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Lowering and phase shifting of temperature profiles with phase change materials in Minergie™ houses

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ABSTRACT

A PCM dephaser and storage module based on a melting/freezing model was built and implemented into the Dymola-Modelica software. This software offers thermal libraries with standard components as tubes, pumps, heat exchangers, etc. Main simulation results of interest include the phase shift (delay time) caused by cylinders filled with a PCM and positioned in the storage/dephasing device. Furthermore, an entire Minergie™ house was modelled by a rather simple (economic in terms of CPU time), but still very effective thermal model. This house is connected to a suitable ventilation system chosen from a list of six different types. Therefore, also by graphical means on an interface, it is possible to create a Minergie™ house with an integrated thermal temperature lowering/phase shifting and heat recovery device. Temperature differences between a Minergie™ house connected to a storage device and a house without such a device are studied. Such systems are planned to be mainly used for hybrid cooling of Swiss Minergie™ houses in summer time. In a multi-functional application, they could also be applied in winter for a heating support. Numerous simulation results are discussed and optimal solutions are presented.

Augmentation et diminution des profils de température à l'aide de matériaux à changement de phase dans les maisons Minergie™

Mots clés : Matériau ; Changement de phase ; Accumulation thermique ; Modèle ; Simulation numérique

1. Introduction

PCM storage tanks have been studied for many years. A comprehensive overview has been written by Lane (1986). Hed and Bellander (2006) have developed a mathematical model of a PCM-air heat exchanger without taking into account the temperature distribution in the PCM. Butala and Stritih (2006) have shown that it is possible to flatten a temperature curve

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with a PCM storage tank connected to a simple ventilation system. Finally, Turnpenny et al. (1999) have shown that they get 30 W m^{-2} for an office building by having a forced air flow in each 15 m^2 office. Haas and Temporin (2007) have studied the aerodynamics of a thermal wave dephasing device with sensible heat storage. The outside air temperature has a daily profile close to a sinusoidal function; therefore it is possible - with 12 h of dephasing - to get a minimal temperature from the dephasing device while the outside air temperature is at its maximum. With such a system it is possible to cool down a house by taking the outside air during the night, whereas during the day the air coming out of the dephasing device is used. In their paper they have shown that it is possible to get 12 h of dephasing with a 0.9 m long dephasing device performed of copper and filled with water. They also found that with these materials the transmission stays above 85%. In this paper the idea of a dephasing device with phase change materials is studied. But the use of a PCM as a storage substance is also of interest and dealt with. Furthermore, a house model is built to compare the interior air temperatures of houses with and without a PCM storage device. The reference house is a villa for four people with 164 m^2 surface of energy reference (SRE). The SRE is the total surface with the walls and with a height factor for taking into account different floors. To get the Swiss Minergie™ label for a new house, the walls must be insulated so that the annual consumption of energy for heating is less than 38 kWh/m^2. That means that the annual consumption of the total house is less than 7600 kWh/year (this is equal to 868 W). The power for cooling has to be smaller than 7 W/m^2. This corresponds to a total cooling power smaller than 1150 W. This cooling power is not sufficient to cover the occurring loads. Therefore, it is advisable to additionally install a "free cooling" device to condition fresh air during temperate, but especially on hot summer days.

2. Physical model

A device with cylindrical Phase Change Material (PCM) modules is modelled by the Continuous-Properties Model (CPM) introduced by Egolf and Manz (1994). It is necessary to apply numerical methods, because of the analytical insolvability of the nonlinear second order partial differential equation. For the bulk in the PCM cylinders, the basic differential equation in cylindrical coordinates is:

$$\frac{\partial T}{\partial t} = \alpha\left[\frac{1}{k}\frac{dk}{dT}\left(\frac{\partial T}{\partial r}\right)^2 + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right], \quad \alpha = \frac{k}{\rho c_p} \tag{1a,b}$$

By energy conservation, the basic differential equation for the heat flux at the inner surface of the cylinders is:

$$-k\frac{\partial T}{\partial r} = h[T(R) - T_F] \tag{2}$$

On the other hand only an algebraic equation occurs to describe the outer boundary condition:

$$\dot{m}_F c_{p_F}\left(T_{F_{out}} - T_{F_{in}}\right) = hA\left[T(R) - T_{F_{in}}\right] \tag{3}$$

In Euler's method the derivatives are replaced by the difference quotients. The index i defines the discrete time and j the discrete radial position. A development of the model of a device has been performed by Muriset et al. (2008) and Muriset (2009). The numerical algorithms are the following:

$$T_{i+1,j} = T_{i,j} + \frac{\alpha\Delta t}{(\Delta r)^2}\left[\frac{1}{k_{i,j}}\frac{dk}{dT}\bigg|_{i,j}\left(T_{i,j+1} - T_{i,j}\right)^2 + \frac{\Delta r}{r_j}\left(T_{i,j+1} - T_{i,j}\right) + \left(T_{i,j+1} - 2T_{i,j} + T_{i,j-1}\right)\right] \tag{4}$$

$$T_{i,n} = \frac{T_{i,n-1} + BiT_{F_{in}}}{1 + Bi} \quad \text{whereas} \quad Bi = \frac{h\Delta r}{k_{i,n}} \tag{5a,b}$$

$$T_{F_{out}} = T_{F_{in}} + St\left(T_{i,n} - T_{F_{in}}\right) \quad \text{whereas} \quad St = \frac{hA}{\dot{m}_F c_{p_F}} \tag{6a,b}$$

3. PCM properties

The enthalpy, specific heat and thermal conductivity in the CPM are functions of the temperature and are each described by two exponential equations. Some are for temperatures lower than the mean temperature of a mushy phase change domain, and the others are developed to describe physical properties in the higher temperature regime. The chosen PCM is the ClimSel 21-22 with the physical properties shown in Table 1. No sub cooling was taken into consideration.

4. Dephasing response

In a report by Muriset (2009) the system parameters for a dephasing device have been optimised. The geometrical parameters are explained in Fig. 1. For a dephasing device two aspects are important. The first is the dephasing itself, which

Table 1 – Properties of the phase change material ClimSel 21-22 PCM are listed. For theoretical parameter studies assuming systems with PCM's showing different melting temperatures than the 21.5 °C (of the ClimSel 21-22), beside the melting temperature all other parameters were taken again from Table 2.

k_1	Thermal conductivity for PCM in solid phase (for $T \to 0$)	0.5	W m^{-1} K^{-1}
k_2	Thermal conductivity for PCM in liquid phase (for $T \to \infty$)	0.7	W m^{-1} K^{-1}
c_{p1}	Specific heat for PCM in solid phase (for $T \to 0$)	3600	J kg^{-1} K^{-1}
c_{p2}	Specific heat for PCM in liquid phase (for $T \to \infty$)	3600	J kg^{-1} K^{-1}
$h_2 - h_1$	Projected latent heat of liquefaction	144,000	J kg^{-1}
ρ	Specific mass	1450	kg m^{-3}
T_m	Average melting temperature	21.5	°C
ΔT	Width of mushy region	1	°C