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Influence of convection and radiation on the thermal environment in an industrial building with buoyancy-driven natural ventilation

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ABSTRACT

The aim of this paper is to investigate the effects of convection and radiation from a high-temperature heat source on the thermal environment in an industrial building. The relevant control parameters include the Grashof numbers, which range from 10^7 to 10^{11}, and the surface emissivity with values of 0.2, 0.5 and 0.8. The ratio between radiation and convection from the heat source is proposed as an important parameter for predicting the effects of heat transfer. Detailed results are discussed regarding the temperature and flow distributions, the heat transfer on the heat source surface and the ventilation rate. The dimensionless temperature and velocity profiles above the heat source are presented for different Grashof numbers. In addition, the Nusselt numbers on the heat source surface and the ventilation rate are investigated. It is observed that the ratio between radiation and convection is a decreasing function of the Grashof number and an increasing function of the surface emissivity. The total Nusselt number and the ventilation rate are both increasing functions of the Grashof number and the surface emissivity.

1. Introduction

Buoyancy-driven natural ventilation is the exchange of air between the indoor and outdoor environment when flow is produced by naturally occurring pressure differences. The pressure differences are produced by temperature differences between the internal and external air [1–3]. Within an industrial building, the high-temperature heat sources release excess heat. The buoyancy-driven natural ventilation method is effective for removing excess heat and various pollutants.

For an industrial building with high-temperature heat sources, the heat transfer modes of the heat source influence the buoyancy-driven natural ventilation and the thermal environment. Two mechanisms including convection and radiation are responsible for the transmission of energy from a heat source [4]. Currently, two simplified methods are used to calculate the effects of radiation on the indoor environments. The first method models radiation as additional heat loads. For this method, all heat transfer is assumed to be convective heat transfer (i.e., pure convection). This method is based on the air conditioning load calculation, which enables the calculation of the indoor air conditioning load [5]. For the second method, radiation is neglected if the heat source temperature is low, or if the heat source temperature is high but the heat source surface emissivity is low ($\varepsilon < 0.3$) [6–8]. In the literature [7], the heat source surface temperature reached 600 K, but nickel was deposited on the external surface of this heat source to limit radiation. In this case, the proportion of radiation is small and can be ignored. However, in an industrial building with a high-temperature heat source, radiation accounts for a considerable proportion of the total heat transfer. Thus, the methods mentioned above may lead to inaccuracies when predicting the thermal environment. These inaccuracies may be prevalent in the high-temperature fields of industrial furnaces, boilers, and gas turbine combustors, where the radiation accounts for 80–90% of the total heat transfer [9]. Therefore, to obtain an accurate prediction of the thermal environment in an industrial building with high-temperature heat sources, a method is required for conjugating convection and radiation.

Conjugate heat transfer by convection and radiation has been studied in various enclosures. Shaija and Narasimham [10] numerically studied the effects of radiation on convection in a horizontal annulus. These authors found that radiation reduces convective heat transfer in the annulus and enhances the overall Nusselt number. Sharma et al. [11] investigated conjugate turbulent natural convection and radiation in rectangular enclosures. In addition, Nouanegue et al. [12] studied conjugate heat transfer by

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Nomenclature

a	absorption coefficient
g	acceleration due to gravity (m/s^2)
Gr	Grashof number ($= g\beta(T_h - T_\infty)w^3/\upsilon^2$)
H	height between inlets and outlets (m)
h	inlets and outlets height (m)
L	industrial building length (m)
l	heat source length (m)
l'	inlets and outlets length (m)
k_f	thermal conductivity of air (W/m K)
n	refractive index
Nu_c	convective Nusselt number ($= q_c w/k_f \Delta T$)
Nu_r	radiative Nusselt number ($= q_r w/k_f \Delta T$)
Nu_t	total Nusselt number ($= Nu_c + Nu_r$)
q	heat flux (W/m^2)
q_c	heat flux by convection (W/m^2)
q_r	heat flux by radiation (W/m^2)
T	temperature (K)
ΔT	temperature difference (K)
u	velocity (m/s)
U	dimensionless velocity ($= uH/\alpha$)
W	industrial building width (m)
w	heat source width (m)
x, y	Cartesian coordinates
X, Y	dimensionless Cartesian coordinates ($X = x/W$, $Y = y/H$)

Greek symbols

α	thermal diffusivity of air (m^2/s)
β	volumetric coefficient of thermal expansion (1/K)
ε	surface emissivity
σ_b	Stefan Boltzmann constant
σ_s	scattering coefficient
Θ	dimensionless temperature ($= (T - T_\infty)/(T_h - T_\infty)$)
υ	kinematic viscosity (m^2/s)
ψ	ratio between radiation and convection

Subscripts

c	convection
h	heat source
r	radiation
t	total
∞	ambient

convection, conduction and radiation in open cavities. These researchers suggested that convection and radiation considerably affect the flow and temperature fields.

Nevertheless, the literature regarding convection with radiation in ventilated buildings is limited. For example, Ergin [13] studied radiation with convection and conduction in a two-floor enclosure containing a low-input power heat source. Chow and Holdø [14] examined the influence of the boundary conditions and radiation on room ventilation simulations. These studies indicated that conjugating convection and radiation are needed to accurately predicting the thermal environment in ventilated buildings.

For an industrial building with high-temperature heat sources, the influence of convection and radiation on the environment is significant. In order to investigate the effect of convection and radiation on the thermal environment in an industrial building with a high-temperature heat source, we analyzed the influence of both the Grashof number and the surface emissivity on the temperature and velocity distribution, the heat transfer and the ventilation rate.

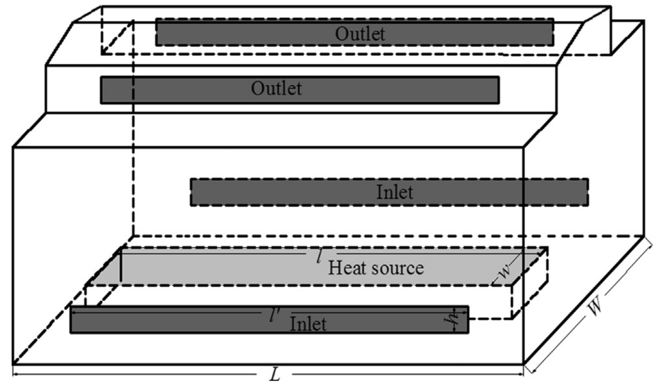

Fig. 1. Schematic of a three-dimensional industrial building.

2. Physical and numerical modeling

2.1. Physical model and assumptions

The schematic of a three-dimensional industrial building with a length L, a width W and a height H ($W/L = 0.3$) is provided in Fig. 1. The constant temperature heat source ($T_h = 483$ K) is positioned in the center of the floor ($w/W = 0.3$, $l/L = 0.8$). The heat source energy is dissipated by convection and radiation. Air inlets are installed near the floor, and outlets are installed near the ceiling ($h/H = 0.1$, $l'/L = 0.8$).

The streamlines through the central plane are shown in Fig. 2. We can see that there is no remarkable air flow and convective heat transfer along the length L. Therefore, for computational efficiency, we assume that the third dimension has a negligible effect on flow and heat transfer. The two-dimension physical model (Fig. 3) will be used and calculated in the following sections. In addition, air is assumed to be incompressible, and the effects of density variation, which cause the buoyancy force, are considered by using the Boussinesq approximation.

2.2. Numerical modeling

The airflow prediction is based on a fundamental flow equation solution, which consists of continuity, energy and momentum equations. These equations are solved by the Computational Fluid Dynamics (CFD) package Fluent, version 6.3.26 [15]. The CFD is a powerful technique that incorporates additional models to account for the effects of turbulence and conjugate heat transfer. The CFD model realistically and accurately describes the buoyancy-driven ventilation flows within a building [16].

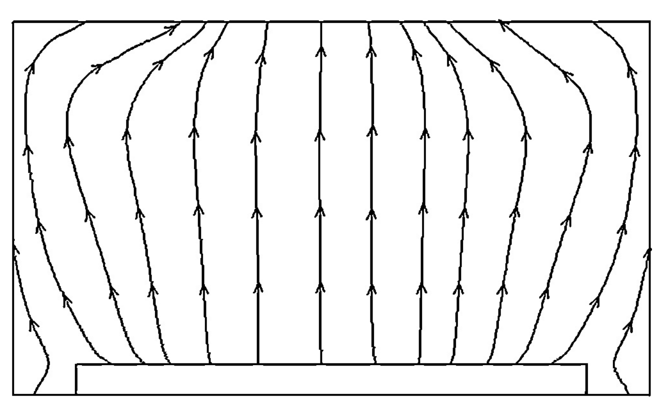

Fig. 2. Streamlines through central plane.