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Experimental and numerical analysis of transient natural convection of water in a high aspect ratio narrow vertical annulus

Shahid Husain*, M. Altamush Siddiqui

Dept. of Mechanical Engineering, Aligarh Muslim University, Aligarh 202002, U.P, India

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A B S T R A C T

Experimental analysis and numerical simulation of transient natural convection flow of distilled water in a high aspect ratio narrow vertical annulus are presented. For the numerical simulation, a CFD model is developed which is solved using ANSYS Fluent and validated with the previous available data. The experimental analysis and numerical simulation have been performed for a heat input range of 300 W–1800 W. The annulus internal diameter is 38 mm and external diameter is 45 mm that results in the annular gap of 3.5 mm while the aspect ratio is 352 and radius ratio is 1.184. The objective of the present work is to develop a CFD model for the prediction of dynamic behaviour of natural convection in a vertical annulus and validate it with experiments. The transient period seems to increase gradually with annulus height. With an increase in heat input, a drop in the transient period is observed. The transient period is predicted fairly well by the computational model. The novelty of the present work is that a very simple CFD model is developed for transient natural convection in a high aspect ratio vertical annulus that can be used in the design of control system for cooling of nuclear reactor cores.

1. Introduction

The heat transfer by using natural convection has many engineering applications. It is particularly important in areas where safety is a primary requirement. The system designed on the basis of natural convection can work even in case of electrical failure and provides enhanced security. The common applications include cooling of nuclear reactor cores, transformers, electronic devices, etc. The annular section is a very common geometry and is utilized in various heat transfer equipment such as heat exchangers, nuclear fuel elements, etc.

The natural convection flow in a vertical annulus before reaching steady state goes through a transient period. This transient period is important in the design of control systems (EL-Shaarawi and AL-Attas, 1993). Also, the understanding of transient phenomenon is crucial in the design and operation of thermal fluid systems (Chiu and Chen, 1996). Many applications like cooling of electronic equipment's, nuclear reactors and solar energy storage also fall in this category (Wang et al., 2012).

Because of its importance, this problem has received attention by numerous researchers all over the world. Bayley and Lock (1965) were among the first to study this problem. They investigated the performance of closed thermo-siphon in a series of thoroughly controlled experiments. The results of theoretical analysis have been done and compared with the experimental results. EL-Shaarawi and AL-Attas (1993) performed transient analysis of natural convection in a vertical annulus of radius ratio 0.5 with air as working fluid. They presented the relation between induced flow rate and annulus height for different values of time.

Papanicolaou and Belessiotis (2002) studied transient natural convection of water at high Rayleigh numbers in a vertical cylindrical enclosure. The range of Rayleigh number considered is $10^{10} < Ra < 10^{15}$ which includes both laminar and turbulent flow regimes. Initially, oscillatory pattern is detected because of secondary flow that interchangeably appears and vanishes, after that steady state is achieved.

Arpino et al. (2016a, 2016b) thoroughly studied dynamic aspects of natural convection in a partially filled porous annulus. The governing equations were solved using fully explicit CBS algorithm. They considered several cases which include cavity aspect ratio, properties of fluid and geometry of the domain. They observed that for high Darcy number the presence of porous layer does not damp periodic oscillations while without porous layer the oscillations dampen eventually reaching to steady state value. Their results show that along with the properties of porous material, its position also has strong effect on heat transfer.

Arpino et al. (2013) performed numerical studies on natural

* Corresponding author.
E-mail address: shahidhusain@zhcet.ac.in (S. Husain).

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Nomenclature

A_s	Surface area of tube ($2\pi d_i L$), (m^2)
b	Annular gap (m)
d	Diameter of tube (m)
h	Heat transfer coefficient (W m^{-2} $^oC^{-1}$)
I	Current (A)
k	Thermal conductivity (W m^{-1} $^oC^{-1}$)
L	Length (m)
g	Acceleration due to gravity (m s^{-2})
p	Pressure (Pascal)
q	Heat flux (W/m^2)
r	Radial distance (m)
R	Non-dimensional Radial distance
T	Temperature (^{o}C)
u	Radial velocity (m s^{-1})
U	Non-dimensional radial velocity
V	Voltage (Volt)
w	Axial velocity (m s^{-1})
W	Non-dimensional axial velocity
z	Axial distance (m)
Z	Non-dimensional axial distance

Greek

α	Thermal diffusivity (m^2/s)
β	Expansion coefficient (K^{-1})
ρ	Density (kg m^{-3})
μ	Dynamic viscosity (N s/m^2)
θ	Non-dimensional Temperature
ν	Kinematic Viscosity (m^2 s^{-1})

Dimensionless parameters

A	Aspect ratio (L/b)
Nu	Nusselt Number $\left(\frac{hb}{k}\right)$
Pr	Prandtl Number $\left(\frac{\nu}{\alpha}\right)$
Ra	Rayleigh Number $\left(\frac{g\beta\,|q|\,b^4}{k\nu\alpha}\right)$
RR	Radius ratio $\left(\frac{r_o}{r_i}\right)$

Subscripts and superscripts

a	Ambient
h	Heated
i	Inner
o	Outer
s	Surfacew Wall

convection in a vertical annulus with the heat generating rod in centre, vertical porous annulus and pipe filled with porous medium. They verified their results with the available experimental and numerical data in the literature.

Study of transient natural convection in cavities that are porous and partially porous was conducted by Arpino et al. (2015) considering several parameters that include cavity aspect ratio, Permeability of porous layer and Rayleigh number. Their results show strong dependence of porous layer on temperature and velocity fields in the cavity. The Nusselt number is found to increase with Darcy number and Rayleigh number. Numerical studies on transient natural convection in tall cavities filled with incompressible fluids have been performed by Arpino et al. (2014). Their results shows significant instabilities for Rayleigh number 5×10^5.

The transient natural convection between two concentric and vertically eccentric spheres is studied by Chiu and Chen (1996). They found that heat and flow fields are primarily influenced by Rayleigh number and eccentricity.

Chiu and Lee (1993) performed a theoretical study of transient free convection between concentric spheres. Their results show that heat transfer and flow are primarily affected by Rayleigh number and radius ratio.

Tsui and Tremblay (1984) studied transient natural convection in a horizontal annulus. They observed that dynamic period is much smaller than the usual operational time.

Yu et al. (2012) performed computational analysis of transient buoyancy driven flow in a horizontal cylindrical annulus with aqueous Nanofluids. They predicted the time to reach steady state and time average Nusselt number with Rayleigh number.

The investigation of natural convection in a large aspect ratio narrow annulus with water as working fluid is also carried out by Usmani et al. (2003), Mustafa et al. (2017) and Husain and Siddiqui (2017).

Also, high aspect ratio and the narrow annulus is chosen because this closely matches with the dimensions of a nuclear reactor as explained in detail by Husain and Siddiqui (2016).

The study of open literature reveals that very few study has been carried on the transient natural convection of water in an annulus of large aspect ratio, although, the study of dynamic behaviour of the system is crucial in the efficient design and operation.

Thus, in the present work experimental analysis and numerical simulation of transient natural convection flow of distilled water in a vertical annulus of large aspect ratio forming a closed loop thermosiphon has been performed. The experimental data that consist of temperature, flow rate, pressure and power supply measurements are transmitted to the computer through Data Loggers for the purpose of analysis. The experiments have been carried for heat inputs between 300 W and 1800 W. For numerical analysis, the inner tube of the annulus consists of a heated zone at the middle, adiabatic at the entrance and partially heated at the exit end, while the outer tube forming the annulus is assumed as adiabatic throughout. This geometry and boundary conditions are similar to the experimental set-up. The governing momentum, continuity and energy equations have been solved by using SIMPLE algorithm implemented with commercial software Ansys Fluent. The novelty of this work is that the simple CFD model developed for transient natural convection in a high aspect ratio vertical annulus can be used in the design of control system for the cooling of nuclear reactor cores.

2. Experimental set-up and data analysis

The experimental system has been designed for heat transfer studies during thermally induced flow of liquids through a vertical annular test section. Fig. 1 shows the schematic diagram while Fig. 2 shows a photograph of the experimental set-up. The system forms a closed loop thermo-siphon having a downflow pipe acting as a cold leg, connected to the heated test section with a separator and a condenser in between them to separate the vapor from liquid and condense it during boiling of the liquid. The test section is an annulus made of two concentric tubes, the inner made of stainless steel while the outer of corning glass. The glass tube has dimensions of 45 mm inner and 48 mm outer diameters, respectively with length equal to 1175 mm. The inner tube is of 32 mm inside diameter and 38 mm outside diameter. This provides an annular gap of 3.5 mm and the flow area of 456 mm^2 in the annulus.