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Experimental and numerical investigation of the first heat-up of refractory concrete

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A B S T R A C T

The first heat-up of furnaces consisting of wet refractory concrete is a challenge due to the pore pressure build-up which can exceed the strength of the concrete. To extend understanding of the complex heat and mass transfer phenomena taking place during the first heat-up, two reproducible heat-up experiments are carried out. These are performed by using a new developed pore pressure sensor. The experiments exhibit an intense change of concrete's thermal conductivity during the process. Further, even in case of one sided heating, two drying fronts are found to occur. In addition to the experimental investigation the first heat-up is simulated using a physical model, based on the coupled balances of energy and the masses of liquid water, water vapour and air as well. By the aid of numerical simulation the first heat-up is further investigated and mass flow behaviour of air, vapour and liquid water is discussed. Within the scope of a sensitivity study the concrete's thermal conductivity and it's permeability are obtained as it's most important material properties and they are used for calibration of the model aiming well representation of the experimental data. The adjusted material properties are found to be in good agreement with refractory concrete properties reported in literature.

1. Introduction

The aspire after wear resistant concrete and a fast relining of furnaces leads in the resulted decades to low porosity concretes which are handled as wet material during the replacement of the furnace lining. These wet concrete walls are becoming dry by raising the furnace to its operating temperature. During the drying process the water in the pores of the wet concrete will start to evaporate and because of the low porosity and therefore low permeability the generated vapour can yield high pressures possibly exceeding the strength of the concrete parts. The result is spalling of the furnace walls and therefore a long outage time and danger to the crew. Because of that the first heat-up needs to be done very slowly and carefully but contrawise as fast as possible to get the furnace available quickly. Actually the first heat-up follows an empirically developed heat-up function which pretends for example the wall-surface temperature over time.

In order to improve safety and to reduce heat-up time the vapour pressures and temperatures are investigated experimentally and also by modelling the coupled process of heat and mass transfer. In the first section an experimental laboratory setup for pressure measurement is shown and the obtained pressure and temperature distributions will be discussed. In the second section a physical model is presented to simulate the first heat-up. In the third section experimental and numerical results will be compared.

2. Experimental investigations

Several experimental investigations of the pore pressure evolution during the heat-up of concrete can be found in literature. The most significant investigation in this field was done by Kalifa et al. [16] based on an experimental setup, including a pore pressure sensor which are both used by many researchers in almost every following investigation in this area. Kalifa et al.'s experiments are carried out on a single side heated concrete brick which is balanced during the heat-up to estimate it's mass loss due to evaporation of the liquid water. The presence of liquid water inside the concrete is due to the mixing procedure and furthermore to chemical transformations performing at typical temperatures during the heat-up. The pore pressures, which will rise strongly during evaporation of that water, are measured by Kalifa et al. by the aid of five pore

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Nomenclature

Formula symbol

b	Klinkenberg factor, Pa
$c_{p,i}$	heat capacity of phase i, J/(kgK)
$\overline{\rho c_p}$	effective heat capacity of concrete, J/(m^{3}K)
$\overline{\rho c_p}$	effective heat capacity rate concrete, J/(m^{3}K)
$D_{a,v}$	coefficient of diffusion for vapour in air inside the pore system, m^2/s
$D^{\infty}_{a,v}$	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
$\dot{E}_d$	rate of dehydration, kg/(m^{3}s)
$\dot{E}_l$	rate of evaporation, kg/(m^{3}s)
Δh_d	latent heat of dehydration, J/kg
Δh_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
Δm_d	relative mass loss due to dehydration, –
p_i	pressure of component i, Pa
ψ	porosity, –
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/(mK)
ρ_i	density of phase i, kg/m^3
ρ^*_s	true density of solid phase, kg/m^3
$\overline{\rho}_i$	mass of phase i defined per unit volume of concrete i, kg/m^3

subscripts

a	air
g	gas
l	liquid
s	solid
v	vapour
0	initial
b	bound
d	dehydration
ref	reference
sat	saturation

pressure sensors. Each of them is consisting of a sintered metal plate which is capsulated into a metal cup, see Fig. 1. The sensors are placed at different distances to the heated surface. In Kalifa et al.'s paper, the highest measured pressure was close to 40 bar. Further investigations by Kalifa et al. [17] and also by Mindeguia et al. in Ref. [19], done by an identical experimental setup, show how difficult reproducible pore pressure measurements are.

While these experiments were done using construction-concretes, Meunier et al. [18] investigated the first heat-up of three different refractory concretes using an identical experimental setup. The obtained pressure maxima are in the range of 20 bar but the experiments were not repeated, in contrast to the above mentioned papers. In some cases the curve shapes seem to be unrealistic, which could be explained by measurement errors.

Considering all these investigations it turned out that it is essential to repeat the experiments several times. Furthermore, it can't be excluded that the questionable results of pore pressure measurements and the lack of reproducibility are caused by misoperation of the pore pressure sensors.

2.1. Pore pressure sensor

Available pore pressure sensors are well described, e.g., in Refs. [1,16,17,21]. These often used kinds of sensors are measuring an averaged pressure above or inside a sintered metal plate which is capsulated into a metal cup. This cup is connected to a metal tube which is placed in normal direction to the isotherms. This tube leaves the block at it's cold side and it is connected to an ordinary pressure transducer. Further there is a thermocouple placed inside the tube to measure the temperature of the sintered metal plate. This kind of sensors have certain disadvantages to accurate temperature and pressure measurement. First, the metal tube with it's high thermal conductivity exhibits a fin-effect. Heat is transported from the point of measurement into the cold zones of the specimen. A temperature decrease of the metal plate, and with it a decrease of saturated vapour pressure will occur. Secondly, vapour, contained in the tube will condense in zones which are colder than the sintered metal plate unfortunately located directly behind the sintered metal plate. The liquified water will be re-evaporated when the drying front moves deeper inside the specimen, and pressure measurements will be influenced by these two effects. Another problem is connected with the existence of the metal cup into which the sintered metal plate is cramped. This cup is bigger than the sintered metal plate and it is impermeable for vapour, air and liquid water. Hence the field distributions behind the sensor will be disturbed as the fluids are not able to move through the measuring zone.

Because of these disadvantages a new sensor type was developed, see Fig. 2. Basic part of the measurement concept is again a porous sintered metal plate having a higher permeability than the surrounding concrete. The plate (40 × 40 × 2) mm is placed inside the specimen, parallel to the isotherms. It is needed to obtain a layer owing a permeability which is much larger ($k \approx 10^{-12}$ m^2, $\psi \approx 0.25$) than that of the concrete under investigation ($k \approx 10^{-15}$ m^2 to $k \approx 10^{-18}$ m^2). Secondly the pressure inside that plate will be equal to the averaged pressure at the plate's outer surface. In the next step, again a metal tube (6 × 2) mm is connected to this plate. It is, however, connected parallel to the isotherms to prevent condensation and fin-effects. During the heat-up, the vapour flowing from the concrete into the plate will build up a pressure increase inside. The remaining part of the vapour can move without further impediment through the porous metal plate into the deeper regions of the concrete. Again a thermocouple should be placed inside the tube to measure the plate temperature and to minimize the hollow-volume inside the tube (to approximately $2.8 \cdot 10^{-7}$ m^3). This kind of sensor will have less negative effects on the measurements than the earlier described ones and it's production is very simple and inexpensive. The latter aspect allows serial heat-up experiments.