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Two-dimensional numerical analysis of a rectangular closed-loop thermosiphon

Gilles Desrayaud [a], Alberto Fichera [b,*], Guy Lauriat [c]

[a] INSSET, Université de Picardie Jules Verne, 48 rue Raspail, BP 422, 02109 Saint-Quentin, France
[b] Dipartimento di Ingegneria Industriale e Meccanica, Università di Catania, Viale A. Doria 6, 95125 Catania, Italy
[c] Université Paris-Est, Laboratoire Modélisation et Simulation Multi Echelle, MSME UMR 8208 CNRS, 5 bd Descartes, 77454 Marne-la-Vallée, France

HIGHLIGHTS

► 2d-numerical investigation of a rectangular natural circulation loop with horizontal heat exchanging sections is studied.
► The numerical simulations are reported for growing *Ra*.
► The vortexes are responsible for the initiation of the oscillations and for the growth of temperature gradients.

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ABSTRACT

The study presents a numerical investigation of the dynamical behavior of a rectangular natural circulation loop with horizontal heat exchanging sections. The study has been developed in a two-dimensional domain considering uniform wall temperatures, UWT, at the horizontal sections and thermally insulated vertical legs as thermal boundary conditions. The governing equations have been solved using a control volume method solving the velocity-pressure coupling with the SIMPLER algorithm. The analysis has been performed for a fixed geometry of the loop and for various Rayleigh numbers, separating the values of Rayleigh for which the system manifests stable and unstable dynamics. In the last case, it is shown that the vortices are responsible for the birth of the oscillations and for the growth of temperature gradients.

1. Introduction

Natural circulation loops are technical devices designed in order to employ the mechanism of natural convection for the heat transfer from a bottom-placed source to a higher heat sink. In these systems, the fluid inside the closed or open loop is moved by buoyancy force created by the temperature difference between the cooling sections and the heating sections, without the use of any mechanical device, such as pumps or compressors. Therefore, these systems are low – cost, noise-free and intrinsically safe; they found applications for cooling purposes in industrial processes such as solar water heaters, geothermal processes, gas turbine blade cooling, and as nuclear emergency core cooling systems. Due to their practical importance there are many experimental and theoretical studies in literature. Rectangular and toroidal loops have been widely investigated for different configurations, such as toroidal loop with uniform isothermal heating and cooling respectively of the lower and of the upper halves of the torous, Gorman et al. [1], Stern et al. [2], or rectangular loops with two differentially heated horizontal sections, Huang and Zelaya [3], Bernier and Baliga [4], Vijayan and Austregesilo [5], Misale et al. [6], Fichera et al. [7]. Generally, the numerical approaches in these studies are one-dimensional and are based on the averaging of the governing equations over the pipe cross-section. One-dimensional approach requires a priori definition of the friction factor, loss coefficients and heat transfer coefficients, assuming that the no-axial direction velocity, the effects of the pipe curvature and the axial conduction are negligible, Greif [8]. In fact, it has been claimed that the disagreement between analyses and experiments arises mainly from the use of the conventional forced flow friction factor correlation, 1D approximation and convection heat transfer correlations in the analysis.

To improve 1D numerical analysis, a 1D/2D numerical analysis was carried out by Bernier and Baliga [4] who proposed for a single phase natural circulation loop to couple the local results of 2D numerical simulation performed in the heating and cooling sections with those of the 1D analysis performed in other sections of the loop. Misale et al. [9] studied the transient behavior of the

* Corresponding author. Tel.: +39 095 7382450; fax: +39 095 738 7950.
E-mail address: afichera@diim.unict.it (A. Fichera).

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Nomenclature

A	loop aspect ratio, $A = H/W$
C_f^*	friction coefficient
$\overline{C_f^*}$	surface-weight average friction coefficient
D	channel gap width, m
d	dimensionless channel gap width, d = D/W
f_D	Darcy friction factor
f_D^*	overall Darcy friction factor
H	loop height, m
g	gravitational constant, m s^{-2}
Gr_m	modified Grashof number, Eq. (8)
K_{eff}	overall loss coefficient
K_i	minor loss coefficient
k	internal block conductivity
ℓ	dimensionless loop length, L/W
L	loop length, m
L_t	total equivalent length of the loop, m
L_i^*	equivalent length of the loop, m
M	dimensionless mass flow rate
$\overline{Nu}$	mean Nusselt number
N_x	number of grid point along X
N_y	number of grid point along Y
P_m	dimensionless head pressure
Pr	Prandlt number
Ra	Rayleigh number
Ra_{2d}	Rayleigh number based on hydraulic diameter
Re	Reynolds number
Re_{2D}	Reynolds number based on the hydraulic diameter
T	temperature, K
T_c	temperatures at the upper horizontal section, K
T_h	temperatures at the lower horizontal section, K
u	velocity along x
U	dimensionless velocity along X, $U = u/(g\beta\Delta TW)^{0.5}$
$\overline{v}$	dimensional average velocity, ms^{-1}
$\overline{V}$	dimensionless average cross velocity,
V	velocity along y
V	dimensionless velocity along Y, $V = v/(g\beta\Delta TW)^{0.5}$
X, Y	dimensionless coordinates, X, $Y = x/W$, y/W
W	loop width, m

Greek symbols

α	thermal diffusivity, m^{2}s^{-1}
β	thermal expansion coefficient, K^{-1}
ΔT	temperature difference, $\Delta T = T_h - T_c$, K
κ	thermal conductivity, W m^{-1}K^{-1}
μ	dynamic viscosity, N s m^{-2}
ν	kinematic viscosity
ρ	density, kg m^{-3}
τ	dimensionless time, $\tau = t/W(g\beta\Delta TW)^{-0.5}$
θ	dimensionless temperature difference, θ=$(T - T_c)/\Delta T$

loop by a 1D/2D numerical analysis considering axial conduction both in the fluid and in the wall. Basaran and Kucuka [10], following the numerical technique proposed by Bernier and Baliga [4], analyzed experimentally rectangular thermosiphon and, obtained the velocity and the temperature profiles in the heating and cooling sections. One-dimensional and three-dimensional computational fluid-dynamic codes have been used by Pilkhwal et al. [11] for the prediction of the dynamical behavior observed in experiments carried out in a single-phase natural circulation apparatus. The three–dimensional code allowed the observation of the origin of pulsating instabilities in the horizontal heater and cooler, not shown by one-dimensional models.

With regard to toroidal configurations, some authors have focused on 2D simulations with the aim at achieving a deeper understanding on the dynamical behavior of the fluid inside the loop. Desrayaud et al. [12] [13] have investigated the two-dimensional natural convection in an annular thermosyphon heated at a constant flux over the bottom half and cooled at a constant temperature over the top half. The numerical investigations have demonstrated the complexity of the dynamics encountered in the experimental studies of toroidal loops: steady flow with and without recirculating regions, periodic motion and Lorenz-like chaotic flow. Ridouane et al. [14] have reported in their paper the 2D numerical simulations of the dynamics of flow reversals in a toroidal loop differentially and isothermally heated at the bottom and upper halves. In particular, the temporal evolutions of temperature distribution, mass flow rate, and local heat flux at selected locations in the loop have been reported.

By using 1D analysis, conventional forced flow correlations for fully developed flows are assumed to be applicable to natural circulation flows. A generalized non-dimensional, non-loop specific correlation was proposed by Vijayan et al. [15]. Vijayan and Austregesilo [5] also developed scaling laws for natural circulation loops for steady state flows and stability analysis. Later on, Vijayan [16] extended the non-dimensional correlation to non-uniform diameter loops. Probably due to the absence of pressure losses due to the presence of bends and flow area changes, Desrayaud et al. [13] have numerically shown that forced flow correlations can be applied for natural circulation flow in 2D-annular loops.

The objective of this paper is to 2D-numerically analyze single-phase rectangular circulation loops with horizontal heat exchanging sections connected by vertical adiabatic legs. In particular, the influence of the Rayleigh number on the behavior of the loop for different aspect ratio and the influence of minor loss on the dimensionless non-loop specific parameters proposed in literature have been studied. To this purpose, a 2D numerical integration of the governing equations for steady and unsteady conditions of the circulating flow has been developed.

2. The mathematical model

A schematic representation of the geometrical configuration under consideration is reported in Fig. 1.

The system is a two-dimensional rectangular loop of height H, width W and constant channel gap width D. The heat transfer boundary conditions consist of constant temperatures at the horizontal sections, T_c and T_h at the upper and lower section respectively ($T_h > T_c$) and thermally insulated vertical legs. The Navier–Stokes and energy equations, expressed in non-dimensional form are solved for two-dimensional, incompressible, Newtonian laminar flows under the validity of Boussinesq's assumption. They are written as follows:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P_m}{\partial X} + \sqrt{\frac{\Pr}{Ra}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P_m}{\partial Y} + \sqrt{\frac{\Pr}{Ra}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \theta \tag{3}$$