Heat-inertial properties of walls of lightweight thermal insulation with phase change materials

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Abstract. In the paper, a building with walls filled with lightweight thermal insulation with a phase change material is considered. Numerical computations were made on the basis of a simple enthalpy model, and the effect of macro-encapsulated phase change material on the heat-inertial properties of walls under conditions of daily fluctuations in the temperature of the outside air was analyzed. The spatial arrangement of the phase-change material has been varied during the calculations, as well as the temperature of its phase transition. Analysis of calculation results shows that addition of a phase-change material allows not only to increase the heat-accumulating capacity of the building envelope, but also to control heat flows on the wall surfaces. As a result, it becomes possible to reduce the peak values of the heat flux on the inner surface of the wall, and also to provide a certain flow direction.

1. Introduction

The fields of application of phase-change materials (PCMs) are constantly expanding [1]. Due to the latent heat of phase transition, these materials have a high thermal energy store capacity. This allows using them as an alternative to bulk systems of heat accumulation [2]. The thermal energy storage system using latent heat stored in PCMs can significantly reduce the volume of cooling systems in buildings, as well as reduce the energy consumption costs that are typical for water cooling systems [3].

It is known that global energy consumption in the building sector of the world is constantly growing. Thus by 2012 it reached 40% of the world's energy consumption. This sector is also responsible for more than 50% emissions of carbon dioxide. At the same time energy costs only for ventilation and air conditioning in buildings can exceed 50%. Therefore, regenerative ventilation systems with the use of heat-storage properties of PCMs have serious perspectives [4].

PCMs are used in the automotive industry [5], as well as in battery thermal management systems of autonomous power supplies [6].

Another important area is the use of PCMs with lightweight thermal insulation materials in building structures [7]. Lightweight thermal insulation materials, having high thermal insulation properties, have low thermal inertia, which limits the area of their use. The use of lightweight thermal insulation materials in conjunction with phase change materials allows significantly increase the thermal energy storage properties of thermal insulation due to the latent heat of the phase transition and significantly improve the thermal protection characteristics of the enclosing structures of buildings.

The aim of the paper is a computational study of the influence of PCMs distribution within walls on the attenuation of external thermal effect in internal spaces.
2. Physical and mathematical modelling

The article considers the process of heat transfer through a layer of thermal insulation material with the addition of PCMs. The propagation of heat through a layer of such an inhomogeneous material, taking into account phase transformations, was modeled using the enthalpy model [1, 8]:

$$\frac{\partial H}{\partial t} = \nabla \cdot (\lambda \nabla T),$$  \hspace{1cm} (1)

where the change in the specific enthalpy $H$ is composed of a change in the sensible enthalpy and phase transition enthalpy:

$$\Delta H(t) = \int_{\Delta f(t)} c(\xi) d\xi + L \cdot \Delta f(t).$$  \hspace{1cm} (2)

Here $c(T)$ is a specific heat capacity of the wall material, $\rho(T)$ is a density of the wall material, $\lambda(T)$ is a thermal conductivity of wall material, $L$ is a latent heat of phase transition of PCMs, $\Delta f(t)$ is the change in the mass fraction of a substance that has undergone phase transition with time $t$. Substitution of expression (2) into (1) leads to an equation which allows simulating heat exchange processes taking into account possible phase transformations:

$$\frac{\partial \rho}{\partial t} = \nabla \cdot (\lambda \nabla T) - \rho L \frac{\partial f}{\partial t}. $$  \hspace{1cm} (3)

The temperature difference between the melting point ($T_l$) and the solidification point ($T_s$) of PCM is considered insignificant and is not taken into account in the model. Phase transitions occur at the same temperature $T_m$. Variable $f$ denotes the fraction of the PCM that is in the molten state, the value of $(1-f)$ corresponds to the solid state.

It is necessary to make the following remarks concerning equation (3). If the temperature does not reach $T_m$ at the considered point of the medium, then the derivative $\frac{\partial f}{\partial t}$ at this point is zero. This derivative will be equal to zero also under the condition that at the considered point the change in the aggregate state of the PCM is completely completed; PCM is completely melted or solidified. In these cases, equation (3) becomes the usual thermal conductivity equation with variable coefficients. When temperature will be reach to $T_m$, the PCM can begin to melt or solidify. At the same time, the fraction of substance $f$ begins changes. The temperature does not change until some aggregate state of PCM is established at which $f = 1$ or $f = 0$ at the consideration point. While the phase transition lasts, the conditions $f \neq 0$ and $T(x,y,z,t) = T_m - \text{const}$ are met. Therefore, equation (3) takes the form

$$\rho \frac{\partial f}{\partial t} = \nabla \cdot (\lambda \nabla T).$$  \hspace{1cm} (4)

Equation (4) describes the dynamics of the change in the aggregate state of the PCMs.

Numerical computations were carried out in a two-dimensional formulation. The control volume method was used.

The macro-encapsulated PCM was located inside the base material in the form of extended regions of a predetermined shape.

3. Result and discussion

In this paper, a numerical study of the construction of a building wall from a basic lightweight thermal insulation material and a layer of macroencapsulated PCM was carried out. As the main material, a flat layer of foamed polyurethane (FPU) 0.15 m thick was considered. A paraffin mixture was considered as PCM. Thermophysical properties of the materials are given in table 1.

In calculations, the volume fraction of the phase change material was 12%. Three configurations for placing the macroencapsulated PCM inside the main material were tested in the calculations.
Table 1. Thermophysical properties of materials.

| Material | Density, kg/m³ | Specific heat capacity, J/(kg K) | Thermal conductivity, W/(m·K) | Latent heat of melting, J/kg |
|----------|----------------|---------------------------------|------------------------------|-----------------------------|
| FPU      | 35             | 1400                            | 0.035                        | -                           |
| PCM      | 920            | 2190                            | 0.268                        | 179000                      |

In the first position, the PCM layer was located directly near the inner surface of the wall, in the second it was located near the outer wall. In the third position, the PCM layer was located in the middle between the inner and outer surface of the wall. The phase transition temperature of the PCM in the calculations was varied in the range from 15°C to 30°C. Suppose that the outdoor air temperature varies harmonically as

$$T_{\text{out}}(t) = 25 + 10 \cdot \sin\left(\frac{2\pi t}{\tau}\right) \text{°C}$$

with amplitude of 10°C relative to the average value of 25°C. Here $\tau$ is the period of the oscillations equal to the duration of the day. Assume also the maximum of the outdoor air temperature is observed at 14.5 o’clock that corresponds to conditions of the June day.

The indoor air temperature was assumed to be constant 21°C (room with air conditioning). Figure 1a shows daily variations in the outdoor air temperature in a dimensionless form. Here, the temperature was normalized on the difference in the temperature of the phase transition $T_m$ and the initial temperature $T_0$. The average value between the average outdoor air temperature and the internal temperature was taken as initial temperature, $T_0 = 23°C$. The Fourier number was determined by the normalization of time $t$ for the time of propagation of temperature disturbances in the base material: $Fo = t\chi/l^2$, where $\chi$ is the thermal diffusivity and $l$ is the thick of wall. The time interval of one day corresponds to $\Delta Fo = 2.74$.

According to the calculation results, the heat flux $q$ on the inner surface, without taking into account phase transitions, performs harmonic oscillations (1, figure 1b). Oscillations on the inner surface are delayed with respect to the change in the outdoor air temperature. The delay is $\Delta Fo = 0.18$ (about 1.5 hours). The duration and the maximum deviations of the heat flux on the inner surface from the mean value, decrease substantially when phase transitions are taken into account (2, figure 1b). The peak values of the heat flux are reduced by 2.5-3 times and are delayed in time by 5.3 hours relative to the maximum and minimum of the outdoor air temperature. If the maximum temperature is observed in the daytime around 14.5 o’clock, the heat flux maximum is reached in the evening about 20 o’clock, when the load on air conditioning in the summer time decreases. When the PCM layer is located at the center of the wall, the most significant effect was obtained at temperature $T_m = 23°C$.

Figure 1. (a) Daily oscillations in the outdoor air temperature; (b) daily oscillations in the heat flux on the internal surface: 1– without taking into account phase transitions; 2– taking into account phase transitions. PCM is located in the center, $T_m = 23°C$. 

![Figure 1](image-url)
which corresponds to the average temperature between the average outdoor air temperature and the indoor air temperature.

At the air conditioning when PCM was located near the outer surface of the wall the results of calculations for various $T_m$ showed that there were no significant changes in the heat flux on the internal surface in comparison with the case of the absence of PCM. There was only some narrowing of the regions near the heat flux peak, without significant phase shifts relative to the outdoor air temperature.

Interesting feature of PCM to perform the function of a "thermal diode" is manifested when layer is located near the inner surface of the wall (figure 2). In this case, there may be significant changes in the heat flux on the inner wall surface in the presence of PCM. If the temperature of the phase transition is close to the temperature of the indoor air, then in this case the heat flux directed from the room (2, figure 2a) is completely eliminated. Thus, the heat loss from the room in the coldest part of the day does not occur. It should be noted that the peak values of heat flux into the room during the warm time of the day practically do not undergo any changes, i.e. both the phase and the maximum value are conserved. If the temperature of the phase transition is higher than the temperature of the indoor air, then in the colder time of the day, on the contrary, the heat flux directed from the room will not change significantly (2, figure 2b). At the same time, the maximum value of the heat flux to the room during the daytime will be halved and will have a time shift of almost 4 hours relative to the outdoor air temperature.

As follows from the calculation, adding PCM inside a lightweight thermal insulating material can significantly increase its heat storage capacity. As follows from the calculation, adding PCM inside a lightweight thermal insulating material can significantly increase its heat storage capacity. It is possible to achieve the necessary shift between the phases of temperature and heat flux by choosing the PCM spatial position and its volume content. This opens up additional possibilities in controlling the amplitude and direction of the heat fluxes.

4. Conclusions

Numerical studies of the effect of macroencapsulated phase change material on the heat-inertial properties of the building walls from lightweight thermal insulating materials were carried out using an enthalpy model. Calculations were made for an air-conditioned room with a constant air temperature at the daily periodical oscillations in the outdoor air temperature. As a result of the calculations, when the PCM was located in center of walls and had the temperature of the phase transition equal the average between the average temperature of the outdoor air and the air temperature in the room, a significant effect is found. The presence of PCM in this region led to a decrease in the

![Figure 2. Daily variations of the heat flux on the inner surface (a) at $T_m = 21^\circ$C and (b) at $T_m = 22^\circ$C: 1- without taking into account phase transitions; 2-taking into account phase transitions. PCM layer is located near the inner surface.](image-url)
peak of the heat flux on the inner surface of the wall by 2.5 to 3 times and its phase shift by 5.3 hours relative to the maxima and minima of the outdoor air temperature.

When the PCM is located near the internal surface, it can perform the function of a "thermal diode" and can pass a heat flux in one direction. Thus, at a phase transition temperature equal to the indoor air temperature, there was no heat flow from the room. So, the loss of heat from the room when the outdoor air temperature was lower than in the room did not occur.

The use of phase-change materials in the structure of wall constructions made of lightweight thermal insulating materials leads to a change in the heat-inertial properties of the walls. This is due to the fact that the latent heat of phase transformations of the PCM upon reaching the temperature of the phase transition makes a significant contribution to the heat transfer. At the same time, it is possible to speak about a dynamic change in the effective heat capacity of the building envelope. Particular interest is the ability of the phase change material to influence the phase and amplitude of the oscillations of heat fluxes on the wall surface. As a result, it is possible to achieve control of thermal processes inside the building envelope.

Acknowledgments
The work was carried out at the expense of the "interdisciplinary integration studies" of the SB RAS (Project No. 32).

References
[1] Kenisarin M and Mahkamov K 2016 Passive thermal control in residential buildings using phase change materials Renewable and Sustainable Energy Reviews 55 371–98
[2] Fang Y, Nin J and Deng S 2018 Numerical analysis for maximizing effective energy storage capacity of thermal energy storage system by enhancing heat transfer in PCM Energy and Building 160 10–8
[3] Souayfane F, Fardoun F and Biwole P H 2016 Phase change materials (PCM) for cooling applications in buildings: a review Energy and Building 129 396–431
[4] Zeinelabdein R, Omer S and Gan G 2018 Critical review of latent heat storage system for free cooling in buildings Renewable and Sustainable Energy Reviews 82 2843–68
[5] Jaguemont J , Omar N, Van den Bossche P and Mierlo J 2018 Phase-change materials (PCM) for automotive applications: A review Applied Thermal Engineering 132 308–20
[6] Li W Q, Qu Z G, He Y L and Tao Y B 2014 Experimental study of a passive thermal management system for high-powered lithium ion batteries using porous metal foam saturated with phase change materials Journal of Power Sources 255 9–15
[7] Li Z, Yang Y, Sarula C and Yong S 2018 Numerical study on the thermal performance of lightweight temporary building integrated with phase change materials Applied Thermal Engineering 138 35–47
[8] Souayfane F, Biwole P H and Fardoun F 2018 Melting of phase change material in presence of natural convection: A simplified model Applied Thermal Energy 130 660–71