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Investigation of laminar natural convection heat transfer within tubular daylighting devices for winter conditions

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ABSTRACT

Recent developments in lighting and energy efficiency such as Tubular Daylighting Devices (TDD) aim at reducing energy consumption and providing homogeneous illumination in buildings. This ensures energy savings by reducing lighting energy consumption.

To prevent the increase of total energy consumption, the heat loss at the TDD should be taken into consideration when using TDD. This paper presents an experimental and numerical study on the laminar natural convection in TDD for winter conditions. The results show that the overall heat transfer coefficient of TDD can be decreased by using a separator plate in the TDD. Moreover, the overall heat transfer coefficient changes significantly with the position of the separator plate.

1. Introduction

Today's life style forces some people to live in places insufficiently illuminated. Experimental studies show that insufficient daylight may result in psychological and physiological problems in humans while adversely affecting work efficiency [1–3].

Recent developments in lighting and energy efficiency such as optical daylighting systems aim at reducing energy consumption and providing homogeneous illumination in buildings. One of these strategies is the use of daylight transmission systems with high efficiency and low maintenance costs. By using these systems sufficient lighting can be provided and electricity consumption of lighting is reduced. Daylight transmission systems are used to homogenize the illumination level, increase visual comfort and achieve energy savings of the space [4–8].

One of these systems is the Tubular Daylighting Device (TDD). TDD transmits the sunlight from skylight to the space by using a reflective channel giving satisfactory results for the areas of the buildings where the sunlight cannot reach [9–11].

TDD (Fig. 1) are composed of five main parts; dome, dome base, roof base, reflective channel and diffuser. In these systems the acrylic dome is placed on the roof and transmits the sunlight to the reflective channel. The sunlight coming into the channel is reflected to the diffuser which provides natural lighting by distributing the sunlight homogeneously.

In the design on these systems the heat loss at the TDD should be taken into consideration. Otherwise, the amount of energy required for heating may be greater than the lighting energy saved and thus the building's total energy consumption may increase.

Although some overall heat transfer coefficient values are given in product catalogs, no papers were found about the heat losses in the TDD. As well as there being very few studies on the heat transfer occurring in the dome skylight which is the closest in geometry to the TDD in the literature.

One of these studies was conducted by McGowan et al. [12] They investigated the thermal performance of pyramidal and barrel vault skylights by conducting measurements and numerical simulations using a commercial computational fluid dynamics (CFD) package. Another study was presented by Klems [13] in which nighttime measurements of the net heat flow through several types of skylights were presented and the measured *U*-values were compared with calculations using WINDOW4 and THERM programs. In the studies presented by Laouadi et al. [14,15] the laminar natural convection within concentric domed cavities was investigated by using the numerical control volume approach. Natural convection heat transfer in horizontal fully hemispheric domed cavities with planar inner surfaces was studied by Saber and Laouadi [16]. Their numerical model was based on the finite-element method. Saber et al. [17] recently studied using convective heat transfer in low-profile spherical cavities with planar bottom surfaces by using a finite-element method.

Literature survey shows that there is limited information about the heat transfer in TDDs. In the present research the natural convection heat transfer occurring TDDs was examined for winter

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Nomenclature

A	surface area, m^2
A_{TDD}	cross sectional area of the TDD, m^2
c_p	specific heat, kJ/kgK
D	diameter of the TDD, m
k	thermal conductivity, W/mK
L	thickness, m
P	pressure, Pa
$\dot{Q}_{TDD}$	total heat transfer rate, it W
$\dot{Q}_H$	measured electrical power supplied to the heaters, W
$\dot{Q}_{S.1}$	experimental conduction heat transfer rate from side wall 1, W
$\dot{Q}_{S.2}$	experimental conduction heat transfer rate from side wall 2, W
$\dot{Q}_{S.3}$	experimental conduction heat transfer rate from side wall 3, W
$\dot{Q}_{S.4}$	experimental conduction heat transfer rate from side wall 4, W
$\dot{Q}_B$	experimental conduction heat transfer rate from base, W
$\dot{Q}_{S.P.}$	experimental conduction heat transfer rate from surround panel, W
T	temperature, K
$T_{m.c.}$	metering chamber temperature, K
$T_{c.c.}$	climatic chamber temperature, K
T_{in}	average temperature of the inner side of insulation, K
T_{out}	average temperature of the outer side of insulation, K
U_{TDD}	overall heat transfer coefficient, W/m^2K

Greek symbols

β	thermal expansion coefficient, 1/K
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Fig. 1. Tubular daylighting device.

conditions. For this purpose, the test system was established and the overall heat transfer coefficient was determined by testing TDD. Then, numerical studies were performed, and thermal transmittance coefficients of various TDD configurations were calculated.

2. Experimental set-up and data reduction

Fig. 2 shows a schematic representation of the experimental set-up which is composed of climatic chamber with refrigeration unit, metering chamber, surround panel, heaters, controller and measurement systems.

The climatic chamber is an open base cabinet, and the refrigeration unit placed at the top of this cabinet. This chamber is used for simulating winter outdoor conditions. For this purpose indoor temperature of the chamber was stabilized at -18 °C with a refrigeration unit during the experiments. The dimensions of the climatic chamber are 980 mm × 980 mm × 650 mm [inner dimensions (width × depth × length)]. All chamber walls are constructed from 10 mm Plywood + 50 mm Styrofoam + 10 mm Plywood plates.

The metering chamber is an open ceiling cabinet and used for simulating winter indoor conditions. The dimensions of this chamber are 980 mm × 980 mm × 650 mm [inner dimensions (width × depth × length)]. All chamber walls are constructed from 10 mm Plywood + 50 mm Styrofoam + 10 mm Plywood plates. During the experiments chamber temperature was stabilized at 21 °C with a heating system. Heating system consisted of 2 heaters, 1 PID temperature controller and a watt-meter. Watt-meter was used for the measurement of the supplied electric power to these heaters.

The surround panel is mounted and placed between climatic and metering chambers. The dimensions of the surround panel are 1100 mm × 1100 mm × 270 mm (width × depth × length) and constructed from 10 mm Plywood + 5 × 50 mm Styrofoam + 10 mm Plywood plates.

Ninety thermocouples were used for temperature measurements. All thermocouples were separately calibrated. Signals from the thermocouples were collected, processed and stored with computer connected seven ELIMKO 680 series universal data loggers. Temperature readings were taken at several locations on the bottom (8 inner side and 8 outer side of styrofoam insulation) and side (8 inner side and 8 outer side of styrofoam insulation) walls of the metering chamber and at several locations on the surround panel (4 inner side and 4 outer side of styrofoam insulation). Indoor temperatures of chambers and ambient temperature were also measured.

The experiments were carried out when the ambient temperature is below 21 °C. Initially all setup was at the thermal equilibrium with the ambient air. After the heaters and refrigeration unit were turned on, the temperature of metering chamber increases and the climatic chamber temperature decreases. The increase in temperature of the metering chamber continues until it reaches 21 °C. At this temperature it was stabilized by using a controller. Similarly the temperature of the climatic chamber was