The overall Nusselt number is invariably low and often orders of magnitude less than 2. The reason for this is that the maximum driving force is not available to all the particles. Alternatively, not all the particle surface area is exposed to hot gas. This, of course, is the theme underlying Zabrodsky's treatment. Since the heat capacity of gas is small compared with that of solids and fluidizable particles have a large surface area per unit volume, heat-transfer rates are always high wherever there is a modest temperature difference so that the calculated overall heat-transfer rate is not particularly sensitive to the hydrodynamic model that is chosen. However, this is not the case when mass transfer is considered, for then the rates may be low for chemical reasons and the calculation becomes critically dependent upon the assumptions made about the details of gas solids contacting. (The symbols d, δ and $Nu_{\min}$ are as defined in Zabrodsky's paper.)

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Note: Zabrodsky's reference [12] should read Wadsworth.

A NOTE ON HEAT TRANSFER BETWEEN SPHERICAL PARTICLES AND A FLUID IN A BED

[A reply to Dr. P. N. Rowe's comments on the author's paper: Heat transfer between solid particles and a gas in a non-uniformly aggregated fluidized bed, *Int. J. Heat Mass Transfer* 6, 23 (1963).]

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In the present issue of this Journal is published a comment by Dr. P. N. Rowe [1] on the present writer's previous paper [2]. This comment is undoubtedly useful to the author since it allows him to elucidate his conceptions while discussing Dr. Rowe's contribution.

The main aim of [2] was to show the principal physical grounds for the very small apparent values of the Nusselt number, namely the actual temperature driving forces caused by micro-non-uniformity of fluid distribution in a bed. For this purpose the author used a model and correlations which were rather approximate but easy to understand. Naturally, the well-known radial asymmetry of the gas "shell" around a solid particle in a bed was not considered at this first step. However, some of Dr. Rowe's remarks show that he is wrong in thinking that the formulae in [2] were suggested as final ones for design calculations. Dr. Rowe, for example, writes about the inaccuracy of Nusselt number estimation for the cubical packing. On the contrary, it would be better to say that since this model is an approximate one, it should be used to determine rough values of Nusselt numbers but not accurate to one decimal place.

Dr. Rowe unfortunately trusts without any reasons or physical grounds that such true film-heat-transfer coefficients are possible in the system of solid particles which correspond to Nusselt numbers far below two. Comparison of the approximate true Nusselt numbers estimated by the present author's model with the Nusselt numbers obtained from Dr. P. N. Rowe's experiments (Fig. 1 of [1]), provides no evidence of such possibility but makes a good proof that Dr. Rowe's methods are not valid in their essence for determining true heat-transfer coefficients for a sphere in a bed. Dr. Rowe has probably not measured the exact temperature distribution around a sphere in a bed, and thus it is out of the question that in this case true values of α and Nu were determined. Dr. Rowe's data plotted in Fig. 1 [1] are nothing but extrapolated apparent Nusselt numbers which should be lower than true ones. To explain this, it is sufficient to consider the same micro-break scheme [2] applying it to the case of non-uniform fluid distribution around a regular sphere in a regular packing of identical spheres, but not to gas breaks in the form of a discontinuous phase. In this case a fluid flow breaks mainly through the thickest portion of the asymmetrical "shell". It follows from [2] that, in the place where the fluid shell (or lens) around a solid sphere is thickest, the local heat-transfer coefficient by conduction, Nu_{cond}, and local temperature of the heated fluid will be high. Thus near a given sphere in a bed the same picture of micro-break (on lower scale but with the same results), or in other words micro-nonuniformity of fluid distribution, will take place. In this way radial asymmetry of gas "shell" affects the local mean temperature driving forces around the solid sphere in a regular bed of identical spheres. The heat-transfer rate between solid particles and fluid heated asymmetrically may decrease (which is followed by decrease in apparent heat transfer coefficients) due to temperature gradient arising inside the solid particle (sphere) itself. But it would be a flagrant error to consider this as a decrease of a true film-heat-transfer coefficient for a sphere, while in this case only diminishing of the overall heat-transfer coefficient owing to inner thermal resistance of solid spheres takes place.

It is not necessary at all to consider (as Dr. Rowe does) the heat transfer of a cylinder, which is remote from the case under consideration, in order to elucidate the effect of a shell radial asymmetry causing decrease in apparent Nusselt numbers of a sphere in a bed as compared with true values.

There are no reasons to expect that true (but not apparent) Nusselt numbers for a sphere asymmetrically surrounded by fluid in a bed would be lower than the one corresponding to a hypothetical spherical shell having a thickness equal to that of the thickest part of the actual shell; and this value is by no means less than two. True, fluid motion which took place in the experiments by Dr. Rowe was not taken into account in the above argument. The present author hopes, however, that Dr. Rowe will not take this amiss since it is rather difficult to believe that convection affects negatively heat-transfer rate and causes a decrease in Nu as compared with a purely conductive Nu.

It would be erroneous to think that the present author is against apparent heat-transfer coefficients and Nusselt numbers (which are as little as a tenth or a hundredth of two) being used for engineering practice. But things should be called by their proper names and the nature of such apparent values should be elucidated. This will obviate misleading conclusions in the solution of various problems.

As to the comments by Dr. Rowe concerning the convective component of heat transfer between solid particles and fluid, the author should not like to dwell on this problem since he does not consider calculations from extrapolated data by Wadsworth and Leva as significant. The aim of this calculation was to show that Nu_{conv} may be sometimes very high, but the formulae were not recommended for calculations in [2]. And vice versa in [2] this component was not taken into account even for approximate estimation of micro-break effects. It is however worth dwelling on the essence of Dr. Rowe's note concerning the impossibility of extrapolating Max Leva's hydrodynamic equation (which is bad enough by itself as Dr. Rowe suggests) to Re of about 200. Despite this note of Dr. Rowe, Leva provided his formula to be used up to $Re = 1000$ by means of the correction plot (Figs 3–15 [3]). In [2] the correction factor $K = 1{\cdot}775\ Re^{-0{\cdot}272}$ (equation (8) of [2]) is introduced which corresponds to the plot over the range of $Re = 10$–200. Thus Dr. Rowe's note and all that follows from it cannot therefore be accepted.

The present author's conception of micro-breaks, and of the significance of micro-nonuniformity of fluid distribution through beds, is not so narrow to demand a single specific mechanism of aggregates formation or bubble rise in a fluidized bed. With highly ordered bubble formation, for example, gas flow will be also non-uniform: in this case there exists the gas "break" through a bubble, a lower gas velocity in the dense phase, and also micro-nonuniformity of a flow around an individual particle in this phase. Thus, Dr. Rowe's comment that the conception of micro-breaks is not valid for the case of a normal bubbling bed should be considered erroneous.

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