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DETERMINING THE OPTIMAL TYPE OF THERMAL INSULATION FOR EXTERIOR WALLS IN RESIDENTIAL BUILDINGS WITH PASSIVE SOLAR HEATING SYSTEMS

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Abstract: In this research work, the external wall materials of passive solar heating systems were selected by calculating the magnitudes of time lag and decrement factor. Calculations are based on building materials such as brick (not heat-treated), ready-made (heat-treated) brick, cinder block, foam block, gas block, ash-gravel concrete and vermiculite-concrete, basalt, stucco and expanded polystyrene (Gost 15588-2014) type of insulation. Calculations were performed using COMSOL Multiphysics modeling software. A one-dimensional, time-dependent heat dissipation equation was used to quantify the magnitude of the time lag and decrement factor. The results showed that the time delay is the largest (17 hours) and the magnitude of the amplitude decay is the smallest ($1{,}841 \cdot 10^{-3}$) when using polystyrene (Gost 15588-2014) insulation on the foam block material. was equal to the value.

Keywords: time lag, decrement factor, solar radiation, temperature, energy, heat transfer, numerical methods, heat balance, heat transfer.

Аннотация: В данной исследовательской работе материалы наружных стен пассивных солнечных систем отопления были выбраны путем расчета величин временной задержки и коэффициента декремента. Расчеты производятся по таким строительным материалам, как кирпич (нетермообработанный), готовый (термообработанный) кирпич, шлакоблок, пеноблок, газоблок, зольно-гравийный бетон и вермикулит-бетон, базальт, штукатурка и пенополистирол. (ГОСТ 15588-2014) вид изоляции. Расчеты проводились с использованием программного обеспечения моделирования COMSOL Multiphysical. Одномерное уравнение рассеяния тепла, зависящее от времени, использовалось для количественной оценки величины временной задержки и коэффициента декремента. Результаты показали, что временная задержка наибольшая (17 часов), а величина затухания амплитуды наименьшая (1,841·10^(-3)) при использовании утеплителя из пенополистирола (ГОСТ 15588-2014) на пеноблочном материале. было равно значению.

Ключевые слова: временной лаг, коэффициент декремента, солнечная радиация, температура, энергия, теплообмен, численные методы, тепловой баланс, теплообмен.

Introduction. Natural resource management is becoming an increasingly important issue for the global world. In the context of population growth, accelerated economic development and increasing demand for natural resources, ensuring the long-term sustainability of these resources remains an urgent task. To address this issue, it is necessary to implement a comprehensive and coordinated strategy. This strategy should include measures aimed at ensuring the efficient use of resources, protecting them and reducing demand. Also, supporting sustainable development and nature conservation should be considered as a priority. It includes such important tasks as nature conservation, preserving and restoring natural habitats, as well as protecting biodiversity in terrestrial and marine ecosystems [1-3].

One of the main energy-consuming sectors worldwide is the construction sector. According to the International Energy Agency (IEA), the construction sector accounts for 40% of total energy consumption and is responsible for approximately 35% of carbon dioxide (CO_2) emissions [4]. In 2018, energy consumption in residential buildings in Uzbekistan accounted for about 40% of the total energy balance, compared to a global average of 20% [5,6]. In 2050, the area of the housing stock in Uzbekistan is expected to increase to 949-987 million m² [7]. Against the background of a sharp decrease in the amount of fossil energy resources, energy saving or the use of alternative energy sources remains relevant.

Heat transfer through walls accounts for the main part of the heating or cooling load of a room [8,9]. The thermal properties of walls play a decisive role in influencing the energy consumption of a building. Therefore, increasing the thermal resistance of walls or determining optimal values of thermal resistance is defined as the main goal of reducing energy consumption [10-12]. When assessing the thermal performance of a wall, two important parameters are often taken into account: the time delay and the magnitude of the amplitude decrease. Typically, a high thermal performance of a wall is determined by a larger time delay and a smaller amplitude decrease [13].

The time delay and the magnitude of the amplitude decrease are very important characteristics for determining the heat storage capabilities of any material. Depending on the thermophysical properties and thickness of the wall materials, they have different time lag and decrement factor values [14].

In this work, the time lag and decrement factor values were calculated by applying basalt, slag and expanded polystyrene (GOST 15588-2014) insulation to building materials such as brick (unheated), fired (heat treated) brick, cinder block, foam block, aerated concrete, and vermiculite concrete.

The time lag and decrement factor value schemes are shown in Figure 1. The time lag is determined as follows:

$$\phi = \begin{cases} t_{T_o^{max}} > t_{T_e^{max}} \Longrightarrow t_{T_o^{max}} - t_{T_e^{max}} \\ t_{T_o^{max}} < t_{T_e^{max}} \Rightarrow t_{T_o^{max}} - t_{T_e^{max}} + P \\ t_{T_o^{max}} = t_{T_{e0}^{max}} \Rightarrow P \end{cases} \qquad (1)$$

where ϕ - time lag; $t_{T_o^{max}}$- time for the inner wall surface to reach maximum temperature; $t_{T_e^{max}}$ time for the outer surface of the wall to reach maximum temperature; P (24 h) is the period of the wave.

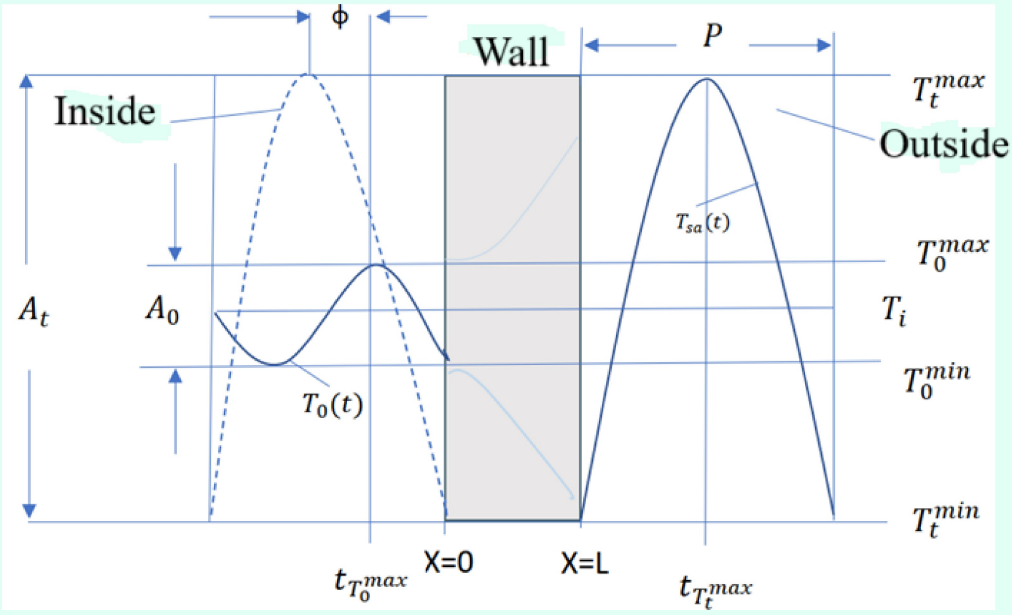


Figure 1. Schematic representation of time lag and decrement factor [13]

The damping value of the calculated amplitude of the external air temperature oscillation in a barrier structure consisting of homogeneous layers is determined as follows:

$$\nu = \frac{A_0}{A_e} = \frac{T_0^{max} - T_0^{min}}{T_e^{max} - T_e^{min}}, \qquad (2)$$

where ν- decrement factor; A_0, A_e - are the amplitudes of the wave in the inner and outer surfaces of the wall, respectively.T_{sa}- the sol–air temperature includes the effects of the solar radiation combined with outside air temperature and changes periodically. This temperature is assumed to follow a sinusoidal law over a 24-hour period. Since time lag and decrement factor are only related to the wall material and not to climatic data [15], The general equation for the calculated temperature T_{sa}resulting from solar radiation and ambient temperature is obtained as follows:

$$T_{sa}(t) = \frac{|T_{max} - T_{min}|}{2} \sin\left(\frac{2\pi t}{P} - \frac{\pi}{2}\right) + \frac{|T_{max} - T_{min}|}{2} + T_{min} \qquad (3)$$

Mathematical model. In this study, the thermal processes occurring in the wall under study were considered only in the x direction and as a function of time (Figure 3). The one-dimensional time-dependent heat transfer equation is expressed as

$$k\frac{\partial^2 T}{\partial x^2} = \rho C_p \frac{\partial T}{\partial t} \qquad (4)$$

where k- thermal conductivity coefficient; ρ – density; C_p - heat capacity for wall material. The boundary condition for the inner surface is expressed as:

$$k\left(\frac{\partial T}{\partial x}\right)_{x=0} = h_i[T_{x=0}(t) - T_i] \qquad (5)$$

On the outer surface of the wall, the boundary condition can be written as follows:

$$k\left(\frac{\partial T}{\partial x}\right)_{x=L} = h_t[T_{sa}(t) - T_{x=L}(t)] \qquad (6)$$

where h_i- heat transfer coefficient of the inner surface of the wall, h_t- heat transfer coefficient of the outer surface of the wall, $T_{x=0}$ - temperature of the inner surface of the wall; $T_{x=L}$- is the wall outer surface temperature T_i- room air temperature; $T_{sa}(t)$ - the sol–air temperature.

As an initial condition, we take the stationary solution of equation (4) at time $t = 0$. In the calculations, the indoor air temperature T_i was assumed to be constant. As shown in equation (3), the calculated temperature $T_{sa}(t)$ resulting from solar radiation and ambient temperature varies between T_{max} and T_{min} over a 24-hour period. A two-dimensional analytical solution of the problem is given in [14].

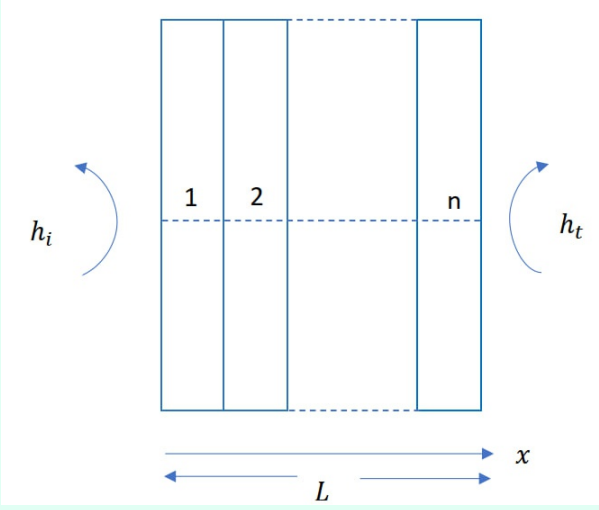


Figure 3. Schematic of an n-layer wall [16].

Equation (4) is solved by the finite element method in the Comsol Multiphysics program. The values entered into the computer program are: specific heat capacity of the material, thickness of each layer, density, heat transfer coefficient and thermal

conductivity coefficient. In equation (3), $T_{min} = 0$ °C and $T_{min} = 0$ °C, and 22 °C were chosen as the internal temperature.

Results and their analysis. Calculations were carried out in the COMSOL Multiphysics modeling program using basalt, expanded clay and polystyrene foam (GOST 15588-2014) insulation for unbaked brick, baked brick, cinder block, foam block, ash-gravel concrete, and vermiculite concrete materials. Using this program, the time delay and the damping magnitude ν of the calculated amplitude of the external air temperature oscillations in the barrier structure consisting of homogeneous layers were calculated for each material. The thermal physical properties of the materials are given in Tables 1 and 2 [17, 18].

The optimal result is determined by choosing the largest value of the time lag and the smallest value of the decrement factor [14]. Figures 4, 5 and 6 show the results obtained when three types of insulation are applied to seven different materials. Figure 4 shows the largest time lag in the foam block material and the smallest decrement factor in the gas block material. A similar situation is observed in Figure 6, but it is important to find the largest time lag and the smallest decrement factor at the same time. The results in Figure 5 and Table 3 correspond to these conditions, i.e., the largest time lag and the smallest decrement factor were determined when the foam block material was insulated with Penopolystyrene (GOST 15588-2014). These values, with a time lag of 17 hours and an decrement factor magnitude of $1.841 \cdot 10^{-3}$ were considered optimal results.

Table 1. Thermal physical properties of materials

№	Material types	Thermal conductivity coefficient $k, \frac{W}{m \cdot K}$	Density $\rho, \frac{kg}{m^3}$	Specific heat capacity $C_p, \frac{J}{kg \cdot K}$
1	Baked brick	0,8	2000	836
2	Unbaked brick	0.75	1900	836
3	Cinder block	0,55	1400	836,8
4	Foam block	0,14	600	880
5	Gas block	0,1	400	840
6	Ash-gravel concrete	0.47	1400	840
7	Vermiculite concrete	0.21	800	840

Table 2. Thermal physical properties of insulation materials

№	Material types	Specific heat capacity $C_p, \frac{J}{kg \cdot K}$	Thermal conductivity coefficient $k, \frac{W}{m \cdot K}$	Density $\rho, \frac{kg}{m^3}$
1	Expanded polystyrene (Gost 15588-2014)	1340	0.038	40
2	Plaster (cement-sand)	840	0.58	1800
3	Basalt	840	0.032	120

Table 3. Time lag and decrement factor magnitude for seven types of materials and three types of insulation applied to them.

№	**Material: Basalt insulation**	Time lag (hours).	Decrement factor, 10^{-3}
1	Gas block	11	3.296
2	Ash-gravel concrete	13	14
3	Foam block	15	4.078
4	Baked brick	12	23
5	Cinder block	12	24
6	Vermiculite concrete	12	5.853
7	Unbaked brick	11	24
	Material: Expanded polystyrene (GOST 15588-2014)		
1	Gas block	14	2.296
2	Ash-gravel concrete	15	3.338
3	Foam block	17	1.841
4	Baked brick	15	3.658

5	Cinder block	14	4.437
6	Vermiculite concrete	16	2.628
7	Unbaked brick	12	3.326
	Material: Plaster (cement-sand)		
1	Gas block	11	2.936
2	Ash-gravel concrete	13	15
3	Foam block	14	3.291
4	Baked brick	9	28
5	Cinder block	12	24
6	Vermiculite concrete	13	7.51
7	Unbaked brick	13	22

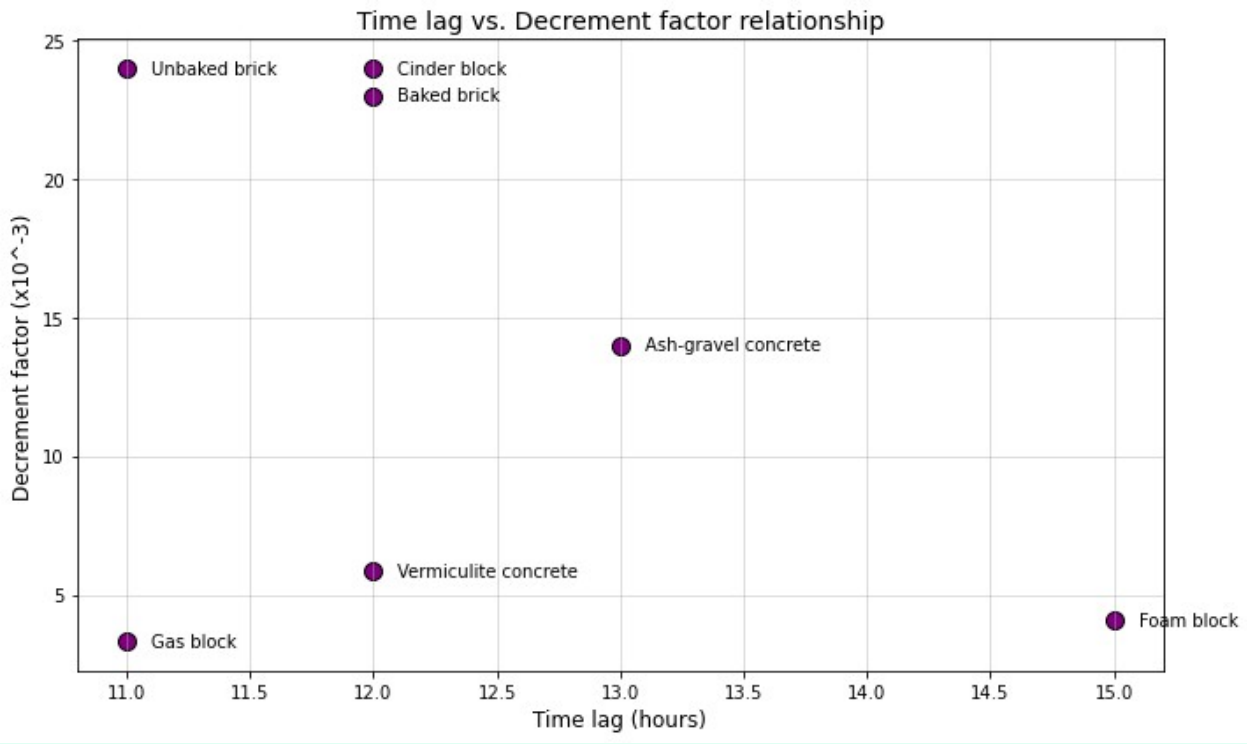


Figure 4. Comparison of time lag and decrement factor values for the case of basalt insulation

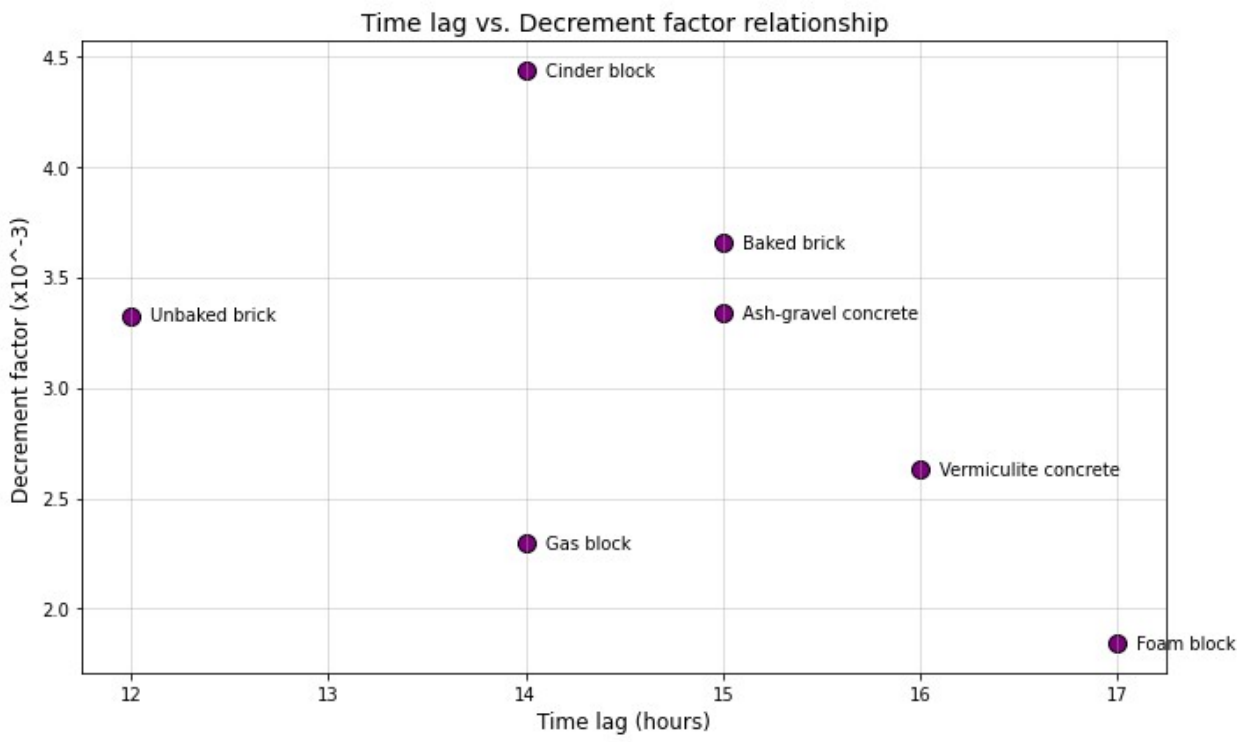


Figure 5. Comparison of time lag and decrement factor values for the case of using expanded polystyrene (GOST 15588-2014) insulation

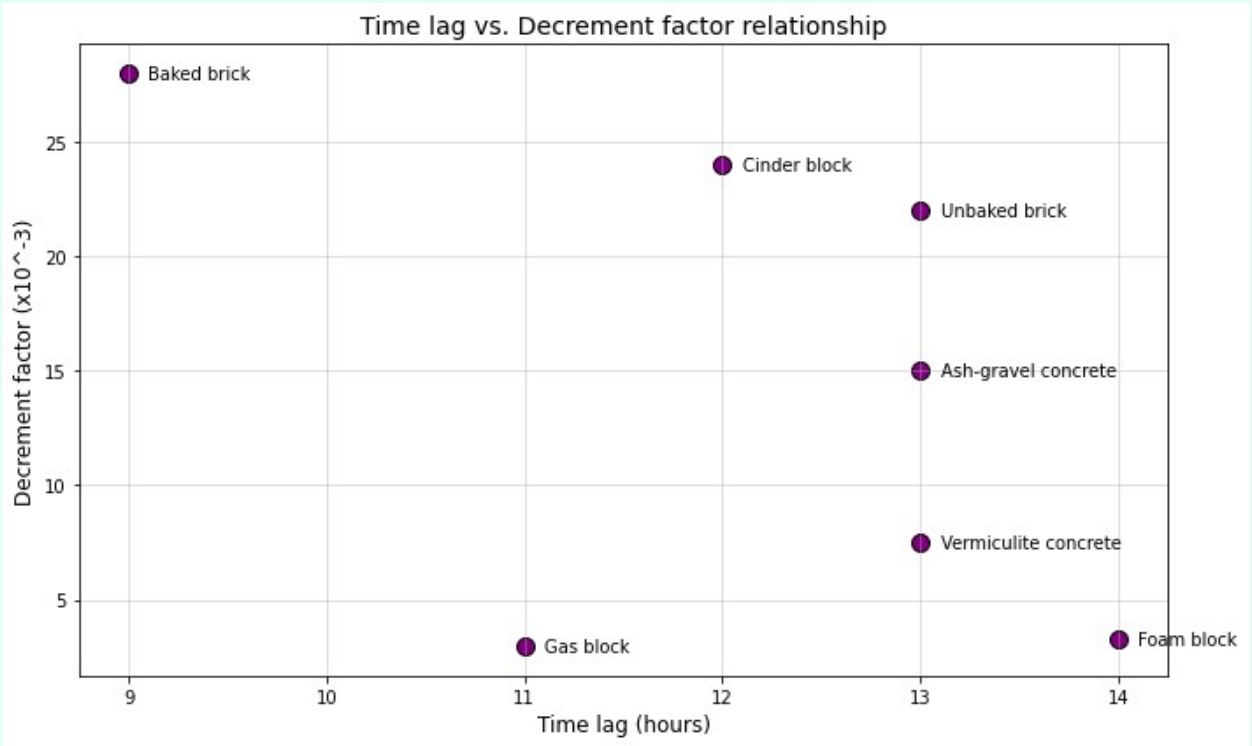


Figure 6. Comparison of time lag and decrement factor values for the case of using a plaster (cement-sand) isolation

Conclusion. This research work aims to determine the time lag and decrement factor values for various wall materials and insulations applied to them. Calculations were performed in the COMSOL Multiphysics modeling program. The solution obtained by the analytical method for the temperature of the inner surface of the wall was validated with the solution obtained by the numerical method. The calculations were carried out by applying basalt, rubble and expanded polystyrene (GOST 15588-2014) insulation to building materials such as unbaked brick, baked brick, cinder block, foam block, gas block, ash-gravel concrete and vermiculite concrete, and among them, the time lag was the largest (17 hours) and the decrement factor value was the smallest ($1.841 \cdot 10^{-3}$) when foam polystyrene (GOST 15588-2014) insulation was applied to the foam block material.

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