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Heat transfer reduction between two finite concentric cylinders using radiation shields; Experimental and numerical studies ☆

Mohammad Sadegh Motaghedi Barforoush *, Seyfolah Saedodin

Faculty of Mechanical Engineering, Semnan University, Semnan, Iran

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ABSTRACT

Energy consumption and its efficient utilization are two important factors of thermal systems. This work concerns with numerical and experimental studies about the surface radiation and natural convection effects on the heat transfer and flow field between two finite concentric cylinders, using one radiation shield between them. This study reveals material and geometric effects of the radiation shield on heat losses from two concentric cylinders enclosure at different temperatures and enclosure pressures. The enclosure consists of two concentric cylinders with hotter inner cylinder and colder outer one. The radiation shield with three different materials (aluminum, copper and steel) is inserted between the cylinders at two different radial positions. Validations are carried out for the temperature of the radiation shield with experimental data and numerical ones. After validation, forty eight different experiments and numerical simulations are carried out by varying the inner cylinder temperature between 373 K and 673 K at two enclosure pressures of 0.2 and 1.0 atm, corresponding to three different materials as radiation shields. The outer cylinder temperature from experiments is used in numerical simulations. The results show that the enclosure pressure and radiation shield emissivity together are responsible for reduction in the total heat loss from the inner cylinder. It was also found that among the three considered materials as radiation shields, copper is the most effective one to reduce the heat loss. In a specific case, the total heat loss with copper radiation shield was 14.99% and 57.7% lower than steel and aluminum shields, respectively.

1. Introduction

Recently challenging issues regarding energy consumption in domestic and industrial facilities as well as their negative footprint of the nature such as CO_2 emission have forced humankind to meticulously analyze and optimize thermal systems from heat transfer point of view. To this end, many studied have been conducted in various thermal systems considering conjugate convection and radiation heat transfer [1–4].

Conjugate radiation and convection heat transfer has attracted considerable attention due to its wide range of scientific and industrial applications such as nuclear reactors [5,6], process industry [7,8], thermal energy storage systems [9], cooling of electronic components [10,11], heat exchangers [12–14], thermal processing of moving plates [15], radiative cooling systems [16] and even for building heating where the radiation and natural convection have considerable effect at the room temperature [17–19]. These studies could be categorized into two types. The first method is to incorporate the convection and radiation effects of the boundary conditions into the energy equation within the solid material. Using this approach and assuming unidirectional heat flow within the material, one is able to model a thermal process with ordinary differential equations [12–16]. This method is mainly used to obtain the temperature distribution within solid materials. The other approach is to solve the coupled partial differential equations of continuity, momentum and energy together, by assuming the effects of convection and radiation [5,7–11,17–19]. In this approach, in most cases, computational fluid dynamics should be employed to tackle the coupled equations. Although this method is more challenging, it can be used to address temperature fields within both fluid and solid materials.

In many articles, the effect of radiation on the temperature and flow fields has been neglected in enclosures [20,21]. Despite numerous studies for natural convection, few of heat transfer investigations have been concentrated on the radiation mode. A meticulous investigation through available literature about conjugate convection and radiation shows the influential effect of radiation on the thermal behavior of a system at high temperatures. Kuznetsov and Sheremet [22], and Martyushev and Sheremet [23] investigated the effect of Grashof number, transient factor, optical thickness and solid walls thermal conductivity on the local thermo-hydrodynamic characteristics and integral parameters in an enclosure having finite thickness conducting walls and local heating at the bottom of the cavity. Sharma et al. [24] studied the conjugate turbulent natural convection and surface radiation

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* Corresponding author.
E-mail address: ms.motaghedi@yahoo.com (M.S.M. Barforoush).

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Nomenclature

a	Absorption coefficient
g	Gravitational acceleration m/s^2
Gr	Grashof number
I	Radiation intensity W/sr
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_s	Scattering coefficient
Ω'	Solid angle sr
ζ	Volume viscosity coefficient Pa-s

Subscripts

al	Aluminum
s	Steel
cu	Copper
in	Inner cylinder
sh	Radiation shield
out	Outer cylinder
tot	Total
con	Convection
rad	Radiation
enc	Enclosure

in rectangular enclosures with various aspect ratios applying finite volume method. The enclosure is heated from the bottom and cooled from other walls, typically encountered in liquid metal fast breeder reactor subsystems. They developed the correlation for the mean convection Nusselt number in terms of Rayleigh number and aspect ratio, which is proposed for design purposes. Rao et al. [25] paid special attention to study the effectiveness considering different values of fin heights, emissivity, and number of fins in a horizontal fin array by natural convection and radiation. Rabhi et al. [26] numerically studied the effects of surface radiation and number of partitions on the heat transfer and flow structures in a rectangular enclosure, inclined by 45° with respect to the horizontal plane. They found that the total heat transfer in the enclosure is increased under thermal radiation heat flux and reduced significantly with increasing the number of partitions. Nouanégué and Bilgen [27] have numerically investigated conjugate conduction, convection and radiation heat transfer in solar chimney systems. Sun et al. [28] studied the effects of radiation interchanges amongst surfaces on the transition from steady, symmetric flows about the cavity centerline to complex periodic flow using the control volume code ANSYS FLUENT. Premachandran and Balaji [29] studied a numerical investigation of conjugate mixed convection from vertical channels with four discrete protruding heat sources mounted on the right side wall of the channel. Special attention has been paid to understand the effects of buoyancy and radiation heat transfer on flow and heat transfer characteristics of the channel.

More recently, Saravanan and Sivaraj [30] considered a theoretical study to understand the interaction of surface radiation and natural convection in an air filled cavity with a centrally placed thin heated plate. The vertical walls of the cavity are cooled while the horizontal ones are insulated. Montiel-Gonzalez et al. [31] validated their experimental data regarding the conjugate natural convection with surface radiation in an open cavity. They used finite volume method and the SIMPLEC algorithm to numerically investigate the problem. They showed that for most of the probed temperatures, the deviation between the two methods is less than 10%.

Apart from direct approaches, the inverse methods have been employed to find various characteristics of convective-radiative systems. Moghadassian and Kowsary [32] interestingly investigated the strength of heaters in a 2D enclosure to produce the desired temperature and heat flux distribution. The Levenberg–Marquardt algorithm was chosen to perform the iterative search procedure. De Faoite et al. [33] have opted in favor of inverse heat flux estimation of a plasma discharge tube using thermocouple data and a radiation boundary condition.

When the atmosphere pressure is considerably low, the convection heat transfer can be neglected within a thermal system [34]. Therefore, the thermal radiation dominates the heat transfer within the system. If one can control heat radiation in this situation, high-temperature insulated structure can be achieved [35]. Under high-vacuum conditions and using radiation shields to reduce the heat transfer [36,37], few studies have been done. In this situation it is possible to introduce a simplifying approach for calculating the radiant energy using the concept of net radiation heat transfer, which provides an easy way for solving a variety of situations. However, less attention has been given to the situation when a low-vacuum is available between two or more radiation shields. Application of multilayer composite materials as radiation shields has been discussed in an interesting patent by Bowers et al. [38]. Miyakita et al. [39] have developed a multilayer material with non-interlayer-contact spacer for space cryogenic missions. They also modeled temperature filed within different layers of the developed blanket. Good agreement between the measured temperature and the numerical results for the outermost layer was achieved. Although it is possible to reduce heat transfer using radiation shields between two surfaces, it is also possible to increase the heat transfer rate by using further number of radiation shields [40]. Therefore, regarding the number of radiation shields, optimization may be needed in a system [40].

The main aim of this work is to present an experimental study together with numerical validation, to reduce radiation and free convection heat transfer by inserting shields between two finite concentric cylinders at different enclosure pressures. For this purpose, two different radial positions between two cylinders with three different materials (aluminum, copper, and steel) as radiation shields have been selected. Due to the direct effect of emissivity on the radiation, temperature-dependent emissivity was considered for all materials. In the numerical modeling, a conjugate analysis is carried out in which the mass, momentum and energy balance equations in the enclosure are concurrently solved. Furthermore, it was assumed that the density of the air is a function of temperature and pressure following the ideal gas law. This study helps researchers and industrial communities to have better insight regarding the heat transfer reduction when using one or two radiation shields between two concentric cylindrical geometries.

2. Experimental setup

Schematic of the experimental setup is illustrated in Fig. 1, which consists of the cylindrical enclosure, temperature sensors, heaters, a vacuum pump, a vacuum gauge, and a data acquisition system. Enclosure consists of two concentric vertical cylinders filled with air