes associated with fluidised bed equipment is achieved. In this study, the transfer of heat between the fluidising medium and the particles is investigated.

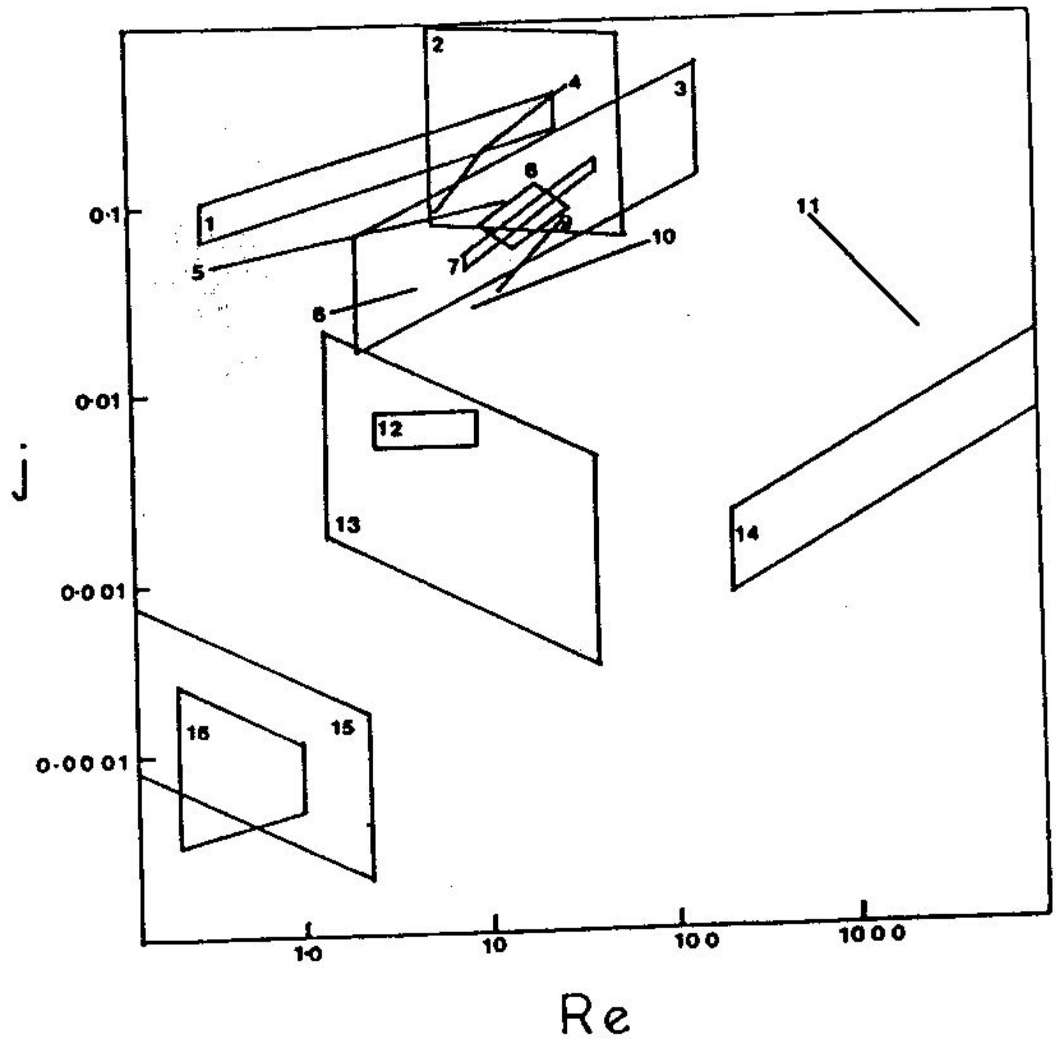
2 LITERATURE SURVEY

The great amount of work that has been done on fluid to particle heat transfer in fluidised beds reflects the considerable degree of interest in the field; however, despite all the published research reports, the mechanism of heat transfer and the magnitude of the heat transfer coefficients have not been established with any acceptable degree of certainty. The reported values of the heat transfer coefficient vary considerably from one investigator to another. This discrepancy between the experimental results is best illustrated in the comparative study by Barker[1]; the results of this study are summarised in Fig.2.1 which is taken from the author's paper. In the figure the heat transfer coefficients obtained by different investigators are shown in terms of the non-dimensional Colburn factor

$$j = \frac{Nu}{Re\ Pr^{0.33}} \tag{2-1}$$

As seen from the figure, the experimental results differ by as much as four orders of magnitude. Barker attributed the differences in the measured data to the shortcomings of techniques used by individual investigators and to the differences betweeen the fluidised beds and the conditions during the experiments. Most of the investigations were dealing with gas fluidisation, the subject of heat transfer in liquid fluidised beds was limited to two published papers by Sunkoori et al[2] and Holman et al[3].

Fig.2.1 Summary of fluid to particle heat transfer coefficients reported in the literature.



Fluid is gas unless otherwise specified.

1) Richardson et al
2) Heertjes
3) Shakhova
4) Donnadieu
5) Juveland et al
6) Frantz
7) Walton et al
8) Heertjes et al
9) Sunkoori et al (water)
10) Kettenring et al
11) Bradshaw et al
12) Anton
13) Wamsley et al
14) Holman et al (water)
15) Ferron et al
16) Fritz

3 MATERIALS AND METHOD

Two types of particles were used; aluminium cylinders 6.32x6.32 mm and alumina spheres of the type R.10-11 catalyst. The fluidising liquids used were water and three glycerol-water mixtures (20, 40 and 50% w/w glycerol).

The experimental equipment described below is shown schematically in Fig.3.1.

In the experiments, the temperature of the liquid entering the bed was subjected to a step change. This was achieved by using the arrangement of pneumatic valves(16-21) shown in Fig.3.1. Initially, the control switch was in a position such that the solenoid valves(S1,S2) kept valves(17,19,21) closed while valves(16,18,20) remained open. Hot liquid was circulated from the hot tank through the hot rotameters back to the tank while the bed was fluidised with cold liquid under steady state conditions. By operating the switch the solenoid valves then opened the pneumatic valves (17,19,21) and closed the valves(16,18,20). This stopped flow of cold liquid and replaced it by a liquid at a higher temperature.

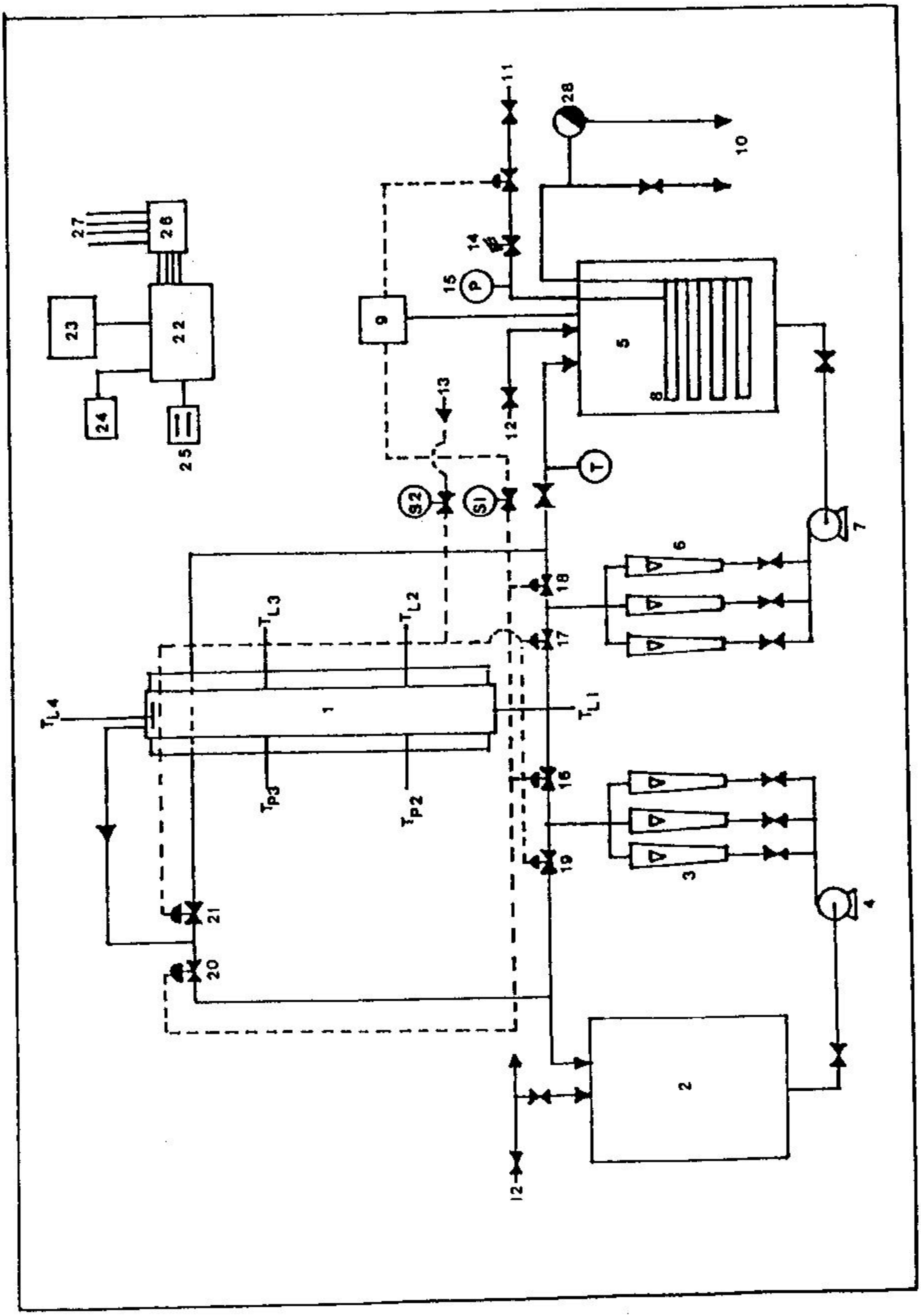
The fluidisation experiments took place in a Perspex column two metres tall with an inside diameter of 0.05 m and a wall thickness of 0.003 m.

Two Perspex collars provided ports for the passage of wires from the liquid and particle thermocouples through the column wall. The collars consisted of two parts which were clamped around the column by two bolts. Holes were drilled through the collars and into the column wall which allowed the introduction of caged liquid temperature thermocouple probes, and also the insertion of particles tagged with a thermocouple. A moveable thermocouple probe was made to fit inside the column and used to measure the liquid temperature at the point just above the bed surface.

The inlet section at the base of the column contained a rubber seal through which a thermocouple was passed with its tip positioned fractionally below the distributor gauze to measure the inlet liquid temperature.

The cold liquid pump was started allowing cold liquid to enter the column. The required flowrate was set and the particles were fluidised. The temperature probe T_{L4} was positioned above the surface of the fluidised bed. The valve controlling the hot liquid flowrate was adjusted

Fig. 3.1   Schematic diagram of the fluidisation apparatus.



Key to Fig.3.1

1	Fluidising column with thermal insulation
2	Cold liquid tank
3	Cold liquid rotameters
4	Cold liquid pump
5	Hot liquid tank
6	Hot liquid rotameters
7	Hot liquid pump
8	Steam coil
9	Liquid temperature controller
10	Condensate drain
11	Steam supply
12	Mains water supply
13	Compressed air supply (from pressure regulator)
14	Pressure relief valve
15	Steam pressure gauge
16	Pneumatic valve
17	Pneumatic valve
18	Pneumatic valve
19	Pneumatic valve
20	Pneumatic valve
21	Pneumatic valve
22	B.B.C. microcomputer
23	Visual display unit
24	Line printer
25	Dual disc drive unit
26	Thermocouple voltage amplifier
27	Thermocouple inputs
28	Steam trap
T_{F2}	Flexible thermocouple position 2
T_{F3}	Flexible thermocouple position 3
T_{L1}	Liquid temperature position 1
T_{L2}	Liquid temperature position 2
T_{L3}	Liquid temperature position 3
T_{L4}	Liquid temperature position 4
S1	Solenoid valve 1
S2	Solenoid valve 2

until the flowrate was equal to that of the cold liquid. The liquid entering the column was switched from cold to hot in order to check whether the hot liquid flowrate was correctly set. With the check completed, the hot liquid flow was diverted back to the hot liquid tank and the cold flow was reintroduced to the column. The bed was allowed to reach steady state conditions. The polystyrene insulation was clamped around the column. After a final check on the liquid flowrates, the switch actuating the step change was thrown and the transient signal introduced to the column. Temperature measurements were made until the hot signal had passed through the bed. Data were gathered and stored using the B.B.C. microcomputer system.

The outlined procedure was used to measure liquid to particle heat transfer coefficients and to obtain information on particle mixing. For both aluminium cylinders and alumina spheres, measurements were taken over a wide range of voidage values. The experiment was then repeated using water and three different glycerol-water mixtures (20, 40, 50% w/w glycerol).

For a chosen bed voidage or liquid flowrate, measurements were repeated three times for both aluminium cylinders and alumina spheres.

4 THEORY

The liquid to particle heat transfer coefficient was calculated from measurements of the particle and the local liquid temperatures in response to the introduction of a step change in the temperature of the incoming liquid.

The thermal energy balance for the unsteady state system may be expressed as

$$m_P \, C_P \, \frac{dT_P}{dt} = h_{LP} \, A_P \, (T_L - T_P) \qquad (4\text{-}1)$$

where

m_P =	Mass of a particle	(kg)
A_P =	Surface area of a particle	(m^2)
C_P =	Specific heat capacity of the particles	($J\ kg^{-1}\ K^{-1}$)
h_{LP} =	Liquid to particle heat tr. coefficient	($W\ m^{-2}\ K^{-1}$)
T_L =	Temperature of the liquid	(K)
T_P =	Temperature of the particle	(K)
t =	Time coordinate	(s)

Upon integrating equation (4-1) and introducing the following initial and boundary conditions

at $t = 0,\ T_P = T_{PO}$ (4-2)

and at $t = t,\ T_P = T_{P1}$ (4-3)

equation (4-1) becomes

$$m_P \, C_P \, T_P = h_{LP} \, A_P \int_{t=0}^{t=t} (T_L - T_P) dt \qquad (4\text{-}4)$$

where

$$T_P = T_{P1} - T_{PO} \qquad (4\text{-}5)$$

The liquid to particle heat transfer coefficient was calculated using equation (4-4). The integral in equation (4-4) was evaluated by applying Simpsons rule, the integrand was obtained from the particle and local liquid temperature measurements. An integration subroutine was included into a BASIC program for the calculation of the liquid to particle heat transfer coefficient.

5 RESULTS AND DISCUSSION

The average values were obtained from repeated measurements of the liquid to particle heat transfer coefficients for each set of experimental conditions. In order to verify the reproducibility of the data, a certain number of single measurements were repeated after an interval of several days. The results obtained indicate the reproducible nature of the measurements.

Figures 5.1 and 5.2 demonstrate the effect of the bed voidage on the liquid to particle heat transfer coefficient for beds containing particles of aluminium and alumina respectively. In the case of the 6.32x6.32 mm aluminium cylinders, there is a tendency for heat transfer coefficient to pass through a maximum, though for the alumina spheres, this tendency is very slight.

Bed voidage is an important parameter which affects the heat transfer coefficient and which is related to the liquid flowrate. Thus it is not surprising that similar effects as those described above are also exhibited in the plots of the liquid to particle heat transfer coefficient against the liquid velocity given by Figures 5.3 and 5.4. This initial increase, followed after passing through the maximum by a decrease in the heat transfer coefficient with the liquid velocity is in agreement with the previous investigations into surface to particle heat transfer carried out by Lemlich and Caldas[4], Richardson and Smith[5], Wasmund and Smith[6], Tripathi and Pandey[7], Richardson et al[8] and Patel and Simpson[10]. All the four figeres indicate that, as the liquid becomes more viscous, the heat transfer coefficient is reduced. This is a similar observation to that made by Khan, Juma and Richardson[9] on heat transfer from a plane surface to solids fluidised by liquids of different viscosities.

The occurrence of a maximum on the curves of heat transfer coefficient can be explained as follows: The main resistance to heat transfer between the liquid and the particles lies in the film of liquid surrounding the particles. Increasing liquid flowrate results in the formation of turbulent eddies which give rise to an increase in the local liquid velocity. The effect of this is to reduce the thickness of the liquid film surrounding the particles and thus cause an increase in the liquid to particle heat transfer coefficient. On the other hand, a decrease in particle concentration reduces the eddy velocity in the liquid phase and thus decreases the heat transfer coefficient. The intensity of particle movements and the reduction in their concentration have opposite

<u>Fig.5.1</u> Plot of heat transfer coefficient versus bed voidage for aluminium cylinders.

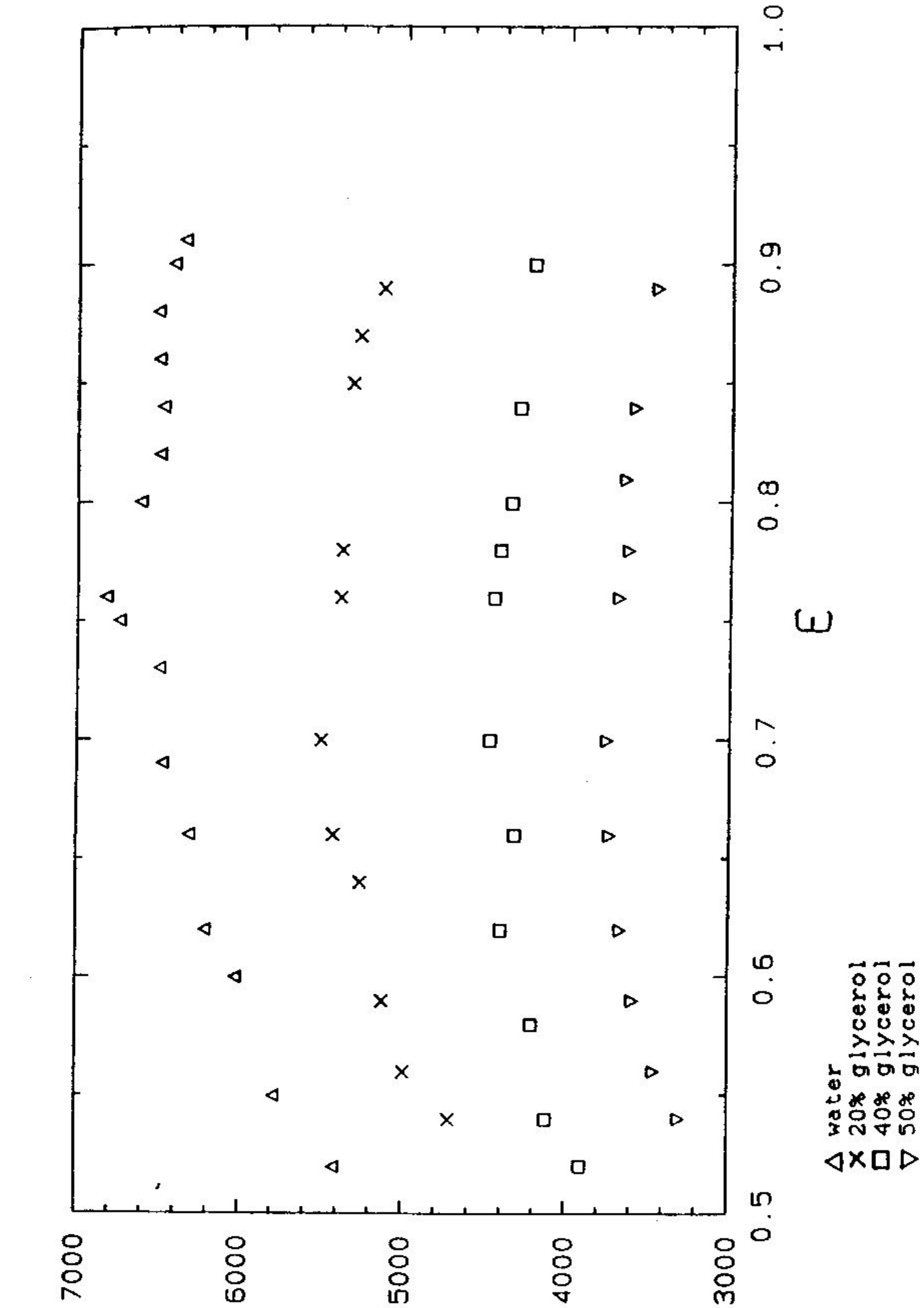


Fig.5.2 Plot of heat transfer coefficient versus bed voidage for alumina spheres.

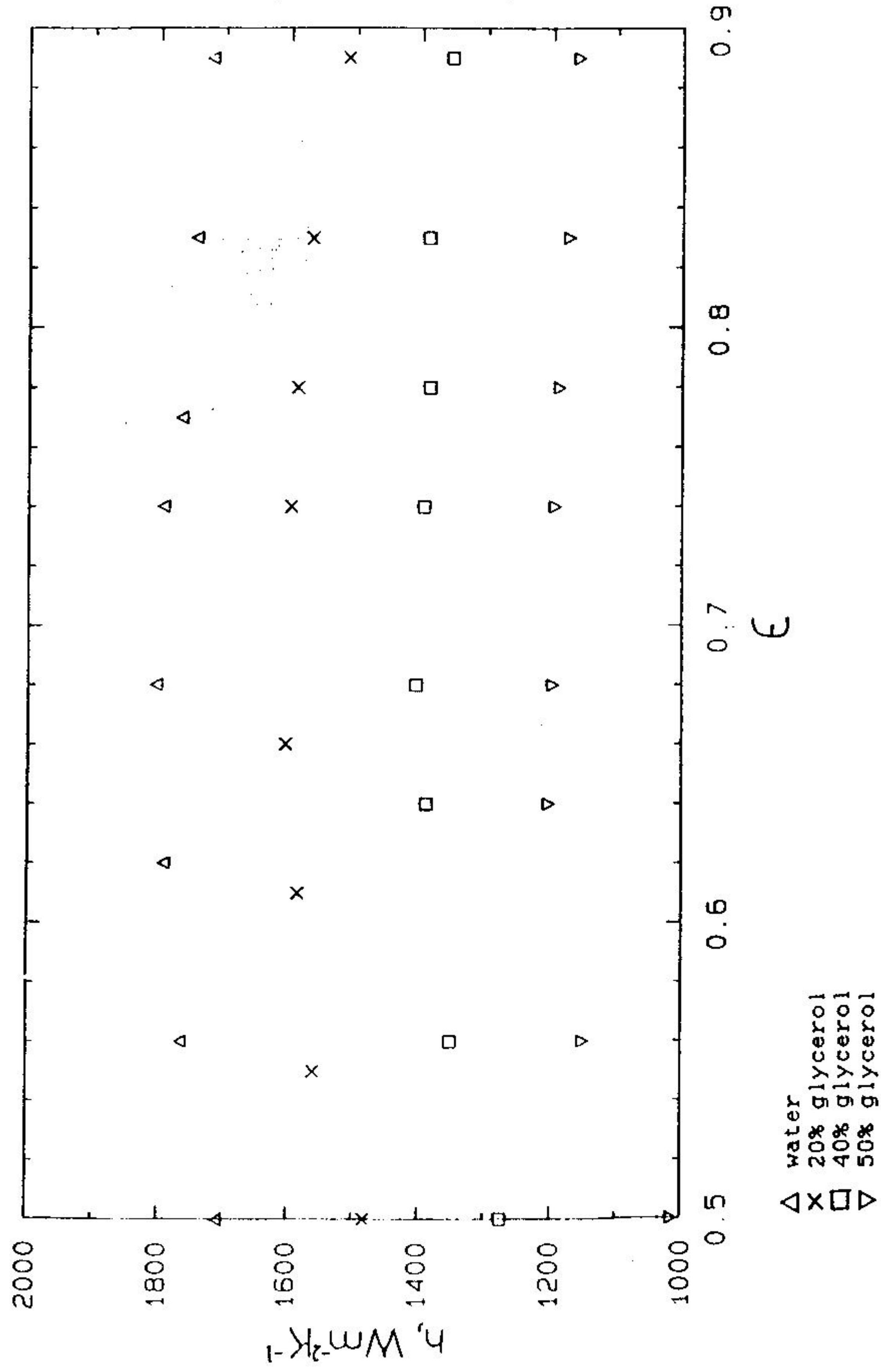


Fig.5.3 Plot of heat transfer coefficient versus liquid velocity for aluminium cylinders.

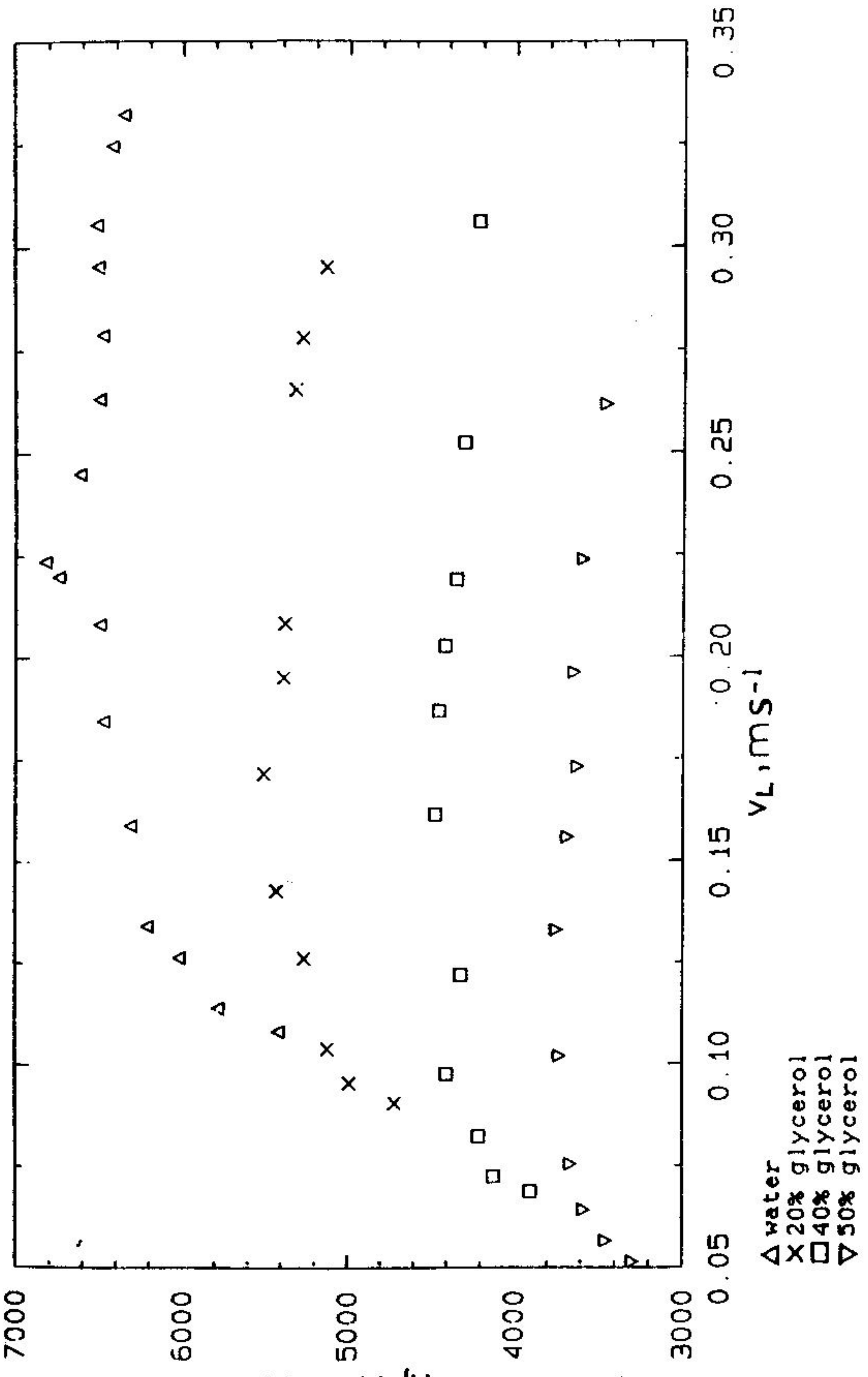


Fig.5.4 Plot of heat transfer coefficient versus liquid velocity for alumina spheres.

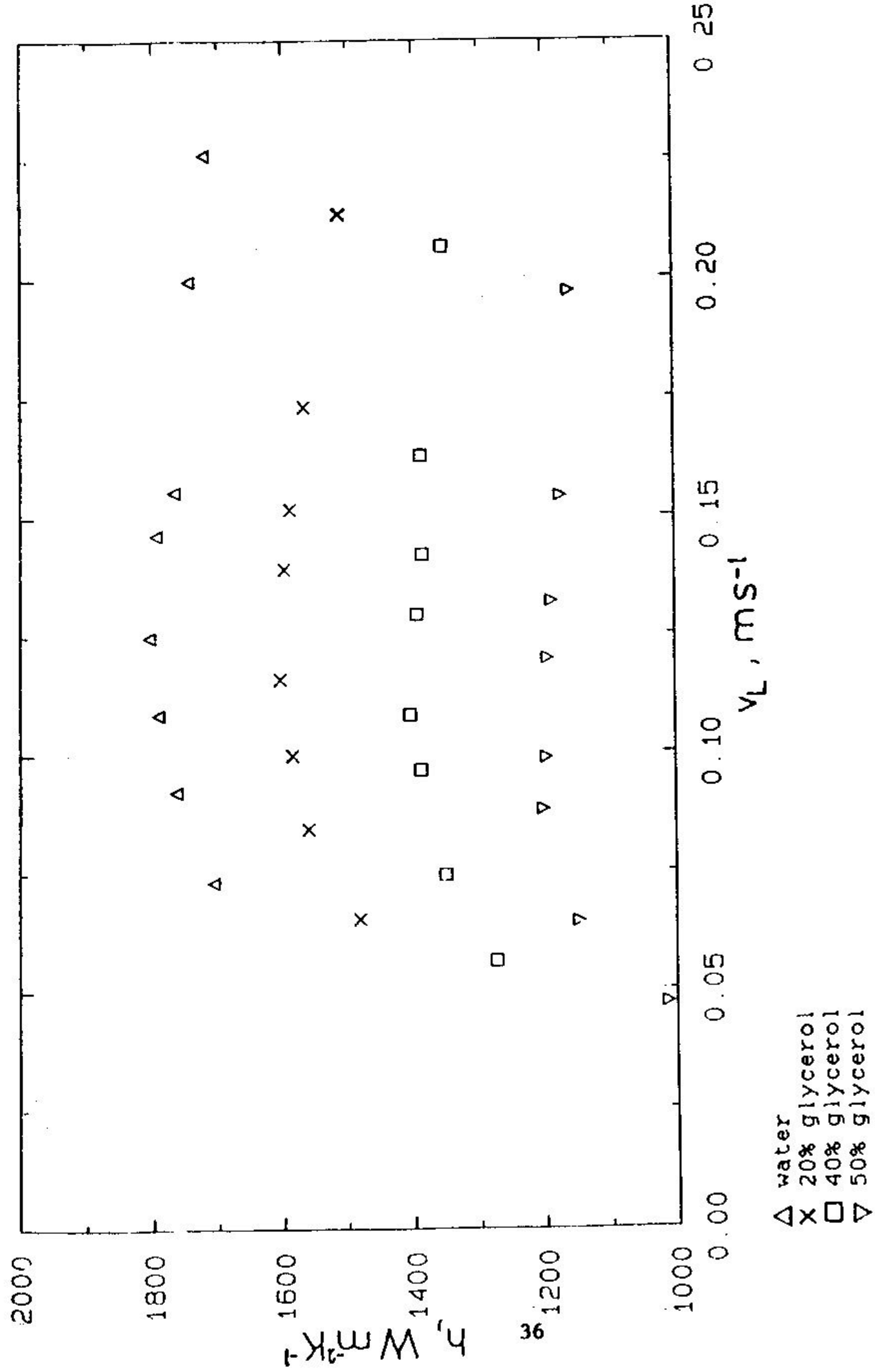


Fig.5.5 Plot of Nusselt number versus particle Reynolds number for aluminium cylinders.

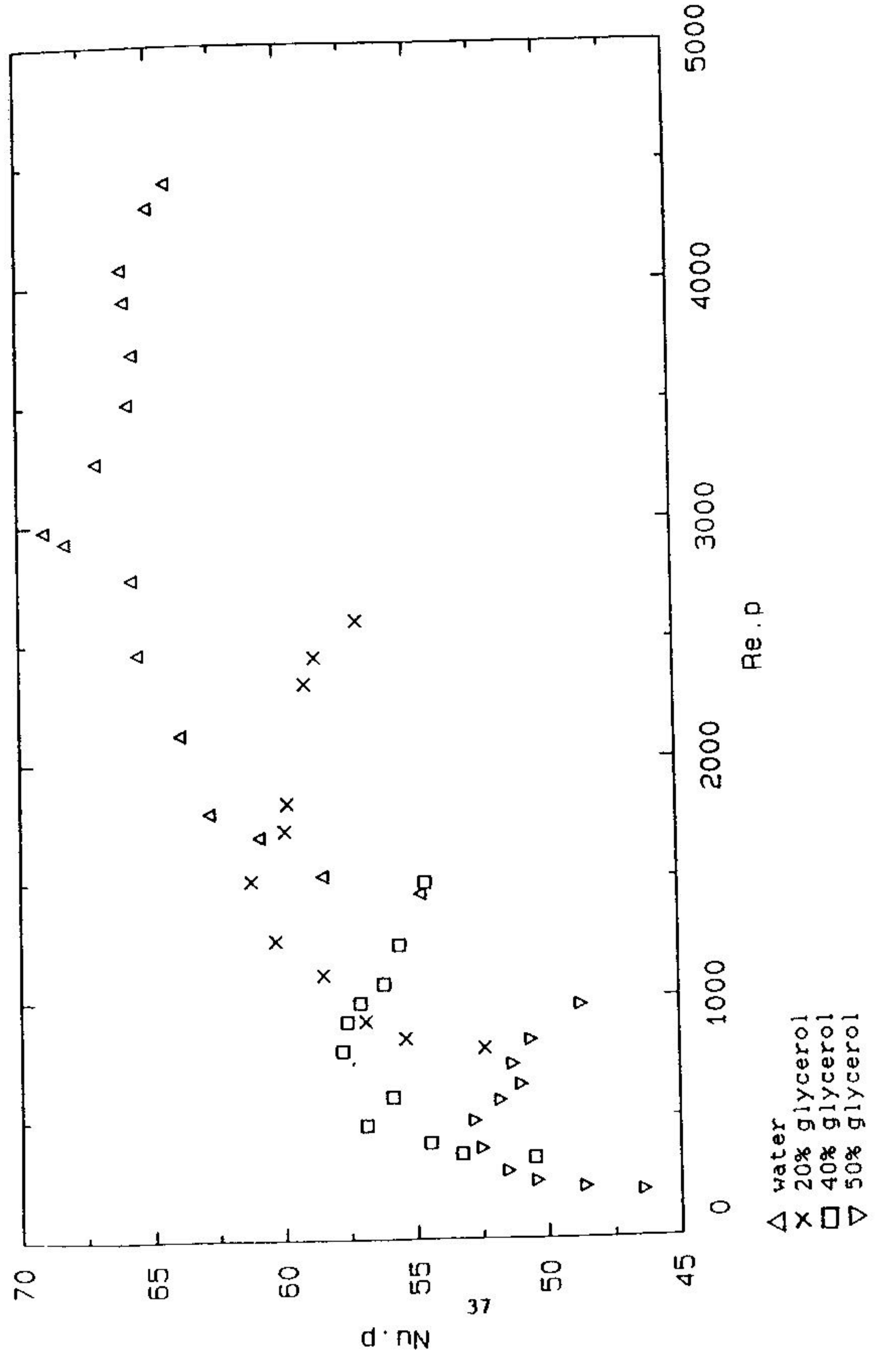
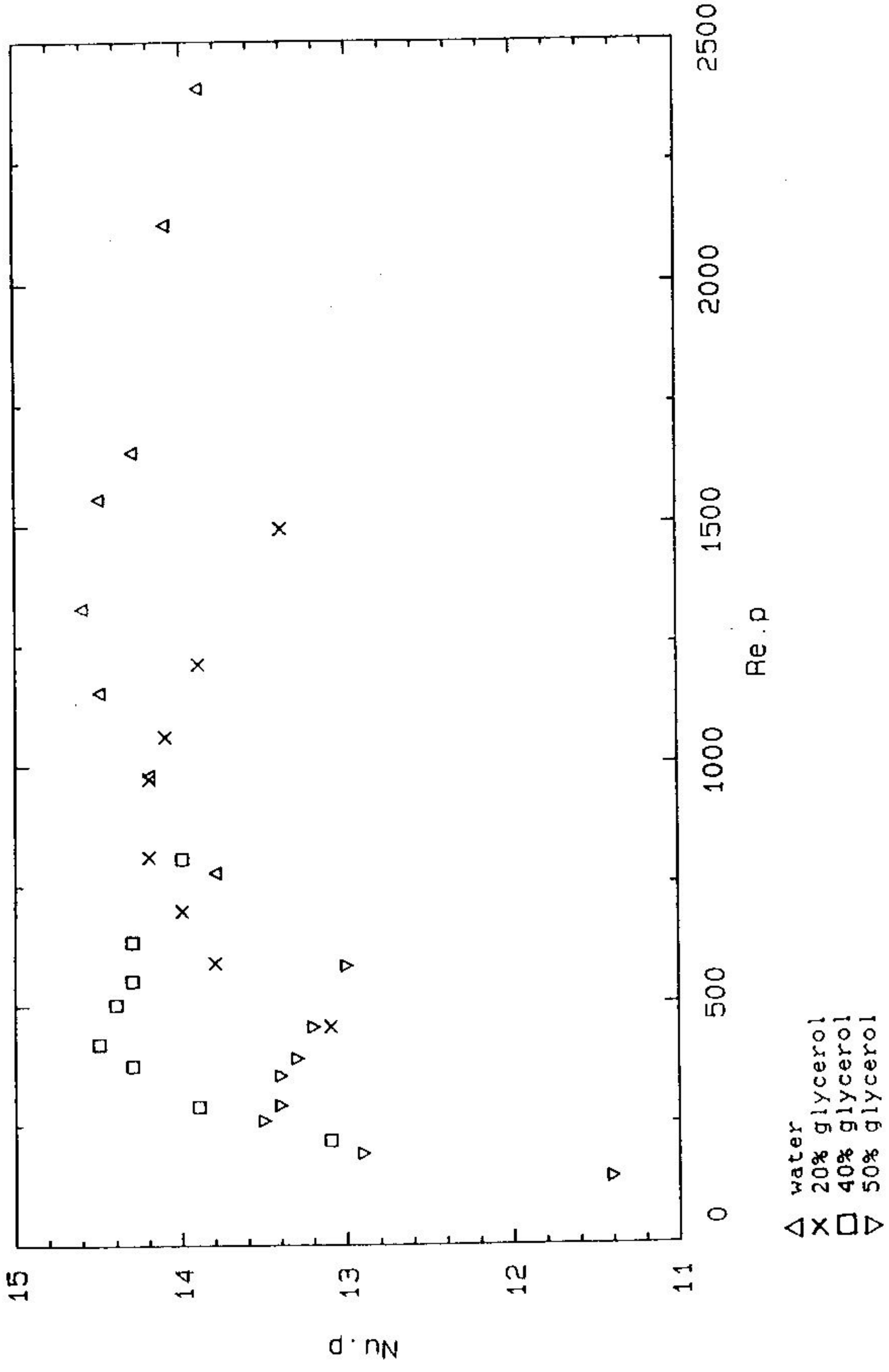


Fig.5.6 Plot of Nusselt number versus particle Reynolds number for alumina spheres.



effects on the heat transfer rate. At first the particle movement is the dominating factor. The heat transfer coefficient increases with the liquid flowrate until a maximum is reached. At this point the effect of the reduced particle concentration becomes more significant and a decrease in the heat transfer coefficient is observed.

In the beds containing the aluminium cylinders with water as the fluidising medium it appears that the former mechanism of increasing turbulence inside the bed is dominant up to a voidage of approximately 0.76. For glycerol-water mixtures, the maxima occur at bed voidage of 0.70. At higher voidages, the second effect begins to take over resulting in a slight decrease of the heat transfer coefficient. In beds containing alumina spheres the overall level of turbulence is much lower. The bed expansion is much more even, and the particle Reynolds numbers are lower than in a bed of aluminium cylinders at the same values of bed voidage. From the instant the alumina spheres became fluidised, the influences of the two opposing mechanisms affecting heat transfer appeared to be approximately equal and hence the maxima are less pronounced.

The tendency to pass through a maximum for both beds of aluminium cylinders and alumina spheres is also illustrated in the plots of the Nusselt number against particle Reynolds number given in Figures 5.5 and 5.6, this bears out the conclusion derived from Figures 5.1, 5.2, 5.3, and 5.4.

6 CONCLUSIONS

The results indicate that, for aluminium cylinders, there is a tendency for heat transfer coefficient to pass through a maximum, and in the case of alumina spheres, this tendency is less pronounced. The results also indicate that, as the liquid becomes more viscous, the heat transfer coefficient is reduced.

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