International Journal of Heat and Mass Transfer 113 (2017) 444–455

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer in a molten salt filled enclosure absorbing concentrated solar radiation

I. Amber *, T.S. O'Donovan

Institute of Mechanical Process and Energy Engineering, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom

ARTICLE INFO

Article history:
Received 12 July 2016
Received in revised form 31 March 2017
Accepted 5 April 2017

Keywords:
Natural convection
Numerical simulation
Molten salt

ABSTRACT

Numerical simulations of the natural convection driven by the direct absorption of concentrated solar radiation by a high temperature molten salt filled enclosures for height to diameter ratios (H/D) of 0.5, 1 and 2 and Rayleigh numbers 10^7–10^{11} is presented. The domain of interest consists of a fluid cavity bounded by rigid adiabatic vertical walls, a heat-conducting bottom wall of finite thickness and an open adiabatic top surface, directly irradiated by a non- uniform concentrated solar flux. The salt volume is first heated non-uniformly by direct absorption of solar radiation and subsequently from the lower absorber plate which is heated by the absorption of the radiation transmitted through the salt.

A Finite Element Method is used to solve the time dependent two dimensional Navier Stokes equations that includes a depth dependent volumetric heat source and temperature dependent thermophysical of molten salts.

Numerical results presented in terms of isotherms and streamlines show a nonlinear temperature profile consisting of distinct layers where thermocapilarity and buoyancy effects are evident. Fluid flow development in the lower layer is found to vary significantly with time and exhibits an initial stage, transitional stage and quasi-steady stages. The magnitude of the natural convection and the duration of each stage is found to decrease as the aspect ratio increases from 0.5 to 2. Calculation of the average heat transfer reveals that the Nusselt Rayleigh number relationship is not uniformly linear and the average heat transfer over the lower boundary surface increased with increasing *Ra*.

1. Introduction

Natural convection plays an important role in design, performance and operating costs in many engineering systems and physical applications. In applications such as buildings, power generation, thermal storage, environmental sciences and electronics cooling, natural convection has been found to strongly influence the operating temperatures and temperature fields [1,2]. natural convection induced by absorption of solar radiation occurring shallow regions of oceans and lakes [3,4] has been found to have significant influence on the fluid temperature distribution, biological activity and water quality due to the mixing of pollutants and sediments.

In the present study numerical simulations are considered for the natural convection in an enclosure containing molten salt (KNO_3-$NaNO_3$) subject solar radiative heating. The principal driving force for the circulation of the fluid comes from the heat exchange from the wall of finite thickness located at the lower boundary.

Natural convection induced by absorption of solar radiation occurring shallow regions of oceans and lakes [3,4] has been found to have significant influence on the fluid temperature distribution, biological activity and water quality due to the mixing of pollutants and sediments.

The present study is motivated by the interest to understand heat and fluid flow interactions and their dependences on defined control parameter within a novel small scale solar thermal store. The thermal store accomodates a heat conducting absorber plate of finite thickness at the lower boundary which promotes isothemalisation required to maximise the storage capacity without damaging the storage medium, which can typically sustain temperatures up to 600 °C [5,6]. KNO_3-$NaNO_3$ salt (60–40 wt%, m.p. 222 °C) has been used up to 565 °C in solar thermal energy collection and storage applications, where its thermal stability has been successfully demonstrated without significant degradation [7–10].

Investigation of the interaction between heat transfer and fluid flow in convective thermal transport in many physical systems has been of primary interests since the classical works of Rayleigh and

* Corresponding author.
E-mail address: ia196@hw.ac.uk (I. Amber).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.04.028
0017-9310/

Nomenclature

A	receiver area [m^2]	q	heat flux [$W\ m^{-2}$]
C	concentration ratio	Ra	Rayleigh number
C_p	heat capacity [$J(kg\ K)^{-1}$]	T	temperature [K]
D	diameter [m]	t	time [s]
g	acceleration due to gravity [ms^{-2}]	u	x velocity component [$m\ s^{-1}$]
H	height [m]	v	y velocity component [$m\ s^{-1}$]
h	mesh element size [m]	w	z velocity component [$m\ s^{-1}$]
I	solar irradiation [$W\ m^{-2}$]	y^*	dimensionless height
k	thermal conductivity [$W(m\ K)^{-1}$]	α	absorption coefficient [m^{-1}]
κ	thermal diffusivity [$m^2\ s^{-1}$]	τ	dimensionless time
Nu	Nusselt number	μ	dynamic viscosity [$N\ s\ m^{-2}$]
P	pressure [Pa]	ν	kinematic viscosity [$m^2\ s^{-1}$]
Pr	Prandtl number	ρ	density [$kg\ m^{-3}$]
Q	volumetric heat generation [$W\ m^{-3}$]	θ	dimensionless temperature
$\dot{Q}$	volumetric flow rate [$m^3\ s^{-1}$]		

Bernard [11,12]. Cavities with differentially heated isothermal or iso-flux end walls have formed idealised models for conducting the fundamental studies for understanding these interactions [11,12]. The differentially heated cavity problem has been extensively studied experimentally and numerically in various contexts (aspect ratios, geometries, orientation, fluids and control parameters) and several boundary conditions. A large body of literature exists for natural convection in differentially heated cavities; three main thermal boundary conditions exists based on heating phase angles, ϕ [11–13]: (i) Heating from below ($0° < \phi < 90°$), typical Rayleigh Bernard flows (ii) Lateral heating from the side ($\phi = 90°$) problem and (iii) heating from above ($90° < \phi < 180°$). In these problems steady state solutions are obtained for idealised isothermal or flux boundaries conditions by time stepping from a prescribed initial state.

Unlike in the differentially heated cavity problem, for radiation induced natural convection problems, it is of fundamental significance to understand the heat and flow behaviour in an enclosure under time dependent heating conditions.

Literature relating to the fluid mechanics and heat transfer interaction in enclosures, where the primary driving force for the natural convective motion, is the volumetric absorption of thermal energy is very limited particularly in high temperature fluids. Webb and Viskanta [14,15] investigated the natural convection in rectangular domains heated by radiative flux at a vertical surface. In the studied domain the primary driving force for the natural convective motion is the volumetric absorption of thermal energy. For two aspect ratios, thin hydrodynamic boundary layers, a stagnant and stratified central core and convective flow regimes were revealed. The thin thermal boundary observed at the vertical walls is associated with a low heat transfer near the base and high heat transfer at the top of the enclosure. The maximum fluid temperature in the cavity increased with increasing aspect ratio. The flow structure revealed a loss of centrosymmetry (eddy centre) characteristic of natural convection flows in cavities with differentially heated walls due to the direct heating of the core of the flow by solar radiation within the fluid.

Li and Durbetaki [16] carried out numerical investigations on the radiation induced transient natural convection boundary layer. In the study a vertical surface of a non-reactive semi-infinite solid was suddenly subjected to a radiative heat flux source. The time required for the surface temperature to attain a specified value and drive natural convection was inversely proportional to the square of the radiative heat flux. Onyegebu [17] numerically demonstrated that natural convection in a rectangular domain subjected to isotropic radiation at the top surface is developed at low fluid depths and albedo, while large fluid depths and low surface boundary emissivity suppressed natural convection. Verevochkin and Startsev [18] in a rectangular domain numerically studied thermal convection in a horizontal water layer cooled from the top and absorbing incident solar radiation. The study identified three different heat transfer regimes: intermittent convection, steady state convection and free convection where flow transition were found to occur at different values for ratios of the downward solar radiation flux at a depth to heat flux through the interface [18]. Numerical [19–22], experimental [23,24] and scaling [25–27] investigations of the unsteady natural convection induced by the absorption of radiation in triangular enclosures have been reported. These have relevance to the daytime natural convection in a side arm and in littoral regions in large water bodies. These investigations report distinct driving mechanisms and flow regimes described as: early flow transition characterised by the thermal boundary layer development, a transitional stage marked by the existence of irregular occurring rising plumes and a quasi-steady state stage.

Recently, Hattori et al. [28,29] and Harfash [30] performed three dimensional numerical simulations of convection induced by the absorption of radiation. In the former, the authors applied a Direct Numerical Simulations (DNS) technique to simulate direct absorption of radiation in a parallelepiped relevant to deep water bodies subjected to a top solar radiative heating, where the authors state that investigations are scarce. Results revealed a non-linear temperature profiles where two distinct layers: an upper stratification region, due to internal heating, provided by the direct absorption of radiation and a potentially unstable boundary layer due to the absorption and re-emission of the residual radiation by the bottom surface are found. The influence of a non-linear temperature stratification on maximum height thermal plumes and the mixing driven by rising thermal plumes. Theoretical calculations to determined the lower mixed layer thickness was presented. Harfash [30] conducted three dimensional numerical simulations of convection induced by absorption of radiation based on linear and non linear analysis. The study reports the linear theory does not predict anything about instability and only provides boundaries for instability because of the presence of non-linear terms. However the non-linear stability theory was demonstrated to overcome the limitations of the linear stability theory and as such is highly desirable, for full assessment of any subcritical regions.

This paper presents two dimensional numerical simulations for the transient natural convection in a fixed volume of binary molten KNO_3-$NaNO_3$ absorbing concentrated solar radiation in enclosures of height to diameter ratios (H/D) of 0.5, 1 and for Rayleigh num-