Thermal performance evaluation of the wall using heat flux time lag and decrement factor

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Decrement factor
Heat flux
Thermophysical properties
Wall

Abstract

The thermal performances of walls have great influences on the energy consumption and the thermal comfort of the room. Because the heat flux through the wall is the direct reason to cause the variations of the indoor air temperature, it directly affects the cooling/heating load and the thermal comfort of the room, the effect of the wall on the wall heat flux should be researched. In this paper, two parameters, which are the heat flux time lag and the heat flux decrement factor, are proposed to evaluate the thermal performance of the wall. Based on the one-dimensional numerical model built in the paper, the effects of the thermal properties of the wall and the thickness of the wall on the heat flux time lag and heat flux decrement factor are investigated. In addition, the heat flux time lag and heat flux decrement factor for several building materials are obtained. This research is useful for knowing the thermal performances of the wall better.

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1. Introduction

The energy consumption of buildings is tremendous in many countries, and the total energy demand is growing every year. As we know, the heat flows through the walls take a large part in the cooling/heating load of the room. Therefore, the thermal performances of walls have great influences on the energy consumption and the thermal comfort of the room. Researchers hope to reduce the energy consumption and enhance the thermal comfort of the room by using more efficient walls [1–5].

For reducing the building energy consumption, we should figure out the thermal performances of the wall and the effects of the wall on the indoor environment firstly. There are two parameters to evaluate the thermal performance of the wall, which are the time lag (ϕ) and the decrement factor (f), respectively. The time it takes for the temperature wave to propagate from the outer surface to the inner surface is named as time lag and the decreasing ratio of its temperature amplitude is named as decrement factor [6]. In general, if the time lag of the wall is high and the decrement factor of the wall is low, the fluctuation of the indoor air temperature will be small, and the thermal comfort of the room will be enhanced. Asan and Sancaktar [6] found the thermophysical properties of the wall had a very profound effect on the time lag and decrement factor, and they got the computed time lags and decrement factors for different building materials. In other papers, Asan [7,8] found the thickness of the material, the type of the material, and the insulation thickness and position also had a very profound effect on the time lag and decrement factor. In order to get the maximum time lag and the minimum decrement factor, researchers tried to find the optimum location and distribution of the insulating layer in the wall, the results showed that the effects of placing two or three pieces of insulating layer in the wall were better [9,10]. Kontoleon et al. [11,12] also studied the effects of the outdoor absorption coefficient and the orientation of the wall on time lag and decrement factor by employing a dynamic thermal-network model. Ulgen [13] investigated the behavior of opaque wall materials under solar energy change to find the time lag and decrement factor for different wall compositions by experimental and theoretical research.

In the previous studies, the researchers mainly focused on the temperatures of the wall and the room, and they proposed the temperature time lag and decrement factor to evaluate the thermal performance of the wall. The time lag and the decrement factor mainly show the relationship between the exterior surface temperature of the wall and the interior surface temperature of the wall. However, as we know, the wall will affect the heat flux into the room firstly, and then the heat flux causes the variations of the indoor air temperature. Compared with the interior surface temperature of the wall, the wall heat flux is the direct reason to cause the variations of the indoor air temperature, it directly affects the cooling/heating load and the thermal comfort of the room. Therefore, the effect of the wall on the wall heat flux should be researched. In this paper, two parameters, the heat flux time lag and heat flux decrement factor, are proposed to analyze the effect of the wall on...
2. The heat flux time lag and decrement factor

As stated above, the interior surface heat flux of the wall is the direct reason to affect the indoor air temperature and the thermal comfort. Therefore, in the paper, the heat flux time lag and heat flux decrement factor of the wall are proposed to evaluate the thermal performance of the wall. Similar to the temperature time lag and decrement factor, the heat flux time lag and decrement factor are defined by the following equations.

\[
\begin{align*}
\varphi_q &= \tau_{qi,max} - \tau_{qe,max} \\
\phi_q &= \frac{q_{i,max} - q_{i,min}}{q_{e,max} - q_{e,min}}
\end{align*}
\]  

(1) (2)

where \(\tau_{qi,max}\), \(\tau_{qe,max}\) are the time that the interior surface heat flux and the exterior surface heat flux of the wall are being maximum, respectively. \(q_{i,max}\), \(q_{i,min}\), \(q_{e,max}\), \(q_{e,min}\) are the maximum and the minimum heat flux of the interior and the exterior surface of the wall, respectively.

The schematic of heat flux time lag and decrement factor is shown in Fig. 1. To simplify the evaluation, the room temperature is assumed to be constant.

3. Numerical model

3.1. The governing equation and boundary conditions

The heat transfer in the wall is assumed to be one-dimensional. The schematic of heat transfer in the wall is shown in Fig. 2.

The governing equation for the wall is

\[
\rho \frac{\partial t}{\partial t} = \lambda \frac{\partial^2 t}{\partial x^2}
\]

(3)

The boundary conditions are

\[
\begin{align*}
-\lambda \frac{\partial t}{\partial x} &= h_e (t_{sa} - t_e) \quad (x = 0) \\
-\lambda \frac{\partial t}{\partial x} &= h_i (t_i - t_m) \quad (x = \delta)
\end{align*}
\]

(4) (5)

where \(h_e\), \(h_i\) are the exterior and interior surface heat transfer coefficient of the wall, respectively. \(t_{sa}\), \(t_e\), \(t_i\), \(t_m\) are the solar-air temperature, the exterior surface temperature of the wall, the interior surface temperature of the wall and the indoor air temperature, respectively.

Fig. 1. The schematic of heat flux time lag and decrement factor.

Fig. 2. The schematic of heat transfer in the wall.
The solar-air temperature is assumed to be sinusoidal variations during a 24-h period. The equation of the solar-air temperature is [6]

\[ t_{ul}(x) = \frac{t_{max} - t_{min}}{2} \sin \left( \frac{2\pi \tau}{P} - \frac{\pi}{2} \right) + \frac{t_{max} - t_{min}}{2} + t_{min} \] (6)

where \( P \) is period, \( t_{max} \) and \( t_{min} \) are the maximum and minimum outdoor temperature, respectively.

In this model, \( t_{max} = 35 ^\circ \text{C}, \ t_{min} = 25 ^\circ \text{C}, \ t_{in} = 26 ^\circ \text{C}, \ h_e = 18.6 \text{W/}(\text{m}^2 \text{K}), \ h_i = 8.7 \text{W/}(\text{m}^2 \text{K}). \)

Assuming the temperature distribution of the wall is linear at the beginning, so the initial condition is

\[ t(x, 0) = t_{min} + \left( \frac{t_{in} - t_{min}}{2} \right) \cdot x \] (7)

3.2. Solving the model

The governing equation along with the boundary conditions is discretized by finite difference method (FDM). Central difference is applied in space and fully implicit method (backwards difference) is applied in time. Although the fully implicit method will take more time to calculate, the program is stable and does not have the limitation on the time step. The space grid size is 0.5 mm and the time step is 20 s. The equations system is solved by tridiagonal matrix algorithm (TDMA).

4. Results and discussions

4.1. Effects of the thermal properties of the wall on the wall heat flux

The thermal properties of the wall not only have great influence on the temperature distribution of the wall, but also have great influence on the wall heat flow. Fig. 3 shows the effects of thermal conductivity and thermal capacity of the wall on the heat flux through the wall (the interior surface heat flux of the wall). The thickness of the wall is 240 mm. As shown in the figures, it is easy to find the heat flux through the wall decreases with the decrease of the thermal conductivity, while the fluctuation of the wall heat flux decreases with the decrease of the thermal conductivity and the increase of the thermal capacity. Fig. 4 shows the effects of the thermal properties of the wall on the “total heat flux” per day. The “total heat flux” per day is calculated by summing the hourly average heat flux over 24 h. As shown in the figures, the lower the thermal conductivity is, the lower the “total heat flux” per day is. However, the increase of the thermal capacity cannot decrease the “total heat flux” per day.

Even though the increase of the thermal capacity of the wall cannot reduce the total wall heat flux, the fluctuation of the wall heat flux will be decreased, and the peak heat flux will decrease and have a time lag with the increase of the thermal capacity. As we know, it is beneficial for the occupants and energy companies: the occupants can use more valley electric power in the night when the price is low, the capacity of the air-conditioning can be reduced, and the difference between the peak electric power load and the valley electric power load will be smaller.

4.2. The variations and distributions of temperatures and heat fluxes

Fig. 5 shows the variations of the temperatures and heat fluxes in four days. Fig. 6 shows the distributions of temperatures and heat fluxes of the wall every two hours during a day. The thickness of the wall is 240 mm, the thermal conductivity of the wall is 0.62 W/(m K), and the thermal capacity of the wall is 1.512 MJ/(m³ K). \( T_{cen}, q_{cen} \) are the temperature and the heat flux in

![Fig. 3. Effects of the thermal properties of the wall on the heat flux through the wall. (a) Thermal conductivity and (b) thermal capacity.](image)

![Fig. 4. Effects of the thermal properties of the wall on the “total heat flux” per day. (a) Thermal conductivity and (b) thermal capacity.](image)
the center of the wall, respectively. As shown in these figures, the maximum exterior surface heat flux is about 37.8 W/m², the maximum interior surface heat flux is about 10.8 W/m², the heat flux time lag is about 10 h, and the heat flux decrement factor is about 0.1154.

4.3. Effects of the thermal conductivity of the wall on the heat flux time lag and decrement factor

Fig. 7 shows the effects of thermal conductivity on the heat flux time lag and decrement factor. The thickness of the wall is 240 mm, and the thermal capacity of the wall is 1.512 MJ/(m² K). As shown in the figures, the heat flux time lag increases with the decrease of the thermal conductivity, while the heat flux decrement factor decreases with the decrease of the thermal conductivity. The values of time lag and decrement factor almost both keep the same when the thermal conductivity is greater than 20 W/(m K), they are about 5 h and 0.31, respectively. On one hand, the decrease of the thermal conductivity can reduce the total wall heat flux, on the other hand, the fluctuation of the heat flux will also be smaller.

4.4. Effects of the thermal capacity of the wall on the heat flux time lag and decrement factor

Fig. 8 shows the effects of thermal capacity on the heat flux time lag and decrement factor. The thickness of the wall is 240 mm, and the thermal conductivity of the wall is 0.62 W/(m K). As shown in the figures, contrary to the thermal conductivity, the heat flux time lag increases with the increase of the thermal capacity, while the heat flux decrement factor decreases with the increase of the thermal capacity. The heat flux decrement factor is close to 0 when the
Table 1
The heat flux time lag and the decrement factor for several building materials.

<table>
<thead>
<tr>
<th>Building materials</th>
<th>Density (kg/m³)</th>
<th>Specific heat [J/(kg K)]</th>
<th>Thermal conductivity [W/(m K)]</th>
<th>Thermal capacity [kJ/(m² K)]</th>
<th>Thermal diffusivity [m²/s x 10⁶]</th>
<th>ϕ</th>
<th>f₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement sheet</td>
<td>700</td>
<td>1050</td>
<td>0.36</td>
<td>735</td>
<td>0.490</td>
<td>9.00</td>
<td>0.1805</td>
</tr>
<tr>
<td>Concrete block</td>
<td>1400</td>
<td>1000</td>
<td>0.51</td>
<td>1400</td>
<td>0.364</td>
<td>10.50</td>
<td>0.1069</td>
</tr>
<tr>
<td>Brick block</td>
<td>1800</td>
<td>840</td>
<td>0.62</td>
<td>1512</td>
<td>0.410</td>
<td>10.00</td>
<td>0.1154</td>
</tr>
<tr>
<td>Gypsum plastering</td>
<td>1200</td>
<td>837</td>
<td>0.42</td>
<td>1004</td>
<td>0.418</td>
<td>9.50</td>
<td>0.1401</td>
</tr>
<tr>
<td>Granite (red) block</td>
<td>2650</td>
<td>900</td>
<td>2.90</td>
<td>2385</td>
<td>1.216</td>
<td>7.50</td>
<td>0.1580</td>
</tr>
<tr>
<td>Marble (white) block</td>
<td>2500</td>
<td>880</td>
<td>2.00</td>
<td>2200</td>
<td>0.509</td>
<td>7.75</td>
<td>0.1515</td>
</tr>
<tr>
<td>Sandstone block</td>
<td>2200</td>
<td>712</td>
<td>1.83</td>
<td>1566</td>
<td>1.169</td>
<td>7.00</td>
<td>0.2105</td>
</tr>
<tr>
<td>Clay sheet</td>
<td>1900</td>
<td>837</td>
<td>0.85</td>
<td>1590</td>
<td>0.535</td>
<td>9.25</td>
<td>0.1386</td>
</tr>
<tr>
<td>Asphalt sheet</td>
<td>2300</td>
<td>1700</td>
<td>1.20</td>
<td>3910</td>
<td>0.307</td>
<td>12.00</td>
<td>0.0503</td>
</tr>
<tr>
<td>Steel slab</td>
<td>7800</td>
<td>502</td>
<td>50.00</td>
<td>3916</td>
<td>12.768</td>
<td>5.75</td>
<td>0.1246</td>
</tr>
<tr>
<td>Aluminum slab</td>
<td>2700</td>
<td>880</td>
<td>210.00</td>
<td>2376</td>
<td>88.384</td>
<td>5.50</td>
<td>0.2070</td>
</tr>
<tr>
<td>Cork board</td>
<td>160</td>
<td>1888</td>
<td>0.04</td>
<td>302</td>
<td>0.132</td>
<td>15.50</td>
<td>0.0345</td>
</tr>
<tr>
<td>Wood block</td>
<td>800</td>
<td>2093</td>
<td>0.16</td>
<td>1674</td>
<td>0.096</td>
<td>19.00</td>
<td>0.0131</td>
</tr>
<tr>
<td>Plastic board</td>
<td>1050</td>
<td>837</td>
<td>0.50</td>
<td>879</td>
<td>0.569</td>
<td>8.75</td>
<td>0.1924</td>
</tr>
<tr>
<td>Rubber board</td>
<td>1600</td>
<td>200</td>
<td>0.30</td>
<td>3200</td>
<td>0.094</td>
<td>19.50</td>
<td>0.0097</td>
</tr>
<tr>
<td>P.V.C board</td>
<td>1379</td>
<td>1004</td>
<td>0.16</td>
<td>1385</td>
<td>0.116</td>
<td>17.25</td>
<td>0.0208</td>
</tr>
<tr>
<td>Asbestos sheet</td>
<td>2500</td>
<td>1050</td>
<td>0.16</td>
<td>2625</td>
<td>0.061</td>
<td>23.50</td>
<td>0.0037</td>
</tr>
<tr>
<td>Formaldehyde bond</td>
<td>30</td>
<td>1674</td>
<td>0.03</td>
<td>50</td>
<td>0.600</td>
<td>7.25</td>
<td>0.3053</td>
</tr>
<tr>
<td>Thermalite board</td>
<td>793</td>
<td>837</td>
<td>0.19</td>
<td>630</td>
<td>0.302</td>
<td>10.75</td>
<td>0.1136</td>
</tr>
<tr>
<td>Fibreboard</td>
<td>300</td>
<td>1000</td>
<td>0.06</td>
<td>300</td>
<td>0.200</td>
<td>12.50</td>
<td>0.0716</td>
</tr>
<tr>
<td>Siporex board</td>
<td>550</td>
<td>1004</td>
<td>0.12</td>
<td>552</td>
<td>0.217</td>
<td>12.50</td>
<td>0.0752</td>
</tr>
<tr>
<td>Polyurethane board</td>
<td>30</td>
<td>837</td>
<td>0.03</td>
<td>25</td>
<td>1.200</td>
<td>5.00</td>
<td>0.5571</td>
</tr>
<tr>
<td>Light plaster</td>
<td>600</td>
<td>1000</td>
<td>0.16</td>
<td>600</td>
<td>0.267</td>
<td>11.50</td>
<td>0.0982</td>
</tr>
<tr>
<td>Dense plaster</td>
<td>1300</td>
<td>1000</td>
<td>0.50</td>
<td>1300</td>
<td>0.385</td>
<td>10.25</td>
<td>0.1168</td>
</tr>
</tbody>
</table>

Fig. 8. Effects of the thermal capacity on the heat flux time lag and decrement factor. (a) Time lag and (b) decrement factor.

The thermal capacity is large enough, which means the wall heat fluxes into the room are almost the same during the whole day.

4.5. Effects of the thickness of the wall on the heat flux time lag and decrement factor

Fig. 9 shows the effects of the wall thickness on the heat flux time lag and decrement factor. The thermal conductivity of the wall is 0.62 W/(m K), and the thermal capacity of the wall is 1.512 MJ/(m² K). As shown in the figures, similar to the thermal capacity, the heat flux time lag increases with the increase of the thickness, while the heat flux decrement factor decreases with the increase of the thickness. The relationship between the time lag and the wall thickness is about linear. Actually, by increasing the thickness of the wall, on one hand, the thermal resistance of the
wall will be increased, on the other hand, the thermal capacity will also be increased.

4.6. The heat flux time lag and decrement factor for several building materials

Table 1 shows the heat flux time lag and the decrement factor for several building materials. The thermal properties of the materials are obtained from Ref. [6]. The thickness of the wall is 240 mm. It is easy to find that the thermal conductivity and the thermal capacity both have influences on the heat flux time lag and decrement factor. Although some materials (formaldehyde board, polyurethane board) have very low thermal conductivities, the thermal capacities of them are also very low, as shown in the table, the time lags are lower and the decrement factors are higher. On the other hand, some materials (steel slab, aluminum slab) have very high thermal capacities, but the thermal conductivities of them are also very high, as shown in the table, the time lags are lower and the decrement factors are higher. Therefore, in order to improve the thermal performance of the wall, we should choose the proper building materials by considering the thermal conductivity, the thermal capacity and the thickness of the wall together.

5. Conclusions

In this paper, two parameters, heat flux time lag and heat flux decrement factor, are defined to evaluate the thermal performance of the wall. Based on the numerical model built in the paper, the conclusions can be summarized as:

1. The fluctuation of the heat fluxes through the wall can be reduced by increasing the thermal capacity of the wall, but the total wall heat flux during a day cannot be reduced.
2. The heat flux time lag increases with the increase of the thermal capacity and the thickness of the wall, decreases with the increase of the thermal conductivity of the wall. While the heat flux decrement factor decreases with the increase of the thermal capacity and the thickness of the wall, increases with the increase of the thermal conductivity of the wall.

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