Original Paper

Development of a simulation model for the expansion of perlite

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New applications of expanded perlite in the building industry lead to a growing demand for process optimization for the expansion of perlite. Perlite expanders aim to adapt their furnaces and/or furnace operation conditions in order to attain more flexibility to produce different expanded perlite qualities. A way to examine the possibilities of an existing installation is the numerical simulation of the perlite expansion process in that installation. The two-phase flow field and combustion in the furnace can be modelled by using currently available Computational Fluid Dynamics (CFD) codes. The only problem is the modelling of the expansion process, which changes the particle size and thus influences the two-phase flow calculations.

In this paper the authors propose a physical model for the simulation of the expansion of perlite. This model is based on the results of fundamental studies concerning the expansion phenomenon. It relies on the calculation of particle temperature and viscosity and thus takes into account the most influential parameters for perlite expansion. It allows the calculation of the perlite particle size as a function of time or of the particle's trajectory inside a furnace. Particle size statistics of the expanded product can be determined in that way. The model has been validated by comparison with experimental results from laboratory and industrial measurements.

Entwicklung eines Modells zur Simulierung der Expansion von Perliten

Neuere Anwendungen expandierter Perlite in der Bauindustrie führten in den letzten Jahren zu einem wachsenden Bedarf an optimierten Perlitexpansionsverfahren. Mehr Flexibilität in der Herstellung verschiedener Qualitäten soll durch Anpassung der Ofengeometrien und/oder Prozeßparameter erreicht werden. Eine Vorgehensweise die existierenden Möglichkeiten einer Anlage zu untersuchen, ist die numerische Simulation der Perlitexpansion in der Anlage. Die Zweiphasenströmung und Verbrennungsvorgänge im Ofen können mittels geläufiger strömungsmechanischer Simulationsprogramme berechnet werden. Das einzige Problem liegt in der Simulation des Expansionsphänomens an sich, durch das die Teilchengröße und -dichte geändert werden, was wiederum die Berechnungen der Zweiphasenströmung beeinflußt.

In diesem Beitrag schlagen die Autoren ein Model zur Simulierung der Perlitexpansion vor, das auf den Ergebnissen von Grundlagenuntersuchungen beruht. Es basiert auf der Berechnung der Teilchentemperatur und -viskosität und bezieht damit die beiden wichtigsten Parameter der Expansion mit ein. Es erlaubt die Bestimmung der Perliteteilchengröße in Abhängigkeit von der Zeit oder der Teilchenbahn innerhalb des Ofens. Teilchengrößenverteilungen des expandierten Produkts können auf diese Weise bestimmt werden. Das Model wurde durch Vergleich der Ergebnisse mit industriellen und Laborexperimenten validiert.

1. Introduction

Despite an abundant literature about trading and utilization of perlite, there are very few papers treating the conception and dimensioning of furnaces for perlite expansion [1 to 3]. Murdock and Stein [1] describe different existing furnace concepts. The expansion techniques in vertical or horizontal furnaces are presented together with their advantages and shortcomings.

Sodeyama et al. [3] present a laboratory fluidized bed furnace concept for the expansion of very fine perlite. To our knowledge, the paper of Papanastassiou [2] is the only existing mathematical analysis of a vertical expansion furnace. He determines in his simplified model the maximal and minimal gas velocities in the furnace by estimating the residence time and trajectory length of the particles. From these parameters he defines rules for dimensioning and controlling of expansion furnaces. This very simplified model assumes constant perlite density and particle diameter. Velocity and temperature in the furnace are supposed to be uniformly distributed. These rather crude assumptions do not allow a more detailed analysis of the expansion process, as it would be necessary to optimize furnace operation.

For that purpose the change in particle size and density during expansion has to be taken into account, in order to simulate correctly the fluid motion in the ex-

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pansion furnace. A detailed analysis of the expansion process is only possible when the following are known:

- the geometry of the furnace and the burner,
- the two-phase flow field in the furnace,
- the imposed perlite and gas mass flows,
- the combustion process in the furnace,
- the heat transfer to the particles,
- the expansion phenomenon.

Numerical simulation of the expansion process in the expansion furnace can help perlite producers to decide about geometrical or operational changes on an existing furnace, or to evaluate the possibilities and flexibility of the furnace to work with other perlite qualities, granulometries etc. These calculations consist of the numerical simulation of the two-phase flow and combustion inside the furnace. Compared to other particle-laden flows, the change of perlite particle size during the particle's trajectory throughout the furnace has also to be modelled.

The simulation of this expansion phenomenon is very crucial for the results of such numerical predictions. It determines whether the results obtained with such a code are useful or not in an industrial context, since the expansion result (particle size, mass fractions) depends on the correct modelling of the expansion process. To our knowledge, there exists no model in the literature, simulating the expansion of perlite or comparable materials. In the mathematical analysis of Papanastassiou [2] the particles are supposed to have a constant diameter during expansion.

In this paper we propose a model in order to simulate the expansion of perlite which takes into account the major influencing parameters, which are:

- the chemical composition of the material and especially its water content;
- the heating of the particle.

Our model is based on the results of previous studies concerning the morphology of perlite [4 and 5], the simulation of bubble growth in perlite [6] and the expansion of single perlite particles under a well-controlled heat flux (laser heating) and observation of the temporal evolution of particle temperature and diameter [7].

2. Basic ideas and model assumptions

The basic ideas of the model, which resulted from previous studies, are:

a) The expansion of perlite needs the simultaneous presence of two phenomena:

- the formation of water vapour in the material and
- softening of the material.

b) The formation of water vapour depends on the water mass fraction in the raw material and on the particle temperature.

c) Softening of the material is characterized by its viscosity, which depends on the temperature and on the chemical composition of the material and especially on its water content [6].

Consequently the expansion model proposed here is based on the calculation of the particle temperature and viscosity as a function of time, by taking into account the particle properties and the flow conditions around the particle. A condition imposed on the viscosity of the particle will determine whether expansion takes place or not. This viscosity condition reflects the necessary softening of the material, which allows water vapour bubble growth. If expansion takes place, an imposed expansion ratio δ allows the determination of the new particle diameter. The expansion ratio is defined as the ratio of the radius or part of the radius of the expanded particle to that of the raw particle. This expansion ratio, as well as the viscosity condition, are parameters of the model.

The assumptions used for the model formulation are:

- The perlite particle is spherical.
- The perlite particle is locally surrounded by a spatially homogeneous environment (temperature, gas velocity). For a given particle, only temporal variations of these parameters are taken into account.
- The particle does not split during expansion. It can only expand, not expand or melt.
- Initially the particle has a homogeneous chemical composition throughout its volume. The only component which changes during expansion is the water content.
- Enthalpy does not change during expansion, the latent heat of vaporization of water is neglected.
- The expanded material contains a certain rest amount of water. This assumption is justified by water content measurements in industrially expanded perlite, where remaining amounts of up to 50 % of the initial water content can be found.
- Physical properties of the material change as a function of temperature and between expanded and non-expanded parts of the particle.

The viscosity of the glassy material can be calculated as a function of the chemical composition and temperature. In our study we use the method of Shaw [8], which has been validated by experimental data found in the literature and by comparison with the results of bubble growth calculations [6].

The particle temperature can be determined in two different ways: as a first step we suppose an isothermal particle, which leads to an isothermal formulation of the expansion model; then we will refine this model and take into acount the temperature profile inside the particle, which will result in a nonisothermal formulation of the expansion model. Both formulations are useful in different circumstances and will be presented in detail in the next sections.

3. Model formulations

3.1 Isothermal model

The temperature determination of the perlite particle is a very important part of the model formulation. It is also essential for the calculation time in a numerical simulation code. In a first step, the particle is considered as isothermal throughout its volume. Its temporal temperature evolution $\frac{\mathrm{d}T_\mathrm{p}}{\mathrm{d}t}$ during heating in a furnace can then be calculated from the convective and radiative surface heat fluxes ϕ_conv and ϕ_rad:

$$m_\mathrm{p}\, c_{\mathrm{p}_\mathrm{p}} \frac{\mathrm{d}T_\mathrm{p}}{\mathrm{d}t} = \phi_\mathrm{conv} + \phi_\mathrm{rad}\,. \tag{1}$$

The convective heat flux ϕ_conv at each trajectory point can be modelled empirically from the calculation of the local Nusselt number *Nu*.

$$\phi_\mathrm{conv} = \pi\, Nu\, \lambda_\mathrm{g}\, d_\mathrm{p} (T_\mathrm{sour} - T_\mathrm{p})\,,$$

$$Nu = 2 + 0.6 \cdot Pr_\mathrm{g}^{1/3} \cdot Re_{\mathrm{d}_\mathrm{p}}^{1/2}\,,$$

where $Re_{\mathrm{d}_\mathrm{p}} = \varrho_\mathrm{g} \cdot u_\mathrm{slip} \cdot d_\mathrm{p}/\mu_\mathrm{g}$, $Pr_\mathrm{g} = c_{\mathrm{p}_\mathrm{g}} \cdot \mu_\mathrm{g}/\lambda_\mathrm{g}$, $Nu = h \cdot d_\mathrm{p}/\lambda_\mathrm{g}$.

The thermodynamical properties (λ_g, $c_{\mathrm{p}_\mathrm{g}}$, ϱ_g and μ_g) of the surrounding gas phase, as well as the gas temperature T_sour and velocity difference u_slip between the gas and the particle velocities are the boundary conditions of the model (e.g. calculated as local values from the particle trajectory in a CFD code).

The radiative heat flux ϕ_rad can be determined from radiation calculations for the surrounding gas and furnace environment. Here we will simplify and suppose either a transparent gas and black-body behaviour of the furnace walls at temperature T_sour, or black-body behaviour at temperature T_sour of the surrounding gasses containing much soot. The radiative exchanges between particles are neglected, due to the very diluted two-phase flow.

$$\phi_\mathrm{rad} = \sigma \cdot d_\mathrm{p}^2 \cdot \pi \cdot \varepsilon_\mathrm{p} \cdot (T_\mathrm{sour}^4 - T_\mathrm{p}^4)$$

with $\sigma = 5.67032 \cdot 10^{-8}$ W/(m^2 K^4) the Stefan-Boltzmann constant.

This a priori rather crude assumption has been verified by temperature measurements in different expansion furnaces, where radiation in the furnace can mainly be described by a black-body behaviour of the furnace walls or of the soot in the gas flow.

The emissivity ε_p of crude perlite has been determined by laboratory measurements [7]. In the examined ranges, it does not depend on wavelength (0.4 to 1.1 µm and 2.75 to 12 µm) and temperature (670 to 867 °C) and a constant value of 0.8 can be adopted. The temperature change of the particle can then be calculated by equation (1).

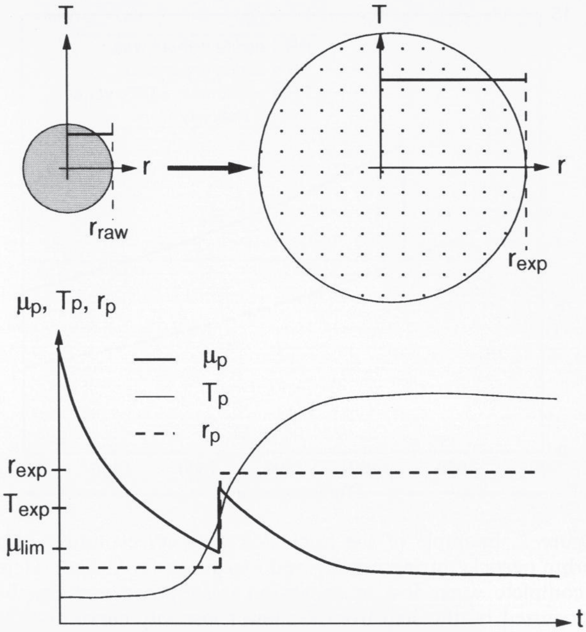


Figure 1. Scheme of the isothermal expansion model; variation of the particle temperature, viscosity and radius in function of time.

When the isothermal temperature of the particle at each trajectory position is known, its viscosity at the same position can be determined, e.g. with the method of Shaw [8], from its chemical composition and the temperature. As temperature T_p will increase during the particle trajectory, viscosity μ_p will decrease as a function of time (figure 1).

By comparing it with a limiting expansion viscosity μ_lim, where the material is sufficiently softened for expansion to take place, it can be decided if the particle expands or not. This limiting viscosity is the main parameter of the expansion model.

If the calculated viscosity is equal or smaller than the expansion viscosity μ_lim, the particle is expanded by an expansion ratio δ, which is also a parameter of the model, and the new particle diameter can be calculated (figure 1). The physical properties (ϱ_p, $c_{\mathrm{p}_\mathrm{p}}$, λ_p) of the particle are changed to the values for expanded perlite. Since expansion is due to the vaporization of a part of the water contained in the material, and since this water content has a major influence on viscosity [7], the calculated viscosity of the particle will increase instantaneously when expansion takes place (figures 1 and 2).

In a two-phase CFD code for the simulation of the whole expansion process, the particle, expanded or not,

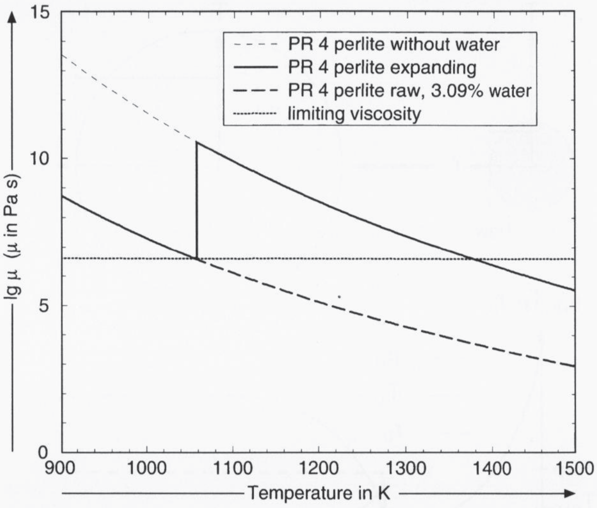


Figure 2. Example of the calculated viscosity evolution of a perlite particle during heating and expansion (bold line). Here a complete water loss at expansion is supposed and can be recognized by the step from the lower viscosity curve (3.09 % of water) to the higher curve (0 % of water). The limiting expansion viscosity (here $10^{6.6}$ Pa s) is shown by a horizontal dotted line.

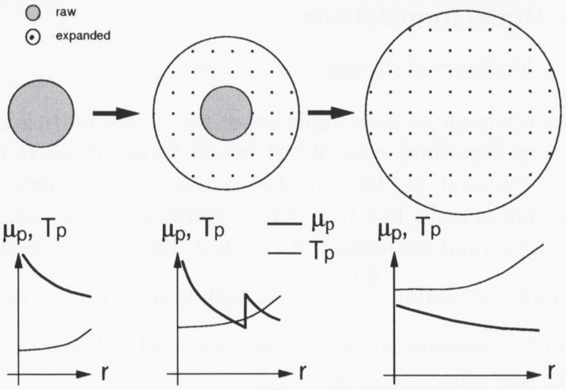


Figure 3. Representation of the nonisothermal expansion model, variation of particle temperature and viscosity as a function of its radius.

would then continue its trajectory in the furnace, eventually with its new physical properties and diameter.

In a numerical code, this isothermal expansion model has the advantage to allow a fast treatment of a large number of particles with a rather low calculation time. It can give a rapid approximation of the result of the expansion process, the percentage of expanded and nonexpanded material can be determined as a function of the operating conditions, such as temperature distribution, perlite injection position or gas velocity. The approximate residence time of the particles can also be determined with this model.

The assumption of an isothermal particle implies the assumption of an instantaneous expansion phenomenon (figure 1). Since the particle has the same temperature and chemical composition throughout its volume, the expansion condition is fulfilled everywhere at the same time. Particles with the same initial diameter expand, with the same imposed expansion ratio δ, to the same final diameter. Consequently with this model formulation, the total expansion ratio $D = d_{\text{exp}}/d_{\text{raw}}$ corresponds to the imposed model expansion ratio δ. The prediction of resulting size of mass fractions is thus not possible with this model.

Previous studies [5 to 7] showed that expansion is a rather rapid process (0.2 to 1 s), but also that its duration is not negligible compared to the residence time of particles in an expansion furnace (about 1 to 3 s). The heating time has a strong influence on the expansion result and the final particle size [7].

Due to this fact, the assumption of an isothermal particle represents a strong simplification of the expansion process, which does not allow the correct simulation of particle size distributions at the furnace outlet. The dynamics of the phenomenon is not taken into account. In a second step, we therefore formulate our model with a nonisothermal temperature calculation of the particle.

3.2 Nonisothermal model

In order to describe the dynamics of the expansion phenomenon, the temperature evolution inside the particles has to be determined. The heat transfer equation for the particle is therefore written in spherical coordinates as:

$$\frac{\partial T_p}{\partial t} = \frac{\lambda_p}{\varrho_p \cdot c_{p_p}} \left(\frac{\partial^2 T_p}{\partial r^2} + \frac{2}{r} \frac{\partial T_p}{\partial r} \right) \tag{2}$$

with boundary conditions:

$$- \lambda_p \cdot \frac{\partial T_p}{\partial r} = h \cdot (T_{\text{sour}} - T_p(R))$$

$$+ \sigma \cdot \varepsilon_p \cdot (T_{\text{sour}}^4 - T_p^4(R)) \quad \text{for} \quad r = R \,,$$

$$\frac{\partial T_p}{\partial r} = 0 \quad \text{for} \quad r = 0 \,.$$

The convective and radiative heat fluxes at the particle surface ($r = R$) are calculated in the same manner as in the isothermal model. The surrounding gas temperatures, velocities and properties once more can be determined in a numerical simulation or given as boundary conditions.

From the temperature profile inside the particle, calculated with equation (2), and the chemical composition of the material, a viscosity profile can be calculated (figure 3). This profile is compared to a limiting expansion viscosity μ_{lim}, and those parts of the particle are determined where:

$$\mu_p(r) \le \mu_{\text{lim}} \,. \qquad (3)$$

These parts Δr of the grain expand with an inner expansion ratio $\delta = \dfrac{\Delta r(\text{exp})}{\Delta r(\text{raw})}$, which is a parameter of the model. The particle now consists of a heart of raw perlite and an outer shell of expanded material (figure 3, centre). The outer shell takes the physical properties and water content of expanded perlite and the viscosity of this part increases due to the lower water content. This "composite" particle can now continue its trajectory and heating in the furnace.

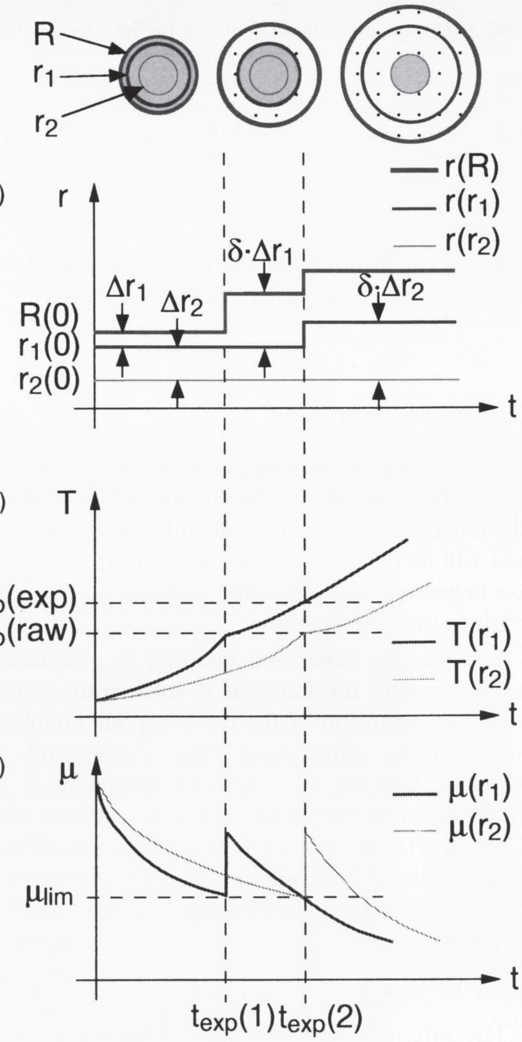
If the outer expanded perlite shell is softened once more sufficiently to fulfil relation (3), the next expansion step can take place. A new part of the particle with $\mu_p(r) \le \mu_{\text{lim}}$ will get expanded and take the properties of expanded perlite. Several steps like this will be necessary to expand the whole particle.

The temporal evolution of the radius, temperature and viscosity of two material layers (Δr_1 and Δr_2) during expansion can be represented as shown in figures 4a to c. The particle has an initial radius $R(0)$ (figure 4a). If it is heated, its temperature T increases (figure 4b) and the viscosity μ decreases (figure 4c). At $t_{\text{exp}}(1)$, the viscosity of the first layer $\Delta r_1 = R - r_1$ will be equal or smaller than μ_{lim}. The temperature of r_1 will, at that moment, be equal to the expansion temperature of the raw material $T_{\text{exp}}(\text{raw})$. The layer Δr_1 expands with the internal expansion ratio δ and the radius R of the particle increases by $\delta \cdot \Delta r_1$. The viscosity of that layer increases due to the water loss at expansion and the material hardens once more at the surface.

If heating of the particle is continued, the viscosity of the expanded layer $\delta \cdot \Delta r_1$ decreases again and will be equal to or smaller than the expansion viscosity μ_{lim} for a second time at $t_{\text{exp}}(2)$ (figure 4c) and expansion temperature $T_{\text{exp}}(\text{exp})$ (figure 4b). This is necessary for the expansion of the next layer, since it can not expand if it is surrounded by static hard material. At that moment, there will exist a radius r_2 inside the raw part of the particle, where the limiting viscosity μ_{lim} is also reached. The temperature of r_2 is equal to $T_{\text{exp}}(\text{raw})$ since the material is still crude at r_2.

Now the second expansion step takes place and the radius r_1 is pushed by $\delta \cdot \Delta r_2$ towards the surface (figure 4a). The particle radius R increases to a lesser extent, since mass has to be conserved in the first layer, which will narrow. The viscosity of layer Δr_2 increases due to the water loss.

If heating continues, the following expansion steps will happen in the same way until complete expansion of the particle. The particle diameter will increase by steps and complete expansion will not be an instantaneous process.



Figures 4a to c. Radius a), temperature b) and viscosity evolution c) of two expanding material layers ($R - r_1$ and $r_1 - r_2$) as a function of time. Expansion takes place at a limiting expansion viscosity μ_{lim}, which corresponds, for a certain perlite composition, to expansion temperatures $T_{\text{exp}}(\text{raw})$ for the raw material and $T_{\text{exp}}(\text{exp})$ for already expanded parts of the particle. δ is the model expansion ratio, a parameter of the model.

With this model, different particles with the same initial diameter will not expand to the same final diameter, since their trajectory and thus temperature history in the furnace will not be the same. Their total expansion ratio $D = d_{\text{exp}}/d_{\text{raw}}$ will be smaller than the inner model expansion ratio δ, depending on the number of expansion steps, during which the material layers are pushed towards the surface and during which they narrow since their mass has to be conserved.

Thus, particles with a shorter characteristic heating time will expand more rapidly and to a bigger final diameter than particles heated up very slowly. The final diameter will vary as a function of the residence time in differently heated zones of the furnace.

In a CFD code for the calculation of the particle trajectories, this model needs the resolution of the tem-

Table 1. Composition in wt% of raw perlite used in this study

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	Na_2O	K_2O	H_2O
74.7	11.6	1.08	1.29	0.51	0.1	3.65	2.84	3.09

perature equation (2) during the whole trajectory. This induces a strong increase in calculation time.

3.3 Model parameters

The expansion model makes use of three model parameters, which have to be chosen carefully in order to obtain reliable calculation results. Generally these parameters will be determined empirically from known expansion behaviour of the specific material during industrial or laboratory expansion.

a) The limiting expansion viscosity μ_{lim} represents the viscosity where the material is sufficiently softened to allow the expansion of the water vapour bubbles in the material. The value chosen here corresponds to the softening viscosity of different commercial glasses, whose chemical composition is in accordance with that of perlite [7]. The expansion ratio measurements of Bagdassarov el al. [9] also showed the biggest growth rate in that viscosity range. The numerical value of this "softening point" is:

$$\mu_{\text{lim}} = 10^{6.6}\ \text{Pa s}\,.$$

b) The internal expansion ratio δ represents the local growth ratio of a material layer at each expansion step of the nonisothermal expansion model. It has to be chosen as a function of the material and its expansion capacity in order to obtain a total particle expansion ratio D which corresponds to industrial values. In our nonisothermal example calculations we used a value of:

$$\delta = 5\,.$$

c) The water content of the material after expansion determines the viscosity of the outer, already expanded, material layers during the expansion process. If it is higher, the viscosity will be lower, and the limiting viscosity will be reached earlier. This means that the expansion will take less time. This parameter can be determined easily from chemical analysis of the industrially expanded perlite. For the material we used here, half of the initial water content was released during expansion. Thus the expanded material will contain 50 % less water than the raw material.

4. Model validation

The particle expansion model can be validated by comparison of the global expansion ratio D and the expansion duration to values known from the industrial expansion process and to laboratory expansion experiments [5 and 7].

Some typical results for the evolution of particle surface viscosity, surface temperature and particle radius are represented in figures 5a to c. They have been calculated with the nonisothermal model. The perlite composition corresponds to the chemical composition of Provatas perlite from the island of Milos in Greece (table 1).

The particle with a radius of 0.5 mm initially has a temperature of $T_0 = 500$ K, at $t = 0$ heating starts at its surface, with a thermal power of 5 W (figure 5b). The internal expansion ratio δ of the nonisothermal model is chosen as $\delta = 5$. The limiting expansion viscosity is $10^{6.6}$ Pa s.

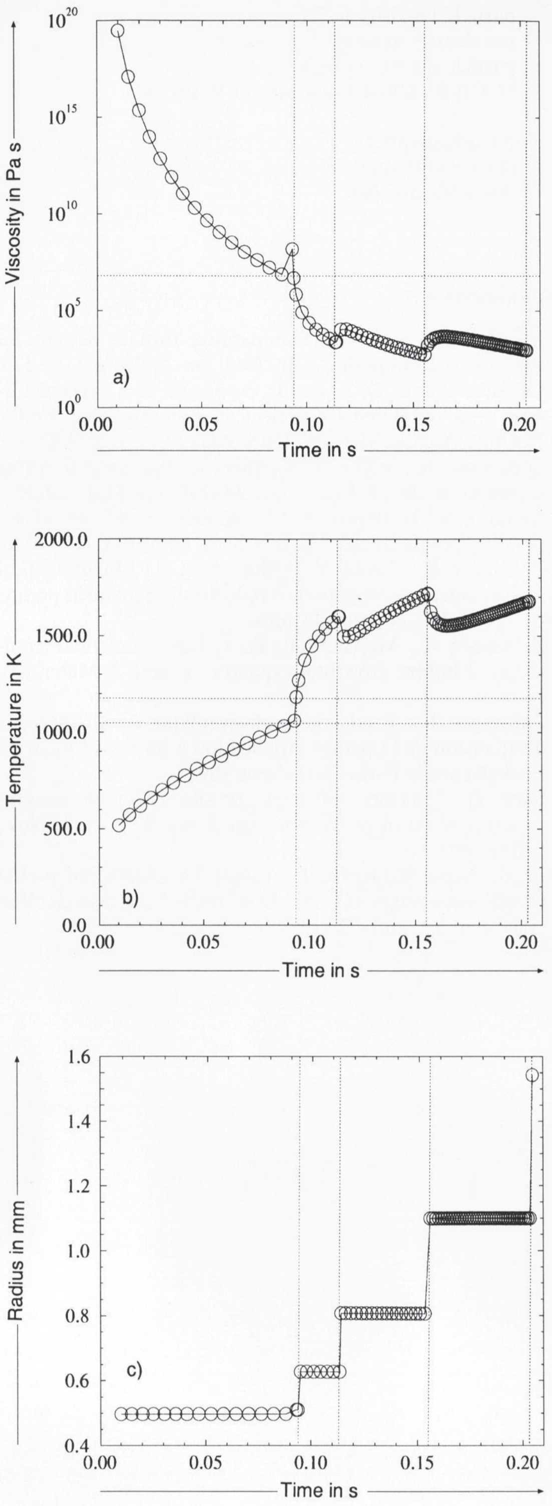
The four expansion steps of the particle are indicated on figures 5a to c by vertical lines. The limiting expansion viscosity μ_{lim} (figure 5a) and the corresponding temperatures for the specific raw T_{exp}(raw) and expanded T_{exp}(exp) material (figure 5b) are represented by horizontal dotted lines.

The surface viscosity decreases very rapidly after heating has started and the limiting viscosity μ_{lim} is reached after 0.093 s (figure 5a). At that moment, the surface has a temperature T_{exp}(raw) of 1056 K (figure 5b), and the first increase of the radius takes place (figure 5c).

The expanded material layer will reach a higher viscosity, since the water content, due to expansion, has been reduced to one half in that case. The particle will harden at its surface.

At $t = 0.113$ s, the particle is again sufficiently heated and the expanded surface layer reaches once more the limiting expansion viscosity (figure 5a). The corresponding temperature T_{exp}(exp) is 1190 K and the radius of the particle will grow further. Two further expansion steps will follow, during which the expansion viscosity is reached by the internal parts of the particle and the radius will grow at each step. After 0.20 s, expansion is completed and the particle radius has reached 1.55 mm, which corresponds to a total expansion ratio D of 3.1 (figure 5c).

If heating a particle of the same initial diameter (0.5 mm) with a thermal power of 10 W, its expansion begins earlier (after 0.035 s) and lasts longer (until $t = 0.15$ s). The final radius will be $r = 1.33$ mm and thus smaller than that of the first particle, since more expansion steps take place due to the steeper tempera-



Figures 5a to c. Temporal evolution of surface viscosity a) surface temperature b) and particle radius c). The expansion steps are marked with vertical dotted lines, the horizontal lines represent the expansion conditions (μ_{lim}, T_{exp}(raw) and T_{exp}(exp)).

ture gradient. Temperature at the end of expansion attains 2000 K. A real particle would have been melted at that temperature, so it is useful to introduce also a melting condition when doing calculations for a real furnace configuration.

The heating powers used in these calculations correspond to those encountered by particles during industrial expansion. The final calculated expansion ratio ($D = d_{\text{exp}}/d_{\text{raw}} = 3.1$ and 2.66) corresponds very well to mean values observed in industrial expansion ($D = d_{\text{exp}}/d_{\text{raw}} \approx 3$). The expansion duration is comparable to that observed in laboratory expansion experiments (0.2 s) [7].

The comparison of the model calculations with experimental data also shows two other effects: due to the higher temperature gradient inside the particle and the bigger number of expansion steps, the final particle diameter is smaller when the heating power is high; expansion will last longer when the heat flux is smaller, due to the slower viscosity change.

These quite satisfactory validation results for the new expansion model enabled us to employ it in a simulation code for the complete expansion process, in order to predict the expanded particle size fractions in an industrial vertical expansion furnace.

5. Conclusions

A model has been developed in order to simulate the expansion of perlite particles. This new model is based on the results of several previous studies. It supposes that expansion takes place if the material is heated up until it reaches a certain limiting expansion viscosity. At this viscosity, the material softens and bubble growth becomes possible. The main parameters of the expansion process are taken into account. These are the chemical composition with the water content, and the heat flux to the particle.

The model has been formulated in two different ways. A first formulation assumes an isothermal particle and allows a rapid estimation of the expansion result in a furnace. It does not allow the determination of expanded particle size fractions, since expansion is supposed to be an instantaneous phenomenon. The second model formulation takes into account the temperature profiles inside the particle. An expansion in several steps which propagates from the outside to the centre of the particle results. Particles with different temperature history will expand to different final diameters with this model. This allows the determination of expanded particle size statistics, but the model demands longer calculation time in a numerical simulation code.

This model enables the complete simulation of the expansion process in industrial expansion furnaces. The two-phase flow with combustion can be calculated by a CFD code, the introduction of the expansion model then allows the correct determination of the particle diameters and trajectories. Such calculations are a rather simple and low-cost way to obtain information about process variations and allow the optimization of the operating conditions of a furnace. Major industrial modifications can be anticipated in that way and industrial tests can be reduced to a minimum.

6. Symbols

$c_{\mathrm{p_g}}$	heat capacity of gas in J/(kg K)
$c_{\mathrm{p_p}}$	heat capacity of particle in J/(kg K)
d_{p}	particle diameter in m
d_{exp}	expanded particle diameter in m
d_{raw}	raw particle diameter in m
D	total expansion ratio
h	heat transfer coefficient in W/(m^2 K)
m_{p}	mass of particle in kg
r	radial coordinate in m
r_{exp}	expanded particle radius in m
r_{raw}	raw particle radius in m
R	surface radius in m
t	time in s
t_{exp}	expansion time in s
T_{exp}	particle expansion temperature in K
T_{p}	particle temperature in K
T_{sour}	temperature for radiation calculations in K
u_{slip}	slip velocity between particle and gas in m/s
δ	model expansion ratio
ε_{p}	emissivity of particle
ϕ_{conv}	convective heat flux in W
ϕ_{rad}	radiative heat flux in W
λ_{g}	heat conductivity of gas in W/(m K)
λ_{p}	heat conductivity of particle in W/(m K)
μ_{g}	dynamic viscosity of gas in Pa s
μ_{lim}	expansion viscosity in Pa s
μ_{p}	particle viscosity in Pa s
ϱ_{g}	gas density in kg/m^3
ϱ_{p}	particle density in kg/m^3
σ	Stefan-Boltzmann constant in W/(m^2 K^4)
Nu	Nusselt number
Pr_{g}	gas Prandtl number
$Re_{\mathrm{d_p}}$	Reynolds number

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