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Mathematical modeling and process simulation of perlite grain expansion in a vertical electrical furnace

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ABSTRACT

Expanded perlite is a lightweight material with remarkable thermal and acoustic insulation properties, rendering it widely useful in the construction and manufacturing industries. Currently applied perlite expansion technology suffers numerous technical disadvantages, which adversely affect product quality and limit the range of its applications. To overcome these established drawbacks, a new perlite expansion process has been designed on the basis of a vertical electrically heated expansion furnace. The novel furnace enables precise control of experimental conditions, in order to allow for efficient adjustment of particle residence time and internal temperature. The quality of expanded perlite strongly depends on raw material thermophysical properties as well as furnace operating conditions, and the experimental investigation of the isolated effect of each parameter on expanded product quality is technically cumbersome and extremely time-consuming and expensive.

A mathematical model for perlite grain expansion has been developed in order to perform a detailed numerical investigation of process efficiency, toward the optimization of the expansion process in the novel pilot-scale furnace. The dynamic model consists of ordinary differential equations for both air and particle heat and momentum balances, as well as nonlinear algebraic equations for both air and perlite melt thermophysical and transport properties, probing the air temperature distribution within the vertical electrical furnace as well as the particle velocity, temperature and size along its trajectory inside the heating chamber. The effect of raw material physical properties (raw feed origin, initial particle size, effective water content) as well as operating parameters (air inlet temperature and flowrate, furnace wall temperature) on evolution of the particle state variables is presented and discussed. Model results indicate perlite expansion is strongly affected by raw ore feed origin, size and water content. Moreover, operating conditions affect expansion considerably, and furnace wall temperature has the strongest effect on the final particle expansion ratio attained. The new dynamic model is instrumental towards achieving a detailed comprehension of perlite expansion in the vertical electrical furnace towards multi-parametric sensitivity analysis, process optimization and efficient control.

1. Introduction

Perlite is a naturally occurring volcanic siliceous rock which consists mainly of amorphous silica (70–76% wt.) but also contains smaller quantities of numerous other metal oxides (Al_2O_3, K_2O, Na_2O, Fe_2O_3, CaO, MgO). Perlite can be expanded

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Nomenclature

A	surface, m^2
a	air thermophysical property polynomial equation coefficient, dimensionless
Bi	Biot number, dimensionless
C_D	drag force coefficient
C_p	constant-pressure specific heat capacity, J kg^{-1} K^{-1}
D	diameter, m
E	expansion ratio, dimensionless
F	force, N
g	gravitational acceleration, 9.81 m s^{-2}
h	heat transfer coefficient, W m^{-2} K^{-1}
H	molar enthalpy, kJ mol^{-1}
J	VFT equation pre-exponential factor, Pa s
k	thermal conductivity, W m^{-1} K^{-1}
K	Morsi–Alexander equation coefficient, dimensionless
L	length, m
$\dot{m}$	mass flow rate, kg s^{-1}
M	molar mass, kg mol^{-1}
n	viscosity equation exponent, dimensionless
N	bubble steam molar mass, mol
Nu	Nusselt number, dimensionless
P	pressure, Pa
q	heat transfer rate, W
$\dot{q}$	heat transfer flux, W m^{-2}
Q	volumetric flow rate, m^3 s^{-1}
R	radius, m
R_g	gas constant, 8.3144 J mol^{-1} K^{-1}
Re	Reynolds number, dimensionless
s	Stefan–Boltzmann constant, 5.6703×10^{-8}W m^{-2} K^{-4}
S	shell thickness, m
T	temperature, K
U	velocity, m s^{-1}
V	volume, m^3
w	mass fraction, dimensionless
X	VFT equation pseudo-activation energy, dimensionless
Y	VFT equation characteristic temperature, K
z	vertical position coordinate, m

Greek letters

γ	acceleration, m s^{-2}
ε	emissivity, dimensionless
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Indices

a	ambient
b	bubble
B	buoyancy
c	convective heat transfer
ch	characteristic value
cr	critical value
D	drag
ev	evaporation
G	gravitational
i	initial value
in	inlet
m	melt
out	outlet
p	particle