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Pressure driven heat-up curves – A numerical and experimental investigation

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ABSTRACT

Furnace walls and bottoms frequently consist of a refractory concrete, which has to be replaced from time to time due to abrasion. After relining, the furnace has to reach its operating temperature again. During this heat-up process, there is a risk of explosive spalling caused by the pore pressure build-up inside the wet concrete. These explosions may be very dangerous to the crew and the furnace-site. Those risks are reduced till today by the aid of empirically developed heat-up instructions (heat-up curves). The application of these curves doesn't really prevent explosive spalling and it is very time-consuming. To improve the first heat-up procedure, the empirically developed heat-up curves are replaced by optimized ones developed by the aid of numerical modeling. These curves are characterized by a constant maximum pressure during the heat-up drying period, and they bring a significant reduction of both, the heat-up time and the maximum pressure inside the concrete. Furthermore their dependency on wall thickness and pressure limit is investigated, as well as effects of previously not expected conditions which can occure during the heat-up of concrete under industrial conditions. Additionally, an optimized heat-up curve is used to dry a concrete brick in a laboratory experiment showing the practical applicability. Good agreement is obtained for the predicted pressure and temperature devolutions and the measured ones.

1. Introduction

The development of wear resistant concrete applied to industrial furnaces resulted in low porosity refractory concrets. The furnace walls and bottoms are casted with wet material when the furnace lining is replaced. During the longsome first heat-up process the wet concrete structures are drying and water starts to evaporate inside the concrete pores. Because of the concrete's low permeability the generated vapour pressure can rise dramatically possibly exceeding the concrete's strength. Since the first heat-up process of an industrial furnace is a slow drying procedure, this mechanism is mainly blamed for the occurrence of explosive spalling of refractory concrets [1–4]. Explosive spalling leads to a long outage time of the furnace as well as to dangerous situations for the employees due to concrete lumps hurling through the air. Although these dangerous accidents occur regularly, the furnaces are heated up by the aid of empirically developed heat-up curves (HUC). These polygonal curves are specifying for example the wall-surface temperature over time. They are prescribing a very slow and inefficient heat-up to reduce – not avoid – the events of damage. Modeling the process provides a chance for reduction of the heat-up time and for getting an increase of safety at the same time. In the first section of this article a physical model is presented to simulate the first heat-up. Subsequently pressure-driven heat-up curves are developed by application of the model and also by the control theory. The third section includes application of a calculated pressure driven heat-up curve in a laboratory experiment.

2. Modeling and numerical results

The present model proceeds the research of Fey et al. published in Ref. [5] and it is completely adopted from this publication. It basically arises from the models reported by Tenchev et al. [6] and Davie et al. [7] improving earlier ones reported by Bazant et al. [8] and Gong et al. [9] who investigated drying of refractory concrete a few decades ago. In the following, the model will be introduced briefly and the most important effects in conjunction with the development of optimized heat-up curves will be explained.

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Nomenclature

Formula symbol

b	Klinkenberg factor, Pa
$c_{\mathrm{p},i}$	specific heat of phase *i*, J/(kg K)
$\overline{\rho c_\mathrm{p}}$	effective heat of concrete, J/(m^3 K)
$\overline{\rho c_\mathrm{p} \vec{v}}$	effective heat capacity rate of fluids inside the pore system, J/(m^2 K s)
$D_{\mathrm{a,v}}$	coefficient of diffusion for vapour in air inside the pore system, m^2/s
$D^{\infty}_{\mathrm{a,v}}$	coefficient of diffusion for vapour in air outside a pore system, m^2/s
D_b	coefficient of diffusion for sorptive bound water, m^2/s
$\dot{E}_\mathrm{d}$	rate of dehydration, kg/(m^{3}s)
$\dot{E}_\mathrm{l}$	rate of evaporation, kg/(m^{3}s)
$\triangle h_\mathrm{d}$	latent heat of dehydration, J/kg
$\triangle h_\mathrm{v}$	latent heat of evaporation, J/kg
$\vec{j}$	mass flux density, kg/(m^{2}s)
S	Pore Saturation with liquid water, –
S_ssp	Solid Saturation Point, –
k_k	Klinkenberg correction, –
k_g	relative permeability of gas phase *i*, –
k_l	relative permeability of liquid phase *i*, –
k	(intrinsic-) permeability, m^2
$\triangle m_\mathrm{d}$	relative mass loss due to dehydration, –
p_i	pressure of component *i*, Pa
ψ	porosity, –
φ	relative humidity, –
τ	tortuosity factor for diffusion, –
t	time, s
T	temperature, K
$\vec{v}$	velocity, m/s
η	dynamic viscosity, m^2/s
ε_i	volume fraction of phase *i*, –
λ	effective thermal conductivity, W/(m K)
ρ_i	density of phase *i*, kg/m^3
ρ^*_s	true density of solid phase, kg/m^3
$\bar{\rho}_i$	mass of phase *i* defined per unit volume of concrete *i* kg/m^3, volume of concrete *i* mass of phase *i* defined per unit volume of concrete *i* kg/m^3, volume of concrete *i*kg/m^3

subscripts

0	initial
a	air
b	bound
d	dehydration
fin	final
g	gas
huc	heat-up cuve
lim	limit
l	liquid
ref	reference
sat	saturation
s	solid
v	vapour

2.1. Governing equations

The macroscopic model is valid for a representative volume element based on three mass balances for liquid water, vapour and air and the energy balance where thermal equilibrium between gas, liquid and solid phases is supposed.

mass balance of liquid water

$$\underbrace{\frac{\partial \bar{\rho}_\mathrm{l}}{\partial t}}_{a} = \underbrace{-\nabla\cdot \vec{j}_\mathrm{l}}_{b} \underbrace{-\dot{E}_\mathrm{l}}_{c} + \underbrace{\frac{\partial \bar{\rho}_d}{\partial t}}_{d} \tag{1}$$

a rate of change of liquid water in a unit volume
b mass of transferred liquid water
c mass lost by evaporation
d mass gained from dehydration of chemically bound water

mass balance of vapour

$$\underbrace{\frac{\partial (\varepsilon_\mathrm{g} \rho_\mathrm{v})}{\partial t}}_{a} = \underbrace{-\nabla\cdot \vec{j}_\mathrm{v}}_{b} \underbrace{+\dot{E}_\mathrm{l}}_{c} \tag{2}$$

a rate of change of vapour in a unit volume
b mass of transferred vapour
c mass gained by evaporation

mass balance of air

$$\underbrace{\frac{\partial (\varepsilon_\mathrm{g} \rho_\mathrm{a})}{\partial t}}_{a} = \underbrace{-\nabla\cdot \vec{j}_\mathrm{a}}_{b} \tag{3}$$

a rate of change of air in a unit volume
b mass of transferred air

energy conservation

$$\underbrace{\left(\overline{\rho c_\mathrm{p}}\right)\frac{\partial T}{\partial t}}_{a} = \underbrace{\nabla\cdot(\lambda \nabla T)}_{b} - \underbrace{\left(\overline{\rho c_\mathrm{p} \vec{v}}\right)\cdot\nabla T}_{c} \underbrace{-\Delta h_\mathrm{V} \dot{E}_\mathrm{l}}_{d} \underbrace{-\Delta h_\mathrm{D} \frac{\partial \bar{\rho}_\mathrm{d}}{\partial t}}_{e} \tag{4}$$

a rate of energy change in a unit volume
b energy transferred by conduction
c energy transferred by convection
d energy required for evaporation of liquid water
e energy required for release of chemically bound water

The transport terms $\vec{j}_i$ include convective flow terms following Darcy's law [10] (*a*), the diffusive gas flow follows the law of de Groot [11] (*b*) and the diffusive adsorbed water flow [12] (*c*):

transport of gases