A Drying and Thermoelastic Model of Fast Microwave Heating of Concrete

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Abstract – The use of high-power microwaves to perform explosive spalling of concrete surfaces is a promising technique with applications in the area of concrete facilities decommissioning. The mechanism that creates explosive spalling is due to a combination of the thermal stress from high temperature gradients and the pore pressure generated from the water vaporization and water transport through a porous medium. In this paper a one-dimensional model solving the heat and diffusion equations for liquid and vapor phase with the COMSOL Multiphysics finite element software is presented. The modelling of the drying process is based on the spatial reaction engineering approach (SREA). This paper discusses the influence of the relative activation energy parameter and effective diffusion coefficients on the temperature, water content and pore pressure in the case of fast microwave heating of concrete. This model is then used for a 3D geometry with a sealed insulated block of concrete and a conical waveguide antenna to compute the thermal stress, pore pressure and total stress.

Introduction

In the case of rapidly heated concrete with high power microwaves, evaporation, moisture transport and condensation mechanisms occur inside the porous material. The thermal stress [1] and pore pressure are calculated by using a coupled heat and mass transport equation together with the use of Lambert's law for the power density distribution [2, 3].

The spatial reaction engineering approach developed by Chen [4] is used to model the drying process of the material. The SREA method is successful in predicting the liquid content and temperature profile for different heating scenarios and many porous materials such as vegetables and fruits in the case of conventional convection drying [5, 6].

To simplify our model, the local liquid and vapor concentration are calculated with the assumption of a closed pore volume and an ideal gas law for the behavior of the vapor and air. In the 3D coupled electro-thermo-mechanical model, the complex permittivity and the thermal properties of the concrete are a function of the solid, liquid and gas phase content. The computation of the temperature, liquid and vapor content allow the calculation of the total pressure. The pore pressure is combined with a thermo-elastic model to compute the total stress. The novelty of this work is the use of the SREA approach to compute the liquid and vapor water content distribution in the concrete under microwave heating.

Mathematical modelling

With a 1D model, the power density from the microwave field is modelled with an exponential attenuation through the thickness (Lambert's law). The attenuation constant is obtained with a 3D electromagnetic model of a conical antenna. For a feasible permittivity for concrete of $\varepsilon_r = 6 - 0.68j$ at 2.45 GHz, the skin depth for the electric field is about 4 cm and the attenuation constant is $\alpha = 23.9$ [1/m]. The power distribution used in the 1D model is: $q(x) = q_0 \exp(-2\alpha x)$ with $q_0 = 70$ MW/m^3. This leads to maximal temperatures around

300° C in 10 s in agreement with the experimental temperature measurements made with an infrared camera.

The following assumptions are made to model the heat and mass transfer in a porous sample of concrete:

- The effect of solid shrinkage or expansion on heat and mass transfer processes is not taken into account. For concrete the volume variation is negligible.
- Cracks formation and sudden increase of permeability are not modelled.
- The porous medium is homogenous and isotropic.
- The diffusion coefficients are assumed to be constant; in reality they depend on temperature and water content, and probably thermal stress.
- The evaporation/condensation rate is related to the difference between the internal saturated vapor concentration $C_{int,sat}$ and the actual vapor concentration C_v inside the solid.
- The saturated vapor density is obtained with the Clapeyron equation.
- Because of fast microwave heating and for simplification of the analysis, the volume is sealed and thermally insulated: no heat flux or mass flux cross its boundaries.
- The initial temperature and moisture content are uniformly distributed.
- The water vapor and the air phase follow the ideal gas law.

The spatial distribution of the liquid C_l and vapor content C_v are calculated with the coupled heat transfer and diffusion equations as shown in Table 1. D_l and D_v are the effective diffusion coefficients of the liquid and vapor phase through the material and depend on its microstructure, temperature, water content and pressure gradients. In our model, D_l and D_v are assumed to be constant to facilitate the interpretation of the solution of the coupled heat and mass transfer equations. In addition, because of fast heating with 10 s duration, it is assumed that $D_l = 0$. The basic idea to model the drying process with the SREA approach is to consider the evaporation as an activation process, which can be described by an Arrhenius equation.

The SREA approach to model the drying of a porous medium considers that additional energy is required to evaporate the liquid inside the solid porous medium (comparable to the evaporation of liquid in free space, but less energy is needed). The evaporation/condensation term is modified and proportional to the difference between the internal saturated vapor concentration $C_{int,sat}$ and the actual concentration C_v.

The internal saturated vapor concentration is scaled with an exponential function from the known saturated vapor concentration in free space (obtained with Clapeyron equation or thermodynamic table).

$$C_{\text{int},sat} = \exp\left(-\frac{\varDelta E_v}{RT}\right)C_{v,sat} \tag{1}$$

$\varDelta E_v$ is the apparent activation energy and can be expressed with a relative energy function f:

$$\varDelta E_v = f(X_l, X_0, X_f)\varDelta\varDelta_f \quad ; \quad \varDelta E_f = -RT_f \ln(RH_f) \tag{2}$$

$\varDelta E_f$ represents the equilibrium activation energy of the dry state with RH_f and T_f the relative humidity and the temperature of the finale dry state. X_0 and X_f are the initial and final water content respectively. When the current vapour concentration C_v is lower (higher) than the internal saturated vapor concentration $C_{int,sat,}$ vapour is produced (consumed) with $I\varDelta H$ being the power per unit volume absorbed (released) by the system during the evaporation (condensation) process. For drying modelling based on the SREA; the relative activation

Table 1. Physical Models and Corresponding Equations Used in the Coupled Multiphysics Model

Physics	Equations	Input	Output	BC
Heat transfer (a)	$\rho c \dfrac{\partial T}{\partial t} = \nabla . k \nabla T + q_{em} - I \Delta H$	q_{em} T_0	T	$\vec{n}.\nabla T = 0$
Liquid diffusion (b)	$\dfrac{\partial C_l}{\partial t} = \nabla . D_l \nabla C_l - I; \quad X_l = \dfrac{m_l}{m_s} = \dfrac{m_l/V}{m_s/V} = \dfrac{C_l}{C_s}$	I C_{l0}	C_l	$\vec{n}.\nabla C_l = 0$
Vapor diffusion (c)	$\dfrac{\partial Cv}{\partial t} = \nabla . D_v \nabla C_v + I$	I $C_{v0} \approx 0$	C_v	$\vec{n}.\nabla C_v = 0$
Evaporation/ Condensation Coupling term (d)	$I = h_{in} A_{in}(C_{int,sat} - C_v); \quad X_v = \dfrac{m_v}{m_s} = \dfrac{m_v/V}{m_s/V} = \dfrac{C_v}{C_s}$	$C_{v,s}$ C_v	-	-
Mechanics, thermo-elastic model pressure contribution (e)	$\rho \overset{\rightarrow}{\ddot u} - \nabla . \overset{\rightarrow}{\bar\sigma} - \vec\kappa = 0 \quad \rightarrow \quad \nabla . \bar\sigma = 0$ (quasi static approx.) $\bar\sigma = \bar\sigma_0 + \dfrac{E \, v}{1 + v}\bar\varepsilon + \dfrac{E \, v}{(1 + v)(1 - 2v)} tr(\bar\varepsilon)\bar{I}$ $- \alpha \bar{I} \dfrac{E}{1 - 2\upsilon}\Delta T$	T p $\bar\sigma_0 = -p\bar{I}$	$\vec{u}$ $\bar\sigma$	$\vec{n}.u = 0$ On all faces, except the front face.

(E = 30 GPa, v = 0.12, α = 10^(-5) [1/K])

energy function should be extracted from water loss measurement versus time during a drying experiment [6].

The function can be of the form:

$$f = \left(\frac{X_0 - X_l}{X_0 - X_f}\right)^n \quad ; f(X_0) = 0 \, ; f(X_f) = 1 \tag{3}$$

At the initial wet state, maximum evaporation occurs, and with $f = 0$ and using eq (1) and (2), $C_{int,sat} = C_{v,sat}$. For $f = 1$, $C_{int,sat} \sim 0$ and limited or no evaporation will occur.

It was not possible to obtain such a function during this short duration of microwave heating and we consider here only the two extreme values of the relative activation energy function $f = 0$ (maximum evaporation) and $f = 1$ with nearly no evaporation. In the case of maximum evaporation, the coupling term (d) from table 1) becomes $I = h_{in} A_{in}(C_{v,sat} - C_v)$. For the case of no evaporation, $I \approx 0$. h_{in} [m/s] is the internal mass transfer coefficient, A_{in} [m²/m³] is the internal surface area. These two parameters depend on the microstructure of the material.

Results and Discussion

1D Model

The power density, temperature, pore pressure and Von Mises stress are plotted for 3 different vapour diffusion coefficients $D_v = (0.01, 10^{-4}, 10^{-9})$ m²/s.

Figure 1 shows the effect of evaporation near the surface of the concrete. As the diffusion increases, the maximum of the power density shifts inside the material.
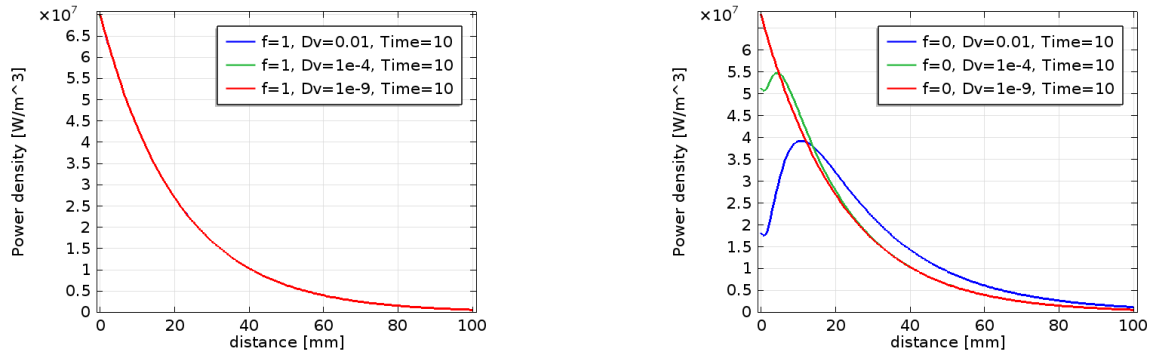
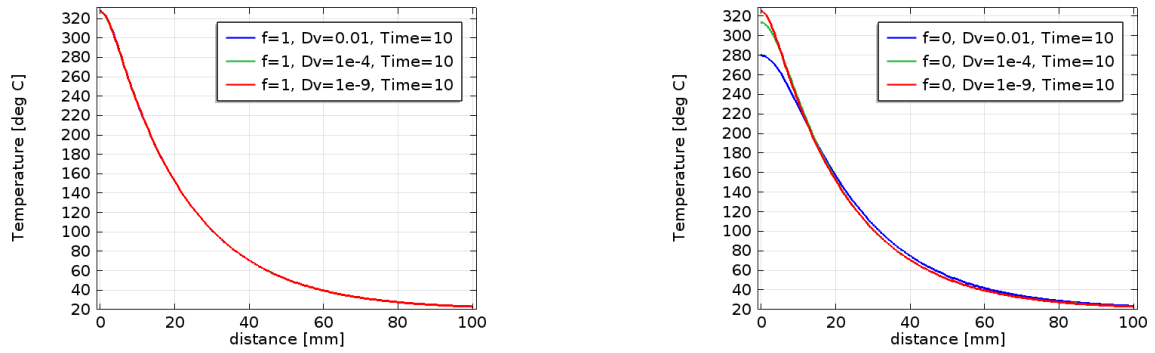Fig. 1: Power density with no evaporation ($f = 1$, left) and with evaporation ($f = 0$, right).

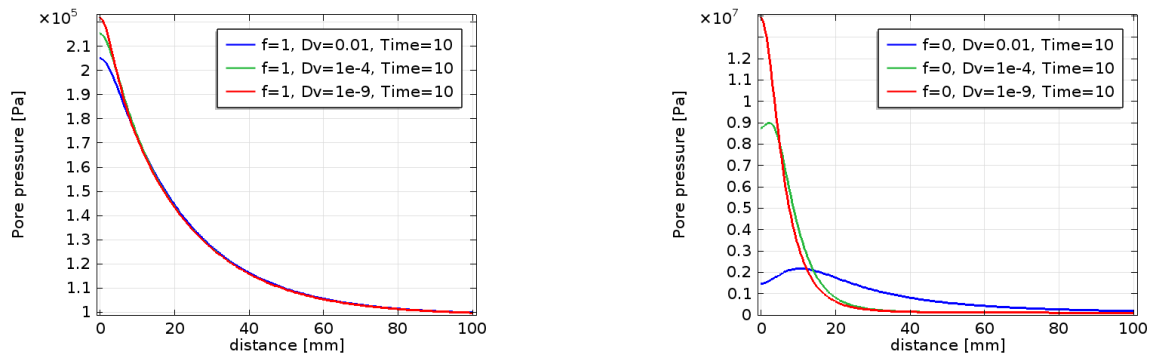Fig. 2: Temperature at $t = 10$ s through the thickness ($f = 1$, left, $f = 0$, right).

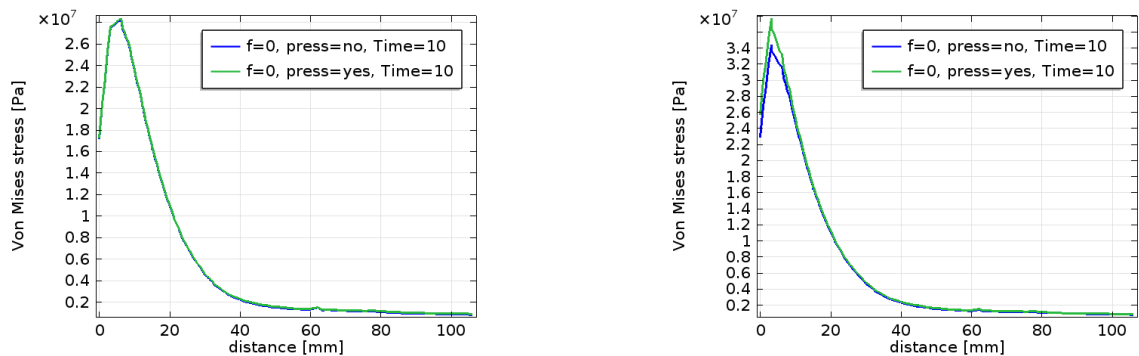Fig. 3: Total pressure without evaporation (left) and with evaporation (right).

Fig. 4. Von Mises stress [Pa] for $D_v = 0.01$ m^2/s (left) and $D_v = 0$ m^2/s (right) with pore pressure included (green) and no pressure (blue).
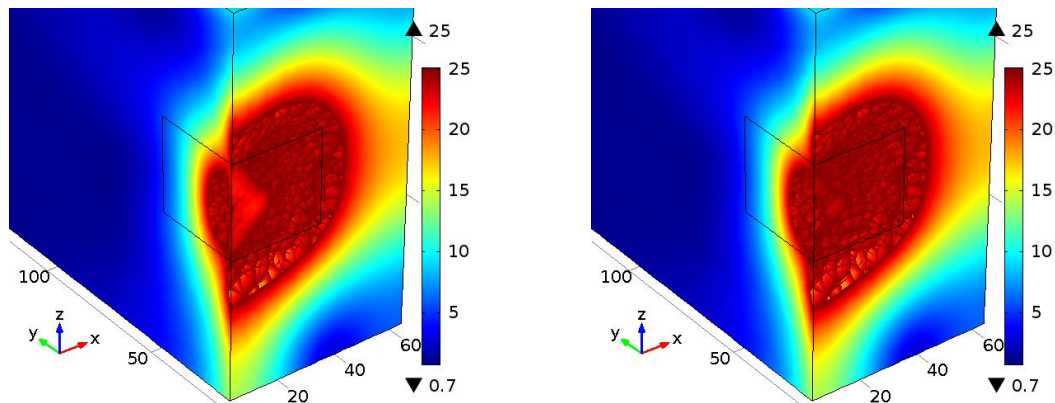
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Fig. 5. Von Mises stress [MPa] after 10 s of microwave heating at 10 kW and no vapour diffusion possible $D_v = 0$ m^2/s. Left picture with no pore pressure from evaporation, right picture with pore pressure from evaporation included. The domains with stress higher than an arbitrary limit of 25 MPa are removed.

Figure 2 shows the temperature within the concrete as a function of the distance to the surface without and with evaporation for three diffusion coefficients. For the largest vapour diffusion coefficient, the difference between temperature with and without evaporation is about 40°C.

Figure 3 shows the calculated pore pressure based on the vapour and air concentration. With no evaporation, the maximum pressure is located at the surface and is about 0.2 MPa. The pressure is mainly due to air and vapour expansion from high temperature. With evaporation, pressures are much higher and about {14, 9, 2} MPa for $D_v = \{10^{-9}, 10^{-4}, 0.01\}$ m^2/s respectively. The maximum is no longer at the surface, but located approximately {5, 10} mm inside for $D_v = \{10^{-9}, 10^{-4}, 0.01\}$ m^2/s.

3D Model

The 3D model allows the computation of the total stress based on the thermal stress and the pore pressure.

Figure 4 shows the Von Mises stress within the concrete as a function of the distance to the surface for two different diffusion coefficients $D_v = \{0, 0.01\}$ m^2/s. The stress is lower when the diffusion of vapour increases. (With $D_v = 0.01$, maximum stress about 28 MPa 8-10 mm inside the concrete). With $D_v = 0$, the stress is about 38 MPa with the pore pressure and 34 MPa without. The thermal stress is clearly dominant in comparison to the pore pressure.

Figure 5 shows the Von Mises Stress inside the concrete. The left picture shows the calculated stress without the pressure from vapour evaporation and the right picture shows the stress including the pressure effect. It can be seen than a small region located at the surface is present (the stress is lower than 25 MPa) whereas with the pressure effect, this domain has stress above this limit and is not represented in the picture. Typical properties of normal strength Portland cement concrete are 2 to 5 MPa for the tensile strength and 20 to 40 MPa for the compressive strength.

Conclusion

A coupled multiphysics model based on heat and mass diffusion equations was developed in order to compute the total stress and compare the thermal stress with the pore pressure. From these first results it seems that the thermal stress is the dominant effect in the case of

explosive spalling of concrete with microwave heating. The pore pressure could have a trigger mechanism role as suggested by Bazant [2].

The use of the SREA approach provides a quick way to model the liquid and vapour content in order to calculate the pore pressure. In this study the relative activation energy function was not available from experiment and therefore only two extreme cases were studied, maximum evaporation and no evaporation.

Acknowledgements

References

[1] B. Lepers, S. Soldatov, G. Link, and J. Jelonnek, A thermoelastic model for microwave ablation of concrete, *14th AMPERE Conf. Microwave and High Frequency Heating, Nottingham UK, 2013*, pp. 217-220.

[2] Z.P. Bazant and W. Thonguthai, Pore pressure and drying of concrete at high temperature, *J. Engineering Mechanics Division*, vol. 52, pp. 1059-1079, 1978.

[3] A. Akbarnezhad and K. Ong, Thermal stress and pore pressure devolopment in microwave heated concrete, *Computers and Concrete*, vol. 8, no 4, pp. 425-443, 2011.

[4] X.D. Chen, The basics of a reaction engineering approach to model Air drying of small droplets or thin layer materials, *Drying Technology*, vol. 26, pp. 627-639, 2008.

[5] X.D. Chen and A. Putranto, Spatial reaction engineering approach as an alternative for non equilibrium multiphase mass transfer model for drying of food and biological materials, *AIChE J.*, vol. 59, no 1, pp. 55-67, 2013.

[6] X.D. Chen and A. Putranto, *Modeling Drying Processes: A Reaction Engineering Approach*, Cambridge University Press, 2013.