A Theoretical Investigation of Enhancement of Mass Transfer from a Packed Bed Using Acoustic Oscillations

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This paper describes a theoretical investigation of the possibility of improving the performance of packed bed dryers using acoustic oscillations. It was motivated by the increasing interest in the use of acoustic oscillations to improve the performance of energy-intensive, industrial processes. Sound propagation in a packed bed was modelled as propagation through a porous medium. The effect of acoustic oscillations on the drying rate was then investigated by numerically integrating the heat and mass transfer equations. The model used quasi-steady correlations for heat and mass transfer. The results show that threshold values for void fractions and sound pressure levels exist, above which significant increase in drying rate can be obtained. The increase in mass transfer decreases with effective particle diameter.

On décrit dans cet article une étude théorique sur la possibilité d'améliorer la performance de séchoirs à lits garnis par des oscillations acoustiques. Cette étude est motivée par l'intérêt grandissant pour les oscillations acoustiques en vue d'améliorer la performance de procédés industriels énergivores. La propagation du son dans un lit garni a été modélisée comme une propagation dans un milieu poreux. Puis on a étudié l'effet des oscillations acoustiques sur la vitesse de séchage en intégrant numériquement les équations de transfert de chaleur et de matière. Le modèle emploie des corrélations quasi stationnaires pour le transfert de chaleur et de matière. Les résultats montrent que des seuils existent pour les fractions de vide et les niveaux de pression sonore, au-dessus desquels une augmentation significative de la vitesse de séchage peut être obtenue. L'augmentation du transfert de matière diminue avec le diamètre effectif des particules.

Keywords: packed beds, acoustic oscillations, mass transfer enhancement.

This technical note describes a theoretical investigation of the possibility of improving the performance of packed bed dryers using acoustic oscillations. The study was motivated by the increasing interest in the use of acoustic oscillations to improve the performance of energy intensive processes such as calcining and drying. In such processes the rate controlling mechanisms are the heat and mass transfer between gas and particulate phases. For instance, the performance of a packed bed dryer depends upon the rate of heat transfer from the hot gas to the bed material and the rate of mass (i.e., moisture) transfer from the bed to the gas. If these rates can be increased by using, for example, acoustic oscillations, the time required to dry the bed material will decrease. This will reduce the drying period for a batch type drying operation or permit a higher flow rate of wet material in a continuous drying operation. Alternately, the decreased drying time will reduce the required size of a new dryer, which will reduce the capital investment costs. In addition, increasing the rate of heat transfer from the gas to the bed material, will increase the fraction of input energy that will be transferred to the bed, resulting in fuel and operating cost savings. Finally, reducing fuel consumption will reduce CO_2 emissions.

The realization that the performance of energy-intensive processes could be improved if the means for increasing the rates of mass, momentum and heat transfer within these processes could be found, has stimulated interest in developing practical means for enhancing these transport processes. It has been shown in many instances that acoustic oscillations (which could be excited in industrial processes using pulse combustors, for example) increase the rates of heat and mass transfer (Bayley et al., 1961; Richardson, 1967; Padmanabha et al., 1970; Al-Taweel and Landau, 1976; Lyman, 1977; Drummond, 1979 and 1981; McQuay and Dubay 1998, Sujith et al., 1994, 1995, 2000). These studies strongly suggest that exciting acoustic oscillations in a packed bed dryer will increase its performance by increasing the rates of external heat and mass transfer, respectively, to and from the bed material. This possibility is theoretically investigated in this technical note.

Acoustic Oscillations in a Packed Bed

The packed bed is modelled as a porous medium that resists fluid flow and also modifies the fluid's compressibility. The porous bed assumption is valid for small amplitude acoustic oscillations that are unlikely to affect packing in the bed. The packed column may be thought of as consisting of a solid material with pores that are interconnected in a random but isotropic manner. The fluid can percolate through these pores in any direction. The fraction of the volume that is not occupied by the solid is called

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void fraction and denoted by ε. The solid is assumed to be perfectly rigid and incompressible.

The actual velocity of the fluid as it passes through the "pores" will not be constant in direction or magnitude. However, for the 1-D model developed here, a mean velocity u (x,t) can be defined as the volumetric flow rate per unit cross-sectional area in the bed in a direction along the bed axis. Consequently, at the interfaces of the bed and the gaseous media upstream and downstream of the bed, the mean velocity u will be continuous.

This study has been performed for a specific (proprietary) application where the mean velocity is less than 0.1 m/s and the mean temperature change of the gas is less than 40°C over a length of 6 m. Therefore, the effect of mean flow and temperature gradient upon the structure of the standing wave in the bed will be negligible.

The acoustic momentum and energy equations for a porous medium can be written as (Morse and Ingard, 1968; Crighton et al., 1992):

$$\frac{\rho}{\varepsilon}\frac{\partial u'}{\partial t}+\phi u'+\frac{\partial p'}{\partial x}=0 \tag{1}$$

$$\varepsilon\frac{\partial p'}{\partial t}+\gamma\bar{P}\frac{\partial u'}{\partial x}=0 \tag{2}$$

Assuming that the solution has a periodic time dependence, i.e., $p'(x,t) = P'(x)\,e^{i\omega t}$ and $u'(x,t) = U'(x)\,e^{i\omega t}$, the momentum and energy equations reduce to:

Momentum:

$$i\omega\rho_p\left[1+\frac{\phi}{i\omega\rho_p}\right]U'=-\frac{\partial P'}{\partial x} \tag{3}$$

Energy:

$$\frac{\varepsilon}{\gamma\bar{P}}i\omega P'+\frac{\partial U'}{\partial x}=0 \tag{4}$$

where $\rho_p=\rho/\varepsilon$, is the effective density. Manipulating Equations (3) and (4) to eliminate the acoustic velocity yields the following wave equation:

$$\frac{\partial^2 P'}{\partial x^2}+\frac{\omega^2}{c^2}\left[1+\frac{\phi}{i\omega\rho_p}\right]P'=0 \tag{5}$$

where $c^2=\gamma\bar{P}/\rho$. The solution for Equation (5) is given by:

$$P' = A\sin kx + B\cos kx \tag{6}$$

where

$$k=\frac{\omega}{c}\left[1+\frac{\phi}{i\omega\rho_p}\right]^{\frac{1}{2}} \tag{7}$$

is a modified complex wave number. Using the derived expression for acoustic pressure and the acoustic momentum equation (i.e., Equation 3), the following expression for acoustic velocity U' can be derived:

$$U'(x)=\frac{i\omega}{\rho_p c^2 k}\left[-A\sin kx+b\cos kx\right] \tag{8}$$

The magnitude of the flow resistance ϕ, in the packed bed is needed to determine the acoustic field in the packed bed. For a steady flow in a porous medium the frictional resistance is given by:

$$\phi=\frac{1}{\bar{u}}\frac{d\bar{p}}{dx} \tag{9}$$

where $d\bar{p}/dx$ is the steady state pressure drop experienced by the flow. The pressure drop experienced by a fluid as it moves through a bed of packed solids such as spheres, cylinders, gravel or sand is given by the Ergun equation (Treybal, 1981) that is:

$$\frac{dp}{dx}\frac{\varepsilon^3 d_p}{(1-\varepsilon)\rho u^2}=\frac{150(1-\varepsilon)}{Re}+1.75 \tag{10}$$

Since there is no data or correlation in the literature to the best of the authors' knowledge, that give the pressure drop in a packed column in the presence of an acoustic field, the Ergun equation (i.e., Equation 11) was used to determine the pressure drop in the packed bed and ϕ respectively. The total velocities in the packed bed are of the order of 1 m/s and the particle diameters are of the order of 1 mm. Therefore, the flow in the packed bed was assumed to be laminar. The turbulent contribution in the Ergun equation was neglected. This yields the following expression for ϕ:

$$\phi=\frac{150(1-\varepsilon)^2\rho u}{Re\,d_p\varepsilon^3}=\frac{150(1-\varepsilon)^2\mu}{d_p^2\varepsilon^3} \tag{11}$$

where d_p is the particle diameter. The term on the left is a friction factor and the first and second terms on the right, respectively, represent contributions of purely laminar flow and the completely turbulent flow to the friction factor.

It is expected that the above assumption will result in small errors in the calculation of acoustic pressure and velocity amplitudes and wave damping in the bed at higher acoustic amplitudes. While these errors can lead to corresponding errors in the magnitude of the computed results, the model should nevertheless correctly predict trends in the effects of the acoustic oscillations upon heat and mass transfer within the packed bed.

Mass Transfer Model

The model, developed to investigate the effect of acoustic oscillations upon the drying process in a packed bed, is described in this section. The assumptions involved are stated below.

1. Empirical, quasi-steady correlations for the transport of mass, momentum and energy were used in this model. These correlations were derived for steady flows. It has been assumed in this study that they are applicable to oscillating flows.

2. The pellets do not move in response to the acoustic oscillations.
3. The pressure drop in the oscillating flow field is calculated using the Ergun equation.
4. While determining the pressure drop, for calculating the acoustic field, the contribution from turbulence was neglected.
5. The Biot numbers for heat and mass transfer are very small. (For the current application, for an effective diameter of 3 mm, the Biot number for heat transfer is of the order of 0.02. The Biot number for mass transfer is of the order 0.01.) The pellets are assumed to have uniform temperature.

The packing is in the form of small pellets. A batch type drying process is considered in this study. Hot dry air enters the column from the bottom. It heats the bed as it moves upwards causing water evaporation and water vapor transfer from the bed to the air. To determine the dryer's performance, the packed bed is divided into small segments and the conservation of mass and energy are solved at each segment. The pressure drop is determined from the Ergun equation and not by solving the momentum equation.

The differential mass (i.e., moisture) transfer rate within one of these segments can be expressed in the following form (Treybal, 1981):

$$d\dot{m} = k_Y[Y_S - Y]dS \qquad (12)$$

where k_Y is the mass-transfer coefficient, Y_s is the saturation humidity at the pellet surface corresponding to the pellet temperature, Y is the humidity of the carrier stream and S the effective surface area. The coefficient k_Y is often expressed as follows (Treybal, 1981):

$$k_Y = j_D \rho u Sc^{-2/3} \qquad (13)$$

where Sc is the Schmidt number and j_D an empirical function of Reynolds number. The correlation which is commonly used is given by the following expression (Treybal, 1981):

$$j_D = \frac{2.06}{\varepsilon} Re^{-0.575}, \text{for } Re < 4000$$
$$j_D = \frac{20.4}{\varepsilon} Re^{-0.815}, \text{for } Re > 4000 \qquad (14)$$

The Reynolds number Re is defined as:

$$\mathrm{Re} = \frac{|u|\, d_p}{\nu} \qquad (15)$$

where u is the "net" velocity that is the sum of the mean and oscillatory components of velocity, that is:

$$u = \bar{u} + U'(x)\sin\omega t \qquad (16)$$

It may be noted that for small enough frequencies (less than 1000 Hz) the effects of acoustic streaming will be negligible (Al-Taweel and Landau,1976; Drummond, 1981), and hence the total velocity can be expressed as the sum of mean and oscillatory components.

The heat transfer coefficient may be expressed as follows (Treybal, 1981):

$$h = j_H C_p \rho u Pr^{-2/3} \qquad (17)$$

where Pr is the Prandtl number and j_H an empirical function of Reynolds number. In these calculations, the heat transfer analogy ($j_D = j_H$) will be used to estimate the heat transfer coefficient. Using the convective heat transfer Q estimated using h calculated from Equation (18), the rate of change of pellet temperature with time can be expressed as:

$$\frac{\Delta T_p}{dt} = \frac{QA - d\dot{m}L_v}{m_p C_s} \qquad (18)$$

where L_v is the latent heat of vaporization and Cs is the specific heat of the pellets. Note that as the Biot number for heat transfer is small, the pellets are assumed to have uniform temperature.

The Mass Transfer Calculation Procedure

The calculations were performed as follows. The pellets were assumed to be present in the bed with a given initial temperature. A hot air stream was then introduced into the bed and the acoustic oscillations were excited at $t = 0$. The oscillatory component of the velocity at any given instant was calculated using Equation (8). The total instantaneous velocity was then given by Equation (16), as the sum of the mean and the instantaneous oscillatory components. The instantaneous velocity thus calculated was used to determine the instantaneous Reynolds number using Equation (15). The mass transfer coefficients j_D, and k_Y were then calculated using Equations (14) and (13), respectively.

The humidity (mass fraction of water vapour) of the drying stream Y and the mass fraction of vapour in the pellet were then determined (the pellet surface was assumed to have saturation vapour pressure). The incremental vapour flow rate to the drying stream, could then be determined using Equation (12).

The heat transfer coefficient, and subsequently the heat transfer, were determined using Equation (17). The gas temperature at the exit of the incremental control volume was determined using energy balance. The new pellet temperature was then computed using Equation (18).

This set of calculations was carried out from one end of the packed bed (the entry point of the carrier gas) to the other. The time step was then incremented and the acoustic velocity at the next instant was calculated. The above calculations were then repeated for an entire acoustic cycle. The values obtained were then averaged over the entire acoustic period. The calculations were also performed in the absence of acoustic oscillations in order to determine the change in the dryer performance caused by the oscillations.

Results and Discussion

The effect of acoustic oscillations upon the performance of a packed bed dryer was calculated using the developed model and the results are presented in this section. Computations were performed for a packed bed whose length and diameter equaled 6 m and 1 m, respectively. The mositure content of the pellets in the bed was assumed to be well below the critical moisture content and in the falling rate zone, which was assumed to be linear. The rate of drying was assumed to be directly proportional to the moisture content, in the entire falling rate zone. In other words, the drying curve for the entire falling rate zone was assumed to be a straight line passing through the origin. Therefore, the computed value of K_Y was corrected by multiplying by the ratio of that actual wet surface are to the total surface area. To determine the effect of acoustic oscillations, drying rates of the packed column in the absence and presence of acoustic oscillations were computed and compared. The values presented for the case with acoustic oscillations are the values averaged over an acoustic cycle. Calculations were performed for a frequency of 203.75 Hz. It should be noted that the quasi-steady correlations used for heat and mass transfer do not depend upon the frequency. Calculations are performed for a range of values of the void fraction (ε) and the equivalent diameter (d_p). Other parameters used in the calculations are presented in Table I.

The increase in mass flow rate with distance along the bed is a measure of the amount of moisture added to the airflow by the drying process. The spatial dependencies of this mass flow rate in the presence and absence of acoustic oscillations are plotted as a function of distance in Figure 1. It shows that acoustic oscillations increase the mass flow rate, indicating that these oscillations increase the moisture transfer from the bed to the carrier stream.

The acoustic enhancement was defined as the percentage change in the net drying rate due to acoustic oscillations. This is determined as follows. The moisture evaporated at the end of the column in the absence of sound is determined and is referred to as *a*. Then the average moisture evaporated over a cycle at the end of the column is determined and is referred to as *b*. The percentage enhancement is then given by $(b-a)/a * 100$. The effect of the acoustic amplitude upon mass transfer is presented in Figure 2 for a range of void fractions, for a given effective particle diameter of 3 mm. Figure 2 shows that for a given effective particle diameter and void fraction, the acoustic enhancement decreases to negative values first, before increasing to significant positive values. In other words, the drying rate decreases at lower acoustic amplitudes and increases at higher acoustic amplitudes. Similar trends were observed in studies of mass transfer from droplets and spheres (Drummond, 1979; Sujith et al., 2000). The heat and mass transfers are proportional to the magnitude of the velocity (i.e., the sum of the mean and the oscillatory components). Drummond (1979) has shown that the time-averaged value of the magnitude of the net velocity reaches a minimum when the mean velocity equals the acoustic velocity and increases thereafter. This causes the acoustic enhancement to initially decrease and then increase as the acoustic amplitude is increased.

Figure 2 also shows that packings with higher void fractions lead to greater increase in the drying rate compared to packings with lower void fraction. The wave damping increases with increase in void fraction (ε) resulting in higher acoustic veloci-

Table 1. Dryer parameters.

Mass fraction of vapour at the inlet	0
Gas temperature at inlet	180°C
Initial temperature of the pellet	90°C
Diameter of the column	1 m
Length of the column	6 m
Mean pressure	1.013×10^5 Pa
Frequency of the acoustic oscillations	203.75 Hz
Ratio of specific heats, ($\gamma = C_p/C_v$)	1.4
Carrier gas velocity at the inlet	0.1 m/s
Schmidt number, *Sc*	0.6

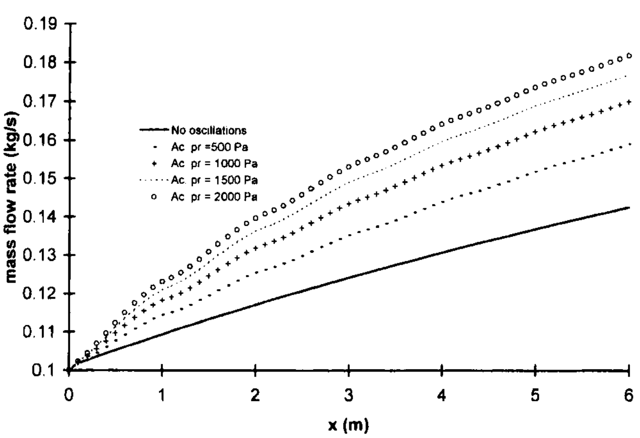

Figure 1. The variation of mass flow rate as a function of distance in the presence and absence of acoustic oscillations. Void fraction = 0.7, effective particle diameter = 3 mm.

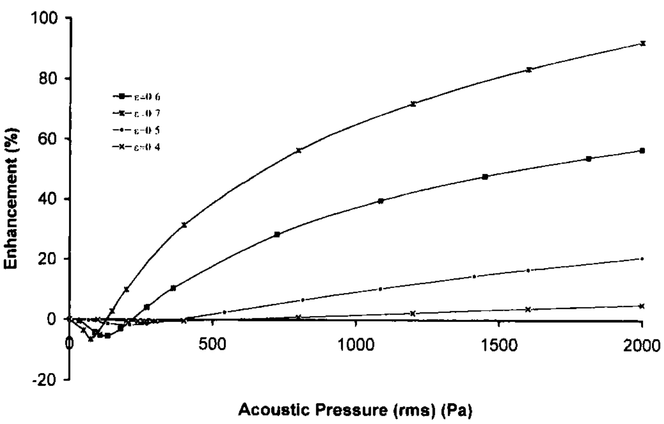

Figure 2. Dependence of enhancement in mass transfer rate on the acoustic amplitude for different values of void fraction (ε). Effective particle diameter = 3 mm.

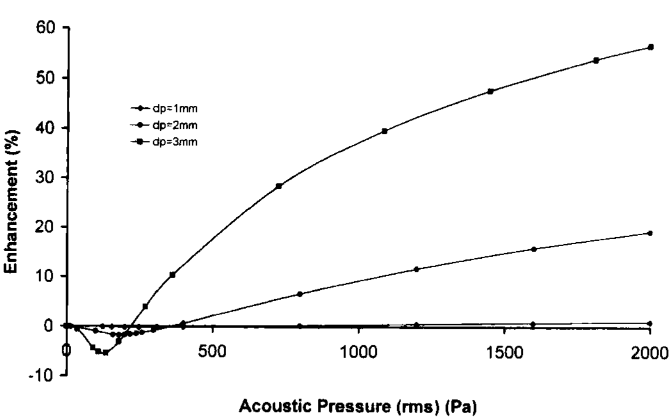

Figure 3. Dependence of enhancement in mass transfer rate on the acoustic amplitude for different values of effective particle diameter (d_p). Void fraction = 0.6.

ties throughout the packed bed. Higher acoustic velocities lead to higher drying rates. Figure 2 shows increases in drying rates for void fractions higher than a threshold value of 0.6, for sound pressure levels higher than a threshold value of 143 dB.

The dependence of the acoustic enhancement upon the particle diameter is shown in Figure 3. It illustrates that for a given void fraction, the acoustic enhancement increases as the effective particle diameter increases. The enhancement is low for particles with small effective diameter since they increase acoustic damping, resulting in lower acoustic velocities. Thus, this study shows that the drying of packed beds with void fractions above a certain threshold value ($\varepsilon > 0.6$) can be significantly increased by using acoustic oscillations.

While determining the pressure drop, the contribution from turbulence was neglected. The turbulence levels will be low for low velocities. However, the turbulence levels will be significant in the case where velocity is high. This will result in increased damping. Therefore the enhancement in mass transfer predicted in this study will be higher than the actual values that will be obtained. The accuracy of the results also depends upon the validity of the quasi-steady assumption. A similar study on the evaporation from droplets in the presence of acoustic oscillations, which used the quasi-steady assumption, predicted the trends observed in the experiments (Sujith et al., 2000) for oscillations with frequencies less than 1000 Hz. Hence, it may be speculated that the quasi-steady assumption, and therefore the predictions of the current study, will be valid for low frequencies. It may be noted that quasi-steady correlations do not inherently contain any frequency effects, and hence the results obtained are independent of the frequency of oscillations. The results of this model have to be compared with experimental results to ascertain the accuracy of the predictions. However, it is expected that the trends observed in this study will be correct, even if the actual values, in particular the thresholds of acoustic amplitude and void fractions for obtaining enhancement, do not compare well with experimental prediction. The results from this study will be compared with the results from an ongoing experimental study at the Pulse Combustion Laboratory at the Georgia Institute of Technology. This will throw light on the answers for the above questions.

The acoustic amplitudes necessary to obtain these increased mass transfer rates can be attained using resonant driving with tunable pulse combustors that are now commercially available. These can be obtained in different power levels and sizes enabling the establishment of the required acoustic field in industrial processes of any scale (Zinn et al., 1991; Zinn, 1992; Stewart et al., 1993). Therefore, the application of this technology to existing drying equipment is relatively easy and could lead to potential energy savings and increased productivity.

Pulse combustors are noisy and their sound emissions must be reduced to acceptable levels. The available technology has been successfully implemented in commercialized water boilers and space heaters (Zinn, 1992). All intakes and exhaust ports should be attached or inserted into decoupling chambers that prevents sound radiation. The pulse combustors are themselves enclosed in sound insulated containers. With the recent advances in active sound control it is quite possible that more economic and effective solutions will emerge in the future.

Conclusions

The possibility of enhancement of drying rates from packed beds using acoustic oscillations was investigated theoretically. The model developed for this study used empirical correlations for the transport of mass, momentum and energy. The model predicts an increase in drying rates in the presence of acoustic oscillations. The increase in drying rate is higher for higher void fractions and higher sound pressure levels. The increase in drying rate decreases with effective particle diameter. The acoustic amplitudes which will lead to significant enhancement in drying rates could easily be attained using pulse combustors. Hence it is speculated that the application of this technology could lead to potential energy savings and increased productivity.

The model employed in this study has a few limitations. While determining the pressure drop, the contribution from turbulence was neglected. Hence, the enhancement predicted will be higher than the actual values obtained. The pressure drop calculated using the Ergun equation under oscillatory conditions will depart from the actual values at higher frequencies. The quasi-steady assumption is also not valid under high frequency conditions. Furthermore quasi-steady correlations do not inherently contain any frequency effects, and hence the results obtained are independent of the frequency of oscillations.

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Nomenclature

A area, (m^2)
c $\sqrt{\frac{\gamma\bar{P}}{\bar{\rho}}} \neq \sqrt{\frac{p'}{\rho'}}$ (m/s)
C_p specific heat at constant pressure, (J/kg·K)
C_s specific heat of the packing material, (J/kg·K)
d_p particle diameter, (m)
dm incremental mass flux, (kg/s)
h heat transfer coefficient, (W/m^2·K)
j_D mass transfer coefficient
j_H heat transfer coefficient
k wave number, see Equation (8), (m^{-1})
k_Y gas mass-transfer coefficient, (kg/m^2/s)
L length of the packed column, (m)
L_v latent heat of vaporization, (J/kg·K)
p' acoustic pressure, (Pa)
P' acoustic pressure amplitude, (Pa)
$\bar{P}$ mean pressure, (Pa)
Q heat flux, (W/m^2)
Re Reynolds number, $\rho v d_p/\mu$
S surface area, (m^2)
S_s mass of dry solid, (kg)
Sc Schmidt number
t time, (s)
T temperature, (K)
u velocity, (m/s)
x distance, (m)
X moisture content, i.e., mass of moisture/mass of dry solid, (kg/kg)
X_c critical moisture content, (kg/kg)
Y relative humidity
Y_s relative humidity at the surface

Greek Symbols

γ ratio of specific heats, C_p/C_v
ε void fraction
μ coefficient of viscosity, (kg/m·s)

ν coefficient of kinematic viscosity, (m^2/s)
ρ density, (kg/m^3)
ρ_p effective density, (kg/m^3)
ϕ flow resistance, ($kg/m^2 \cdot s$)
ω angular frequency, (radians/s)

Subscripts

g gas
p pellet
s surface

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