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An investigation of flow and conjugate heat transfer in multiple pane windows with respect to gap width, emissivity and gas filling

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A parametric study is carried out numerically to investigate fluid flow and heat transfer characteristics in double, triple and quadruple pane windows considering various gap widths together with different emissivity coatings. A comprehensive numerical study has been conducted to investigate fluid movements and conjugate heat transfer of natural convection, conduction and radiation in the multiple pane window arrangements. Computations are performed for both air-filled and argon-filled windows. Indoor and outdoor temperatures are kept constant and convective boundary conditions are applied on the inner and outer pane surfaces of the window units to reflect realistic conditions. Computations show that the most reasonable gap width is 12 mm for all cases considered in this study. The effect of gas filling on the *U*-value is more pronounced for the windows coated with low emissivity materials. Installing quadruple pane windows having low emissivity coatings and low conductance gas filling, the *U*-value can be decreased to the level of 0.4 W/m^2 K. The main contribution of this study is to present correlations for predicting the glazing *U*-value considering the number of the panes, emissivity of the glass surfaces and gap width of the cavities for air-filled and argon-filled multiple pane windows.

1. Introduction

Windows are one of the key elements of a building, since large glazing area creates a spacious feel and provides daylight, thus playing a major part in the character of a building. However, their energy performance is questionable due to large amount of heat loss or heat gain. Heat loss related to windows contributes over 30% of the total heat loss through the building envelope [1]. In order to reduce heat loss through windows, single-glazed windows have been nearly abandoned in many countries and double-glazed windows have become widespread due to lower *U*-values. Optimization of gap width of double glazing can significantly improve energy efficiency [2]. Filling the window cavity with low conductive gases such as argon and krypton instead of air is beneficial to reduce heat transfer by conduction and convection [3]. Coating the pane surfaces with low emissivity materials is an effective solution to reduce heat transfer by radiation. Introducing triple or quadruple panes is another effective method. In order to improve window efficiency, several other methods exist such as evacuating the cavity, filling the cavity with aerogel, choosing low conductive framing materials and spacers whose details can be found in Ref. [4].

Manz and Menti [5] investigated the energy performance of glazing in eight European cities (Bucharest, London, Madrid, Moscow, Rome, Stockholm, Warsaw and Zurich). They considered number of panes, distances between glass panes, gas filling and, number and properties of the coatings used. They concluded that in all interested cities and façade orientations, modern triple glazings perform best and enable net gains at south-facing façades in December even in Moscow and Stockholm, while air filled double glazings without any coatings lead to net losses at all façades except for most southern locations. Hassouneh et al. [6] studied the influence and performance of windows on the energy balance of apartment buildings in Amman by using self-developed simulation code based on the ASHRAE tables and reported that the flexibility of choosing the glazed area and orientation increases if energy efficient windows are used. Yoo et al. [7] investigated thermal transmittance of window systems and effects on building heating energy use in South Korea and concluded that high-efficiency window systems can play an important role in reducing energy consumption in buildings. Karabay and Arıcı [8] carried out a thermoeconomical optimization of multiple pane windows for various cities of Turkey considering different fuel sources. They showed that the

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Nomenclature

a	correlation coefficient, dimensionless
AR	aspect ratio of cavity, (H/L), m/m
b	correlation coefficient, dimensionless
c	correlation coefficient, dimensionless
C_p	specific heat at constant pressure, J/(kg K)
d	correlation coefficient, dimensionless
g	gravitational acceleration, m/s^2
H	height of window, m
h	combined heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
L	gap width of cavity, m
n	number of panes, dimensionless
Nu_L	Nusselt number, dimensionless
P	pressure, Pa
Ra_L	Rayleigh number, dimensionless
T	temperature, °C
t	time, s
U	overall heat transfer coefficient, W/(m^2 K)
$U_{convection}$	convective heat transfer coefficient, W/(m^2 K)
$U_{radiation}$	radiative heat transfer coefficient, W/(m^2 K)
u	velocity component in the x direction
v	velocity component in the y direction
x	cartesian coordinate
y	cartesian coordinate
Greek symbols	
ε	emissivity of pane surface, dimensionless
ρ	density, kg/m^3
μ	dynamic viscosity, kg/(s m)
Subscripts	
f	fluid
i	inner
o	outer
p	pane

optimum number of panes varies between two and four depending on climate zone and fuel source, and recommended that multiple pane windows should be seriously considered particularly in cold climatic regions of Turkey. Thalfeldt et al. [9] studied façade design principles in the cold climate of Estonia. They reported that windows with higher number of panes and low emissivity coatings improved energy performance and optimal window-to-wall ratios were larger for quadruple and hypothetical quintuple glazed windows. They also showed that the cost optimal solution is triple pane low emissivity glazing with 25% of size while quintuple windows with size of 60% provided best energy performance. Larsson et al. [10] investigated thermal performance of a well-insulated window (krypton-filled triple pane windows with low emissivity coatings) experimentally and numerically. They concluded that the numerical predictions agreed well with the experimental results and the studied window has very good resistance to heat transmission which gives a relatively high surface temperature on the inner pane. ElSherbiny et al. [11] conducted heat transfer measurements by natural convection across vertical air layer which is bounded by flat isothermal plates at different temperatures and around the edges by a perfectly conducting boundary over very wide ranges of Rayleigh number and aspect ratio. They provided a correlation from which convective heat transfer across vertical air layers can be calculated. Korpela et al. [12] investigated the flow and heat transfer through a double pane window numerically disregarding radiative heat transfer. They suggested a formula for window spacing. Aydın [13] analyzed conjugate heat transfer through a double pane window numerically, where convective boundary conditions are applied for the outer surfaces facing inside and outside. It was reported that energy losses through the double pane windows can be considerably reduced by optimizing thickness of air layer or replacing air with a lower thermal conductivity gas. Gustavsen and Thue [14] investigated the effect of the horizontal aspect ratio on heat transfer through cavities with a high vertical aspect ratio such as glazing units. They showed that three-dimensional cavities with a horizontal aspect ratio larger than five can be considered as two-dimensional cavities when considering heat transfer rates. A similar conclusion is drawn in Ref. [15] where laminar natural convection in three-dimensional air filled cavities having two opposite isothermal vertical walls and four adiabatic walls is investigated. It was stated that Nusselt numbers obtained in three-dimensional cavities would be the same as that of two-dimensional cavities for large horizontal aspect ratios. Ganguli et al. [16] performed a CFD simulation to investigate flow and heat transfer in two-dimensional tall vertical enclosures with aspect ratio up to 200. They reported that the computed Nusselt number agrees well with the literature data and presented a generalized correlation considering various heights, gap widths and temperature differences with laminar flow assumption in the cavity.

In the literature, there are a growing number of studies which analyze fluid flow and heat transfer in tall, vertical and rectangular slots. However, most of these studies only deal with natural convection and do not consider radiative heat transfer, which cannot, in fact, be ignored, particularly for ordinary glass windows since more than half of the heat is transferred by radiation. Besides, there are few studies dealing with flow and heat transfer in triple pane windows and to the best knowledge of the authors, there is no study which investigates the flow and heat transfer in quadruple pane windows. In this work, a comprehensive parametric study is carried out numerically to investigate flow and conjugate heat transfer in double, triple and quadruple pane windows considering various gap widths together with different emissivity coatings in which convective boundary conditions are employed at the inner and outer pane surfaces to mimic more realistic conditions. The computations are performed for both air-filled and argon-filled window units. A correlation to predict overall heat transfer coefficient (U-value) is obtained considering number of panes, emissivity of glass surfaces and gap width for both air-filled and argon-filled windows which is useful for engineers and architects in order to evaluate the impact of these four parameters on the heat loss through windows.

2. Problem description and numerical method

Schematic representations of double, triple and quadruple pane windows considered in this study are shown in Fig. 1. Five different gap widths ($L = 6$ mm, 9 mm, 12 mm, 15 mm and 18 mm) and five different emissivity values (ε = 0, 0.25, 0.50, 0.75 and 1) are considered. The all glass surfaces of the window unit are assumed to be coated with the same coating material. Height of window (H) is taken to be 1 m. Indoor (T_i) and outdoor temperatures (T_o) are assumed to be constant and equal to 20 °C and −15 °C, respectively. The combined heat transfer coefficients on the inner surface (h_i) and outer surface (h_o) of windows are taken to be 8.29 W/m^2 K and