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SOME CONSIDERATIONS ON THE INTERACTION BETWEEN THE FLUID AND WALL TUBE DURING EXPERIMENTS IN A SINGLE-PHASE NATURAL CIRCULATION LOOPS

MARIO MISALE(1) , FRANCESCO DEVIA, and PIETRO GARIBALDI
Energy and Environmental Conditioning Department
University of Genoa - Via Opera Pia 15-A
I – 16145 Genova – Italy

(1) Corresponding Author

Abstract: In this paper an experimental study on single-phase natural circulation loops is presented. Several parameters such as loop inclination, and tube wall thermal conductivity (Plexiglas or Stainless-steel AISI-304) were systematically investigated. The experiments were conducted analysing the interaction between the pipe material and liquid properties as well as the inclination of the loop. For a wide range of power transferred to the liquid, different thermo-hydraulic behaviours were observed:
the stainless-steel/distilled water combination shows always stable behaviour, probably the higher thermal conductivity of stainless-steel causes the "extension" of the heated section in the lower heat source; at the same time, this can be interpreted as a virtual reduction in the distance between the heater and the cooler. This behaviour was observed for the most part of loop inclinations.

Key-Words: Single-Phase, Experiments, Natural Circulation, Chaotic Behaviour, Lorenz's Model

1. INTRODUCTION

The principal characteristic of the natural circulation system (*thermosyphon*) is that liquid circulation is generated by buoyancy force, which is the result of thermally induced density differences in the liquid, in presence of a body force. At least three thermo-hydraulic behaviours may appear in a single-phase natural circulation loop: *stable* (steady temperature difference across the heat sinks), *neutral* (oscillations of the temperature differences across the heat sinks without amplification), and *unstable* (amplification of the oscillations of the temperature differences across the heat sinks and flow reversals).
Although forced convection is more efficient than natural circulation in conveying thermal energy in heat transfer processes, the latter does not require the use of any moving parts (pump). Thus, natural circulation can be utilized in any engineering application in which reliability must be guaranteed. Indeed, natural circulation loops are extensively used in energy conversion systems, like solar heaters and the cooling systems of nuclear reactors, as well as in many other industrial fields, such as geothermal power production, cooling of turbine blades, engines and computers; in the future, it may also be used in space applications, such as in bases on the moon or Mars.
As is well known, the instability of the loop depends on the interaction between the buoyancy force generated by density gradients and the friction along the loop. Several experimental and theoretical studies are reported in the literature dealing with the physics of flow and how it influences heat transfer in thermosyphons. In particular, in [1-3] reviewed thermosyphonic flows in the most common geometries and their applications. In the case of closed and open rectangular loops, particular attention has been devoted to transient, steady state, as well as to stability analysis of the system under various heating and cooling conditions.
Obviously, in engineering applications, thermo-hydraulic stability is highly desirable. In fact, some theoretical maps are available in literature, to predict loop behaviour. These maps were obtained experimentally [4] and theoretically [4]. However, they are not able to take into account many of the parameters capable of influencing loop behaviour, such as the thermal conduction in the loop, the inclination of the loop, the mode of supplying the heat flux and so on.
In the literature, some studies have focused on the influence of the inclination of the loop. The studies available regard the rotation of a toroidal loop [6,7]. These authors observed, experimentally and theoretically, that the inclination of the loop plays an important role. In the former study, the existence of, at least two, steady-state velocities with opposite directions was shown theoretically, though the authors observed only one of these experimentally; at the same time, they observed flow reversal across the section of the loop. In the latter study, the authors' theoretical analysis revealed the thermo-hydraulic behaviour is stable if the angle is greater than 20°. Acosta et al. [8] investigated the same kind of rotation, but for a square loop. They confirmed the existence of the multiplicity of steady-state velocities.
Kim et al. [9] adopted a different approach to the displacement of the natural circulation loop. On studying the influence of the inclination of a simulated

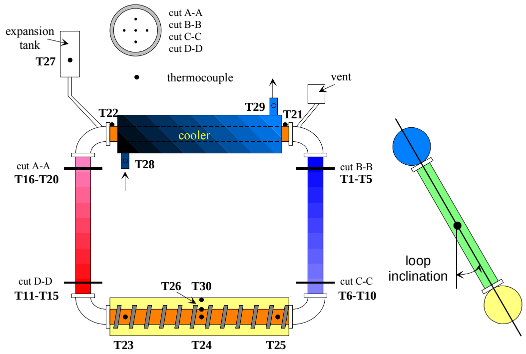

Fig. 1 Scheme of the experimental apparatus.

nuclear reactor, both experimentally and theoretically, they found that the flow rates decreased as the inclination increased.

Another parameter that could cause different thermo-hydraulic behaviour in a single-phase natural circulation loop is the material used to connect the lower and the upper thermal sections. The influence of thermal conductivity of the connecting tubes was theoretically investigated or theoretically/experimentally investigated [10,11]. The former study analysed a rectangular loop in which two different materials was considered for vertical tubes (glass or copper); the latter one investigated the influence of thermal conductivity in a toroidal loop. The two halves (bottom/upper) were made of copper/copper, glass/copper, and glass/glass, respectively. The authors of both papers observed that higher value of thermal conductivity could cause the stabilization of the loop. However, this conclusion is not valid in general. In fact, Misale et al. [12] showed that for a single-phase rectangular loop with two connecting tubes made of stainless steel (higher thermal conductivity of glass), the thermo-hydraulic behaviour depends of the proprieties of working liquid.

In this paper, it is reported an experimental investigation on the influence of several parameters, such as loop inclination, and materials used in the loop construction, on the thermo-hydraulic behaviour of a single-phase natural circulation loop .

Table 1 Geometrical dimensions of the rectangular loop (dimensions in mm).

Loop height	1245
Loop width	1480
Loop inner diameter	40
Heating section length	1400
Cooling section length	1200
Expansion tank height	668
Expansion tank diameter	50
Loop total length	5616
Length - diameter ratio	140.4

2. EXPERIMENTAL APPARATUS

A rectangular loop was used in the experiments. Basically, the circuit consists of two horizontal copper tubes (heat transfer sections) and two vertical tubes (legs) made of stainless steel (AISI304) or Plexiglas, considered as adiabatic to the ambient, connected by means of four 90° bends made of stainless steel. The loop inner diameter was of 40 mm, whereas the thickness of the copper tubes, stainless steel tubes, and Plexiglas tubes, was 2.5 mm, 2.5 mm, and 5.0 mm, respectively.

A sketch (Fig. 1) of the rectangular loop is shown; the main dimensions of the loop used in the experiments are reported in Table 1.

The lower heating section consists of an electrical heating wire made of nicromel on the outside of the copper tube; the upper cooling system is a coaxial cylindrical heat exchanger with tap water flowing through the annulus. In this way, the loop has an imposed heat flux in the lower heating section and an imposed temperature in the cooler. The temperature of the cooler can be fixed by using a high water flow rate so as to minimize the temperature difference between the inlet and the outlet of the water (less than 2 K). An expansion tank open to the atmosphere was installed on the topmost elevation of the loop, to allow the liquid inside the system to expand. In order to minimize the heat exchange between the loop and the ambient, all parts of the system were thoroughly insulated. The heat transfer rate through the insulation, evaluated on the basis of usual heat transfer correlations, was always less than 3% of the heat input into the heater.

The loop was equipped with 30 calibrated (± 0.1 °C) and insulated T-thermocouples (0.5 mm OD) located as follows:

- thermocouples from T1 to T20 were utilized to measure the temperature of the liquid: in each of the 4 sections on the adiabatic legs (A, B, C and D in Fig. 1). In each section, one thermocouple was placed on the axis of the tube and the other fours at $0.25 \cdot D$ from it;
- T21, T22, T24, T24, T25, and T26 were lodged in holes drilled into the copper pipes;
- T27 measured the liquid temperature in the expansion tank;
- the inlet and outlet temperatures of the secondary liquid in the cooler were measured by thermocouples T28 and T29, respectively;
- T30 measured the temperature in the outer layer of the insulation.

Data were acquired and stored by means of a high-speed data-acquisition system by National Instruments (Lab PC+, SCXI-1102, SCXI-1303), moreover, an electronic ice point was used as reference temperature. Each temperature was obtained as averages of 80 readings, whereas the time interval

between to data acquisition was 1 sec. Distilled water was used as the working liquid during the tests.
Since the temperature measurements presented three-dimensional distributions across the sections A-D [13], the experimental data were averaged on the same section. In particular, the data were analysed in terms of temperature differences across the heater or the cooler. However, negligible differences were measured on the average temperature values of the liquid on the left or right side of the loops. This probably means that considering the vertical legs to be adiabatic is a valid. For example, the temperature difference across the heater was evaluated as follows:

$$\Delta T_{heater} = \frac{\sum_{i=1}^{5} T_{10+i}}{5} - \frac{\sum_{i=1}^{5} T_{5+i}}{5} \quad (1)$$

During the experiments, different parameters were investigated in order to ascertain their influence on the thermo-hydraulic behaviour of the loop. In particular, the effect of loop inclination as well as the material of the connecting tubes were experimentally investigated.
The main characteristics of the tests were as follows:
constant power (Sorensen DHP150 power supply): 500 W, 1000 W, 1500 W, 2000 W, and 3000 W .. For each power value, different loop inclinations were investigated: 0°, 30°, 60°, and almost 90° (Fig. 2). The interval time for each loop inclination was:
0° → 10800 s
30° → 7200 s
60° → 7200 s
close to horizontal → 7200 s
The following experimental procedure was used during each test:

- the uniformity of the system temperature was checked and compared with the ambient temperature;
- data acquisition started, the cooling flow rate was established; the heating power was supplied;
- every 1 second, the 30 measurement signals were recorded (time needed to record all the signals was less than 1 second);
- every 20 minutes, the flow rate at the cooler and the level of the expansion tank were checked.

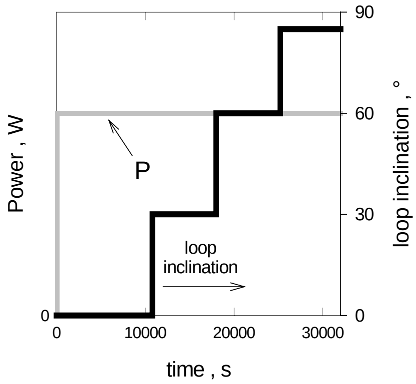

Fig. 2 Test procedure.

3. RESULTS AND DISCUSSION

Experimental observations of the thermo-hydraulic behaviour of the rectangular loop are presented in this section. The loop inclination effect as well as the effect of the material used for the connecting thermal sections liquid were experimentally studied. The loop inclination was varied from 0° (vertical loop) to very close to 90° (horizontal loop). In this way, the difference in geodetic coordinates between the diabatic sections of the loop (vertical distance between the sink and the source of heat) decrease, thereby reducing the buoyancy forces.
This is substantially like decreasing the value of gravity acceleration and therefore like analysing the gravitational effects on the stability behaviours of the single-phase natural circulation loop. This approach can be seen as an attempt to take into account the effect of reduced gravity, as would be the case in a moon or Mars base. Obviously, the aim of scaling space-oriented heat transfer systems is to develop reliable systems whose performance in conditions of reduced gravity could be correctly predicted from the results of terrestrial experiments with scale models [14]. The procedure utilized in this study is only a first attempt to simulate reduced gravity in a terrestrial experiment.

3.1 Water experiments

The aim of these experiments was to investigate the influence of loop inclination and the power transferred to the liquid in a rectangular single-phase natural circulation loop in the case of different combinations between the working liquid and tube materials.
Figures 3 4, 5, 6 and 7 show the temperature differences across the heater as a function of time for the constant power levels adopted and for the different loop inclinations [from vertical (0°) to close to horizontal (≈90°), see the red line and the different area colours] and in the case of connecting tube made of stainless-steel or Plexiglas. On y-axis it is plotted ΔT_{heater} that is the difference between the average temperature $T_{avg(B-L)}$, evaluated as the mean of thermocouples T11-T15, and the average temperature $T_{avg(B-R)}$ evaluated as the mean of T6-T10 thermocouples. Since the loop is thermally insulated, the average temperatures evaluated as the mean of T1-T5 and T16-T20 thermocouples are the same of those represented in Figs. 3-7, but not in phase. The difference of phase could be exploited to evaluate the mean velocity of the liquid in the loop.
As can be observed examining the Figs. 3-7, the material of the connecting tubes induces different thermo-hydraulic behaviour in the loop. The Plexiglas tests show always an instable behaviour for three values of loop inclinations: vertical (0°), 30°, and 60°; only when the displacement of the loop is very close to 90°, the drastic reduction of the buoyancy force causes a stable behaviour. Moreover, for this inclination, the pipe material doesn't influence the asymptotic values ΔT_{heater} (right side of Figs. 3-7), in fact this value depends of the

heat power. These numeric values were obtained averaging the last 4000 s of the stored data.

Completely different is the loop behaviour in the case of stainless-steel tubes. for all power levels and loop inclinations, the loop behaviour is always stable, even when the loop inclination is vertical (0°). In this loop configuration, the buoyancy force is higher than in other loop inclinations. However, additional conclusions can be drawn from the experimental results: at the power levels of 500 W and 1000 W, the typical unstable behaviour occurs during the initial transient [15,16], whereas, at the power levels of 2000 W and 3000 W, the transient disappears more rapidly and stable behaviour is soon achieved. The loop behaviour probably depends on the combination of liquid properties and thermal conduction along the vertical legs, which is also related to their thermal inertia of the adiabatic legs. At low power levels (500 W and 1000 W) at the beginning of the run, the heat flux finds a better path within the water rather than by thermal conduction along the adiabatic legs, whereas at high power levels (2000 W and 3000 W) at the beginning of the run, the significant thermal conduction along the adiabatic legs causes an apparent extension of the heating section: if the thermal conduction along the adiabatic legs is coupled with the properties of the water, this interaction could be likened to reducing the distance between the heater and cooler, thereby reducing the buoyancy force whilst maintaining the friction force almost constant. Moreover, at a given power level, the effect of changing the loop inclination from vertical (0°) to 30° and 60° is negligible except during the initial transient; by contrast, the loop inclination very close to 90° (quite horizontal)shows a significant increase in the temperature difference across the heater, due to the pronounced reduction of the buoyancy force. Moreover, for this extreme loop inclination the absolute value of ΔT_{heater}, for each power level seems not to be influenced by pipe material. Probably, in this case the main heat transfer effect is due to both the conduction in the liquid and the reduced convection, whereas it is negligible the conduction in the pipe.

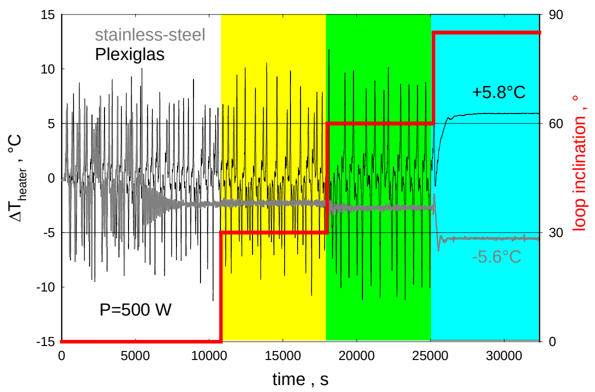

Fig. 3 Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=500 W).

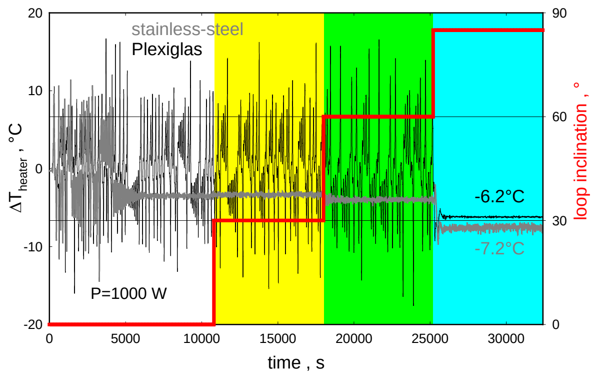

Fig. 4 Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=1000 W).

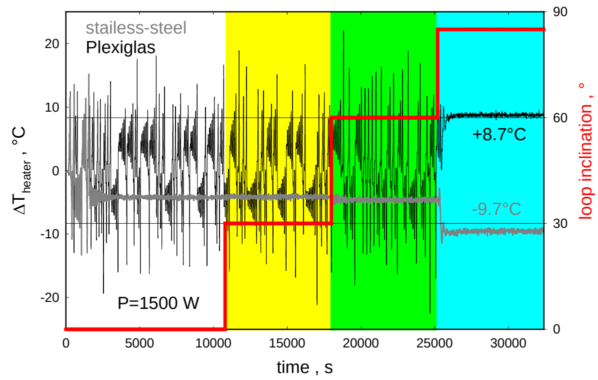

Fig. 5 Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=1500 W).

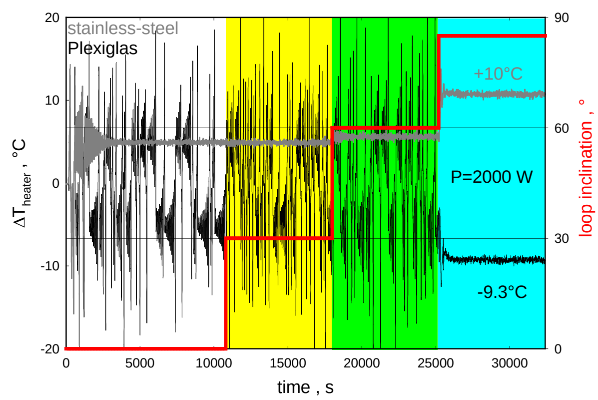

Fig. 6 Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=2000 W).

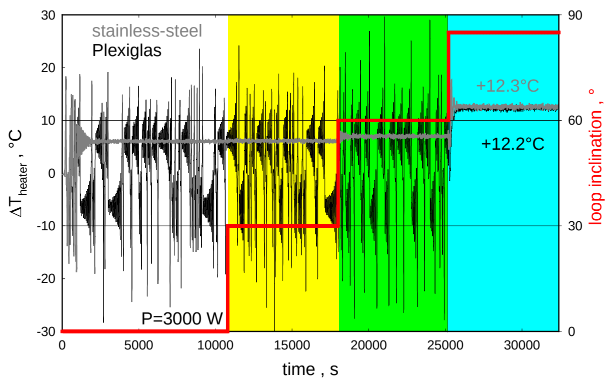

Fig. 7 Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=3000 W).

3.2 Loop Chaotic behaviour

As observed by [17] and [11], the single-phase natural circulation loop can be analysed using the chaos theory, and in particular they showed that the Lorenz model [18] can be used to qualitatively and quantitatively describe the characteristics of chaotic flow.

In this paper only qualitatively analysis is reported. Fig. 8 shows the water data at P=1000 W, when the connecting tubes are made of Plexiglas for different values of loop inclinations. In the x-axis are reported the temperature differences between the average temperature at the bottom right (T6-T10) and the ambient one, whereas on the y-axis are reported the temperature differences between the average temperature at the bottom left (T11-T15) and the ambient one. To better represent the data at 30°, 60°, and close to horizontal, the temperature differences are shifted of a Δ value of 5°C, 10 °C, and 15 °C, respectively.

As can be deduced from Fig. 8, the trajectory is that typical of chaos, in particular after the extinction of the initial transient, the graphs show the typical attractor of the chaos, during the experiments having loop inclination of 0° (vertical), 30°, and 60°, whereas when the loop is almost horizontal can be observed (pink line) the disappearance of the oscillations in the flow.

Since the stable behaviour is what it guarantees the maximum reliability of the thermal system, in literature some models are described which try to calculate the flow and temperatures in the liquid in case of unstable behaviour and try to predict which ones of these parameters could be controlled to stabilise the loop. One of this model is the Lorenz model [18]. It was applied at a toroidal loop [11] considering some parameters such as thermal conductivity in the pipe and modality to supply power, whereas Cammarata et al. [19] confirmed that the dynamic in a single-phase rectangular could be simulated adopting Lorenz model. As an example, the Eqs. 1-3 give the set of Lorenz's model characterised by Jiang and Shoji [11] for a toroidal loop:

$$\frac{dx}{d\tau} = \sigma(y - x) \tag{1}$$

$$\frac{dy}{d\tau} = -zx + (Ra)x - \eta y \tag{2}$$

$$\frac{dz}{d\tau} = xy - \eta z \tag{3}$$

where: $y=[0.25\pi(Ra)]a_1$, $z=0.25\pi(Ra)]b_1+(Ra)$ and η is given by

$$\eta = \left[1 + \left(\frac{(Ra)}{8\pi^2}\right)\right]\varsigma$$

where

$$\varsigma = \frac{2r_i}{R}\frac{A_w}{A_f}\frac{1}{Bi}$$

This set of differential equations takes into account both the liquid parameters such as the Rayleigh number (Ra), the thermal conductivity of the pipe (Bi, Biot number), and σ=16(Pr/Nu) defined as the measure of thermal inertia of the loop (Pr, Prandtl number; Nu, Nusselt number). More details about the symbols employed in the set Eqs. 1-3 are reported in [11].

The main conclusion of the Jiang and Shoji paper [11] is that the high thermal conductivity of the pipes stabilise the flow, because the axial conduction in the wall tube decreases the vertical temperature gradient and helps the system to remove thermal disturbance from the flow.

Finally, the similarity between dynamics brought by the Fig. 8 and those found in the Lorenz model [18] suggest the possibility to adopt it also for the rectangular sigle-phase natural ciculation loops.

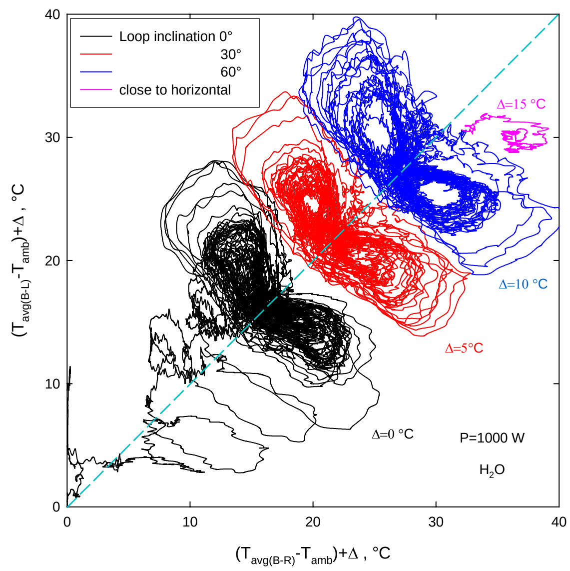

Fig. 8 Trajectories of average temperature difference bottom left vs. average temperature difference bottom right (P=1000 W).

4. CONCLUSIONS

This study experimentally investigates both the effect of loop inclination and thermal conductivity of the pipes on the behaviour of a rectangular loop, filled with distilled water. Another parameter investigated was the input power at the lower heat sink (heater). More attention was devoted to the influence of loop inclination because, even though this condition is clearly not the same as that encountered in space applications (reduced gravity), such investigations could yield useful information on the thermo-hydraulic behaviour of single-phase natural circulation loops in reduced gravity. Indeed, increasing the loop inclination from 0° (vertical) to about 90° (horizontal) reduces the buoyancy force.

The water runs showed stable or unstable behaviour. In particular, in case of the vertical pipes was made of stainless steel, the stable behaviour was soon achieved, even tough at the start of the tests, some temperature oscillations were detected. These transients went out more rapidly when the power was increased. At the beginning of the experiment, thermal conduction in the adiabatic legs probably plays an important role: when the power is increased, the amount of heat conducted through the adiabatic legs is greater, thus causing an "extension" of the heating surface of the lower heat source; at the same time, this can be interpreted as a virtual reduction in the distance between the heater and the cooler. However, to better understand the loop behaviour, thermal conduction in the adiabatic legs should be coupled with the proprieties of the liquid used in the experiments.

Finally, the apparent similarity between the dynamic beahviours found in our hydraulic loop and those showed by the Lorenz model suggests the possibility of adapting it to analyse the rectangular sigle-phase natural ciculation loops.

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