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Experimental and numerical study of the thermal and hydrodynamic characteristics of laminar natural convective flow inside a rectangular cavity with water, ethylene glycol–water and air

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ABSTRACT

Laminar natural convection in a rectangular cavity with three different heat transfer fluids: water, ethylene glycol (EG)–water and air were studied experimentally and numerically. The enclosure has a uniform aspect ratio (AR). The EG–water mixture is made up of 60% EG and 40% water. The main experiments aimed to reach proper thermal boundary conditions for the two differentially heated vertical walls of the cavity. Hence, two heating and cooling heat exchangers with water as the heat transfer fluid were attached to the cavity walls. All other walls were properly insulated. Early experiments revealed that it is hard for the heated and cooled walls to reach a uniform temperature when the cavity is filled with water or EG–water, while a uniform distribution of temperature was achieved when it is simply filled with air. Commercial computational fluid dynamics (CFD) software, ANSYS-FLUENT 15, simulated the entire setup to include two special heat exchangers and the cavity between them to investigate all the transport phenomena. The simulation results were in good agreement with measured data. The distortion of air flow is much higher than with the other two fluids. Water flow inside the cavity is flatter and a big circulation area was captured in the middle of the EG–water fluid flow. The local Nusselt number's three-dimensional distribution was presented on the walls. When compared to other fluids, the impact of the adiabatic walls in the air flow cavity on the Nusselt number was found to be considerable. Eventually, the roles of energy equation terms were studied. Convective terms were noticeable when compared to thermal diffusion.

1. Introduction

Rectangular enclosures are widely employed in many industries. Examples include tank storage, energy transfer devices, reactor systems, solar collectors and engine cooling systems. One of the most common thermal boundary conditions is constant or uniform temperature on two opposite walls. A large number of studies have focused numerically and experimentally on natural air convective flow inside enclosures. This is discussed below.

Benchmark and comparison studies of air-filled cavities were carried out by Davis [1,2] in a laminar regime for Rayleigh numbers up to 10^6. The Nusselt number at the mid-plane of the cavity was found to be almost similar to average Nusselt numbers in these studies. Schmidt et al. [3] conducted experimental and two-dimensional investigations for a water-filled cavity in a laminar regime for Rayleigh numbers up to 10^8. They showed that the hydrodynamic boundary layer is extremely thin in the walls and the flow is thermally stratified in most parts of the core region. A comparison between theory and experimentation by Heindel et al. [4] for a Prandtl number higher than air (water with $Pr \sim 5$ and Fluorinert™ Electronic Liquid FC-77 with $Pr \sim 25$) in a cavity with a two-dimensional analysis provided a 20% underestimation for the Nusselt number. However, the aspect ratios (the vertical length of the diabatic walls in relation to the horizontal distance between them) were chosen to be above 4. A Nusselt correlation for a cavity filled with air and aspect ratios above 40 was presented in experimental work by Shewen et al. [5]. Fusegi and Hyun [6] and Hiroyuki et al. [7] reviewed air- and water-filled cavities, mainly with the two-dimensional assumption. Lartigue et al. [8] captured the existence of secondary flow inside an air-filled cavity with a laminar Rayleigh number less than 10^5. They found good agreement between two-dimensional numerical model and experimental results. Ampofo and Karayiannis [9] conducted experiments on an air-filled cavity in a turbulent regime with a Rayleigh number above 10^9 and differentially heated vertical walls. They explained

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Nomenclature

c_p	specific heat (J/kg K)
k	thermal conductivity (W/m K)
k_t	kinetic energy (m^2/s^2)
L	characteristic length (m)
$\dot{m}$	mass flow (kg/s)
Nu	Nusselt number
u'	fluctuating velocity (m/s)
u, V	velocity (m/s)
P	pressure (Pa)
q''	heat flux (W/m^2)
Ra	Rayleigh number
T	temperature

Abbreviations

AR	aspect ration
CFD	computational fluid dynamics
EG	ethylene glycol

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/k)
ε	turbulent dissipation rate (m^2/s^3)
μ	dynamic viscosity (kg/m s)
μ_t	turbulent viscosity (kg/m s)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

c	cold wall
exp	experimental
h	hot wall
in	pipe inlet
num	numerical
out	pipe outlet

that the maximum Nusselt number occurs at the bottom and top of the hot and cold walls, due to the very thin thermal boundary layer. They stated that air-filled cavities with an aspect ratio above 1.8 can be treated as two-dimensional models. Bairi et al. [10] performed an experimental study on an air-filled cavity with a turbulent flow and a Rayleigh number up to 10^8. The Nusselt number correlation achieved from their work was compared to previous correlations for aspect ratios of 0.75 and 1.5. They also reported that two-dimensional numerical results are in good agreement with the measurement.

In recent years, many studies of water-filled cavities focused on the application of nanofluids (mostly numerical approaches) [11–14]. A few experimental works are presented for water inside a cavity [15,16], especially transient analyses of the thermal boundary layer for a Rayleigh number higher than 10^{10} [17]. Imberger [18] measured the temperature and velocity inside a differentially heated water-filled cavity with vertical walls and aspect ratios less than 0.02. He illustrated the presence of a parallel flow and the lack of a flat distribution of temperature from the hot to the cold walls. Moreover, a sinusoidal profile of velocity was captured between two horizontal insulated walls.

Turan et al. [19] numerically investigated the laminar convective flow inside air- and water-filled cavities with various aspect ratios. They proposed new correlations for the Nusselt numbers in terms of aspect ratio, as well as Prandtl and Rayleigh numbers. Wu and Ching [20] performed experiments on an air-filled cavity in a laminar regime with Rayleigh numbers below 10^8. Through the use of adjustable electrical heaters mounted on the hot walls, and cold heat exchangers attached to the cold walls with water as the working fluid, they stated that a uniform wall temperature was reached in both the hot and the cold walls due to the low heat flux. They presented the general form of correlation for the Nusselt number as $C{\cdot}Ra^n$, with constant numbers depending on the aspect ratio. They also reported the separation from the top wall and secondary circulation flow in all three aspect ratios. Kumar and Eswaran [21] employed a non-Boussinesq approach for the buoyancy-driven force in momentum equation. The laminar natural air flow inside the cavity was three-dimensionally modelled. To keep the hot and cold walls in an isothermal situation, Corvaro and Paroncini [22] used two thermostatic baths to circulate the working fluid with a constant temperature. Turbulent natural convection inside a water-filled cavity with a high aspect ratio was numerically studied by Kizildag et al. [23]. The Rayleigh number was chosen to be above 10^{11} in their study. They explained that applying a non-Boussinesq approach for density may improve the results. On the other hand, no reports were found for an EG–water mixture inside a cavity, and most of the studies were recently numerically focused on the mixture of EG and ultrafine particle systems [24,25].

The literature review shows that much research in natural convection cavity flow is focused on air-filled cavities, and only a few experimental works are available on water-filled cavities. There are no reports for an EG–water mixture. A large part of the numerical analysis of the cavity was also conducted on two-dimensional models. Therefore, a comparison study on the nature of the flow inside a cavity with these fluids would be worthwhile for future work. The main aim of this paper is to experimentally and numerically compare the nature of the water and EG–water flow in the cavity. The simulation results for air-filled cavities are also presented for further discussion. The range of Rayleigh numbers is in the order of 10^8 for water and EG–water, which shows that all the tests were conducted in the laminar regime.

2. Experimental instrumentation

Fig. 1 illustrates the schematic and arrangement of the experimental setup used in this study. The cavity can be seen in the middle. It has an aspect ratio of 0.94 and is 96 mm × 120 mm in size (in the Y and Z directions respectively) for the differentially heated walls. The distance between the hot and cold walls is 102 mm (in the X direction). The other walls of the cavity are insulated. Two novel shell and tube counter flow heat exchangers were designed for this research and presented as the diabatic walls to produce a constant temperature. The fabricated material in all parts of the heat exchangers is copper, with polyvinyl chloride (PVC) plates placed on the other walls and the lid of the cavity. The size of the rectangular box of the heat exchanger (or shell) is 96 mm × 120 mm × 18 mm. The hydraulic diameter of the shell is almost equal to the tube to split the total mass flow rate between them adequately. As a result, a better distribution of temperature on the diabatic walls would be expected. The inside diameter of the tube is 10.7 mm and the wall is 1 mm thick. Two copper plates 2 mm thick on the sides and another plate 4 mm thick in the