PARTICLE-STAGNANT FLUID HEAT TRANSFER COEFFICIENTS IN PACKED BEDS*

NORIAKI WAKAO, YOSHINOBU TAKANO

AND D. C. T. PEI**

Department of Chemical Engineering, Yokohama National University, Yokohama, Japan

The Nusselt number for heat transfer between particle and stagnant fluid in packed beds is theoretically computed and found to be $Nu=2.0$. This may be regarded as the lower limiting Nusselt number for beds where each particle is in good contact with flowing fluid.

Recently Miyauchi³⁾ has experimentally obtained a limiting Sherwood number with stagnant fluid as $Sh=0.5$ for such packed beds that mass transferring particles were dispersely embedded in beds of dummy particles of the same size as the transferring ones. This would be equivalent to $Nu=0.5$ for heat transfer between stagnant fluid and heated particles which are dispersed in a bed of inert particles of zero thermal conductivity.

The purpose of this note is to determine a Nusselt number with stagnant fluid in beds having no inert particles. For such usual packed beds the following work has been done: Pfeffer and Happel⁴⁾ applied free surface model for creeping flow around a sphere and have obtained a limiting Nusselt (Sherwood) number of 12 for beds of $\varepsilon=0.4$. Miyauchi²⁾ has theoretically calculated the limiting Sherwood number as 17 at $\varepsilon=0.4$. From correlation of experimental data, Shirai⁵⁾ has proposed the limiting Nusselt (Sherwood) number as $2/\varepsilon$. Wakao, Oshima and Yagi⁸⁾ have assumed the limiting Sherwood number as 2.0 for their mass transfer correlation.

For fine particles-flowing fluid system, there have been a number of experimental measurements. The observed Nusselt numbers are surprisingly low, and keep decreasing with decrease of Reynolds number. As pointed out by Kunii and Suzuki¹⁾, this is due to channeling or local heterogeneity in fluid-to-particle contact. However, the heat transfer for such heterogeneous system is outside the scope of this investigation.

Unlike heat transfer coefficients, effective thermal conductivities are easily measurable, and a number of

data have been published. Wakao and Kato⁷⁾ have theoretically computed effective thermal conductivities for the heat transfer unit cell of **Fig. 1**. At zero fluid velocity there is obviously no heat transfer resistance at solid-fluid interfaces, which means equal temperatures between fluid and solid at the surfaces.

However, the heat transfer coefficient (h_p) has been defined as follows (refer to Fig. 1):

$$Q = h_p A (\bar{t}_s - \bar{t}_f) \quad (1)$$

where Q is a rate of heat transfer from hemispherical surface (of area $A = \pi D_p^2/2$ and average temperature $\bar{t}_s$) to fluid and $\bar{t}_f$ is a mixed mean temperature of the fluid in the void.

For the estimation of h_p , the following quantities must first be known: Q , $\bar{t}_s$ and $\bar{t}_f$. These may be computed on condition that the temperatures at AB (heat inflow face) and CD (heat outflow face) are, respectively, unity and zero in nondimension. Since $\bar{t}_f$ is equal to the temperature at CD ($\bar{t}_f=0$), the problem is only to calculate Q and $\bar{t}_s$. For this a relaxation method described elsewhere⁶⁾ is applied. The calculation procedures are as follows:

In regard to a certain combination of k_s and k_f values:

Fig. 1 Heat transfer model for relaxation calculation

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** Department of Chemical Engineering, University of Waterloo, Ontario, Canada

〒233 横浜市南区大岡町

横浜国立大学工学部化学工学教室 若尾法昭

Table 1 Calculated Nusselt numbers for some k_s/k_f values

k_s/k_f	Nu
1.0	2.00 (a)
3.0	2.03
10.0	2.18
30.0	2.23
100.0	2.24
300.0	2.25
1000.0	2.25
3000.0	2.25

a) When $k_s = k_f$, heat flows unidirectionally and then $Nu=2.0$ is easily obtained analytically.

- (1) compute steady temperature at each nodal point of grids within the unit cell.
- (2) based on thus-determined temperatures, compute Q and $\bar{t}_s$. Hence, Q is calculated as the rate of heat flowing through the solid section (of area $\pi D_p^2/4$) on face AB , while $\bar{t}_s$ is estimated by determining every local surface temperature.

As illustrated in **Table 1**, the computed Nusselt numbers are slightly affected by k_s/k_f values. Obviously the heat transfer coefficients cannot depend on k_s values, and the relaxation calculations are supposed to give more reliable data in the vicinity of $k_s/k_f \sim 1$. Thus, one can conclude that

$$\frac{h_p D_p}{k_f} = 2.0 \quad (2)$$

It is interesting that this limiting Nusselt number is equal to that for a sphere in infinite stagnant medium. Compared with the limiting Sherwood number 12 and 17, respectively, estimated by Pfeffer and Happel⁴⁾ and Miyauchi²⁾ our limiting value is quite low, but most experiments for beds with flowing fluids do not seem to endorse the limiting value being greater than ten.

Nomenclature

D_p	= particle diameter	[m]
h_p	= particle-to-fluid heat transfer coefficient	[kcal/m ² ·hr·°C]
k_f	= fluid thermal conductivity	[kcal/m·hr·°C]
k_s	= solid thermal conductivity	[kcal/m·hr·°C]
Nu	= $h_p D_p / k_f$	[—]
ε	= void fraction	[—]

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