Heat flux measurements for determination of the liquid water diffusivity in capillary active materials

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ABSTRACT

A method is described to determine the liquid water diffusivity in capillary active materials and a model for the mathematical description of this material property is proposed.

Heat flux measurements by means of a guarded hot plate apparatus are employed for the assessment of the total energy transfer through dry and water-saturated calcium silicate samples. The radiative and conductive contributions to the heat transfer are estimated using an empirical model and separated from the enthalpy fluxes, connected to the water (liquid and vapor) transfer. After mathematical transformation the liquid water diffusivity can be calculated.

The proposed method differs significantly from other procedures generally employed to the same aim, and is advantageous since no further equipment but a guarded hot plate and a balance is needed.

Considerations on the effect of the water content on the vapor diffusion resistance factor are made, taking into account the experimental results.

The obtained results are compared with data by other authors and an error estimation is included.

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1. Introduction

A prerequisite for the proper planning of a building insulation system according to high energy efficiency standards is a deep knowledge of heat, vapor and liquid water transfer in the employed materials. This is particularly relevant in cases where an existing building is refurbished by applying internal insulation [1]. For this reason, a great effort in both numerical modeling and experimental research has been recently made to correctly describe the hygrothermal behavior of construction materials and building components [2–7]; the purpose of this work is to extend this knowledge, focusing on the material scale.

In view of this, a semi-empirical function for mathematical description of the liquid water diffusivity is proposed, where a physical interpretation is given considering both the phenomena contributing to the liquid transfer, means surface diffusion and capillary suction. Moreover, a new procedure is introduced to determine this material parameter.

A review of existing methods for experimental determination of the liquid water diffusivity is reported in Table 1. The considered methods differ for the kind of performed experiments, the water content range in which the diffusivity is determined and the employed mathematical procedure.

Method A allows direct determination of the capillary water flux and liquid water distribution through a sample at steady state conditions.

Methods B, D and E are based on transient absorption or desorption tests: the water content distribution inside a material sample is measured at different times using, for instance, NMR (nuclear magnetic resonance), X-ray or γ-ray method; then, an analytical procedure (e.g. Boltzmann transformation) is applied for direct calculation of the liquid water conductivity.

In other cases (C and F) the liquid water diffusivity is derived from the pore size density distribution by assuming simplified capillary models (cylindrical, parallel capillaries) and applying the Hagen–Poiseuille law. The mathematical form obtained in this way contains one or more empirical parameters to be determined by inverse procedure, through comparison with absorption or desorption trends. Similarly, in method G a relation between the liquid water diffusivity and the water content is assumed. The model is calibrated using a water-uptake test.

Method H is based on diffusion tests and can be applied in the hygroscopic range only (relative humidity below 95%).

Since in all cited cases experiments are performed under isothermal conditions, the fluxes of vapor and liquid are superimposed and some difficulty may arise to determine them separately. To overcome this limitation, in method I a gradient of temperature is imposed over a material sample, open on the warmer side and

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Nomenclature

a	parameter Eq. (18) [–]	θ	Celsius temperature [°C]
C	radiation parameter Eq. (16) $\left[\frac{W}{m\,K^4}\right]$	μ	diffusion resistance factor [–]
d	specimen thickness [m]	ξ	parameter Eq. (12) [m]
D	diffusivity $\left[\frac{m^2}{s}\right]$	ρ	density $\left[\frac{kg}{m^3}\right]$
h	specific enthalpy $\left[\frac{J}{kg}\right]$	σ	surface tension $\left[\frac{N}{m}\right]$
I	total flux	φ	relative humidity [–]
N	number of terms Eq. (12)	ψ	porosity [–]
j	mass flux $\left[\frac{kg}{m^2\,s}\right]$		
k	material function Eq. (12) [m]	*Subscripts*	
K_{ij}	transfer parameter	a	air
p	pressure [Pa]	e	energy
$\dot{q}$	heat flux $\left[\frac{W}{m^2}\right]$	eff	effective
r	interface resistance $\left[\frac{s}{m}\right]$	f	free saturation
R	gas constant $\left[\frac{J}{kg\,K}\right]$	int	interface
s	standard deviation	m	mean value
T	absolute temperature [K]	$meas$	measured
u	water content $\left[\frac{kg}{m^3}\right]$	I, II	parallel, series
x	coordinate [m]	rad	radiative
η	viscosity $\left[\frac{kg}{m\,s}\right]$	s	saturation
λ	thermal conductivity $\left[\frac{W}{m\,K}\right]$	sm	solid matrix
ζ	parameter Eq. (12) [–]	v	water vapor
		w	liquid water

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absorbing vapor from the surrounding air. In this way, opposed fluxes of liquid and vapor occur in the sample during the experiment. The mass gain is monitored during time and the water content distribution is measured by means of an NMR apparatus once dynamic equilibrium is reached. Then the liquid water diffusivity is determined by inverse simulation of the experiment.

Non-isothermal conditions have been used also in [8], where time dependent heat flux measurements are applied to evaluate the vapor diffusion resistance factor of different bulk insulation materials (e.g. foam glass gravels). In the present study, this technique is improved and adapted for application to capillary active materials and for determination of the liquid water diffusivity.

The new procedure differs from the other ones reported in Table 1 for the following aspects: (1) type of experiment (heat flux measurement) and imposed boundary conditions; (2) equipment (guarded hot plate and balance) and (3) employed mathematical procedure. Moreover, with a single experiment, most relevant different material parameters are obtained simultaneously as functions of temperature and water content in super-hygroscopic range. These parameters are: (1) the effective thermal conductivity; (2) the liquid water diffusivity and (3) the vapor diffusion resistance factor.

2. Mathematical model

In this section the coupled fluxes of heat and moisture are defined. The transfer coefficients are introduced by giving a physical interpretation.

2.1. Coupled heat and moisture fluxes

We consider the transfer of heat, liquid water and vapor inside a porous hygroscopic material in presence of phase change (evaporation of liquid or condensation of vapor).

The following assumptions apply: (1) the solid phase is a rigid matrix in an inertial frame; (2) the three phase system (air, liquid water, solid) is in local equilibrium; (3) the porous medium is continuous at the macroscopic scale. Hence, referring to a representative element of volume (REV), local material properties can be defined.

According to [14], the diffusive fluxes of heat and mass are given by linear laws where thermodynamic forces are multiplied by corresponding transfer coefficients. Neglecting the flux of dry air due to total pressure drops and in absence of thermal and mass sources, the total fluxes of energy and moisture are:

Table 1
Methods for experimental determination of the liquid water diffusivity.

Id.	Reference	Experiment	Mathematical procedure	Conditions
A	[9]	Absorption test, capillary flux measurement	Analytical	Isothermal, steady state
B	[9,10]	Desorption	Analytical	Isothermal, transient
C	[9]	From pore size density distribution	Analytical	Isothermal, steady state
D	[10–12]	Absorption	Analytical	Isothermal, transient
E	[11]	Water redistribution	Analytical	Isothermal, transient
F	[5]	From pore size density distribution	An., num	Isothermal, steady state
G	[5]	Absorption	Analytical	Isothermal, transient
H	[11]	Diffusion resistance (cup test)	Analytical	Isothermal, steady state
I	[13]	Capillary condensation redistribution	Numerical	Non-isoth., transient
L	This study	Heat flux, water redistribution	Analytical	Non-isoth., steady state