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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 CalA 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%.

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

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Nomenclature

a	absorption coefficient [m^{-1}]
A	area [m^2]
b	length of the linear thermal bridge [m]
c	specific thermal capacity [$J\,kg^{-1}\,K^{-1}$]
d	diameter [m]
D	turbulence cross-diffusion [J]
e	Euler's mathematical constant [–]
E	total energy [$J\,kg^{-1}$]
g	acceleration of gravity [$m\,s^{-2}$]
G	generation energy of turbulence [J]
h	surface heat loss coefficient [$W\,m^{-2}\,K^{-1}$]
H	enthalpy [$J\,kg^{-1}$]
I	radiation intensity [$W\,m^{-2}$]
J	diffusion flux of species [$kg\,s^{-1}\,m^{-2}$]
k	turbulent kinetic energy
L^{3D}	thermal coupling coefficient [$W\,K^{-1}$]
n	refractive index [–]
p	static pressure [Pa]
Q	heat loss [W]
r	position vector [–]
s	direction vector [–]
T	local temperature [K]
$TT3D$	point thermal transmittance [$W\,K^{-1}$]
u	unit vector [–]
U	thermal transmittance [$W\,m^{-2}\,K^{-1}$]
v	velocity [$m\,s^{-1}$]
Y	mass fraction [–]
ε	thermal emissivity [–]
Γ	effective diffusivity [Pa s]
θ	air temperature [°C]
λ	thermal conductivity [$W\,m^{-1}\,K^{-1}$]
μ	molecular viscosity [Pa s]
π	mathematical constant [–]
ρ	bulk density [$kg\,m^{-3}$]
σ	Stefan-Boltzmann constant [$W\,m^{-2}\,K^{-4}$]
τ	stress tensor [Pa]
Φ	phase function [–]
Ψ	linear thermal transmittances [$W\,m^{-1}\,K^{-1}$]
ω	specific dissipation energy
Ω	solid angle [–]

Subscript

e	external
eff	effective conductivity
eq	equivalent
es	external surface
h	horizontal surface
i.e.	between indoor and outdoor
i	notation index
is	internal surface
j	notation index
k	related to turbulent kinetic energy
p	constant pressure
ref	reference temperature
t	total
ε	related to turbulent dissipation energy
ω	related to specific dissipation energy
$\rightarrow$	direction vector

pipe without any bends was selected for the evaluation. The reason for the new evaluation was to analyse the thermal and velocity profiles of special light pipes with an additional glass unit which can be used for thermally insulated roofs of low energy buildings. The glass unit embedded inside of the light pipe can reduce heat loss, mainly by convection and conduction transfer, see Fig. 2.

An additional glass unit reduces overall optical transmittance to 10.6% in case of single glass unit, 20.1% in case of double glass unit and 28.5% in case of triple glass unit, according to ASHRAE [20]. An additional glass unit is embedded 50 mm into the thermal insulation frame of extruded polystyrene. This frame is connected to the main thermal insulated layer of the flat roof, see Fig. 3. This system serves to reduce heat loss and eliminate condensation risk. On the other hand it is necessary to consider that the additional glass unit inside of the light pipe reduces light transmittance due to light absorption in the glass units and backward reflections.

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: is a model of heat transfer by convection, conduction and ventilation in the studied light pipes. This model was evaluated on