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SINGLE-PHASE NATURAL CIRCULATION IN A MINI-LOOP: PRELIMINARY RESULTS

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Abstract. *This study reports an experimental investigation into using a rectangular single-phase natural circulation mini-loop, which consists of two horizontal copper tubes (heat transfer sections) and two vertical tubes (legs) made of copper, connected by means of four glass 90° bends. The loop inner diameter is 4 mm. The lower heating section consists of an electrical heating wire made of nicromel on the outside of the copper tube; the upper cooling system consists of a coaxial cylindrical heat exchanger with a water-glycol mixture, set at controlled temperature and flowing through the annulus. The loop has an imposed heat flux in the lower heating section and an imposed temperature in the cooler. The mini-loop was placed onto a table which can assume different inclinations. The parameters investigated during the experiments were: power transferred to the fluid and inclination of the loop. The preliminary results show a stable behaviour with a steady temperature difference across the heat sinks. It has been confirmed that the fluid velocity is very small (order of millimetres per second).*

Keywords. *Single-Phase, Mini-loop, Natural circulation, Loop inclination*

1. Introduction

Natural circulation loops are able to convoy heat passively from heat sources to heat sinks without need of mechanical pumps. For this reason they can be applied in many technological applications such as solar heaters, energy conversions, nuclear power plants and thermal control of electronic components. In particular for the last two examples; their reliability must be guaranteed more than the other thermal systems cited above. Although these two thermal systems utilise the same mechanism to convoy the heat flux, they are characterised by very different geometrical dimensions. The total length of the loops varies between a few meters for the former type and a few centimetres for the latter.

Extensive experimental and theoretical research into single-phase natural circulation has already been completed and deals with the physics of flow and how it influences heat transfer in thermosyphons, characterised by macro-geometrical dimensions. In particular, Grief (1988), Vijayan et al. (1992), and Zvirin (1981) 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 both transient and steady-state flows as well as to stability analyses of the system under various heating and cooling conditions. Moreover, different thermal boundary conditions such as loop inclination (Misale et al. (2005)) and thermal conduction of the pipe were considered (Jiang, Y.Y. and Shoji, M. (2003)). All the above cited studies refer to loops characterized by large scale geometrical dimensions. Only in the case of two-phase natural circulation loops are geometrical dimensions limited to a few millimetres or less.

Muhkherjee and Mudawar (2003a-2003b) studied the thermal performance of a two-phase natural circulation loop. In particular, they studied both flat and a finned surfaces inside a channel as the heating section of a natural circulation loop. The boiler gap between the boiling surface and the wall confinement varied between 0.13 mm up to 21.5 mm. In the case of flat surface the corresponding hydraulic diameter corresponded at 0.065 mm or 10.65 mm respectively.

More recently, Tuma and Mortazavi (2006) studied a two-phase natural circulation loop for cooling electronic devices. They utilized this heat transfer technique to remove a power of 200 W dissipated by a silicon chip.

Concerning mini and micro-thermal systems, two-phase natural circulation loops have been investigated both experimentally and theoretically, while single-phase loops have not still been examined. A preliminary study of a single-phase mini-loop characterised by a hydraulic diameter of 4 mm was completed. For defined geometrical loop dimensions (width and height), experiments were conducted by varying both the power transferred to the fluids and the inclination of the loop. The results were compared with a theoretical model (Vijayan (2002)) that was previously proposed for vertical single-phase rectangular loops characterised by geometrical dimension of several orders of magnitude higher than the loop dimensions utilised in this study. A correlation factor was introduced in order to take into account the value of loop inclination.

2. EXPERIMENTS

2.1 Experimental apparatus

A rectangular loop was used during the experiments and consisted of two horizontal copper tubes (heat transfer sections) and two vertical tubes (legs) made of copper. These were connected by means of four 90° bends made of glass. The inner uniform diameter was of 4 mm.

A sketch of the experimental apparatus is shown in Fig. 1. The geometrical dimensions of the loop as well as the thermocouple locations are shown in Fig. 2.

The lower heating section (L=136 mm) 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 a mixture of 50% water and 50% glycol 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 cryostat. The flow rate of the liquid coolant was higher than 1 litre per minute. This value guarantees that the temperature difference between the inlet and the outlet of the coolant is less than 1 degree Kelvin. 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 external air, 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 5% of the heat input.

The loop was equipped with 4 calibrated (± 0.1 °C) metal-sheathed K-thermocouples (0.2 mm OD – see Fig. 2). Two additional metal-sheathed K-thermocouples were used to measure temperature in the ambient and in the cryostat bath, respectively.

The thermocouples (T1, T2, T3 and T4) in the loop were placed on the axis of the tube. In natural circulation systems the presence of the any sensors into the fluid influences the pressure losses in the loop; for this reason the outer diameter of the thermocouples was chosen to be 0.2 mm. The presence of this sensor reduced the cross sectional area by 3.2%, however, this reduction is lower than the critical value found for a bigger loop (inner diameter of 40 mm) (Misale and Frogheri (2001), where it was demonstrated that the presence of localized pressure drops could influence thermo-hydraulic behaviour if the reduction of the internal diameter cross sectional area is greater than 64.0%.

Experimental data was acquired over a period of 5400 seconds and stored by means of a high-speed data-acquisition system by National Instruments (Lab PC+, SCXI-1102, SCXI-1303). An electronic ice point was used as reference temperature and temperatures were based on an average of 80 readings with a time interval between two data acquisition steps being 1 second. Distilled water was used as the working fluid during the experiments.

2.2 Experimental campaigns

The power transferred to the fluid and the loop inclination were the experimental variables used for the parametric investigation. The power varied between 2.5 W and 25 W, and the loop inclination (α) between 0° (gravitational orientation) and 75°, respectively, as shown in Table 1.The experimental procedure adopted was: Displacement of the loop inclination; Control of the coolant liquid temperature in the cryostat bath (during the tests the temperature bath was fixed at 0° C) as well as of the uniformity of the liquid temperature in the mini-loop; Starting the data acquisition system after 100 seconds by simultaneously switching on the power and opening the cryostat valves reaching the desired temperature at the upper heat sink.

Due to the fact that this was the first time that a mini-natural circulation loop had been experimentally examined, several runs were repeated. The runs at 0° were performed with the aim of reaching the lowest limit of the critical power value; which allowed single-phase conditions to remain. For this geometry loop configuration, the critical value was slightly above 25W. This will be shown in the next sections.

3. RESULTS

3.1 Experimental data

The overview of the experimental results is shown in Figures. 3-11 (one picture for each power input and loop inclination combination). The temperature difference across the heater for each run is reported on the left-y-axis whereas the maximum temperature of the liquid is shown on the right-y-axis. Since several runs are plotted in each figure, the maximum temperature depicted in each figure is referred to the run showing the maximum value of temperature overshoot.

It is very easy to observe that the thermo-hydraulic behaviour is stable (clockwise circulation) for all thermal and geometrical configurations of the loop (steady temperature difference across the heat sinks). After the quiescent state, when thermal conductivity is the dominant heat transfer mechanism, the fluid starts circulating through the loop and shows an initial temperature difference overshoot, successive stabilisation occurs, caused by the total friction losses along the loop.

The quiescent state depends on power input as well as on loop inclination. As the power increases, the time required for the transient state to end is reduced. The loop inclination has the opposite effect. When the loop inclination is increased, the quiescent state duration increases as well as the value of temperature overshoot. The runs at P=2.5 W and α=75° in particular show a very smooth trend. The overshoot is not pronounced when compared with the others runs. As the mass flow rate is very low for this operating condition, conduction becomes more important in the global heat transfer mechanism causing soft temperature overshoots.

The runs at P=7.5 W and 10 W do not show typical temperature overshoots after the quiescent state, instead the temperature variations and consequently the flow rates show clockwise/anticlockwise transient circulations, however when the flow is developed the instabilities are suppressed. When steady state conditions are reached, the fluid always circulates in a clockwise direction. This tendency is most likely caused by small geometrical imperfections in the tubes that make the loop asymmetric and drive the fluid motion to a preferred direction.

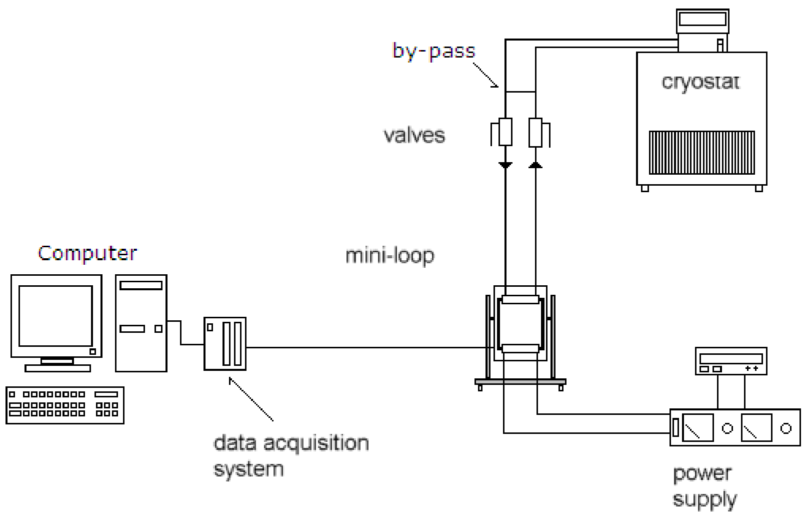

Fig. 1 – Experimental apparatus.

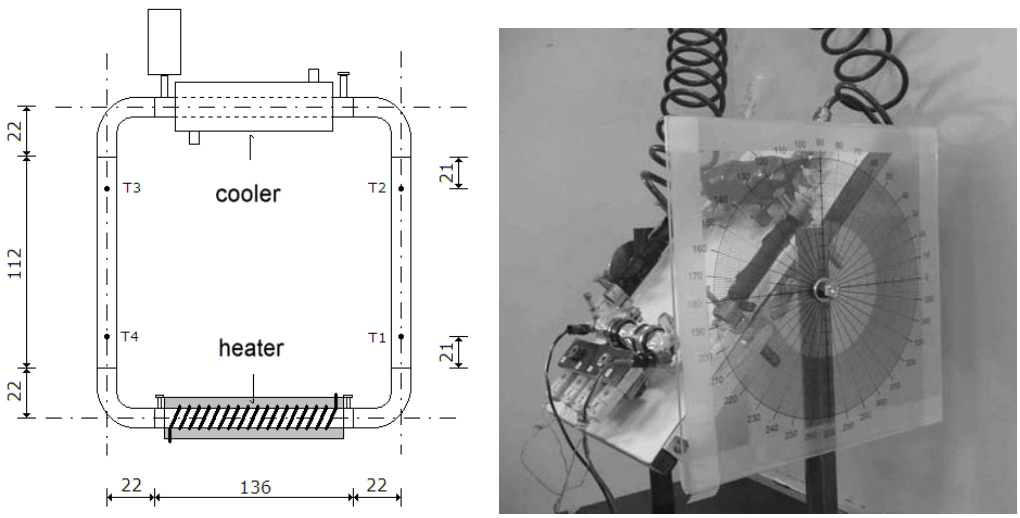

Fig. 2 – Geometrical dimensions of the rectangular loop, thermocouples locations (dimension mm), and a picture of the mini-loop.

Table 1 – Experimental campaigns data

Run no.	Loop inclination, °	Power, W
#1	0°	5, 15, 25
#2	0°	5, 15, 25
#3	0°	5, 15, 25
#4	0°	5, 15, 25
#5	30°	2.5, 7.5, 10
#6	30°	2.5, 7.5, 10
#7	75°	2.5, 10
#8	75°	2.5, 10
#9	75°	2.5, 7.5, 10
#10	0°	5, 15, 25
#11	0°	5, 15, 25
#12	0°	5, 15, 25
#13	30°	2.5, 7.5, 10
#14	30°	2.5, 7.5, 10
#15	30°	2.5, 7.5, 10
#16	30°	2.5, 7.5, 10
#17	75°	2.5, 7.5, 10
#18	75°	2.5, 7.5, 10
#18	75°	2.5, 7.5, 10
#19	75°	2.5, 7.5, 10
#20	75°	2.5, 7.5, 10
#21	75°	2.5, 7.5, 10
#22	0°	10

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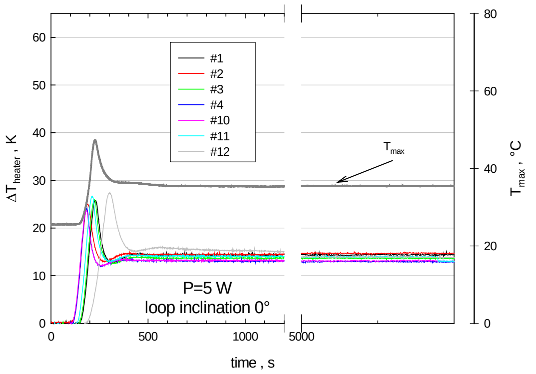

Figure 3 – Temperature differences across the heater and maximum temperature vs time (P=5 W, α=0°)

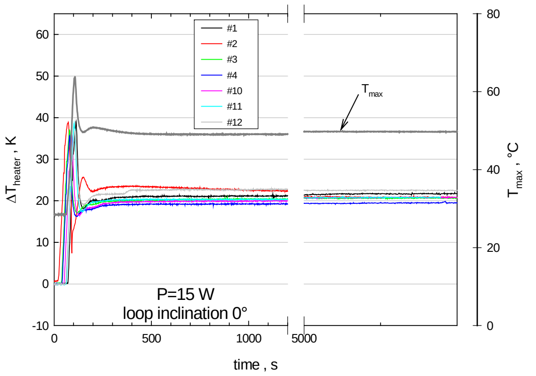

Figure 4 – Temperature differences across the heater and maximum temperature vs time (P=15 W, α=0°)

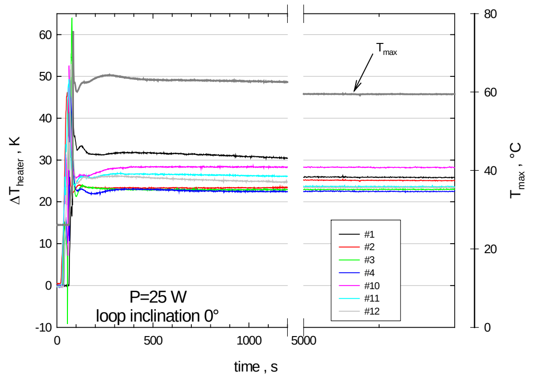

Figure 5 – Temperature differences across the heater and maximum temperature vs time (P=25 W, α=0°)

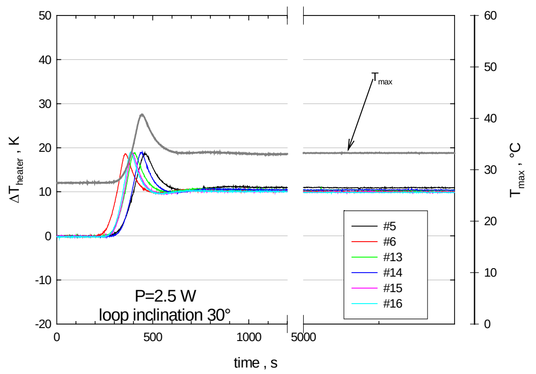

Figure 6 – Temperature differences across the heater and maximum temperature vs time (P=2.5 W, α=30°)

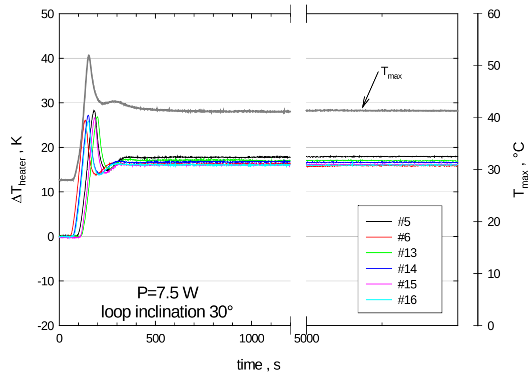

Figure 7 – Temperature differences across the heater and maximum temperature vs time (P=7.5 W, α=30°)

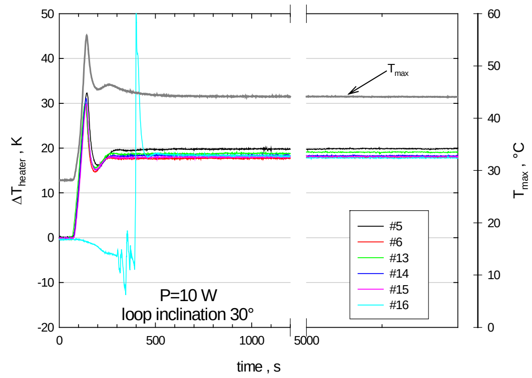

Figure 8 – Temperature differences across the heater and maximum temperature vs time (P=10 W, α=30°)

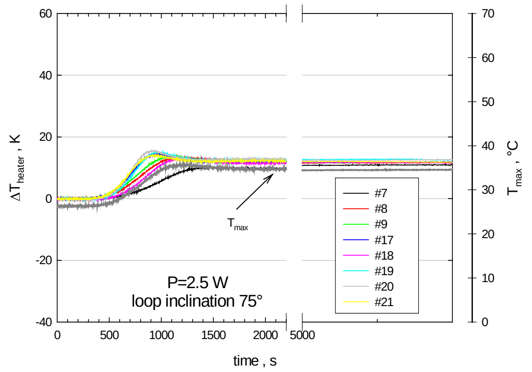

Figure 9 – Temperature differences across the heater and maximum temperature vs time (P=2.5 W, α=75°)

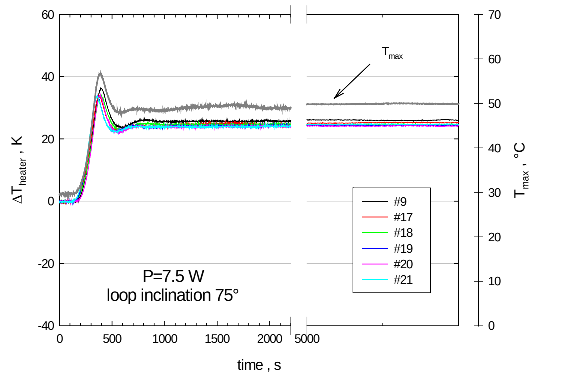

Figure 10 – Temperature differences across the heater and maximum temperature vs time (P=7.5 W, α=75°)

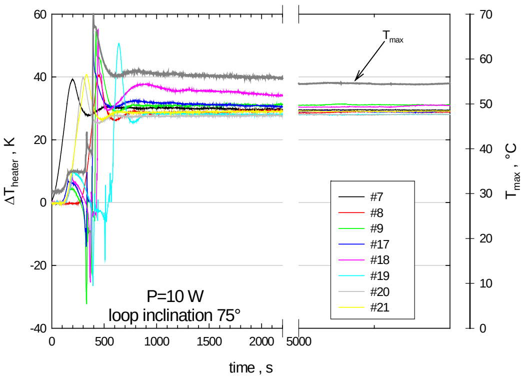

Figure 10 – Temperature differences across the heater and maximum temperature vs time (P=7.5 W, α=75°)

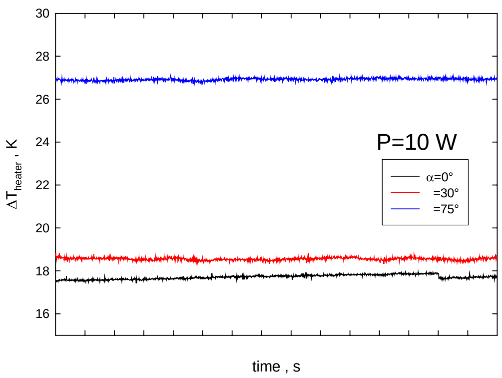

Figure 12 – Temperature difference across the heater vs time for different loop inclinations (P=10 W)

With regard to the repeatability of the runs, for fixed power and loop inclination, Table 2 details the temperature differences $(\Delta T_h)_{ss}$, the average temperature differences $\overline{(\Delta T_h)_{ss}}$, and the associated standard deviation σ, respectively: The best thermal performance (maximum power with acceptable temperature difference) of the system, expressed in term of $\overline{(\Delta T_h)_{ss}}$, occurs for the 25 W and vertical displacement of the loop (α=0°) case, i.e., with the same temperature difference, and a loop inclination of 75°, the system is able to transfer only 7.5W from the heat source to the heat sink.

The upper limit of the steady state fluid temperature for this first experimental campaign was 60°C, reached with the heating power of 25W, 10°C higher than the tests at 15 W. As is known, the heat transfer capability of natural circulation loops depends predominantly on geometrical parameters. The present loop is characterized by H/W=0.87 and L_{tot}/D=165.5. Using a higher loop, the upper power limit due to high fluid temperature could certainly increase.

A potential application of this could be for the thermal control of electronic components. A few parallel connected single-phase mini-loops could potentially cool computer processors using only natural circulation.

Finally a simple consideration of the influence of the loop inclination is made. In Figure 12, data measured during the test at P=10 W are reported for three different loop inclinations. The data show there to be a significant incremental change of ΔT_{heater} for α=75°. This consideration is in agreement with the results obtained by Misale et al. (2005) for a large scale natural circulation loop.

Table 2 – Different values of steady-state temperature difference across the heater

Power, W	α, °	$(\Delta T_h)_{ss}$, K	$\overline{(\Delta T_h)_{ss}}$, K	σ, K
5	0°	13.9,14.3, 13.3, 12.8, 12.9, 13.6, 13.7	13.5	0.5
15	0°	20.9, 20.2, 20.1, 19.1, 20.2, 20.3, 21.9	20.4	0.8
25	0°	25.1, 25.1, 22.4, 21.9, 27.5, 23.0, 22.9	24.0	2.0
2.5	30°	10.7, 10.1, 10.3, 10.3, 9.9, 9.9	10.2	0.3
7.5	30°	17.3, 15.5, 16.6, 16.1, 15.8, 15.2	16.1	0.8
10	30°	19.1, 17.5, 18.6, 17.8, 17.6, 17.4	18.0	0.7
2.5	75°	10.2, 11.0, 11.1, 11.4, 11.3, 12.3, 12.1, 11.6	11.4	0.7
7.5	75°	24.2, 23.7, 23.4, 23.3, 23.8	23.7	0.4
10	75°	28.1, 27.5, 27.8, 29.4, 27.0, 27, 28.3	27.9	0.8

3.2 Steady state data analysis

In a single-phase natural circulation loop it is essential to predict the mass flow rate as function of the boundary conditions, particularly of the power transferred to the liquid and, as additional parameter in our study, the loop inclination.

As detailed previously, the present apparatus shows always steady state conditions with laminar flow for the entire range of power input and angle values investigated. In this case, the gravitational forces balance the shear stresses and it is possible to develop a correlation between Re_{ss}, the steady state Reynolds number, and Gr_m, a modified Grashof number, which depends on heat flux, geometry and mean fluid temperature.:

$$\mathrm{Re}_{ss} = \frac{w \cdot D}{\nu} \quad ; \quad \mathrm{Gr}_m = \frac{D^3 \cdot \rho^2 \cdot P \cdot H}{A \cdot \mu^3 \cdot c_p} \cdot \beta \cdot g \cdot \cos(\alpha) \qquad (1)$$

The modified Grashof number was used by Vijayan (2002) but in this study it has been modified (the cos(α) term) to account for loop inclination. The Vijayan’s model assumptions (large scale natural circulation loop) are:

- 1D model is assumed to be valid,
- Viscous heating and axial conduction effects are neglected,
- Heat losses are negligible (<5%) and
- The Boussinesq approximation is valid.

For the loop used in this study, the diameter is assumed to be uniform; hence the flow cross sectional area is constant.

In the general case when assuming a 1D model, the mass flow does not depend on space coordinates:

$$\frac{\partial \dot{m}}{\partial s} = 0 \qquad (2)$$

The integral momentum equation can be written as:

$$\frac{L}{A}\frac{d\dot{m}}{dt} = g\rho_0\beta\oint T dz - \frac{\dot{m}^2}{2\rho_0 A^2}\left(f\frac{L}{D} + k\right) \qquad (3)$$

The parameter N_G is introduced as:

$$N_G = \left(\frac{L}{D} + \frac{k}{f}\right) \qquad (4)$$

Assuming that the fully developed forced flow correlations are valid, the friction factor (f) in the region of laminar flow can be expressed as:

$$f = \frac{64}{\mathrm{Re}} \qquad (5)$$

The energy equation varies along the loop and can be expressed by:

$$\frac{\partial T}{\partial t} + \frac{\dot{m}}{\rho_0 A}\frac{\partial T}{\partial s} = \frac{P}{\rho_0 c_p A L} \qquad \text{Heater (6a)}$$

$$\frac{\partial T}{\partial t} + \frac{\dot{m}}{\rho_0 A}\frac{\partial T}{\partial s} = -\frac{\pi D}{\rho_0 c_p A} h_c (T - T_s) \qquad \text{Cooler (6b)}$$

$$\frac{\partial T}{\partial t} + \frac{\dot{m}}{\rho_0 A}\frac{\partial T}{\partial s} = 0 \qquad \text{Pipes (6c)}$$

In the current case the flow is always stable, therefore it is possible to drop all the time dependent terms. By means of a dimensionless procedure and introducing the N_G parameter and the laminar flow friction factor as expressed above, it is possible to rewrite equation (3) as:

$$\frac{\mathrm{Gr}_m}{\mathrm{Re}_{ss}^{\ 3}}\oint \vartheta dZ = \frac{64 N_G}{2\,\mathrm{Re}_{ss}} \qquad (7)$$

Where: $\vartheta = \dfrac{T - T_s}{\left(\Delta T_h\right)_{ss}}$ and $Z = \dfrac{z}{H}$

Solving the temperature integral along the loop, it is possible to rewrite eq.(7) as the correlation presented by Vijayan, [9]. This is plotted in Fig 13 together with experimental data:

$$Re_{ss} = 0.1768\left[\frac{Gr_m}{N_G}\right]^{0.5} \qquad (8)$$

As shown in Fig. 13 there is a good agreement between the correlation proposed by Vijayan (2002) and the experimental data. In particular, it is important to consider that Vijayan's model was developed for a large scale loop and it has been applied to a mini-loop here. Furthermore, loop inclination was also accounted for by the modification made to the Grashof number Gr_m.

The predicted mass flow values are lower than the experimental results in the case of low power and high inclination angle (2.5W, 75°). This poor correlation could be caused by three-dimensional effects on the temperature and velocity fields, which invalidate the assumption that the model is one dimensional.

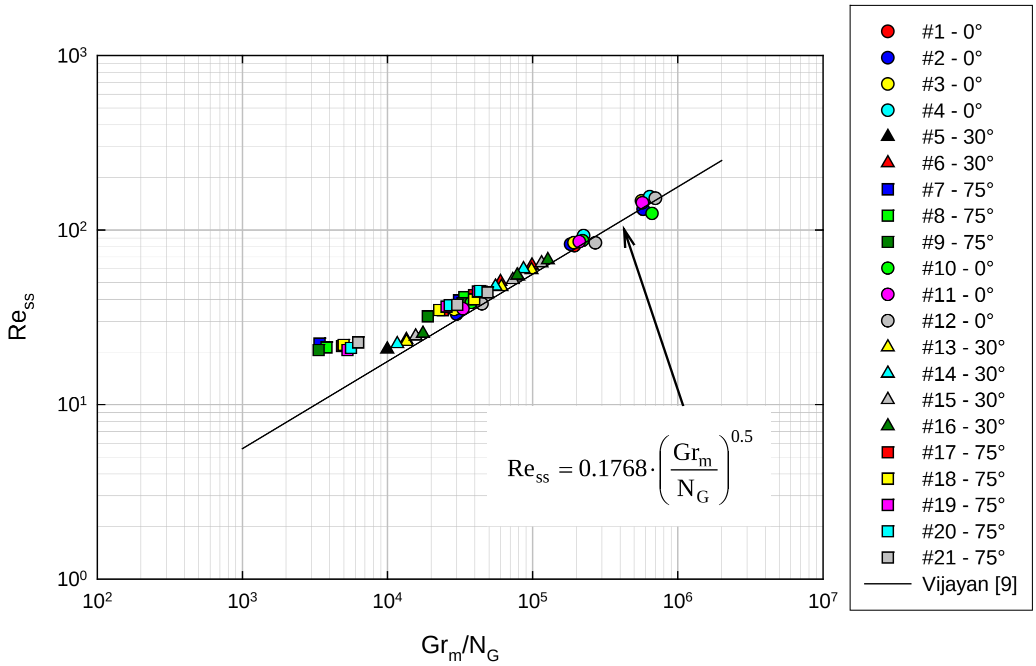

Figure 13 – Steady-state data analysis

4. CONCLUSIONS

An experimental investigation in a single-phase natural mini-loop, characterised by an internal uniform diameter of 4 mm, is presented. In particular the effect of power transferred to the fluid and loop inclination was systematically investigated.

The main conclusions are detailed as follows:

- For each experimental run, the thermo-hydraulic behaviour is stable (steady temperature difference across the heat sinks), i.e., after quiescent state, when thermal conductivity in the fluid is the dominant heat transfer mechanism, the flow starts circulating through the loop, showing an initial temperature overshoot followed by a successive stabilisation caused by the total friction losses along the loop. The quiescent state duration increases as the power decreases and the loop inclination increases; whereas the temperature overshoot increases as the power and loop inclination increase.
- The loop inclination influences the temperature of the fluid only when the angle is 75°. When the loop inclination is 0° (vertical) or 30° the effect is quite negligible even as observed for a large scale natural circulation loop [4]
- The loop displacement at 75° shows instabilities during the transient case, i.e., instead of observing the typical temperature overshoot after the quiescent state, the temperature trends and consequently the flow both show clockwise/anticlockwise unstable circulation. This is most probably because during the initial transient flow, the conduction is the predominant mechanism to convoy the heat.

- The steady-state analysis, expressed in terms of the typical dimensionless numbers (Re_{ss} vs Gr_m/N_G), shows a good agreement with the correlation proposed by Vijayan (2002). This was originally proposed for large scale natural circulation loops, but has been modified to take into account the loop inclination.
- From the data obtained in this experimental research,, the best thermal performance of the mini-loop is referred to the operating condition of P=25 W and vertical inclination of the loop (0°). A potential application of this could be the thermal control of electronic components. A number of single-phase mini-loops connected in parallel should have the ability to cool computer processors using only natural circulation.
- The data reported in this study could be considered as the first step to construct a database regarding the single-phase natural circulation mini-loop.

Acknowledgments

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NOMENCLATURE

Symbol	Quantity	SI unit
A	flow area	m^2
c_p	specific heat	kJ/kgK
D	internal diameter	m
f	friction factor	-
g	gravitational acceleration	m/s^2
Gr_m	modified Grashof number	-
H	loop height	m
h_c	cooler heat transfer coefficient	$W/\ m^2K$
k	local pressure loss coefficient	-
L	heater length	m
$\dot{m}$	mass flow rate	kg/s
N_G	dimensionless parameter	-
P	heat flux	W
Re	Reynolds number	-
s	spatial coordinate around the loop	m
t	Time	s
T	Temperature	°C
ΔT_h	heater temperature difference	K
$\overline{(\Delta T_h)_{ss}}$	average temperature difference at the heater	K
W	loop width	m
w	fluid velocity	m/s
z	Elevation	m
Z	dimensionless elevation	-
α	loop inclination	degree
β	thermal expansion coefficient	1/K
ρ_o	reference density	$kg/\ m^3$
θ	dimensionless temperature	-
σ	standard deviation	

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SINGLE-PHASE NATUTAR CIRCULATION IN A MINI-LOOP: PRELIMINARY RESULTS

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Abstract. *This study reports an experimental investigation into using a rectangular single-phase natural circulation mini-loop, which consists of two horizontal copper tubes (heat transfer sections) and two vertical tubes (legs) made of copper, connected by means of four glass 90° bends. The loop inner diameter is 4 mm. The lower heating section consists of an electrical heating wire made of nicromel on the outside of the copper tube; the upper cooling system consists of a coaxial cylindrical heat exchanger with a water-glycol mixture, set at controlled temperature and flowing through the annulus. The loop has an imposed heat flux in the lower heating section and an imposed temperature in the cooler. The mini-loop was placed onto a table which can assume different inclinations. The parameters investigated during the experiments were: power transferred to the fluid and inclination of the loop. The preliminary results show a stable behaviour with a steady temperature difference across the heat sinks. It has been confirmed that the fluid velocity is very small (order of millimetres per second).*

Keywords*. Single-Phase, Mini-loop, Natural circulation, Loop inclination*