The Effect of Orientation on Optimum Insulation Position in the Wall of a Building with Natural Ventilation in Hot and Dry Climate

M. Najafian*
Department of Mechanical Engineering,
Islamic Azad University, Majlesi Branch, Isfahan, Iran
E-mail: mnajafian@iaumajlesi.ac.ir
*Corresponding author

A. R. Bahrami
Department of Mechanical Engineering,
Islamic Azad University, Majlesi Branch, Isfahan,Iran
E-mail: arbahrami@iaumajlesi.ac.ir

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Abstract: In this study, the effect of wall orientation on the optimum insulation position in the wall from different perspectives is studied numerically. Using Crank- Nicolson One dimensional transient heat conduction equation is solved for the wall with convection boundary conditions. Outdoor temperature is considered as a periodic function of time. Since natural night ventilation is used in the building, indoor temperature is constant during day time while air conditioning (AC) system is ON and is time dependent when AC is OFF. A time dependent indoor temperature is calculated and used as a boundary condition at the wall inner side. For the position of insulation in the wall six practical configurations are considered and time lag (TL), decrement factor (DF) and total conduction heat gain (TCHG) is calculated for all configurations. It is seen that, from minimum TCHG perspective, the best configuration for all directions is when insulation is used in the inner side of the wall. The minimum TCHG is occurred at an angle of 200^0 from the south. It can be concluded that different perspectives may lead to different results for the optimum insulation position in the wall.

Keywords: Building Orientation, Decrement Factor, Natural Ventilation, Time Lag, Total Conduction Heat Gain

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Biographical notes: M. Najafian received his MSc in mechanical engineering from university of science and technology and BSc. in mechanical engineering from Isfahan University of Technology. He is currently lecturer at the department of engineering, Islamic Azad University, Majlesi branch, Isfahan, Iran. **A. R. Bahrami** is an instructor in mechanical engineering at the Islamic Azad University, Majlesi branch, Iran. He received his MSc. degree in mechanical engineering from Tehran University, Iran and BSc. in mechanical engineering from KNT University, Iran.

1 INTRODUCTION

Large values of daily range, numerous sunny day and low relative humidity are characteristics of hot and dry climate in central Iran. These characteristics cause hot summers and cold winters in this region. Traditionally, inhabitants used natural phenomena to prepare comfort condition in their dwellings, using natural ventilation and thick adobe walls for instance. Nowadays, Systems which employ natural energy sources for AC are called passive system [1]. In passive systems, building use natural renewable energy sources and heat form the building is removed to natural heat sinks. In these buildings walls can act as energy storage elements which store heat during day and remove it back to the environment at nighttime [2], [3].

Two important parameters which are used to represent heat storage capability of the wall are time lag (TL) and decrement factor (DF). TL is the difference between occurrence of maximum temperature at outside surface of the wall and that of the inner wall surface and decrement factor is the ratio of temperature changes at the outer wall surface to that of inner wall surface. In the walls with large values of TL maximum heat convection from inside wall surface to indoor air occurs at a time that other cooling load factors, radiation for instance, are not significant. Low values of DF denote high heat resistance of the wall [4], [5]. Using proper masonry material highly increases TL and decreases DF [5-8].

Location of insulation in the wall, insulation thickness and the number of insulation layers can also affect TL and DF [4], [9-11]. Researchers surveyed the effect of wall orientation and the outside surface absorption coefficient on a TL and DF in the buildings without natural night ventilation [2], [12], [13]. As solar radiation to the wall has a significant effect on conduction load of the building, TL and DF are changing with the orientation of the wall. Moreover, wall absorption factor or its color can extensively influence temperature changes on the wall surface. In all above mentioned researches indoor air temperature is assumed to be constant and sol-air temperature which is periodically changes with time throughout the day is used as boundary condition at the outer surface of the wall.

In this study, six different wall configurations of two layers of polystyrene insulation and two layers of aerated brick with respect to changes in wall orientation in hot and dry climate are investigated. Natural night ventilation is applied to the building regarding to large values of daily range in hot and dry climate. Since there is no heat removal from the building through AC system during night time a new parameter called total heat gain (TCHG) is introduced in thermal analysis of the wall. Optimum configuration is studied from different viewpoints, TL, DF and TCHG and the results are compared.

2 TIME DEPENDENT THERMAL ANALYSIS

a. Heat conduction equation:

Since indoor and outdoor temperatures change with time throughout a day one dimensional heat conduction equation is applied:

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} \quad (1)$$

In this equation 'T', 't' and 'x' are local temperature, time and location respectively and $\kappa = k/\rho c_p$ is thermal diffusivity. Boundary condition on external surface of the wall is nonlinear and time dependent. According to the situation inside the building, boundary condition at the internal surface of the wall can be either time dependent or steady. If AC system is always ON, it keeps indoor temperature quite constant. Accordingly boundary condition at inside surface is assumed not to be time dependent. On the other hand, if natural night ventilation, through which AC system is OFF at night time, is applied indoor temperature changes with time and as a result, corresponding boundary condition is time dependent. Using heat balance on external surface of the wall, its boundary condition is determined [14]:

$$-\left(k \frac{\partial T}{\partial x}\right)_{x=0} = h_o(T_o(t) - T_{os}) + \alpha G_t \quad (2)$$

Where 'h_o' is combined convection and radiation coefficient. $T_o(t)$ and 'T_{os}' denote outdoor air and wall outside surface temperature respectively and 'α' and 'G_t' represent heat absorption factor and solar heat gain. Heat convection boundary condition on wall inside surface is also applied. Radiation is included in combined convection and radiation heat transfer coefficient 'h_i'. This boundary condition is stated as:

$$-\left(k \frac{\partial T}{\partial x}\right)_{x=L} = h_i(T_i(t) - T_{is}) \quad (3)$$

where $T_i(t)$ and 'T_{is}' are indoor time dependent temperature and wall inside surface temperature. Eq. (1) is solved implicitly using Crank-Nicholson method.

b. Outdoor time dependent temperature:

Outdoor temperature changes as a periodic function of time throughout a day [15]. This function can be approximated as a sinusoidal function:

$$T_o(t) = \Delta\bar{T}_o \sin\left(\frac{\pi}{12}t - \frac{5\pi}{6}\right) + \bar{T}_o \quad (4)$$

where '$\bar{T}_o$' and '$\Delta\bar{T}_o$' are mean outdoor temperature and amplitude of outdoor temperature fluctuation.

c. Indoor time dependent temperature:

In natural night ventilation systems, AC system is turned OFF when outdoor air cools down to the point that it can be directly circulated in the building to provide comfort condition. According in the buildings wherein natural night ventilation is used indoor temperature is constant only when AC system is ON afterward apparently it is a function of outdoor time dependent temperature. Indoor temperature in night ventilation period is also depending on ventilated air volume flow rate, set temperature of AC system, and the capacity of heat storage of building materials. Indoor temperature for night ventilation period is calculated through two heat balance equations on the wall and indoor air [16]. The heat balance for the wall is:

$$Mc_m\frac{\partial T_m}{\partial t} + Q_{conv,out} + Q_{conv,in} = 0 \quad (5)$$

For indoor air the balance is:

$$Q_{conv,in} = Q_{vent} \quad (6)$$

In these equations 'M', 'c_m' and 'T_m' are mass, specific heat capacity, and temperature of thermal mass and $Q_{conv,out}$ and $Q_{conv,in}$ represent convection from the wall inward and outward and finally Q_{vent} denotes heat removed by ventilation.

d. Time lag and decrement factor:

Two important parameters in building dynamic thermal analysis are TL and DF. TL is the time that it takes for the maximum temperature at the outside surface of the wall to reach the inside surface of the wall. DF is the ratio of amplitude of temperature fluctuation at inside surface to that of outer surface [4]. TL is expressed as:

$$\phi = t_{T_{max,i}} - t_{T_{max,o}} \quad (7)$$

where 'φ' is time lag and $t_{T_{max,i}}$ and $t_{T_{max,o}}$ denote the time of occurrence of maximum temperature at inside and that of outside respectively. Large value of the time lag means that the maximum convection heat flux from the inner wall surface to the indoor air occurs at a time when other heat gain parameters are not at their maximum values. Accordingly in maximum load calculation this conduction will not superpose the rest of maximum loads and this leads to selection of a smaller AC system which works steadily for a longer time.

DF is determined as:

$$f = \frac{T_{max,i} - T_{min,i}}{T_{max,o} - T_{min,o}} \quad (8)$$

where 'f' represents DF. This factor shows how fluctuation in outside surface of the wall is transported through the wall. Low amount of DF represents high thermal resistance of the wall [4], [5], [11-13].

e. Total heat conduction gain (TCHG)

As maximum temperature at inside surface of the wall usually occurs a time that AC is OFF, TL cannot completely represent heat consumption in the building. What is important in this case is how much heat is conducted to the building when AC is ON. This is the heat which AC system is removing. TCHG during AC period is:

$$Q_t = h_i A \int_{t_{on}}^{t_{off}} (T_{is}(t) - T_{set})dt \quad (9)$$

where $T_{is}(t)$ is indoor time dependent temperature and 't_{on}' and 't_{off}' represent ON and OFF time of AC system.

3 RESULTS AND DISCUSSION

This study is conducted for a typical building with 200m^2 area in the city of Esfahan as a sample of hot and dry climate. AC period works only 13 hours a day from 10 to 23 and outdoor air is circulated in the building out of this period. The wall of the building is 26cm thick including two 10cm thick layers of aerated brick, a 1cm thick gypsum plaster layer and two 2.5cm thick layers of polystyrene insulation. All calculations are done for the month of June as the warmest month of the year in Esfahan [17]. Thermo-physical properties of materials used in the wall are listed in Table 1, and meteorological properties of air are shown in Table 2.

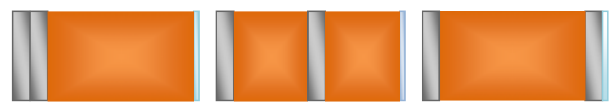
Table 1 Thermo-physical properties of wall materials

	k (W/m K)	ρ (kg/m^3)	c_p (J/kgK)	$\kappa = k/\rho c_p$ (m^2/s)
Aerated	0.3	1000	840	36×10^{-8}
brick	0.035	23	1470	104×10^{-8}
Polystyrene	0.18	800	1090	21×10^{-8}
Gypsum				

Table 2 Meteorological Properites

	Value
Average maximum daily temperature	37°C
Average minimum daily temperature	18.5 °C
Outdoor mean temperature	27.75 °C
Amplitude of outdoor temperature	9.25 °C
fluctuation	22.7 w/m²K
Outside convective heat coefficient	8.29 w/m²K
Inside convective heat coefficient	25°C
Set point temperature	

Six possible configuration of material-insulation for the wall are considered(Fig. 1). TL, DF and TCHG are calculated for these six configurations at different angles.



Conf.1 Conf.2 Conf.3

Conf.4 Conf.5 Conf.6

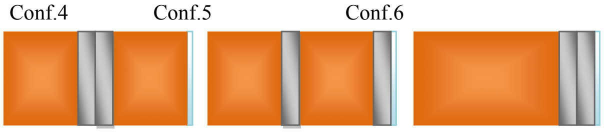


Fig 1 Six possible wall configurations using two masonry material layers, two insulation layers and one gypsum layer

A FORTRAN code has been prepared to simulate heat transfer in the wall and calculate required parameters. Changes in TCHG, TL and DF for different orientations of wall have been determined for different configurations to figure out the best configuration for different wall orientations.

a. Results for TCHG:

Fig. 2 shows TCHG for different material-insulation configuration with respect to orientation of the wall. Psi represents the angle from south wall so that 0^0 corresponds to south wall, 90^0 to east wall, 180^0 to north and 270^0 to west wall. As can be seen TCHG keeps increasing when wall is turned form south to east, other words 0^0 to 90^0 orientations for all configurations. It decreases when the wall is turned from east toward north, 90^0 to 180^0 for all configurations. When wall is turned form north to west TCHG decreases for first 30^0 and then increases form the angle 210^0 to 270^0 and finally there is a pure decrease in turning the wall from west to south, 270^0 to 0^0.

For all orientations Conf.1 which corresponds to both layers of insulations outward is best and Conf.6 is worst configuration from TCHG viewpoint. As it is shown the trends in changes of TCHG for different configurations are almost parallel with changes in orientation as a result it is concluded that orientation does not have any effect on best and worst material-insulation configurations.

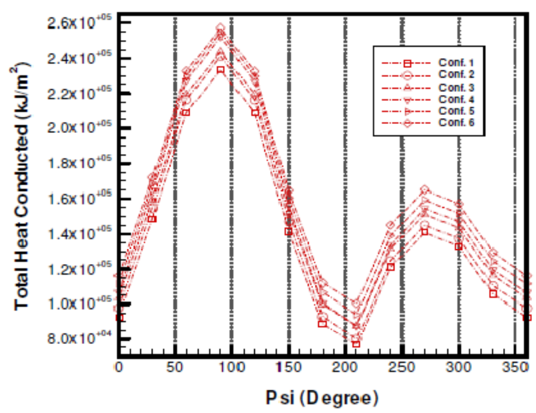


Fig. 2 TCHG for different configurations in with respect to changes in wall orientation

b. DF Results

Fig. 3 shows the DF for different configurations with respect to changes in orientations. From 0^0 to 30^0, 90^0 to 150^0 and 240^0 to 360^0 DF increases for all configurations. DF has maximum value around 150 and minimum value around 240^0 for all wall configurations. For all orientations Conf.1 has minimum DF, therefore it can be concluded that best wall configuration from DF viewpoint is Conf.1 regardless of the orientation angle. From 0^0 to 90^0, south to east, and 150^0 to 360^0 the order of DF from low values to large values is Conf.1, Conf.3, Conf.6, Conf.2, Conf.5 and Conf.4. From 90^0 to 150^0 this order changes to Conf.1, Conf.3, Conf.2, Conf.6, Conf.5 and Conf.4. This means that unlike TCHG, DF changes with orientation but in all orientation Conf.4 is worst.

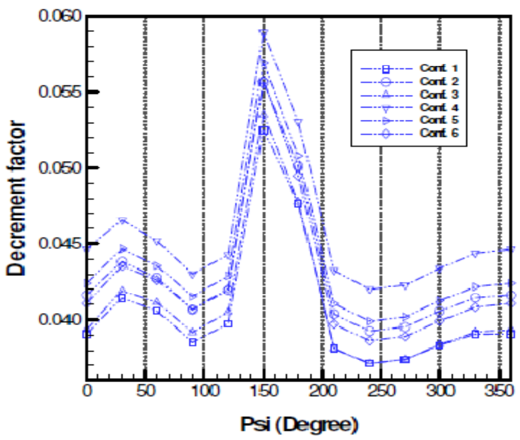


Fig. 3 DF for different configurations in with respect to changes in wall orientation

c. TL Results

Fig. 4 shows the results for TL for different configurations in different orientations. For all configurations TL increases as the orientation angle increases from 0^0 to 150^0 and increases from 150^0 to 180^0. As the wall turns around from north to south in west direction TL increases for all configurations. For all orientations Conf. 4 has the lowest TL value and is worst configuration but depending on the angle Conf.1 or Conf.3 has highest TL value and are best configurations. It can be deduced that wall orientation has effect on configuration selection of the wall from TL perspective.

As it is observed, in optimization based on TCHG Conf.1 is the best for all orientations. It is also seen that form TL viewpoint this configuration is mostly the best. Conf.1 is also the best from DF perspective. Therefore it can be concluded that Conf.1 which represents both layer of insulations in the outer part of the wall is optimum configuration for the wall of a building with natural ventilation. It is worth to mention that, these results are just for aerated brick and polystyrene wall composition and cannot be generalized to other materials.

Minimum TCHG for Conf.1 which is the best configuration occurs around the orientation of 210^0.

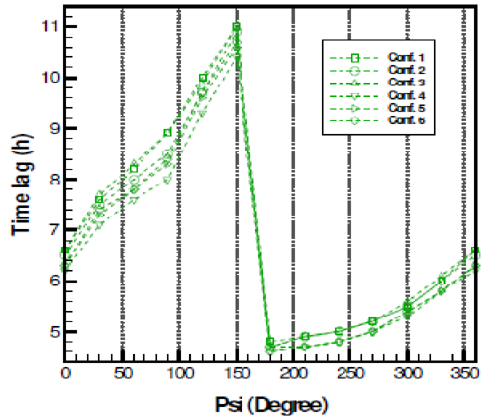


Fig. 4 TL for different configurations in with respect to changes in wall orientation

To better explain TCHG for this configuration around this angle Fig. 5 shows TCHG for Conf.1 with more detail. As can be seen minimum value of TCHG corresponds to the angle 200^0. For this angle and configuration TL is 4.9h and DF is 0.039 which are reasonable values.

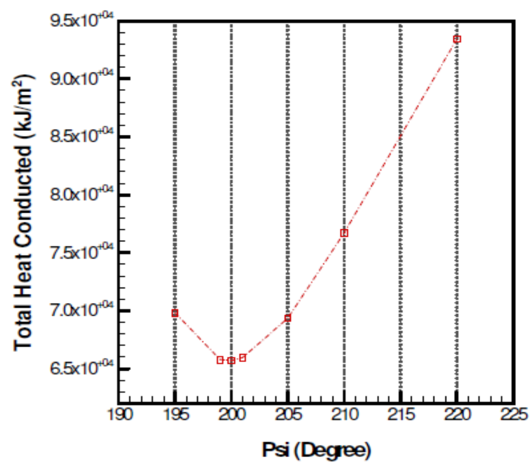


Fig. 5 TCHG for Conf.1 around wall orientation angle of 210^0

4 CONCLUSION

It can be observed that from minimum TCHG aspect, the best configuration for all directions is when insulation is used on the inner side of the wall. The minimum TCHG occurs at an angle of 200^0 from the south. It can be concluded that viewing from different aspects, may lead to different results for optimum insulation positions on walls.

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