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Modelling of long-term hygro-thermal behaviour of vacuum insulation panels

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ABSTRACT

The low thermal conductivity of Vacuum Insulation Panels (VIPs) degrades with time due to gas permeation through VIPs barriers. There is additional ageing of their envelope and core material. Accelerated experiments are carried out in order to better understand this ageing process but they are not sufficient to predict the long term performance of panels. Models have to be used to connect the short term evaluation and the long term behaviours in order to improve the prediction of the thermal conductivity evolution over 50 years. This paper describes the development of a VIP model in the Dymola® software. This model takes into account the envelope and core material hydro-thermal characteristics and behaviours, and integrates the actual solicitations of the panels during accelerated ageing tests. The thermo-activation of the envelope permeance is integrated. Many properties of the core material are modelized: type of core material, sorption isotherm, hygro-thermal ageing, pore size distribution, etc. Simulations in constant conditions in temperature and humidity have been carried out. The results show that the real behaviour of the VIPs conductivity can't be simply evaluated through a linear extension of its short-term evolution. Given the important impact of the core material detailed characteristics, it is absolutely necessary to get an accurate determination of the core material sorption curve and of the ageing of this curve.

1. Introduction

Vacuum Insulation Panels (VIP) is a super-insulated product consisting of a core material maintained under vacuum by an envelope. Its thermal performance is based on the nanoporous property of the core material and on the barrier envelope efficiency which prevents the increase of moisture and internal pressure (cf. Fig. 1).

Different types of VIPs exist with different core materials and envelopes. At initial state, the mean thermal conductivity of VIPs made with nanoporous silica is around 4 mW m^{-1} K^{-1} at the center of panel. In practice, its thermal performance is not stable but increases with time due to gas permeation through VIPs barriers and ageing of their envelope [1,2] and core material [3–6]. The global thermal conductivity of the panel depends on many physical characteristics of the core materials, and on their interactions with gases (dry air and water vapour) [7–10]. To commercialize VIPs for building insulation application, it is necessary to estimate their long-term mean thermal performance. Several authors have proposed methods to model the changes in thermal conductivity of panels [11–17]. These predictions are commonly realised by making simplifications and for most of them, without taking into account, that also barrier complex as well as core do change over time.

The aim of this study is to develop a VIP model and simulate, over a 50-year period and as accurately as possible, its hygro-thermal behaviour. This in order to analyse its thermal performance when subjected to different temperature and humidity conditions. The paper is split in seven parts. First, methods and modelling tools are presented. Then, the different equations on which the model is based are described. The two next parts are devoted to the sensibility analysis and the presentation of the simulation results in constant climatic conditions. The fifth part describes how

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Nomenclature

Greek letters

α	Parameter of the rate of ageing –
β	Non-dimensional coefficient –
λ_c	Core material's thermal conductivity W m^{-1} K^{-1}
λ_f	Barrier complex's thermal conductivity, in transversal direction W m^{-1} K^{-1}
λ_g	Gaseous thermal conductivity W m^{-1} K^{-1}
λ_r	Radiative thermal conductivity W m^{-1} K^{-1}
λ_s	Solid thermal conductivity W m^{-1} K^{-1}
λ_{cs^0}	Initial solid thermal conductivity W m^{-1} K^{-1}
λ_{eq}	Equivalent VIP's thermal conductivity W m^{-1} K^{-1}
$\lambda_{f,\,i}$	Thermal conductivity of the barrier complex layer *i*, in transversal direction W m^{-1} K^{-1}
λ_{g^0}	Gaseous thermal conductivity of not confined gas W m^{-1} K^{-1}
λ_{memb}	Apparent thermal bridge conductivity W m^{-1} K^{-1}
λ_{sil}	Solid thermal conductivity of non-porous silica W m^{-1} K^{-1}
λ_{VIP}	Global VIP's thermal conductivity W m^{-1} K^{-1}
ϕ	Relative humidity %
Φ_i	Mass flow of gas *i* kg s^{-1}
Φ_{memb}	Heat flow of the linear thermal bridge *W*
Π_i	Apparent permeance to the gas *i* kg m^{-2} s^{-1} Pa^{-1}
Ψ_{memb}	Linear thermal bridge coefficient W m^{-1} K^{-1}
ρ	Density or mass concentration kg m^{-3}
τ_w	Mass content of water %
ε	Porosity –
φ_i	Mass flow density of gas *i* kg s^{-1}

Other symbols

Ø	Pore mean size m

Physical constants

σ	Stefan-Boltzmann's constant 5.67 × 10^{-8} W m^{-2} K^{-4}
C	Constant depending on gas J K^{-1} m^{-2}
k_B	Boltzmann's constant 1.381 × 10^{-23} J K^{-1}
R	Ideal gas constant 8.314459848 J K^{-1} mol^{-1}
r_i	Specific gas constant of gas i J kg^{-1} K^{-1}

Roman letters

A	Panel's area m^2
B	Influence of water content increase on the thermal conductivity W m^{-1} K^{-1}%$^{-1}$
d	Panel's thickness m
d_c	Core material's thickness m
d_g	Effective diameter of gas molecule m
D_i	Diffusion coefficient of gas *i* m^2 s^{-1}
E	Extinction coefficient m^{-1}
G	Influence of pressure increase on the thermal conductivity W m^{-1} K^{-1} Pa^{-1}
h_i	Convection heat transfer coefficients W m^{-2} K^{-1}
I_i	Sensitivity index of input i %
k_i	Fitting parameters for sorption isotherm model –
l	Barrier complex's thickness m
l_i	Thickness of the barrier complex layer *i* m
m_{ads}	Mass of adsorbed water kg
M_{H_2O}	Molar mass of water kg mol^{-1}
m_{sil}	Mass of dry core material kg
m_w	Mass of water kg
m_{wv}	Mass of water vapour kg
n	Refractive index –
n_l	Number of layers of the edge –
P	Panel's perimeter m
p_a	Partial pressure of dry air Pa
p_t	Internal total pressure Pa
p_v	Partial pressure of water vapour Pa
Q_D	Activation energy of diffusion J mol^{-1}
Q_S	Activation energy of sorption J mol^{-1}
Q_Π	Activation energy of permeance J mol^{-1}
R_c	Core material's thermal resistance K m W^{-1}
R_f	Barrier complex's thermal resistance K m W^{-1}
R_{eq}	Equivalent VIP's thermal resistance K m W^{-1}
R_{memb}	Apparent thermal bridge resistance K m W^{-1}
S	Solubility coefficient kg m^{-3} Pa^{-1}
S_{BET}	BET Specific surface area m^2 kg^{-1}
T	Temperature K
t	Time s
t_{aged}	Time for which the silica is fully aged s
V	Variance contribution –
V_{VIP}	VIP's volume m^3
Var	Variance –
X_i	Model input variable –
Y_i	Model output variable –

the silica ageing has been implemented in the modelling process and its impact on the long-term thermal behaviour of the panels. The sixth part is devoted to the model validation and discussion about traditional ageing prediction. Then, the last part is devoted to the conclusion.

2. Methods and modelling tools

Dymola® platform has been used to develop the model in the Modelica modelling language. This software has been developed to simulate the dynamic behaviour and complex interactions between systems in various engineering fields.

The developed model consists of an assembly of six macro-components: two barrier complexes, one core material, one thermal bridge and two convective heat exchangers. All components are interconnected with ports. The whole system is further submitted to boundary conditions that mimic external exchange. Each port carries three potential variables: temperature, water vapour partial pressure and total gas pressure; and three flux associated to these three potentials: heat flow, water vapour mass flow and total mass flow. Each component behaviour is described by physical equations and necessary parameters.

A schematic illustration of the model is represented in Fig. 2. The model takes into account the thermal behaviour and gas transfer through the complex and in the core material.

3. Physical model description

3.1. Thermal transfer modelling

3.1.1. Panel

The overall thermal behaviour of the VIP can be represented with a set of series-parallel thermal resistances (cf. Fig. 3).

In practice, the thermal resistance of the complex barriers (R_f) can be neglected. The equivalent thermal resistance of the panel can result in two parallel resistances (Eq. (1)) : the resistance of the core material (R_c), and that of the thermal bridge of the envelope (R_{memb}).

$$\frac{1}{R_{eq}} = \frac{1}{R_c} + \frac{1}{R_{memb}} \tag{1}$$