International Journal of Heat and Mass Transfer 55 (2012) 680–694

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Effect of natural convection on oscillating flow in a pipe with cryogenic temperature difference across the ends

T.R. Ashwin [a], G.S.V.L. Narasimham [a,*], Subhash Jacob [b]

[a] Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India
[b] Centre for Cryogenic Technology, Indian Institute of Science, Bangalore 560012, India

ARTICLE INFO

Article history:
Received 6 July 2011
Received in revised form 12 September 2011
Accepted 18 September 2011
Available online 24 November 2011

Keywords:
Natural convection
Oscillating flow
Conjugate conduction

ABSTRACT

The effect of natural convection on the oscillatory flow in an open-ended pipe driven by a timewise sinusoidally varying pressure at one end and subjected to an ambient-to-cryogenic temperature difference across the ends, is numerically studied. Conjugate effects arising out of the interaction of oscillatory flow with heat conduction in the pipe wall are taken into account by considering a finite thickness wall with an insulated exterior surface. Two cases, namely, one with natural convection acting downwards and the other, with natural convection acting upwards, are considered. The full set of compressible flow equations with axissymmetry are solved using a pressure correction algorithm. Parametric studies are conducted with frequencies in the range 5–15 Hz for an end-to-end temperature difference of 200 and 50 K. Results are obtained for the variation of velocity, temperature, Nusselt number and the phase relationship between mass flow rate and temperature. It is found that the Rayleigh number has a minimal effect on the time averaged Nusselt number and phase angle. However, it does influence the local variation of velocity and Nusselt number over one cycle. The natural convection and pressure amplitude have influence on the energy flow through the gas and solid.

1. Introduction

Oscillating flow problems have practical applications in equipment like Stirling engines and refrigerators, regenerators, combustor pipes, pulse tube coolers, pipe manifolds and in biological systems in relation to blood flow. The effect of natural convection on the oscillating flow is important in devices like pulse tubes with a cold heat exchanger of cryogenic temperature at one end and ambient hot heat exchanger at the other end. Oscillating flow problems in pipes have received relatively less attention. Buoyancy effect in oscillating flows has received even less attention. The work reported in the area of natural convection in pipes is mostly confined to through flow produced by buoyancy in vertical and inclined pipes. A few studies have considered pipes with closed ends. The present authors have earlier considered the problem of oscillating flow and heat transfer in an open tube with negligible buoyancy forces [1]. Hence the results reported are applicable to a horizontal pipe or for situations with negligible gravity. However, for vertical geometries, the effect of buoyancy becomes important, which is the subject of the present study. The study is performed with low pressure amplitudes with buoyancy acting upward and downward to differentiate the effect of natural convection in oscillating flows.

Natural convection in a vertical cylinder with adiabatic lateral walls with constant but different temperatures on the end surfaces has been studied numerically by He et al. [2]. The results extend the chart of Catton and Edwards for L/D ratios 2.5–10. In the case of large temperature difference ($\Delta T = 200$ K), the natural convection in the enclosure is quite strong in that the convective heat transfer rate is about two orders larger than that of pure heat conduction. This occurs when the cold end is placed down. Other contributions relevant to oscillating flows are Al-Haddad and Al-Binally [3], Cho and Hyun [4], Faghri et al. [5], Moschandreou and Zamir [6], Guo and Sung [7] and Chattopadhyay et al. [8]. These are already covered in Ashwin et al. [1].

2. Formulation

2.1. Geometry

Fig. 1 shows the physical model and coordinate system. Cylindrical polar coordinate system is chosen with the assumption of axisymmetric flow and temperature distributions. The model consists of a cylindrical pipe open at both ends, with a finite wall thickness. Two configurations are studied. In the first one the gravity vector is parallel to the z-axis and acts vertically downwards

* Corresponding author. Tel.: +91 80 22932971; fax: +91 80 23600648.
E-mail address: mecgsvln@mecheng.iisc.ernet.in (G.S.V.L. Narasimham).

0017-9310/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2011.10.042

Nomenclature

c_p	constant pressure specific heat (J kg^{-1} K^{-1})
D, d	diameter (m)
$\dot{E}$	enthalpy flow (W)
Ec	Eckert number, $v_c^2/c_{p,c}\ T_c$ dimensionless
f	frequency (Hz)
Gr	Grashof number $g\epsilon L_c^3/v_c^2$ dimensionless
g	acceleration due to gravity (m s^{-2})
H	length of tube (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length m
$\dot{M}$	mass flow rate kg s^{-1}
Nu	Nusselt number, $h\ R_i/k$ dimensionless
p	pressure (Pa)
Pr	Prandtl number, $\mu\ c_p/k$ dimensionless
R	radius (m)
Ra	Rayleigh number $g\epsilon L_c^3/v\alpha$ dimensionless
Re	Reynolds number, $\omega R_i^2\ \rho/\mu$ dimensionless
T	temperature (K)
t	time (s)
v	velocity (m s^{-1})

Greek Symbols

ΔT_c	characteristic temperature difference K
γ	ratio of specific heats dimensionless
α	thermal diffusivity m^2/s
ϵ	overheat ratio dimensionless
μ	dynamic viscosity (kg m^{-1} s^{-1})
v	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
ω	angular frequency (rad s^{-1})

Subscripts

a	amplitude
av	average
c	characteristic
e	evaporator or cold
f	fluid region
h	hot or ambient
i	inner
o	outer, charge pressure
p	time period
r	radial direction
s	solid region
w	wall
z	axial direction

Superscript

$*$	dimensionless quantity

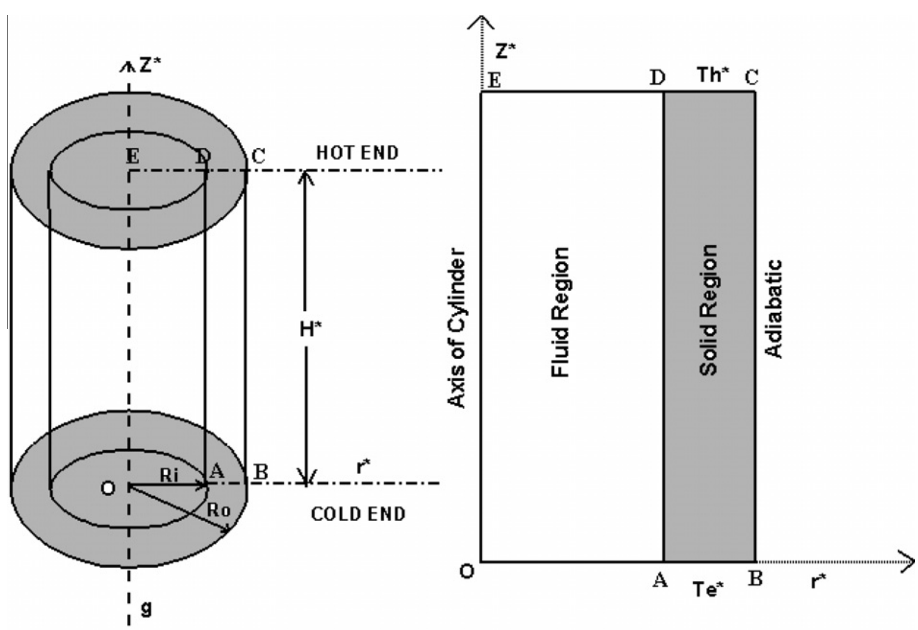

Fig. 1. Physical model and coordinate system.

(i.e. the angle between gravity vector and z-axis is 180°). The other one is an inverted configuration with the gravity vector acting vertically upwards (i.e. the angle between the gravity vector and z-axis is 0°). The working medium at the ends of the tube is assumed to be isothermal but at different temperatures. For example, these regions could be the cold and warm heat exchangers of a thermal system. The working medium when entering one of the ends does so at a cryogenic temperature T_e, while the working medium entering the other end of the tube is at a higher temperature T_h (typically room temperature). The oscillating flow in the tube is driven by a sinusoidally varying pressure at the cold end of the tube. Since the so called DC component is absent, the fluid flow during a cycle takes place partly into and partly out of the tube at either end. The height of the tube and the inner and outer radii are H, R_i and R_o, respectively. Clearly the wall thickness δ_w is $R_o - R_i$. The oscillating heat transfer between the wall and the gas is taken into account through the coupling between the fluid and the solid at the interface. The annular surfaces of the solid at