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Experimental and numerical investigations on enclosure pressure effects on radiation and convection heat losses from two finite concentric cylinders using two radiation shields

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A B S T R A C T

The energy crisis has led humankind to drastically think about optimization of facilities which are in closed connection with energy resources. Therefore, optimization of thermal systems from heat transfer point of view, to decrease heat losses and therefore energy consumption, is an explicit goal in the field of thermal sciences. This work is about conjugate radiation and convection heat transfer in a cylindrical enclosure using two radiation shields, to decrease heat loss. The experimental study applies three different materials, namely aluminum, copper and steel, as radiation shields. Numerical investigation is performed and validated against experimental data, using three-dimensional finite volume method. Different positions for radiation shields within the enclosure are considered. Both experimental and modeling studies adopt two different enclosure pressures, i.e., 0.2 and 1.0 atm. The inner cylinder is assumed to have two different temperatures, i.e., 473 K and 673 K. Seventy six different experiments are carried out to capture the best heat reduction with different radiation shield materials, inner cylinder temperatures, enclosure pressures and radii for radiation shields. Results show that both enclosure pressure and radiation shield emissivity are responsible for reduction of the total heat loss from the inner cylinder.

1. Introduction

The growth rate of energy demand for both domestic and industrial facilities around the world is a side effect of modern life style. The dramatic increase in the energy consumption has brought humankind a new problematic issue which is known as energy crisis. Two important heat transfer modes which can lead to severe energy losses are convection and radiation. To reduce heat loss by these two modes and finally reduce energy consumption within a system, many studies have been conducted in various thermal systems by considering conjugate convection and radiation heat transfers [1–4].

The combined convection and radiation heat transfer modes are important in many industries. The significant interest in such problems originates from their importance in many engineering applications such as nuclear reactors [5,6], process industry [7,8], radiative cooling systems [9], heat exchangers [10–13], thermal energy storage systems [14], cooling of electronic components [15,16], thermal processing of moving plates [17], and even for buildings heating where the radiation and natural convection have considerable effect at the room temperature [18–22]. From the modeling point of view, two categories can be assumed to classify the above mentioned problems. The first category simplifies the convection and radiation effects, which have been set on the available boundary conditions, into the energy mathematical equation. These simplifications vastly lessen the complexity of the governing energy equation of the problem. By further assuming that the heat merely transferred through a specific direction, due to the dimensions of the system, the problem is reduced into a linear or nonlinear ordinary differential equation [9–12,17]. Although this method is cheap and available from the computational point of view, it mainly used to calculate the temperature of solid medium and may lack from the precision point of view. To overcome this weakness, another procedure has to be used. This approach is to tackle the partial differential equations of the system. If the system consists of fluid/gas materials, continuity, momentum and energy equations together by assuming the effects of convection and radiation should be solved [5,7,8,14–16,18–20]. Therefore,

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Nomenclature

a	absorption coefficient
g	gravitational acceleration, m/s
Gr	Grashof number
I	radiation intensity, W/sr
k	thermal conductivity, W/mK
L_c	characteristic length, m
n	refractive index
p	pressure, atm
q''	heat flux loss
R	radius, m
$\vec{s}'$	scattering direction vector, m
$\vec{s}$	direction vector, m
T	temperature, K
V	velocity, m/s

Greek letter

β	volume expansion coefficient, 1/K
ε	emissivity
Φ	scattering phase function
μ	dynamic viscosity, Pa-s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	Stefan–Boltzmann's constant, W/m^2K^4
σ_s	scattering coefficient
Ω'	solid angle, sr
ζ	volume viscosity coefficient, Pa-s

Subscripts

Al	aluminum
con	convection
Cu	copper
enc	enclosure
f	fluid
in	inner cylinder
inc	incident
out	outer cylinder
sh1	first shield
sh2	second shield
rad	radiation
St	steel
tot	total
w	wall

computational fluid dynamics should be employed to solve the coupled equations of these systems. Although this approach is costly and more challenging compared to the previous method, it has the advantage that has the ability to address the temperature field within both fluid and solid materials.

The effect of radiation on the temperature and flow fields has been neglected in enclosures [23,24]. Despite numerous studies for natural convection, small amount of investigations have concentrated on the radiation transfer. The effect of radiation on the temperature and flow fields has been unfairly neglected for the analysis of heat transfer in enclosures which are filled with fluids [23,25] and nanofluids [26,27]. A conscientious investigation within the literature regarding heat transfer in convective-radiative environments reveals that the radiation effects play a significant role in these systems. Temperature distribution within these systems can greatly change by introducing the effects of radiation. In two different studies, Kuznetsov and Sheremet [28], and Martyushev and Sheremet [29] investigated the effect of Grashof number, transient factor, optical thickness and the solid wall thermal conductivity on the local thermo-hydrodynamic characteristics and on the integral parameters in an enclosure having finite thickness heat-conducting walls with local heating at the bottom of the cavity. Regarding thermo-hydrodynamic specifications of the system streamlines and temperature distribution were plotted and about integral parameters the average Nusselt number on the heat source surface was calculated. A conjugate study about turbulent natural convection and surface radiation in rectangular enclosures with various aspect ratios using a finite volume method was performed by Sharma et al. [30]. The analyzed geometry which is typically seen in liquid metal fast breeder reactor subsystems is heated from the bottom and cooled from other walls. A formula was proposed to calculate mean convection Nusselt number in terms of Rayleigh number and aspect ratio, which is an important design parameter for these systems. Special attention was paid to study the effectiveness in the horizontal fin arrays by Rao et al. [31]. It was assumed that both natural convection and radiation are participating in heat transfer mechanism. The effectiveness was calculated by considering different values for number of fins, fins height and surface emissivity parameter. In another interesting study, Rabhi et al. [32] numerically studied the effects of surface radiation, and number of partitions on the heat transfer and flow structures in a rectangular enclosure. The enclosure had an inclination of 45° with respect to the horizontal plane. It was found that the value of total heat transfer is considerably increased under thermal radiation heat flux and reduced significantly with increasing the number of partitions. Nouanégué and Bilgen [33] have numerically investigated conjugate conduction, convection and radiation heat transfer in solar chimney systems. By adopting a control volume code ANSYS FLUENT, a study was performed on radiation interchanges between surfaces on the transition from steady, symmetric flows about the cavity centerline to complex periodic flow by Sun et al. [34]. Premachandran and Balaji [35] considered conjugate convection and radiation from vertical channels with four discrete protruding heat sources mounted on the right side wall of the channel. The effects of buoyancy and radiation heat transfer on flow and heat transfer characteristics of the thermal system have been analyzed.

More recently, Saravanan and Sivaraj [36] have opted in favor of a numerical simulation of an air filled cavity with a centrally placed thin heated plate. Both convection and radiation modes have been considered. It was assumed that vertical walls of the cavity are cooled while the horizontal ones are insulated. A comparison between the experimental data and numerical simulation has been performed by Montiel-Gonzalez et al. [37]. They used SIMPLEC algorithm for the numerical approach and found that for most probed temperatures the deviation between the two methods is less than ten percent.

De Faoite et al. [38] have opted in favor of inverse heat flux estimation on a plasma discharge tube using thermocouple data and a radiation boundary condition. Apart from direct approaches, inverse methods have been employed to find various characteristics of convective-radiative systems. Moghadassian and Kowsary [39] interestingly investigated the impact of heaters in a 2D enclosure to produce the desired temperature and heat flux distributions. The Levenberg–Marquardt algorithm was chosen to perform the iterative search procedure.