



Modelling heat and moisture transfer in timber exposed to fire



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ABSTRACT

The paper presents a simplified model for coupled heat and moisture transfer and charring behaviour of timber exposed to fire. A numerical method to calculate temperature, bound water, water vapour and pressure distribution over two dimensional domain in timber specimen exposed to fire was developed. In the model, a modified description of sorption for the temperatures above the boiling point is proposed. In addition, the model also accounts the char formation. Due to the non-linear system of governing equations describing coupled heat and moisture transport, together with the char formation, the solution is obtained numerically with the finite element method. Finally, the result from the numerical analysis are validated against experimental measurements.

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1. Introduction

The behaviour of wood exposed to fire is highly dependent on its material structure and chemical composition. Being non-homogeneous, porous and hygroscopic material, the heat and moisture transport in timber exposed to fire represents a complex system of coupled processes. The transfer of moisture takes place along several transport paths. These are related to the different phases of water observed inside timber. In case of timber in buildings, wood fibres are usually below saturation point. Therefore only bound water and water vapour is present in the timber. Water vapour transfer is restricted to the cell cavities, lumens, rays and canals, whereas the bound water transfer takes place within the cell walls [1]. Similarly, the transfer of heat in timber takes place along different transport paths as well. Furthermore, wood is flammable and combustible material. Exposed to fire it is subjected to thermal degradation or so-called pyrolysis [2,3]. As described, the problem of heat and moisture transfer together with the pyrolysis of timber presents highly complex process. The phenomenon is transient, non-linear and the material properties of separated phases (solid, liquid, gas) are state dependent.

Many models for coupled heat and moisture transfer were developed in the nineties, mainly with the purpose to simulate the drying of wood. Di Blasi [4] simulated multi-phase moisture transfer in the high-temperature drying of wood particles. The model accounted for the convective and diffusive transport of gas

(vapour and air), capillary water convection in the pores and bound water diffusion in the solid wood. In the energy equation latent heat of evaporation due to the phase change between free water and vapour was taken into account. Similar model was developed by Johansson et al. [5] where convective drying of wood with super heated steam was considered. A comprehensive 2D and 3D drying model was developed by Perré et al. [6,7]. Nijdam [8] developed a high-temperature drying model especially for softwood timber. More recent work in this field was presented by Turner et al. [9] where product of pyrolysis were included in a coupled heat and moisture transfer model in the temperature range of 200–260 °C.

The present study will continue in this line of work. The model presented in the following is developed to be applicable for timber exposed to fire. For this reason, temperature dependent charring is implemented. Since charring depth increases during fire, moving boundary surface to prescribe vapour flux and pressure at the contact between virgin timber and char layer is introduced. Furthermore, the model accounts for a modified description of sorption suitable for the temperatures above the boiling point of water. Finally, the diffusion of bound water is refined by also including the Soret effect.

2. Governing equations

Mathematically, coupled problem of heat and moisture transport is described with a system of continuity equations for mass conservation, supplemented with an equation describing the conservation of enthalpy. In the following parts of this section all the governing equations for the coupled problem are described.

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2.1. Conservation equations

Mass conservation equations are written for each phase:

$$\text{bound water : } \frac{\partial c_b}{\partial t} + \nabla \cdot \mathbf{J}_b = \dot{c} \quad (1)$$

$$\text{water vapour : } \frac{\partial(\varepsilon_g \tilde{\rho}_v)}{\partial t} + \nabla \cdot \mathbf{J}_v = -\dot{c} \quad (2)$$

$$\text{air : } \frac{\partial(\varepsilon_g \tilde{\rho}_a)}{\partial t} + \nabla \cdot \mathbf{J}_a = 0 \quad (3)$$

The concentration of bound water c_b is defined per unit volume of timber. The concentrations of water vapour and air, $\tilde{\rho}_v$ and $\tilde{\rho}_a$, are defined per unit volume of gaseous mixture. ε_g is the porosity of timber. Mass fluxes for bound water, water vapour and air, \mathbf{J}_i ($i = b, v, a$), are defined per unit volume of timber. \dot{c} is sorption rate which interconnects mass conservation of bound water and water vapour, ∇ is the nabla operator.

The enthalpy conservation equation is:

$$\begin{aligned} \frac{\partial}{\partial t} (c_b h_b + \varepsilon_g \tilde{\rho}_v h_v + \varepsilon_g \tilde{\rho}_a h_a + \rho_0 h_0) \\ = - \underbrace{\nabla \cdot (h_b \mathbf{J}_b + h_v \mathbf{J}_v + h_a \mathbf{J}_a)}_b + \underbrace{\nabla \cdot (\mathbf{k} \nabla T)}_c \end{aligned} \quad (4)$$

The change of enthalpy of timber (term a) is balanced by the heat conduction (term c) as well as heat convection through mass transport of each moving media ($\alpha = b, v, a$) with its enthalpy h_α (term b). The \mathbf{k} matrix contains thermal conductivities for the different timber direction. The density and enthalpy of dry wood are denoted ρ_0 and h_0 respectively.

2.2. Constitutive relations

2.2.1. Bound water

Bound water transfer in the cell wall is driven by concentration (∇c_b) and temperature gradients (∇T). Mathematical model for this was proposed in [10] as:

$$\mathbf{J}_b = -\mathbf{D}_b \nabla c_b - \mathbf{D}_{bT} \nabla T \quad (5)$$

In (5), the Soret effect is recognised as the second term in the right side. The matrices \mathbf{D}_b and \mathbf{D}_{bT} contains diffusion coefficient and thermal coupling diffusion coefficients. They are derived from:

$$\mathbf{D}_b = \mathbf{D}_0 \exp\left(-\frac{E_b}{RT}\right) \quad (6)$$

$$\mathbf{D}_{bT} = \mathbf{D}_b \frac{c_b E_b}{RT^2} \quad (7)$$

where R is the universal gas constant and the diffusivity matrix \mathbf{D}_0 contains base values for diffusion coefficient in the different material directions, i.e., longitudinal and transverse (D_L^0 and D_T^0).

Water is bound to wood by hydrogen bonds between water molecules and hydroxyls or carboxyls groups of the wood polymer chains. Energy required to break hydrogen bond E_b is according to [11]:

$$E_b = (38.5 - 29m) \cdot 10^3 \quad (8)$$

where moisture content is defined as:

$$m = \frac{c_b}{\rho_0} \quad (9)$$

The increase of diffusion coefficients over base values for diffusion coefficient as a function of moisture content is presented in Fig. 1. The results are shown for different temperatures. It is observed that D_{bT}/D_0 is significantly larger than D_b/D_0 at elevated temperatures ($T > 100^\circ\text{C}$) and at moisture content above 15%. It is concluded that bound water flux in this range of temperatures and moisture content is driven mainly by the Soret effect.

2.2.2. Water vapour and air

The gaseous mixture inside timber, excluding the products of pyrolysis, is comprised of water vapour and air. The gas mixture concentration is therefore defined as: $\tilde{\rho}_g = \tilde{\rho}_v + \tilde{\rho}_a$. Convection of gas in porous media is driven by pressure gradient as described by Darcy's law. Furthermore, the diffusion between water vapour and air and is defined by Fick's law. The fluxes of air and vapour are therefore:

$$\mathbf{J}_a = \varepsilon_g \tilde{\rho}_a \mathbf{v}_g - \varepsilon_g \tilde{\rho}_g \mathbf{D}_{av} \nabla \left(\frac{\tilde{\rho}_a}{\tilde{\rho}_g}\right) \quad (10)$$

$$\mathbf{J}_v = \varepsilon_g \tilde{\rho}_v \mathbf{v}_g - \varepsilon_g \tilde{\rho}_g \mathbf{D}_{va} \nabla \left(\frac{\tilde{\rho}_v}{\tilde{\rho}_g}\right) \quad (11)$$

Following the Darcy's law, the velocity of gaseous mixture, \mathbf{v}_g , is:

$$\mathbf{v}_g = \frac{\mathbf{K} \mathbf{K}_g \nabla P_g}{\mu_g} \quad (12)$$

The \mathbf{K} matrix contains specific permeability of dry wood for different material directions, K_g is relative permeability of gas, μ_g dynamic viscosity of gas and ∇P_g gas pressure gradient. According to the Dalton's law, the pressure of gaseous mixture is equal to the sum of partial pressure of air and partial pressure of water vapour: $P_g = P_a + P_v$. It is assumed that the ideal gas law can describe the pressures with sufficient accuracy:

$$P_a = R_a \tilde{\rho}_a T \quad (13)$$

$$P_v = R_v \tilde{\rho}_v T \quad (14)$$

Diffusion coefficient of air into water vapour \mathbf{D}_{va} is identical to the diffusion coefficient of water vapour into air \mathbf{D}_{av} . They are defined in [12] as:

$$\mathbf{D}_{av} = \zeta 1.87 \left(\frac{T^{2.072}}{P_g}\right) \cdot 10^{-5} \quad (15)$$

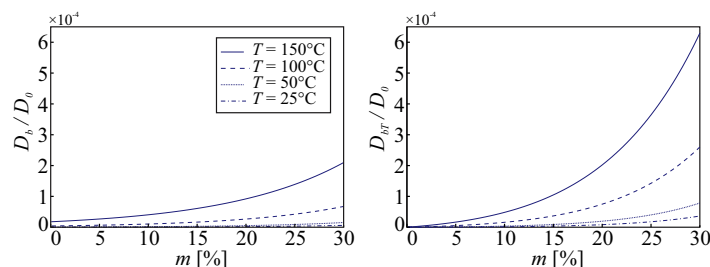


Fig. 1. The development of D_b/D_0 and D_{bT}/D_0 as a function of moisture content, at different temperatures. Data used: $\rho_0 = 500 \text{ kg/m}^3$, $R = 8.314$.

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