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EXPERIMENTAL DETERMINATION OF TRANSPORT COEFFICIENTS IN TWO-COMPONENT FLUID BED DRIERS

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ABSTRACT

Heat and mass transfer coefficients between immersed spheres of different size and gas fluidized beds have been experimentally determined in the range of operative conditions of interest for drying processes. Variables investigated include: nature and size of the bed material, radial and axial position of the sphere and fluidization velocity. A comparison with existing as well as with modified literature correlations is also presented and a new form of relationship is proposed.

INTRODUCTION

Fluid bed processes are used in a wide number of thermally controlled operations, due to their excellent heat transfer properties. While the fluidization of granular solids is a plain operation, however, processing of large objects, that cannot be directly fluidized at acceptable gas velocities, requires different fluidization techniques. One of these is the so-called indirect or two-phase fluidization. In this case a bed of fine particles is used as heat transfer medium, in which the big objects are plunged to get a better contact and a higher exchange rate between the gas stream and the objects. This technique has been already considered for many applications, such as: the combustion or gasification of solid wastes and other low rank fuels, the quench of metal bodies, the drying and the freezing of foods (1,2,3).

In particular, fluid bed drying, which is widely used in processing particulate material through direct fluidization, can be regarded as an attractive application for drying large size vegetables or wooden shell fruits (4). The design of two-component fluid bed dryers requires an accurate determination of heat and mass transfer coefficients between the bed and the immersed objects.

While many investigations have been focused on the study of the transport mechanism between fluid bed and immersed tubes (1,5), very few has been done on the evaluation of the heat transport mechanisms between fluid bed of fine particles and fixed or floating immersed bodies (6,7). Moreover, available experimental results very often completely disagree one with the other, even when obtained in similar experimental apparatus and operative conditions, and consequently, literature correlations show a very poor predictive value. When considering mass transfer, available data are almost unexistent (8).

This work aims at evaluating experimentally heat and mass transfer rates in a system simulating a two-component dryer, consisting of relatively large spheres immersed in bed of inert fine materials. The experiments have been carried out to test the effect of a number of parameters, such as fine particles size, size and mobility of the immersed bodies, radial and axial position of the fixed objects, fluidization velocity and bed temperature on the values of the transport coefficients. The range of temperatures investigated has been limited to that of interest for drying processes of solid foods. Correlations, based on the modification of the exsisting theories, have been also developed and compared with experimental data.

EXPERIMENTAL APPARATUS AND TECHNIQUE

The experimental apparatus, sketched in Figure 1, consists of a steel fluidization vessel 150 mm ID, 800 mm high, fitted with a plate distributor made out of sintered steel. The fluidizing and drying medium is air, monitored through a set of rotameters and preheated to the test temperature by an electrical heater. Additional heat is supplied and thermal guard is provided by ribbon electrical resistances coating the column. The power of the preheater is regulated by an electronic controller. The temperature of the air is measured at the exchanger outlet and inside the bed by thermocouples, and recorded on chart.

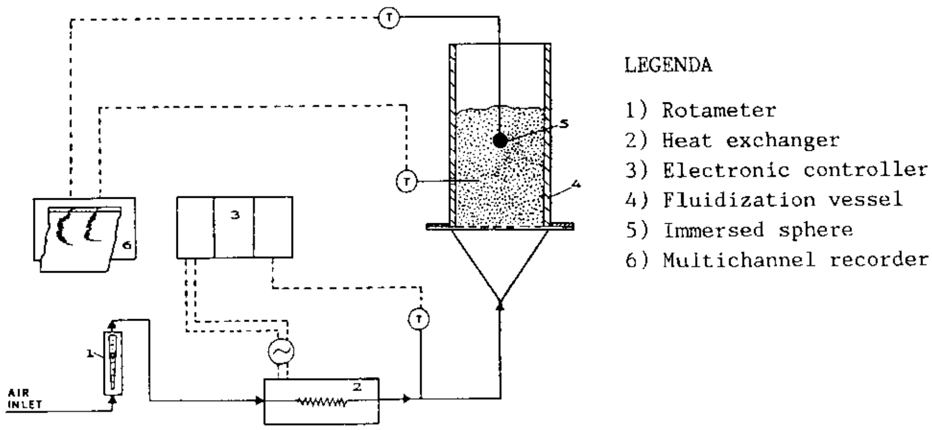

FIGURE 1. Sketch of the experimental apparatus

Experiments are performed using silica sand particles as inert bed material and metal (copper or aluminium) spheres as immersed bodies. Samples of sand of different size, with relatively narrow distribution are used, as shown in Table 1.

Material	Particle Density g/cm^3	Sphericity Factor	Sauter diameter µm	U_{mf} cm/s
Sand	2.5	0.92	220	4.2
Sand	"	"	440	11.5
Sand	"	"	715	21.0

TABLE 1 Physical Properties of Inert Bed Materials

In the determination of heat transfer rates, metal spheres of the following size are used: 8, 12, 16 and 20 mm. Wooden spheres of the same size have been used for measuring mass transfer rates. Different flow velocities are investigated, for all the bed materials and sphere sizes. Two temperature levels, 50 and 95 °C are also tested.

The experimental technique for heat transfer tests involves the continuous recording of the temperature at the center of the sphere, by means of a thin (0.5 mm OD) thermocouple.

Being the thermal conductivity of the immersed spheres very high, the Biot number can be considered always close to 0. Accordingly, the temperature of the sphere is considered uniform, and a simple exponential relationship can be used as heating/time law.

Mass transfer coefficients have been determined by extracting periodically from the bed and weighing the wooden spheres, which had been previously saturated with water by immersion.

Mass transfer coefficients are determined in the constant rate period, so that also the mass transfer Biot number is close to zero, and surface temperature can be taken as wet bulb temperature of the gas.

Procedures above enable a straightforward calculation of both transport coefficients: on the basis of the experimental pattern of sphere temperature as a function of time for heat transfer, and of the drying curve of the sphere for mass transfer.

Most experiments have been performed in the conditions of fixed spheres. In this case the thermocouple is inserted in a stiff steel tube which acts as constraint to the free motion of the sphere, while no shield is used when investigating floating sphere conditions.

RESULTS

Axial and radial position of the fixed body in the fluid bed, tested in all experimental conditions, have an effect on the heat transfer coefficients, whose values are higher in the upper part of the bed and along the central axis of the column. Both these effects are smoothed when increasing gas flow velocity. All the experimental values shown in the following are those measured 100 mm above the distributor in central position.

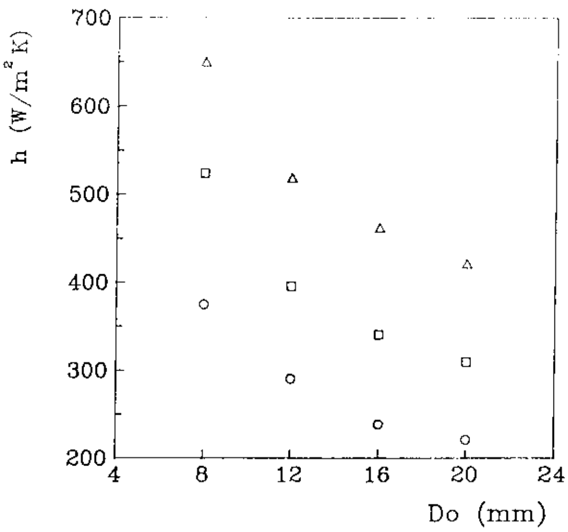

FIGURE 2. Heat transfer coefficients for fixed spheres as a function of their diameter at different gas velocities in a bed of sand of 220 μm. (○)Ug=.05 m/s; (□)Ug=.07 m/s; (△)Ug=.10 m/s

Figures 2, 3 and 4 show the effect of the gas flow velocity on the heat transfer coefficients for fixed spheres immersed in a bed of sand of 220, 440 and 715 µm (mean diameter), respectively. The influence of gas velocity on the values of the heat transfer coefficients clearly appears for all materials tested and for all sizes of the immersed spheres. Increasing gas velocity, the heat transfer rate of the bed increases, probably due to the more intense bubble circulation in the bed. The size of the particles of sand and of the immersed bodies seem to be the key parameters in determining the behaviour of the system. When decreasing bed particles size, the heat transfer coefficients increase, probably due to a more effective contact between fluid bed and immersed bodies. An increase of the heat transfer coefficient is observed when decreasing the size of the immersed object, probably because of the absence of defluidized zones on the top of the spheres.

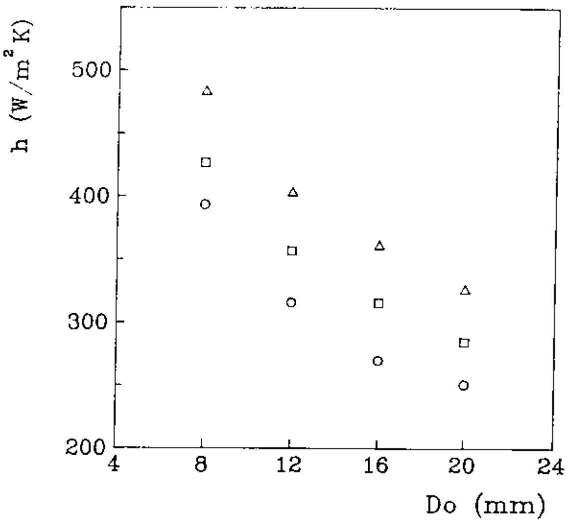

FIGURE 3. Heat transfer coefficients for fixed spheres as a function of their diameter at different gas velocities in a bed of sand of 440 μm. (O)Ug=.14 m/s; (□)Ug=.16 m/s; (Δ)Ug=.19 m/s

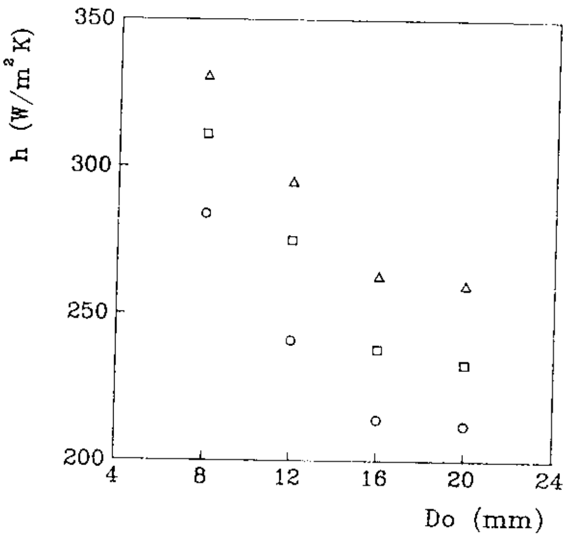

FIGURE 4. Heat transfer coefficients for fixed spheres as a function of their diameter at different gas velocities in a bed of sand of 715 μm. (O)Ug=.35 m/s; (□)Ug=.38 m/s; (Δ)Ug=.42 m/s

Also the effect of the mobility of the immersed bodies has been tested. Typical results are shown in Figure 5 for a bed of sand of 440 µm at three different gas velocities and compared with those obtained, for the same gas velocity, for fixed spheres. By increasing the mobility of the sphere, the heat transfer coefficients increase for all sphere diameters.

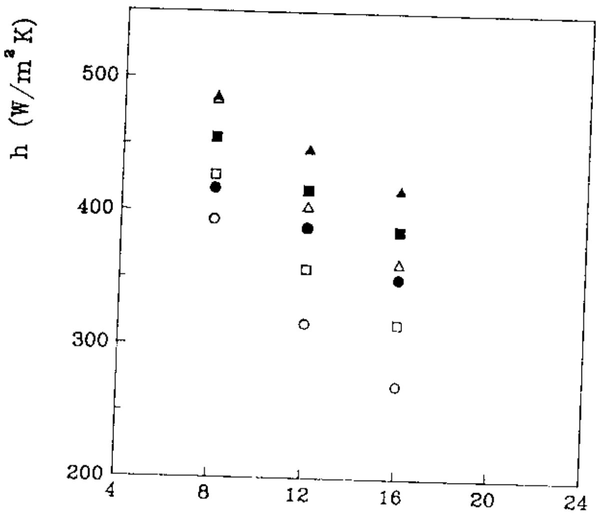

FIGURE 5. Heat transfer coefficients for fixed and floating spheres as a function of their diameter at different gas velocities in a bed of sand of 440 µm.
Closed simbols: floating spheres; open symbols: fixed spheres.
(○,●)Ug=.14 m/s; (□,■)Ug=.16 m/s; (△,▲)Ug=.19 m/s.

Figure 6 shows two typical experimental drying velocities as a function of the water content of the wooden sphere. They refer to two spheres of different diameter dried in a bed of sand of 715 µm at a temperature of 40 °C. The constant rate period is easily recognized, and results are easily worked out as mass transfer coefficients.
Experimental mass transfer coefficients are compared with those calculated from heat transfer coefficients during the constant rate period. This in the hypothesis that the temperature at the solid surface keeps at the wet bulb value and that the heat flux between gas and solid due to mass transfer is balanced by that due to temperature difference. Data fit fairly well. According to this consideration, mass transfer data have been measured only in selected conditions. In the remaining range of experimental conditions, mass transfer coefficients are evaluated from heat transfer data. These values have been used, together

with experimental data in selected conditions, to have a general view of the trend of mass transfer coefficients.

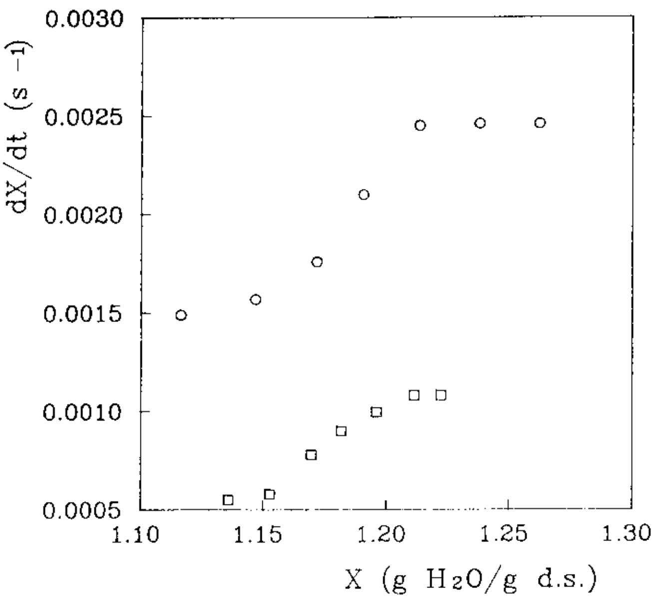

FIGURE 6. Drying rate of two wooden spheres of different diameter as a function of water content in a bed of sand of 715 μm. Ug=.4 m/s; T=40 °C; (○)Do=13 mm; (□)Do=22 mm.

DISCUSSION

Present experimental results confirm that the key parameters in determining heat and mass transfer rates between immersed objects and fluidized beds are the size of the object and the particle size of the bed material. Fluidization velocity is an important parameter for floating as well as for fixed objects. These findings are not universally accepted. The effect of the size of the fixed body is excluded by Gilbert and Rios (3), while a more marked effect of the bed particle size is reported by Prins et al. (7) for heat transfer coefficients. As far as mass transfer coefficients are concerned, the same Authors report an opposite effect, which is in contrast with the parallelism between heat and mass transfer fluxes found in our work.

Due to the unconsistency of data from different authors, existing literature correlation are contradictory. None of them, moreover, is able to predict the effect of some of the key parameters such as the size of the immersed sphere .

Even when following a different approach, similar to the classical Ranz and Marshall correlation (9), which considers a single sphere immersed in the fluid bed acting a pseudo-fluid, the effect of the fine particle size is not predicted at all. This is shown in Figure 7, where all experimental data of heat transfer for spheres in fixed position are reported in a plot giving the Nusselt number as a function of the Reynolds number.

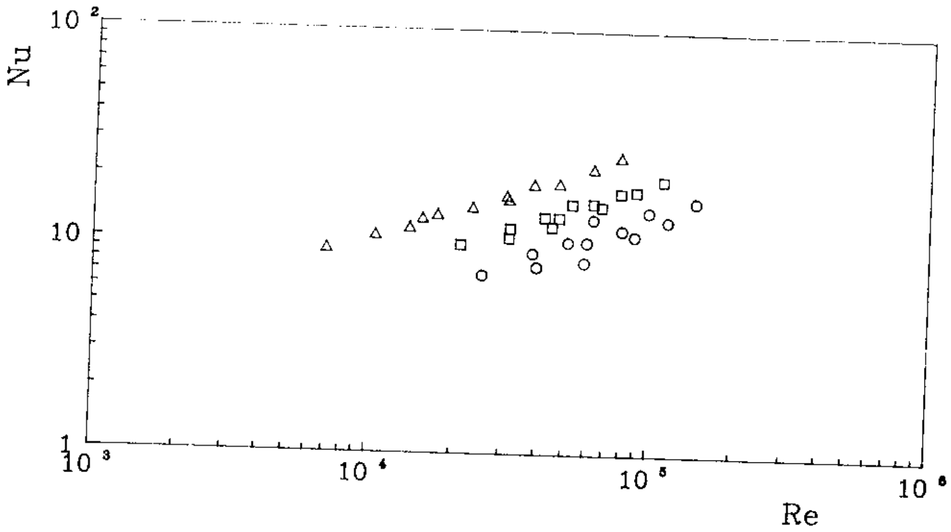

FIGURE 7. Experimental heat transfer data as Nusselt number vs. Reynolds number. (O)dp=715 μm, all spheres; (□)dp=440 μm, all spheres; (Δ)dp=220 μm, all spheres.

It can be observed that all data referred to the same particle size collect fairly well on straight lines of similar slope.

On the basis of the condiderations above, a different correlation is proposed for heat transfer coefficients. It includes the Nusselt number referred to the diameter of the immersed sphere, and takes into account the effect of the fine particle size through the Archimedes number, as suggested by Prins et al. (10). Results are shown in Figure 8, in the form:

$$Nu = \frac{h\ Do}{k} = C\ Re^a\ Ar^b \qquad (1)$$

where the Reynolds number is $Re=(U-Umf)\rho p\ (1-\varepsilon)\ Do/\mu g$, defined by considering the fluid bed as a continuum in respect to the sphere particle size, i.e. with reference to the effective velocity of the dense phase, (U-Umf), to the effective density of the dense phase, $(1-\varepsilon)\varrho_p$, to the sphere diameter and to the gas viscosity.

The numerical constant C embodies the effect of the Prandtl number, being the range of temperature investigated not so wide to affect the physical properties of the gas stream.

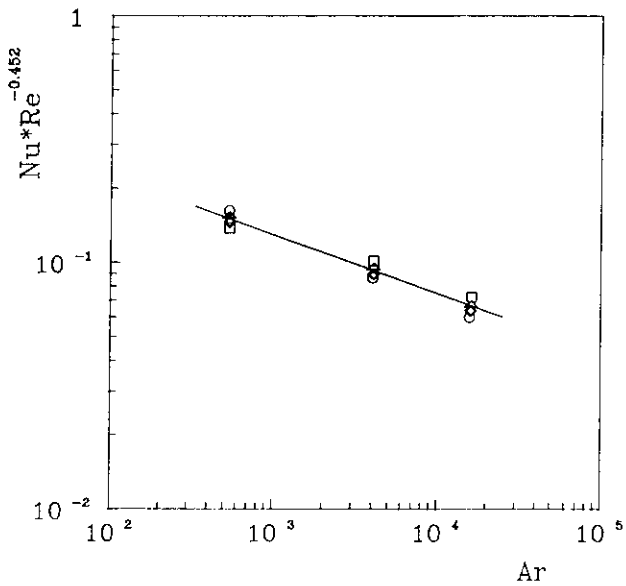

FIGURE 8. Experimental heat transfer data compared with the proposed correlation. (O)Do=8 mm (◇)Do=12 mm (△)Do=16 mm (□)Do=20 mm

The curve reported refers to the following best-fitting values of the parameters: a=0.452; b=-0.224 and C=0.655.

It can be observed that data referred to the same particle size collect fairly well together, irrespective to the immersed sphere diameter. The small spread of data corresponding to the higher value of the Archimedes number, i.e. of the fine particles size, may be due to the fact that the fine particles size is not completely taken into account by the proposed form of dependance. However, it has to be remarked that the proposed correlation embodies only parameters which have a precise physical meaning.

The same attempt has been performed for mass transfer coefficients, through the definition of a Sherwood number based on the diameter of the immersed sphere. On the basis of the same definition of Reynolds number given above, it results:

$$Sh = \frac{k_g D_o}{\mathbb{D}} = C' \, Re^{a'} \, Ar^{b'} \qquad (2)$$

This correlation is reported in Figure 9, for the following values of the parameters: a'=0.452; b'=-0.224; C'=8.80. However, because of the present lack of experimental data of mass transfer rates, most values of mass transfer coefficients are evaluated from heat transfer data as described above, so that the proposed correlation cannot yet be compared with experimental data. It should be considered as a first approximation proposal, to be verified in a wider range of experimental conditions.

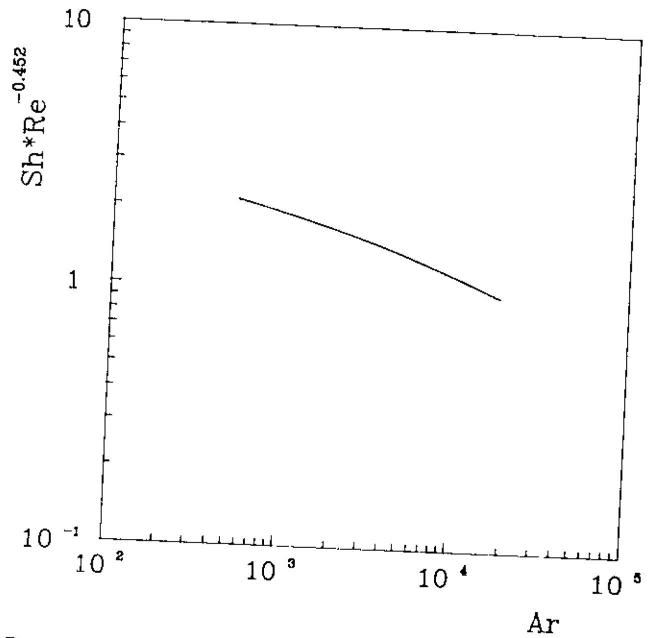

FIGURE 9. Proposed correlation for mass transfer.

CONCLUSIONS

This work confirms that overall transport coefficients between fluidised beds of relatively fine particles and fixed or floating objects are excellent, so that applications of two-component fluidization techniques to drying processes can be favourably considered.

In the range of temperatures and fluidization velocities of interest for drying processes, a complete scanning of heat transfer coefficients has been performed for different size of fine particles and of immersed objects. The correlation proposed, differently from existing relationships, is very simple, based on currently used adimensional groups and does not include any fitting parameter, so that can be used for preliminary evaluation of heat transfer coefficients in the study of thermal processes based on two-component fluidization technique. It predicts correctly the effect of both particle and immersed body size, differently from existing relationships.

The correlation proposed for mass transfer data has not been validated at the moment in a so wide range of conditions and needs more experimental work to be confirmed. However, the approach seems to be sound and the finding of a trend parallel to that found for heat transfer is physically consistent.

Work in progress will enable us to set fully predictive correlations for the evaluation of transport properties in all the range of drying conditions.

LIST OF SYMBOLS

a,a'	numerical constants in Eq.(1) and (2),	(-)
Ar	Archimedes number, $gd_p^3\ \varrho_g(\varrho_p-\varrho_g)/\mu^2$	(-)
b,b'	numerical constants in Eq.(1) and (2),	(-)
Bi	Biot number $h\ D_o/2k$	(-)
C, C'	numerical constants in Eq.(1) and (2),	(-)
c_p	specific heat	$J\ kg^{-1}\ K^{-1}$
D	mass diffusivity,	$m^2\ s^{-1}$
d_p	particle diameter	m
D_o	diameter of the immersed sphere,	m
h	convective heat transfer coefficient	$W\ m^{-2}\ K^{-1}$
k	thermal conductivity	$W\ m^{-1}\ K^{-1}$
K_g	mass transfer coefficient	$m\ s^{-1}$
Nu	Nusselt number $h\ D_o/k$	(-)
Pr	Prandtl number $\mu c_p/k$	(-)
Re	Reynolds number $U\ \varrho\ d_p/\mu$	(-)
T	temperature	K
t	time	s
U_g	gas velocity	$m\ s^{-1}$
U_{mf}	minimum fluidization velocity	$m\ s^{-1}$
X	water fraction	kg H_2O/kg d.s.
ε	bed voidage	(-)
μ	viscosity	$kg\ m^{-1}\ s^{-1}$
ϱ	density	$kg\ m^{-3}$

Subscripts

b bed g gas p particle

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