Thermal analysis of light pipes for insulated flat roofs

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ABSTRACT

Light pipes transmit daylight into building interiors. Their installation into thermally insulated roofs of low energy buildings can be a problem because of thermal bridges and condensation problems. This article is focused on a CFD simulation thermal analysis that includes four variations of light pipes with a segment of a flat roof. Common light pipes with a hollow light guiding tube were compared to special light pipes containing an additional glass unit located inside the tube. The additional glass units increase thermal resistance and reduce condensation risks of the light guiding systems. The light pipes were compared in two different simulation models run in ANSYS Fluent software and the CaA program. Temperature profiles and air flow patterns of the cross sectional profiles of the light pipes served to determine the total heat transmittance and heat losses of the studied light pipes installed in a segment of a thermally insulated flat roof. The paper compares simplified 2D rotational–symmetrical numerical model based on the thermal diffusion equation with the complex 3D CFD numerical simulation. The results confirm that the simplified 2D numerical model is suitable for the thermal evaluation of the light pipes containing an additional glass unit, too. The additional glass unit with the triple glass improves thermal resistance up to 88% in case of light pipe with diameter 600 mm and reduces optical transmittance to 28.5%.

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1. Introduction

Light pipes are systems for guiding daylight into buildings. They consist of transparent roof domes, light guiding tubes with internal mirrored surfaces and transparent roof covers, diffusers (Fig. 1a). These light pipe systems can have a positive influence in providing daylight to internal and windowless parts of buildings [1–4]. Light pipes represent the weakest place of thermal protection because they cause thermal bridges to develop. They are commonly installed in roof constructions. Light pipe installations in highly thermally insulated roofs of low energy buildings can especially cause problems with surface condensation at the boundary between the light pipe and the roof insulation. For this reason special types of light pipes with an additional glass unit (Fig. 1b) are used to reduce heat loss and eliminate thermal bridging effects.

This study is focused on the thermal evaluation of light pipes and the possible locations thermal bridges. Thermal bridge problems in building constructions were studied for many characteristic details [5–7]. The results of the thermal resistance assessment of one type of light pipe were published [8,9] and the analysis of light pipes for lighting and ventilation systems were studied [10–13]. Studies focused on the direct thermal evaluation of light pipes were not widely published. The reason is simple; there are many types of light pipes of different geometric and optical properties in practice. The proper function of light guiding systems also depends on their installation in roof constructions. It is necessary to pay attention to the details of the light pipe connection. It is recommended to gather as many details in predicting the proper thermal transmission through light pipes. Computer simulations of light pipe thermal profiles for specified boundary conditions can be very useful for design studies. Computer fluid dynamics (CFD) simulations, for example in ANSYS Fluent software are convenient for light pipe thermal profiles evaluation [14,15]. Special light guides with concentric tubes for light transmittance and for natural ventilation were evaluated on the basis of the CFD simulations [16,17]. CFD models of heat transfer and natural ventilation in light pipes were studied. Thermal evaluations of light pipes [18] aimed at physical and geometrical models and their optimisations for simulation accuracy and reduction of calculation time were published [19]. The aforementioned studies provided results that are useful for the following evaluation of special types of light pipes presented in this article.

2. Light pipe model

2.1. Types of light pipes studied

This article presents the results of the thermal study of light pipe systems based on previous investigations [18,19]. A straight light
Variation 0: common light pipe with a hollow pipe without an additional glass unit (Fig. 3a).

Variation I: light pipe with an additional single glass of thickness 4 mm (Fig. 3b).

Variation II: light pipe with a double glass unit (glass 4 mm – Argon 16 mm – glass 4 mm). The double glass unit is placed in a thermal insulation frame of extruded polystyrene 120 mm × 120 mm (Fig. 3c).

Variation III: triple glass unit (glass 4 mm – Argon 16 mm – glass 4 mm – Argon 16 mm – glass 4 mm). Thermal insulation frame of extruded polystyrene 140 mm × 140 mm (Fig. 3d).

The light pipe is located in the flat roof composition (top waterproofing layer, thermal insulation 200 mm, reinforced concrete floor structure 200 mm). Additional thermal insulation is placed in the roof structure in connection with the light pipe so as to eliminate the thermal bridge effect as much as possible.

2.2. Simulation model

The simulation model of the light pipe has rotational–symmetrical geometry. The rotational symmetrical model is convenient because a reduction in computational time compared to the full 3D segment model. For the evaluation, the 2D rotational–symmetrical model was selected in the end, see Fig. 4. This model was tested in previous studies and compared with 3D models [18].

It was shown that the simulation outputs for 3D and 2D rotational–symmetrical segment model of room with light guide produce comparable results and for this reason it was possible to accept the 2D rotational–symmetrical model. Thus the model geometry can be simplified and also reduce simulation time. The meshing of the 2D rotational–symmetrical geometrical model gave a set of nodal points to determine temperature profiles and air velocity patterns [19]. The segment was described with materials and their physical properties and boundary conditions were specified, see Fig. 5. The simulations were run with variable length and diameter of light pipe for constant outdoor temperature –15 °C, according to [21]. Risk of condensation on inner surfaces was evaluated with the indoor temperature +20 °C and relative humidity 60%.

The rotational–symmetrical segment model with specified boundary conditions served as the specification for the two types of light pipe models as:

Model A: a model of heat transfer by convection, conduction and ventilation in the studied light pipes. This model was evaluated on
a non-structured computational mesh in program ANSYS Fluent, see Fig. 6a;
Model B: is a model of heat conduction through the light pipe (Fig. 6b) with specifications of equivalent thermal conductivity  \( \lambda_{eq} = 1.875 \, \text{W m}^{-1} \text{K}^{-1} \) provided by Eq. (1) according to [21] of the light pipe with a non-ventilated air cavity and vertical heat flux. The heat transfer coefficient  \( h_{\text{ex}} = 5 \, \text{W m}^{-2} \text{K}^{-1} \) is set on the internal surface while taking into account the indoor climate. Outdoor conditions on the external surface are assigned by the heat transfer coefficient on value  \( h_{\text{ex}} = 25 \, \text{W m}^{-2} \text{K}^{-1} \), according to [21].

The value of equivalent thermal conductivity  \( \lambda_{eq} \) [W m\(^{-1}\) K\(^{-1}\)] for Model B specified for the roof segment with the light pipe is calculated [22]

\[
\lambda_{eq} = \frac{\ell}{A_h} \frac{\Delta \theta_{\text{si}}}{Q}
\]

where  \( \ell \): length of the studied light pipe segment in the heat flux direction [m];  \( A_h \): horizontal projected area of the light pipe [m\(^2\)];  \( Q \): heat flux through the air cavity in the light pipe [W];  \( \Delta \theta_{\text{si}} \):
2.3. Theoretical background for the model

The physical model for the types of light pipes studied is based on the theoretical background [23] of heat transfer through tubular systems. This model is an updated assessment of the author's preliminary study of CFD thermal profiles in light pipes simulated in ANSYS Fluent [18,19]. These simulations were completed on the basis of a study of referenced research focused on models of air flow inside non-ventilated air cavities and pipes [23–30].

2.3.1. Model A – (rotational–symmetrical 3D model)

The air in the tube of the tested light guide was considered as non-compressive and diathermic, it means permeable by radiant heat of the infrared range of an electromagnetic spectrum. The optical thickness of the participating medium – air equals zero. The discrete ordinates model (DO) was selected, because it solves the heat transfer for rotation symmetrical geometric models with semi-transparent materials partially specular reflection surfaces [23]. Model $k$–$\omega$ SST was tested with good results for the model of the cavity with a dominant natural convection, see [24,25].

2.3.1.1. Heat convection model. Continuity equation

$$\Delta (\rho \vec{v}) = 0 \quad (2)$$

Equation of motion

$$\Delta (\rho \vec{v} \cdot \vec{v}) = - \Delta p + \Delta (\vec{f}) + \rho \vec{g} \quad (3)$$

Laminar model

$$\vec{f} = \mu \Delta \vec{v} \quad (4)$$

![Fig. 4. Rotational–symmetrical geometrical 3D segment model of a flat roof with a light pipe.](image)

![Fig. 5. Geometry and boundary conditions for the rotational–symmetrical segment model.](image)

![Fig. 6. Alternatives of the used computational meshes – an example for the light pipe with an additional double glass unit (Variation II), light pipe length 0.56 m, diameter 0.60 m.](image)
Fig. 7. Temperature distribution [°C] in the segment of a flat roof with a light pipe installation – Variation II with a double glass unit, light pipe length 0.56 m and diameter 0.60 m.

Turbulence model

\[ \overline{\tau} = \mu \left[ (\nabla \overline{\tau} + \nabla \overline{\tau}^T) - \frac{2}{3} \nabla \cdot \overline{\tau} \right] \]

The SST \( k-\omega \) model

\[ \nabla \rho \overline{\tau} = F'_k \nabla k + G_k + Y_k \]

\[ \nabla \rho \overline{\omega} = F'_\omega \nabla \omega + G_\omega - Y_\omega + D_\omega \]

Energy equation

\[ \nabla \cdot \left( \bar{\tau} (\rho E + p) \right) = \nabla \cdot \left( k_{\text{eff}} \nabla T - \sum_j H_j \bar{\tau}_j + (\bar{\tau}_{\text{eff}} \cdot \bar{\tau}) \right) \]

2.3.1.2. Radiation model. The DO model is based on the transport Eq. (12) of radiation intensity in spatial coordinates.

Radiative transfer equation (RTE)

\[ \frac{dT(\vec{r}, \vec{s})}{ds} + (a + \sigma) \cdot l(\vec{r}, \vec{s}) = a n^2 \frac{\sigma T^4}{\pi} - \frac{\sigma}{4\pi} \int l(\vec{s}, \vec{s}') \cdot \Phi(\vec{s}, \vec{s}') \cdot d\Omega' \]

2.3.2. Model B – (rotational–symmetrical 2D model)

Model B is a steady state rotational–symmetrical 2D model based on the diffusion Eq. (13) in cylindrical coordinates used in CalA software [31].

\[ \lambda \frac{\partial^2 T}{\partial r^2} + \lambda \frac{1}{r} \frac{\partial T}{\partial r} + \lambda \frac{\partial^2 T}{\partial z^2} = 0 \]

Fig. 8. Temperature distribution [°C] in a light pipe of diameter 0.30 m, length 0.56 m and 3.00 m, Variation 0 – common light pipe, Variation 1 – light pipe with an additional single glass unit.
3. Results

The CFD simulations were completed for the specifications of the thermal profiles of four variations of light pipes installed in a flat roof segment. Temperature distribution profiles are important for estimating the places with condensation risks. Air flow CFD velocity profiles were also studied. The mentioned simulations were run for light pipes of diameters 0.30 m, 0.60 m and 0.90 m and from lengths of 0.56 m to 9.00 m. The simulation results serve as a base of the thermal characteristic properties of the light pipes studied and for the estimation of their heat losses.

The main result of the evaluation is to establish an ANSYS Fluent 3D simulation model [25] which provides similar outputs compared to the simplified 2D rotational–symmetrical model run in the CaA software [31]. The evaluations were carried out for the features of heat transmission, convection and radiation loss without considering solar gains and other heat sources.

Model B was evaluated in CaA [31] and calculated for the structured computational mesh, Fig. 5. A comparison of the simulated graphical results for Model A and Model B is presented in Fig. 7. The analysis was carried out for Variation II – a light pipe with a double glass unit and for this reason the specifications are Model A/II and Model B/II.

The temperature distribution in a light pipe with 0.30 m diameter for Variation 0 and Variation I is in Fig. 8. It is obvious that the part of the light pipe connected to the flat roof is the place with the lowest temperatures because of the metal pipe thermal bridging effect. The thermal bridge is visible in the contact of the pipe with the thermal insulation layer in the roof. Longer light pipes are warmer because the internal air cavity is preheated in the indoor climate. Very short light pipe outputs are more influenced by low outdoor temperatures.

Wider light pipes with a bigger air cavity are also colder compared to pipes of the same length, but of a smaller diameter Fig. 9. The temperature distribution within the light pipes of diameters 0.90 m and 0.30 m, length 0.56 m and 3.00 m, simulated in Variation I and Variation II are presented in Fig. 9. Double glazed units installed within the light pipe have a more positive influence on the elimination of the thermal bridge compared to a single glass light pipe. A similar temperature distribution as in Variation II is achieved in Variation III for a light pipe with a triple glass unit.

Air flow distribution pattern is presented in Figs. 10 and 11 for light pipes with additional single and double glass units. There is higher air flow velocity in light pipes of Variation 0 and Variation I compared to the ones designed in Variation II and Variation III. One additional glass placed in the light pipe in Variation I can reduce air flow velocity about 30 percent compared to the air flow velocity pattern of the common hollow tube in Variation 0. The influence of the double glazed unit separating the light pipe air cavity in the smaller parts with reduced air ventilation is obvious from Fig. 11. Longer light pipes have limited circulation of air inside the pipe cavity due to warmer and more uniform temperature distribution. But in the case of shorter and wider pipes, the circulation is more efficient because of the temperature differences between the internal and external parts of the light guiding system.

Low surface temperature on the internal surface of the roof where it is in contact with the light pipe is a place which is affected by unwanted condensation and mould appearance in building applications. This place should be controlled in designed details of thermal evaluation and compared with dew point temperatures in accordance with indoor temperatures and relative humidity conditions. Surface temperatures selected from the temperature graphical distributions for all studied light pipes are summarised in Fig. 12.

Surface temperatures on the internal surface of the roof construction detail with light pipe installation are decreased in case of common light pipes in Variation 0 and for light pipes with a single additional glass in Variation I. These types of light pipes have thermal bridges in the position of the metal tube installation in the roof thermal insulation layer. The internal surface temperature is markedly decreased for wider light pipes. It means that common light pipes of larger diameters are places with thermal bridges and places of potential surface condensation in thermally insulated roof constructions. The condensation appears when the surface temperature drops below the dew point temperature [20]. Light pipes with additional double or triple glass units, Variation II and Variation III,
have a more uniform temperature profile and the surface temperatures on the interface between the tube and the insulated roof are mostly higher so that the condensation risk is eliminated.

Temperature profiles and air flow patterns for the CFD simulations served for the calculations of the light pipe heat losses; see graph in Fig. 13. The graph shows that heat losses of common hollow tubes are increased with the length and diameter of the light pipes. Massive heat loss increase is for common light pipes of a length about 1.50–2.00 m.

Heat loss is not greatly increased for longer light pipes. This is caused by the preheating of the non-ventilated air cavity of the pipe installed in the indoor heated space. The indoor temperature +20°C is one of the boundary conditions for the simulation models. A different situation would be in case of longer light pipe installations in heated and non-heated spaces. For example, the installation of a light pipe connecting a pitched roof, going through an unheated loft and guiding daylight into a heated room located under the loft space.

The graph in Fig. 14 compares the influence of the light pipe diameter on heat loss. The study was completed on light pipes of the length 0.56 m and diameters from 0.30 m to 0.90 m. The results from this graph serve as the technical parameters for thermal evaluations in during construction [20,32]. The thermal evaluation of the studied light pipes can be summarised in the

![Fig. 10. Air flow velocity in a light pipe [m s⁻¹].](image)

![Fig. 11. Air flow velocity [m s⁻¹] inside of a light pipe with an additional double glass unit (Variation II), light pipe of length 0.56 m and diameter 0.60 m.](image)
Table 1
Values of $U$ [W m$^{-2}$ K$^{-1}$] and $TT3D$ [WK$^{-1}$] for light pipes, length 0.56 m and diameters 0.30 m, 0.60 m and 0.90 m.

<table>
<thead>
<tr>
<th>Length [m]</th>
<th>Variation 0</th>
<th>Variation I</th>
<th>Variation II</th>
<th>Variation III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [m]</td>
<td>$U_{in}$ [W m$^{-2}$ K$^{-1}$]</td>
<td>$TT3D$ [WK$^{-1}$]</td>
<td>$TT3D$ [WK$^{-1}$]</td>
<td>$TT3D$ [WK$^{-1}$]</td>
</tr>
<tr>
<td>0.300</td>
<td>4.107</td>
<td>0.280</td>
<td>2.599</td>
<td>0.173</td>
</tr>
<tr>
<td>0.600</td>
<td>3.548</td>
<td>0.961</td>
<td>2.240</td>
<td>0.591</td>
</tr>
<tr>
<td>0.900</td>
<td>3.369</td>
<td>2.049</td>
<td>2.145</td>
<td>1.270</td>
</tr>
</tbody>
</table>

Fig. 12. Comparison of the surface temperature on the interior side of a light pipe installation inside a flat roof, light pipe length 0.56 m and diameters from 0.30 m to 0.90 m.

Fig. 13. Heat loss of the studied roof segment with a light pipe [W], dependence on light pipe length between 0.56 m and 3.00 m, comparison with common light pipes without an additional glass unit – completed study [19].

Fig. 14. Heat loss of light pipes, length 0.56 m and diameters between 0.30 m and 0.90 m.

values of the overall heat loss coefficients–thermal transmittance $U$ [W m$^{-2}$ K$^{-1}$] and point thermal transmittances $TT3D$ [WK$^{-1}$]. The value of $TT3D$ is calculated according to ISO standard [32]

$$TT3D = L^{3D} - \sum_{i=1}^{I} \sum_{j=1}^{J} \Psi_{i,j}b_{j}$$

where $L^{3D}$: thermal coupling coefficient [WK$^{-1}$]; $U$: thermal transmittance [W m$^{-2}$ K$^{-1}$]; $A$: area [m$^2$]; $b$: length of the linear thermal bridge [m]; $\Psi$: linear thermal transmittances [W m$^{-1}$ K$^{-1}$].

Equivalent thermal transmittance $U_{eq}$ [W m$^{-2}$ K$^{-1}$] of the studied light pipes is determined on the basis of the CFD simulation results from the following formula

$$U_{eq} = \frac{Q_{e} - Q}{A_b (\theta_i - \theta_e)}$$

where $Q_{e}$: heat loss of the roof segment with the light pipe–from CFD simulation [W]; $Q$: heat loss of the roof segment (1D) without the light pipe [W]; $A_b$: horizontal projected area of the light pipe [m$^2$]; $\theta_i$: indoor air temperature [°C]; $\theta_e$: outdoor air temperature [°C].

The values of $U_{eq}$ [W m$^{-2}$ K$^{-1}$] and $TT3D$ [WK$^{-1}$] are summarised in Table 1 for light pipes of the length of 0.56 m and diameters 0.30 m, 0.60 m and 0.90 m installed in an insulated roof segment in Variations 0–III.

The CFD simulation results can be summarised:

1) Maximal rise of the heat loss through light pipe $Q_{e}$ is up to 2.00 m in length, for longer light pipes the heat loss is not significant so that the light pipe is installed in heated rooms.

2) The additional (single, double or triple) glass unit improves thermal resistance of the light pipe and decreases thermal conduction loss. This additional glass unit reduces air convection in the cavity, as well. Another positive effect of the additional glass unit is the elimination of heat radiation transfer between the cold upper transparent dome and the warmer bottom face of diffuser.

3) Comparison of 3D and 2D rotational–symmetrical simulations of the studied light pipes provides the possibility simplify the simulation model for the 2D rotational–symmetrical heat conduction model completed with equivalent thermal conductivity calculated for the roof segment with examined light pipes. This model is convenient because it produces sufficiently accurate results comparable with the fundamental 3D analysis but it offers a more flexible evaluation for more simulation results in a reduced computational time.

4. Conclusions

Light pipes are often used as light guiding roof systems. They can transmit daylight form a long distance into internal parts of buildings. For this reason they can have a positive influence on a building’s visual comfort. But from a thermal protection point of view, light pipes can cause thermal bridging and condensation problems. This negative effect can be observed mainly in low energy buildings with highly thermally insulated roofs. Some types of light
pipes have an additional glass unit installed to reduce heat transmission and thermal bridge condensation problems.

The comparable study of thermal and velocity profiles of four different light pipes was presented in this article. CFD thermal analysis has proven that the additional double or triple glass unit installed in the light pipes has a positive effect on the reduction of air movement and temperature distribution in the whole profile of the light pipes in insulated roof segments. Negative effect of the additional glass unit is lower overall optical transmittance reduced to 28.5% for the triple glass unit, 20.1% in the case of double glass unit and 16.6% in the case of single glass unit, according to [20]. Obtained results show that the complex 3D CFD models simulated in ANSYS Fluent software have comparable results as the outputs from the 2D rotational–symmetrical simulation model based on the thermal diffusion equation. These results are very convenient for a possible simplification of light pipe simulation models. The 2D rotational–symmetrical geometry is a convenient method to reduce the calculation time needed. The model can be useful for optimisations based on many design alternatives of light pipe systems and their possible installations in roof constructions.

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