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***Full Paper***

# Heat transfer analysis and thermal optimisation of building envelopes in Tibetan Plateau

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**Abstract:** Tibetan Plateau has an extremely harsh and cold climate and scarce natural resources but abundant solar energy. Optimisation of thermal design for buildings is highly essential for indoor thermal comfort improvement and energy efficiency of buildings. In this paper a modified heat transfer model of building envelopes in Tibetan Plateau is established, considering locally unique climatic features. Furthermore, the influence of low air density on convection is analysed and heat transfer correction factor is used to evaluate the effects of solar and long-wave radiations on external walls of buildings from different directions. The results show that the convection coefficients decline with rising elevation and heat-transfer correction factor decreases with increasing solar radiation. It also indicates that by aiming at minimising overall heat loss, the optimal thermal resistance of each external wall should be in positive proportion to the square root of its heat-transfer correction factor. A case study in Lhasa illustrates that inserting thermal insulation materials into the external walls can significantly improve indoor thermal comfort. Compared to balanced thermal insulation, the integrated uncomfortable degree of unbalanced thermal insulation can be reduced by about 20% after optimisation. This work is important for guiding the practical thermal design of buildings in plateau areas.

**Keywords**: Tibetan Plateau, heat transfer, building envelope, external wall, thermal insulation

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## INTRODUCTION

Tibetan Plateau, also called Qinghai-Tibet Plateau in China, is a vast elevated plateau in Central Asia. With an average elevation of over 4500 m and an area of 2.5 million $km^2$, it is the world's highest and largest plateau, accommodating over 3.4 million residents [1]. However, over the past half century, desertification and global warming have led to a considerable damage of the environment and ecosystem in the Tibetan Plateau [2]. On the other hand, owing to the extremely

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harsh cold weather and local natural resources scarcity, growing demands for indoor heating stimulate the search for sustainable, energy-efficient and eco-friendly buildings in this area.

The optimisation of building design, especially the building envelope, plays an important role in improving indoor comfort and saving of energy consumption of space heating and cooling [3]. Luis et al. [4] pointed out that the dominant indoor heating or cooling load stems from heat loss or gain through external envelopes of buildings including walls, windows and ceilings. Sivasankaran et al. [5] analysed and optimised a passive system to reduce heat transfer through building envelopes. Thermal resistance and overall heat-transfer coefficient were used to assess their thermal performances. Mirsadeghi et al. [6] maintained that a high thermal resistance is necessary to maintain a comfortable indoor environment even if outside temperatures are extremely cold or hot. Gregory et al. [7] investigated effects of thermal mass on the thermal performance of residential buildings and defined the decrement factor for building envelopes based on temperature difference. Asan [8] simulated the transient heat-transfer process of building envelopes and obtained the time lag and decrement factors for typical building envelope materials. Wang and Xu [9] and Fang et al. [10] built different heat-transfer models for the thermal design of buildings. Talyor and Miner [11] studied the influence of thermal-physical properties of building envelopes on the temperature variation and distribution in order to evaluate the indoor uncomfortable degree.

Moreover, it proves effective to decrease the user load by inserting insulating materials with a low heat-transfer coefficient into the external walls of buildings [12]. Khoukhi et al. [13] found that a well-insulated building can provide a more uniform indoor environment and there is less temperature gradient both vertically and horizontally. Ozel [14] used a dynamic model to study the building insulation with different orientations and determined the optimal location of insulating layers in the external walls of buildings. Furthermore, Yang et al. [15] stated that the optimal thermal design of a building envelope for a specific zone highly depends on the local geological and meteorological conditions, and Lam et al. [16] developed a mapping for the dynamic properties of external walls of buildings under actual periodic conditions. Barrios et al. [17] stated that for passive buildings, both the outdoor and indoor air states are coupled with the external walls. Kontoleon and Eumorfopoulou [18] studied the solar absorptivity of the passive building envelope. Kamaruzzaman et al. [19] integrated solar technologies and traditional energy systems to supply energy for buildings. In addition, combined solar energy and passive building systems have drawn growing attention. Maurer et al. [20] proposed novel models for building-integrated solar system, and Mateus and Oliveira [21] conducted a thermal and economic analysis for an integrated solar radiation system and obtained the energy consumption of a building through a numerical simulation.

Nevertheless, although available research is well grounded on the optimal thermal design of buildings over most areas throughout the world, still there exists a relatively unexplored gap, i.e. the high plateau area. As reported, plateau areas often have a low atmospheric pressure, low ambient temperature, high atmospheric transparency and intense solar radiation [22]. However, traditional and classical methods provided by building design handbooks or standards are based on more common and less elevated zones regardless of the aforementioned unique climatic features, which results in calculation errors in load determination of buildings and system design for plateau areas. As a consequence, a growing number of researchers recognise that the building design and calculation method call for modifications according to specific geological and meteorological conditions of plateau areas [23].

Thus, how to precisely calculate and analyse the thermal process for plateau buildings is an important but still unsolved problem. In this paper a modified heat-transfer model for the external envelope of buildings in the Tibetan Plateau is established, taking into account the local climate features of low atmospheric pressure, high air transparency, and high solar and long-wave radiations. Moreover, the influence of low air density on the convection coefficient is analysed and a heat-transfer correction factor is used to evaluate and compare the effects of solar and long-wave radiations on the external walls from different directions. In addition, a case study in Lhasa is conducted to demonstrate the optimisation design of external walls with insulating materials.

## METHODS

### Heat-Transfer Model for Building Envelope in Tibetan Plateau

For buildings in Tibetan Plateau, the heat loss via the external envelope constitutes the dominant part of heating load because of the low outdoor temperature. Hence the optimisation of the external envelope proves to be an effective way of reducing overall heating demands and consequent saving of primary energy usage.

Figure 1 gives a typical heat-transfer process at the external walls of buildings in the Tibetan Plateau. The transient heat-transfer equation and boundary conditions for the external walls are [22]:

$$\rho_w c_{p,w} \frac{\partial T_w}{\partial \tau} = k_w \frac{\partial^2 T_w}{\partial x^2}, \tag{1}$$

$$h_{out}(T_{out} - T_{w,out}) + q_{sol} + q_{lw} = -k_w \frac{\partial T_w}{\partial x}|_{x=0},\ h_{in}(T_{in} - T_{w,in}) + q_{in} = k_w \frac{\partial T_w}{\partial x}|_{x=L}, \tag{2}$$

where $T$ represents temperature (K); $\rho_w$, $c_{p,w}$, $k_w$ are density (kg/m$^3$), specific heat (J/kg·K) and conductivity (W/m·K) of walls respectively; $h_{out}$ and $h_{in}$ are convection coefficients (W/m$^2$·K) of external and internal surfaces of walls respectively; $L$ is wall thickness (m); $\tau$ is time (s); and $q_{sol}$ and $q_{lw}$ are heat flux gains (W/m$^2$) from solar and long-wave radiations respectively.

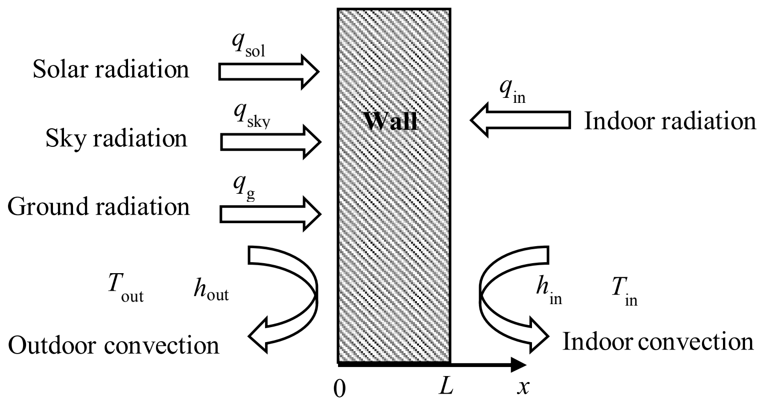


**Figure 1**. Heat transfer processes at external walls of buildings

For the exact calculation of thermal design for buildings in plateau areas, the situation is different from that for low-altitude areas. For one thing, the convection coefficients ($h_{out}$, $h_{in}$) vary due to the low atmospheric pressure. For another, the amount of solar radiation ($q_{sol}$) and fluctuation are more intense at high elevation. In addition, the high atmosphere transparency makes the

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influence of sky radiation ($q_{lw}$) more important in the Tibetan Plateau. Therefore, existing standards and calculation methods [24, 25] cannot be used directly for the design of buildings in the Plateau.

## Convection Coefficient Modification

The convection coefficient of the building envelope is an important parameter for indoor environment analysis, simulation and control. The reference values in available building-design handbooks and standards are the calculated ones under standard atmospheric pressure (i.e. about 101 kPa). However, the atmospheric pressure in the Tibetan Plateau is much lower than that in low-altitude areas, which may also produce a great impact on the convection coefficient.

Generally speaking, some thermal-physical properties of air, including the Prandlt number (Pr), dynamic viscosity ($\mu$), specific heat ($c_p$) and thermal conductivity ($k$), can be regarded as independent of atmospheric pressure in the ordinary air pressure range (i.e. $0.1\times10^5$-$10\times10^5$ Pa). Available research [24] indicates that air density, atmospheric pressure and altitude meet the following semi-empirical equation:

$$\frac{\rho}{\rho_0}=\frac{p}{p_0},\ p = p_0(1-2.25577\times10^{-5}\times H)^{5.2559}, \tag{3}$$

where $H$ is altitude (m), $p$ and $\rho$ are atmospheric pressure (Pa) and density (kg/m$^3$) respectively, and subscript 0 denotes value under standard atmospheric pressure (i.e. about 101 kPa). Based on that, the modified convection coefficients of internal and external surfaces of the plateau buildings can be obtained.

### *Internal surface*

According to the different mechanisms, convection can be categorised into two types: natural and enforced [26, 27]. Most types of convection for the wall internal surface fall into the natural one, whose Nusselt number (Nu) is depicted by [25]

$$Nu = \frac{hl}{k}=f(Gr,Pr)=f(\frac{g\alpha\Delta TL^3}{v^2},\frac{v}{a}). \tag{4}$$

In equation (4), Nu, Gr and Pr are Nusselt number, Grashof number and Prandlt number respectively, $a$ is heat diffusion rate (m$^2$/s) and $v$ is motive viscosity (m$^2$/s) [25]. So the lower air density in the Tibetan Plateau can lead not only to a higher Pr, but also to a lower Gr, both of which greatly impact the convection coefficient of the internal surface.

### *External surface*

Unlike the internal surface, the outside air flow results in enforced convection. In most building design handbooks, the convection coefficient is supposed to be constant or obtained through a linear fitting with outdoor air-flow velocity [28]. Therein, the semi-empirical non-dimensional model proposed by Hagisima and Tanimoto [29] is widely used. Then through integration along the length of the external wall, the average convection coefficient can be deduced [29]:

$$h_{out} = \frac{\int_0^L \frac{0.023}{k_w}(\frac{V}{v})^{0.891}x^{-0.109}dx}{L} = \frac{0.0258}{k_w}L^{-0.109}(\frac{V}{v})^{0.891}, \tag{5}$$

where $h_{out}$ is convection coefficient of the external surface (W/m$^2$·K), $k_w$ and $L$ are conductivity (W/m·K) and thickness (m) of the walls respectively, $V$ is outdoor air-flow velocity (m/s), and $v$ is motive viscosity of air (m$^2$/s).

**Equivalent Radiation Temperature**

Because of the high elevation of the Tibetan Plateau, the solar and long-wave radiations ($q_{sol}$) have a greater influence on the thermal performance of the building envelope. The equivalent temperature of solar radiation ($T_{sol,eq}$) is related to the outdoor convection coefficient ($h_{out}$) and the solar absorption ($r_{sol}$) of the wall surface:

$$T_{sol,eq} = \frac{r_{sol} q_{sol}}{h_{out}}. \tag{6}$$

The long-wave radiations consist of two parts: sky radiation and ground radiation. According to the heat radiation principle, the total heat gains from long-wave radiations can be expressed by [25]

$$q_{lw,out} = q_{sky} + q_g = \sigma e_{sky} \varphi_{w,sky} [T_{w,out}{}^4 - T_{sky}{}^4] + \sigma e_g \varphi_{w,g} [T_{w,out}{}^4 - T_g{}^4], \tag{7}$$

where $\sigma$ is Boltzmann constant (i.e. 1.38×10$^{23}$ J/K), $e$ is emissivity, $\varphi$ is view factor, and subscripts sky and g denote sky and ground respectively. Then the equivalent temperatures of long-wave radiations can be deduced [30]:

$$T_{sky,eq} = \frac{\sigma e_{sky} \varphi_{w,sky} [T_{w,out}{}^4 - T_{sky}{}^4]}{h_{out}}, \; T_{g,eq} = \frac{\sigma e_g \varphi_{w,g} [T_{w,out}{}^4 - T_g{}^4]}{h_{out}}. \tag{8}$$

Based on the equivalent radiation temperatures, the overall heat transfer of building walls can be integrated into a simpler form [22, 30]:

$$Q = \varepsilon AU(T_{in} - T_{out}) = \varepsilon A \frac{(T_{in} - T_{out})}{R} = \varepsilon A \frac{1}{\frac{1}{h_{in}} + \frac{1}{h_{out}} + \frac{L}{k}} (T_{in} - T_{out}), \tag{9}$$

where $R$ is thermal resistance (m$^2$·K/W), $A$ is area (m$^2$), $k$ is heat-transfer coefficient (W/m$^2$·K), $T_{in}$, $T_{out}$ are indoor and outdoor temperatures (K) respectively, and $\varepsilon$ is heat-transfer correction factor:

$$\varepsilon = 1 - \frac{T_{sol,eq} - T_{sky,eq} - T_{g,eq}}{T_{in} - T_{out}}. \tag{10}$$

Equation (10) indicates that the value of $\varepsilon$ highly depends on the equivalent temperatures of solar and long-wave radiations. The introduction of heat-transfer correction factor can simplify the heat transfer analysis for the building envelope. It is clear that the heat-transfer correction factor always decreases with increasing solar radiation ($T_{sol}$) and decreasing long-wave radiations ($T_g$, $T_{sky}$).

**Optimisation of Unbalanced Thermal Insulation**

For buildings in plateau areas, thermal insulation of the building envelope is very important for reducing the heating load since the annual average ambient temperature is relatively low (often lower than 0$^o$C). Adding a thermal insulating material to the external wall of the building is an effective way to increase the thermal resistance and decrease the indoor heat loss [13].

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Considering the high solar radiation difference for external walls in different directions (i.e. north, south, east, west) in plateau areas, the heat-transfer correction factors vary. Figure 2 indicates that the overall heat loss can be expressed by the sum of heat transfer through all external walls. Thus, for a given limited thermal insulating material, how to allocate this material for each external wall to decrease the overall heat loss is an important problem. Based on the established model in the last section, the overall heat loss through the external walls of buildings can be expressed by

$$Q=\sum_i \varepsilon_i A_i \frac{T_{in}-T_{out}}{R_i}=\varepsilon_E A_E \frac{T_{in}-T_{out}}{R_E}+\varepsilon_W A_W \frac{T_{in}-T_{out}}{R_W}+\varepsilon_S A_S \frac{T_{in}-T_{out}}{R_S}+\varepsilon_N A_N \frac{T_{in}-T_{out}}{R_N}, \quad (11)$$

where $Q$ is overall heat-transfer loss through external walls (W); $R$, $A$ and $\varepsilon$ are thermal resistance ($m^2 \cdot K/W$), area ($m^2$) and heat-transfer correction factor defined by equation (10) respectively; and subscripts E, W, S, N denote east, west, south and north walls respectively.

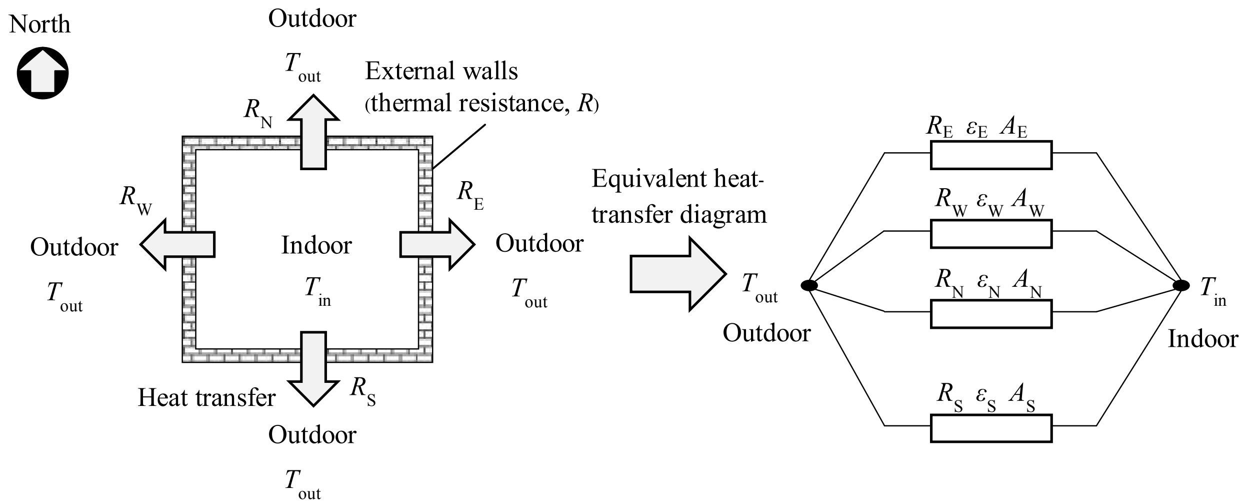


**Figure 2**. Thermal resistance of heat transfer of external walls of buildings

For the given amount of insulating material ($C$) with low thermal conductivity ($k$), the following constraint condition should be met:

$$\sum_i A_i \frac{L_i}{k}=\sum_i A_i (R_i-\frac{1}{h_{in}}-\frac{1}{h_{out}})=C. \quad (12)$$

where $R$ is thermal resistance ($m^2 \cdot K/W$), $A$ is area ($m^2$), $L$ is thickness (m), $k$ is heat-transfer coefficient ($W/m^2 \cdot K$), and $T_{in}$, $T_{out}$ are indoor and outdoor temperatures (K) respectively. For a certain building, $A_i$, $h_{in}$ and $h_{out}$ are often known parameters. So in order to minimise the overall heat loss, the optimisation model of this problem is as follows:

$$\min \sum_{i=1} \varepsilon_i A_i \frac{T_{in}-T_{out}}{R_i} \quad \Leftrightarrow \quad \min \sum_{i=1} \frac{\varepsilon_i A_i}{R_i}, \quad (13)$$

$$\text{s. t.} \quad \sum_i A_i (R_i-\frac{1}{h_{in}}-\frac{1}{h_{out}})=C \quad \Leftrightarrow \quad \text{s. t.} \quad \sum_i A_i R_i = C+\sum_i A_i (\frac{1}{h_{in}}+\frac{1}{h_{out}}). \quad (14)$$

Multiplying the objective (equation (13)) by constraint condition (equation (14)) and applying the Cauchy-Buniakowsky-Schwarz inequality principle [31], it can be obtained that

$$(\sum_{i=1}^{n}\frac{\varepsilon_i A_i}{R_i})\cdot(\sum_{i=1}^{n}A_i R_i)=(\frac{\varepsilon_1 A_1}{R_1}+\cdots\frac{\varepsilon_1 A_1}{R_n})(A_1R_1+\cdots A_nR_n)\geq(A_1\sqrt{\varepsilon_1}\cdots+A_n\sqrt{\varepsilon_n})^2 . \quad (15)$$

According to Cauchy theorem [31], the minimal value can be obtained only if

$$\frac{\sqrt{\varepsilon_1}}{R_1}=\frac{\sqrt{\varepsilon_2}}{R_2}=\cdots=\frac{\sqrt{\varepsilon_n}}{R_n} . \quad (16)$$

Equation (16) shows that to reduce the overall heat loss, the thermal insulating material should not be distributed equally. Instead, the optimal thermal resistance of each external wall should be in positive proportion to the square root of its heat-transfer correction factor.

## RESULTS AND DISCUSSION

### Convection Coefficient

Because of the low air density, the convection coefficient must be modified for the design of buildings in the Tibetan Plateau. The convection between the internal surface and indoor air can be categorised as a natural-convection heat transfer. So for vertical internal walls, equation (4) can be expressed by [25]

$$\begin{cases} Nu=0.68+\dfrac{0.67(GrPr)^{1/4}}{[1+(0.492/Pr)^{9/16}]^{4/9}}, & 10^{-1}<GrPr<10^{9} \\ Nu=\{0.825+\dfrac{0.387(GrPr)^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}}\}^2, & 10^{9}<GrPr<10^{12} \end{cases} . \quad (17)$$

It is assumed that the wall height is 3.6 m and the surface temperature is 12$^{o}$C. Then combining equations (3), (4) and (17), the convection coefficient of the internal surface at different altitudes can be calculated (Figure 3). The convection coefficient decreases moderately with increasing height. For instance, the average altitude of the Tibetan Plateau is assessed to be as high as 4500 m. Hence the convection coefficient of the internal walls of buildings can be reduced by about 25%, compared to that in low-altitude areas.

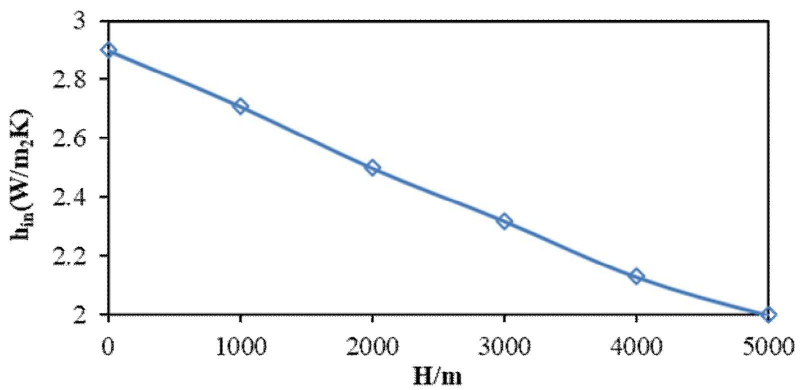


**Figure 3.** Convection coefficient of internal surface ($h_{in}$) at different altitudes

On the other hand, the convection between the external surface and outdoor air is often caused by outside air flow. According to equation (5), both the air density and velocity have much more influence on the convection coefficient of the external surface than does the length of the wall. As Figure 4 shows, the convection coefficient of the external surface decreases with increasing

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elevation and decreasing air-flow velocity. With the same air flow velocity, the convection coefficient at 4500 m can be reduced by about 33%. Comparing Figures 3 and 4, it can be found that at the same altitude the convection coefficient of the external surface is much higher than that of the internal surface. In addition, the convection coefficient dropping rate of the external surface is greater than that of internal surface, with growing altitude. Hence the influence of altitude on the convection coefficient should be considered, especially for the external surfaces of walls of buildings in the Tibetan Plateau.

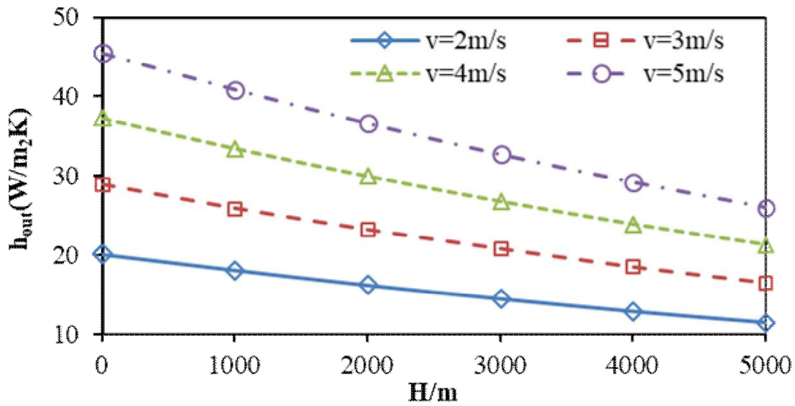


**Figure 4.** Convection coefficient of external surface ($h_{out}$) at different altitudes ($v$=outdoor air flow velocity)

**Heat-Transfer Correction Factor**

The heat-transfer correction factor ($\varepsilon$) has a close relationship with the solar and long-wave radiations. For a given building in the Tibetan Plateau, the equivalent temperatures of long-wave radiations can be regarded as the same for the external walls in different directions (e.g. $T_{sky,eq}$ = 3.0°C, $T_{g,e\,q}$= 0.6°C) [22]. However, equation (9) indicates that the equivalent temperature of solar radiation highly depends on the solar absorptivity ($r_{sol}$) and solar radiation amount ($q_{sol}$). Thus, the heat-transfer correction factors ($\varepsilon$) vary for different envelope materials and directions. Taking Lhasa, a city in the centre of Tibetan Plateau (Figure 5) as example, Figure 6 gives the hourly solar radiation amounts in different directions on a typical midwinter day (i.e. December 1) in Lhasa [32]. The solar radiation on the southern wall is always greater than the others, whereas there is no direct solar radiation on the north wall. On the east and west walls, the average solar radiations are nearly equal, only with time difference.

The building material determines the solar absorption ratio ($r_{sol}$) for the external envelope surface. As Figure 7 shows, the equivalent solar-radiation temperature ($T_{sol,eq}$) increases with increasing solar-radiation absorption ratio ($r_{sol}$) of the building envelope, $T_{sol,eq}$ of the south wall being much higher than that of the east and west walls, whereas it is equal to zero on the north wall.

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**Figure 5.** Location of Lhasa

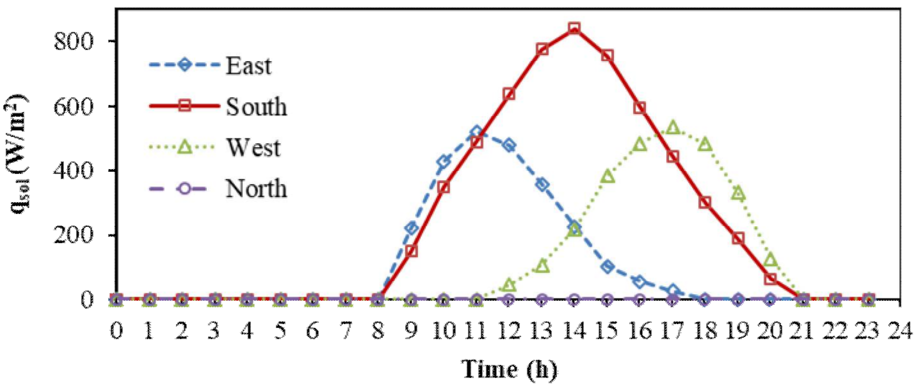


**Figure 6.** Solar radiation ($q_{sol}$) in different directions on a typical midwinter day (December 1) in Lhasa [32]

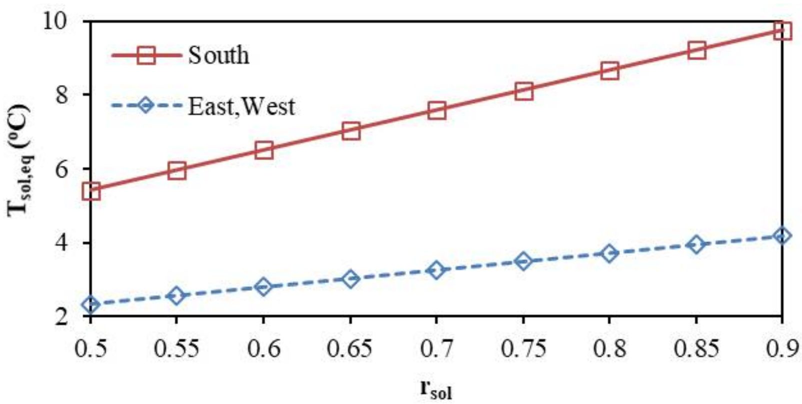


**Figure 7.** Equivalent temperature of solar radiation as a function of solar absorption ratio ($r_{sol}$) of wall surface (equation (6)) in Lhasa

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Concrete, cement and lime are three main wall materials of buildings in Lhasa, their solar-radiation absorption ratio ($r_{sol}$) being 0.73, 0.70 and 0.48 respectively [22]. The annual average ambient temperature ($T_{out}$) is assessed to be 1.6°C, and according to China heating ventilation and air conditioning design standard, the lower indoor temperature limit for thermal comfort zone ($T_{in}$) is 16°C [24]. So based on equation (10), the heat-transfer correction factors of the external walls with different orientations can be obtained in Lhasa (Figure 8).

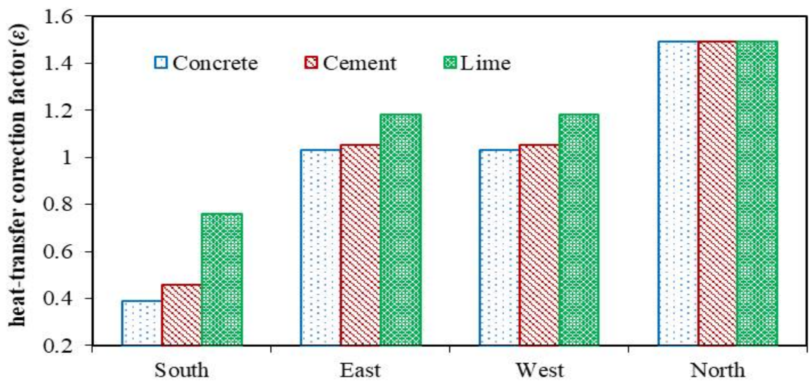


**Figure 8.** Heat-transfer correction factors of external walls of buildings in Lhasa

A higher solar-radiation absorption ratio leads to a lower heat-transfer correction factor for different envelope materials. For the south wall, large heat gain from solar radiation is favourable for reducing heat loss ($\varepsilon < 1$). By contrast, such an advantage disappears and long-wave sky and ground radiations increase the heating load ($\varepsilon > 1$) on the north wall where there is no direct solar radiation. For the west and east walls, the average solar-radiation heat gain is the same and it compensates for the heat loss caused by long-wave radiations to some extent. As a result, the heat-transfer correction factors approximately approach unity ($\varepsilon \approx 1$).

## Illustrative Example of Unbalanced Thermal Insulation

A typical room in a multi-storey office building in Lhasa is chosen as an illustrative example. The main geometrical and thermal-physical parameters of the studied room are shown in Figure 9 and Table 1. The climate information including ambient temperature and solar radiation of Lhasa in a typical year is shown in Figure 10.

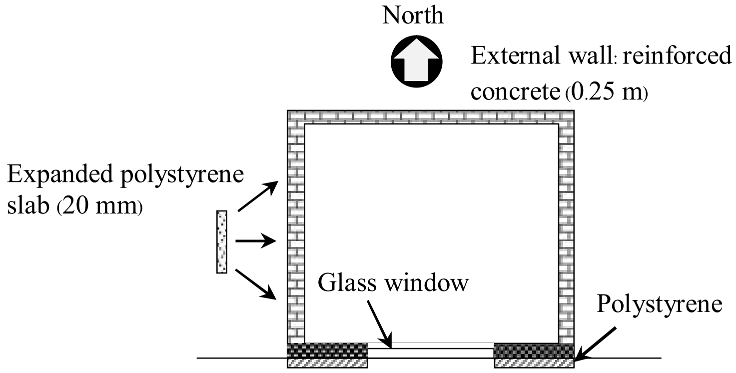


**Figure 9.** A south-facing office room in Lhasa

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**Table 1.** Room information for an office building in Lhasa

| Item | Value |
|---|---|
| Length×Width×Height | 6.0 m× 4.0 m×3.5 m |
| Ratio of window to wall | 0.3 |
| External wall | 0.25 m reinforced concrete ($\rho c_p$=2.3 MJ/m$^3$°C, $k$=1.74 W/m °C) |
| Double-glazed window | heat-transfer coefficient $U$=3.1 W/m$^2$ °C, ratio of window to wall=0.44 |

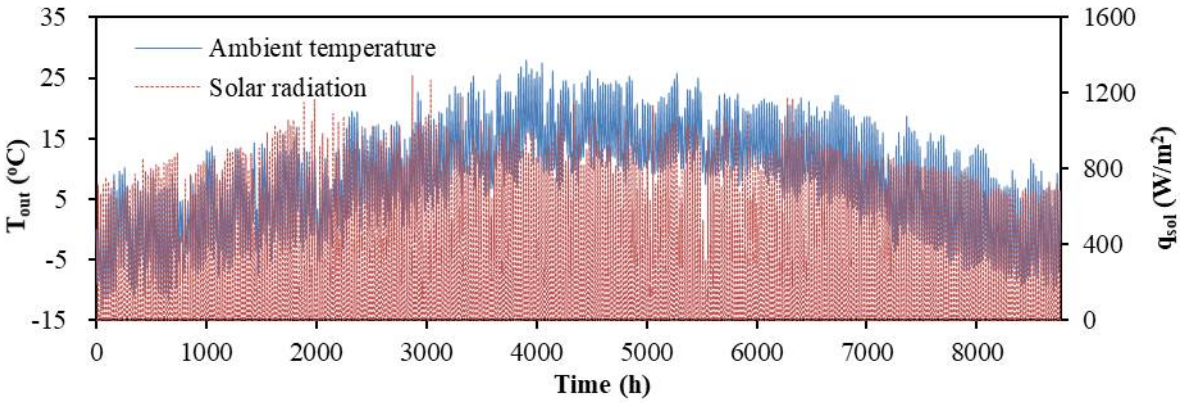


**Figure 10.** Climate information in a typical year in Lhasa [32]

Based on the heat-transfer model (equations (1-11)), the indoor air temperature of such a passive room can be obtained (Figure 11). The parameter $I_{year}$ (integrated uncomfortable degree) is defined as [30]

$$I_{year} = \int_{\substack{year \\ T_L > T_{in}}} (T_L - T_{in}) d\tau + \int_{\substack{year \\ T_{in} > T_H}} (T_{in} - T_H) d\tau \ , \quad (18)$$

where $T_H$ (28°C) and $T_L$ (16°C) represent the upper and lower indoor temperature limits of thermal comfort zone respectively [30]. $I_{year}$ reflects the integrated degree of deviation of the indoor temperature from the thermal comfort zone.

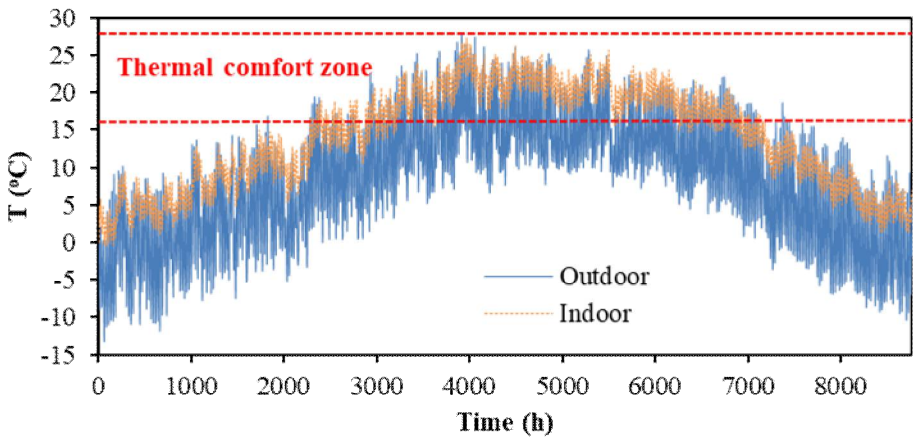


**Figure 11.** Indoor annual temperature in a passive room without thermal insulation [30]

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Figure 11 shows that for nearly half a year, the indoor temperature is lower than 16°C without air conditioning and the integrated uncomfortable degree is 32437°C·h, leading to a huge energy consumption for space heating. In order to improve the indoor thermal comfort and reduce heating load, an insulating material of low thermal conductivity may be inserted into the external walls of this building. Therein, expanded polystyrene slab (EPS) (thermal mass $\rho c_p$=0.048 MJ/m$^3$°C, thermal conductivity $k$ = 0.046 W/m °C) is widely used for thermal insulation [13]. With a given quantity of EPS (6.8 m$^3$), there are two ways of using this material: balanced or unbalanced insulation. For the balanced insulation, the material of the same thickness is equally distributed to all external walls. For the studied room (Figure 9), the wall areas are $A_S$=$A_N$=20 m$^2$, $A_E$=$A_W$=14 m$^2$, so for the material thickness, $L_S$=$L_W$=$L_E$=$L_N$=10 cm.

However, for the unbalanced insulation, the material is unequally distributed according to the heat-transfer correction factors for different walls. Based on the previous analysis (equation (16)), the optimal thermal resistance of each external wall should be in positive proportion to the square root of its heat-transfer correction factor in order to decrease the overall heat loss. For such an office room with concrete external wall, the heat-transfer correction factors can be calculated to give $\varepsilon_S$ = 0.39, $\varepsilon_W$ =$\varepsilon_E$=1.03, $\varepsilon_N$=1.49. So according to equation (16), $R_S$:$R_W$:$R_E$:$R_N$=1:1.63:1.63:1.97. Then the optimal values of EPS thickness in different walls are $L_S$=6.5 cm, $L_W$=$L_E$=10.5 cm, $L_N$=12.8 cm. This indicates that due to the influence of solar radiation, the EPS thickness of the south-facing wall can be reduced and more polystyrene material should be allocated to the north-facing wall to decrease the heat loss.

Based on the established model (equations (1-11)) and the definition of $I$ value (equation (18)), the integrated uncomfortable degree in this room can be obtained on that typical winter day. Figure 12 gives the indoor temperature comparison between different layouts of insulating material. After inserting EPS into the external wall, the average indoor temperature increases and it fluctuates more moderately during the year. With balanced thermal insulation, the integrated uncomfortable degree decreases to 18220°C·h. By comparison, with unbalanced thermal insulation after optimisation, it decreases further to only 14702°C·h, so that the heating load declines significantly by about 20%.

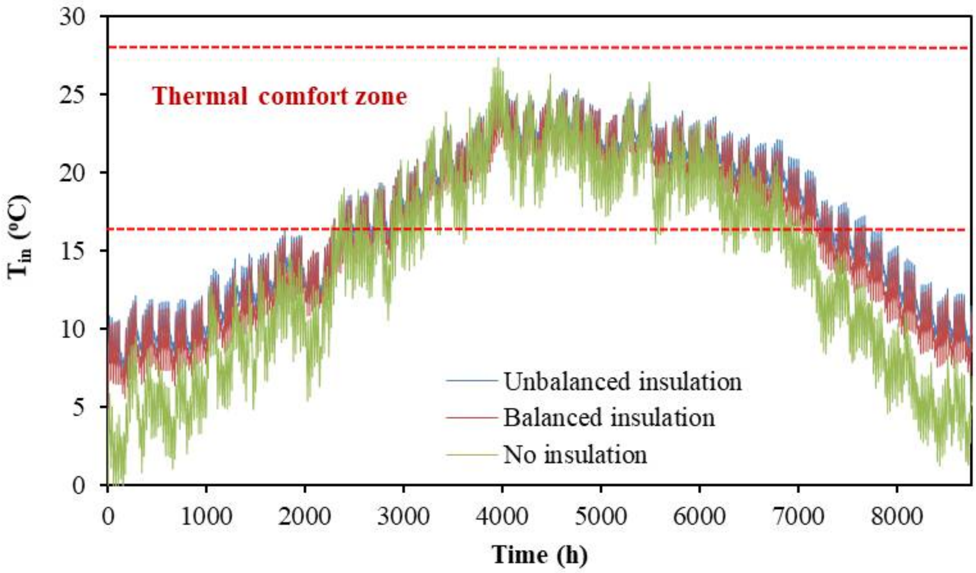


**Figure 12.** Indoor temperature in a room with thermal insulation

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## CONCLUSIONS

In this paper a modified heat transfer model of building envelopes in the Tibetan Plateau has been established, considering locally unique climatic features. Furthermore, the influence of low air density on heat convection has been analysed and the heat-transfer correction factor used to evaluate the effects of solar and long-wave radiations on external walls of buildings from different directions. Moreover, a case study of an office building in Lhasa has been conducted to investigate the effects of unbalanced thermal insulation. The main conclusions are as follows.

(1) A low atmospheric pressure in the Tibetan Plateau leads to low air density. The convection coefficients declines by 25% and 33 % for the internal and external surfaces of building walls respectively when the elevation rises from 0 m to 4500 m.

(2) The equivalent temperature of solar radiation mainly depends on the orientation and solar absorptivity of the external surfaces of the building envelope. The heat-transfer correction factor always decreases with increasing heat gains from solar radiation.

(3) To minimise the overall heat loss through external walls, the optimal thermal resistance of each external wall should be in positive proportion to the square root of its heat transfer correction factor.

(4) Inserting insulating materials into the external walls can improve indoor thermal comfort. For an illustrative example in Lhasa, the integrated uncomfortable degree can be reduced by about 20% with unbalanced thermal insulation after optimisation.

The present work proposes a modified thermal model and discusses a simple case to show its preliminary application. In real application, the use of thermal insulation materials in building walls depends on various factors, notably capital investment, since such materials are often more expensive than traditional building materials. Although the specific results obtained from the case study may not be applicable to all situations, the analysis approach is general. This work may provide guidance for practical building design in plateau areas.

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