International Journal of Advancements in Mechanical and Aeronautical Engineering – IJAMAE
Volume 1 : Issue 3 [ISSN 2372 –4153]
Publication Date : 30 September, 2014

Overview on single-phase natural circulation loops

Mario Misale

Abstract - Analytical and experimental studies on single-phase natural circulation loops (thermosyphons - NCL) have been performed in the past years by several authors,. However the problem of the stability of the loops, that is of interest in many industrial applications, cannot be considered solved. The present paper is focused on the experimental aspects that could be interesting in the study of these thermal systems. In particular, the following NCLs aspects will be discussed: applications, models, thermo-hydraulic behaviour, and influence of loop size. Finally a broad reference list is cited.

Keyword – natural circulation, single-phase, instabilities, nanofluids)

I. Introduction

In general, the essential hardware of a natural circulation system (known also as thermosyphon or natural convection system) consists in a heat source, a heat sink and the pipes connecting them in such a way that it forms a continuous circulation path filled with a working fluid. In a natural circulation system, fluid circulation starts automatically following the activation of the heat source under the influence of a body force field like gravity. With both the source and sink conditions maintained constant, a steady circulation is expected to be achieved. The fluid circulation is the result of buoyancy forces, which are the result of the density differences thermally induced by the heat transport from the source to the sink. Usually, the heat sink is located above the source to promote natural circulation. The primary function of a natural circulation loop (NCL) is the heat transfer from a source to a sink. The main advantage of a natural circulation system is that no fluid moving machinery is needed, making the system less prone to failures and reducing the maintenance and operating costs. The motive force for the flow is generated within the loop simply because of the presence of the heat source and the heat sink. Therefore, natural circulation loops find several engineering applications in conventional as well as nuclear industries. Notable among these are solar water heaters, transformer cooling, geothermal power extraction, cooling of internal combustion engines, gas turbine blades, and nuclear reactor cores.

Figure 1 schematically shows the working principle of a NCL, i.e., due to the difference in densities between the vertical legs ($\rho_c>\rho_h$) in the presence of a body force, a pressure difference is created between stations a and b which is the cause of the flow. At steady state the driving buoyancy force is balanced by the retarding frictional force thus providing a basis for the estimation of the flow rate:

$$g \cdot H \cdot (\rho_c - \rho_h) = \frac{R \cdot W^2}{2 \cdot \overline{\rho}} \tag{1}$$

where g, R, and W are the acceleration due to the gravity, the hydraulic resistance, and the mass flow rate, respectively.

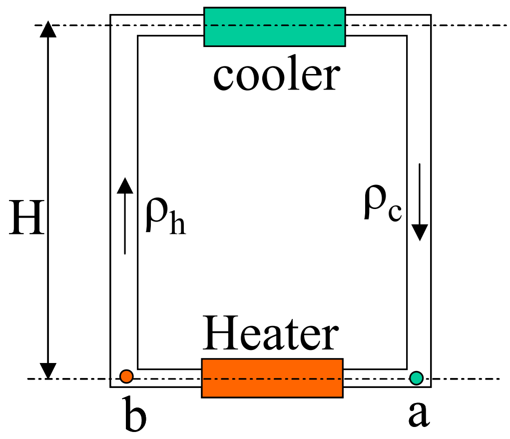


Fig. 1. Single-phase Natural Circulation Loop (NCL)

Various authors used simple physical models capable of retaining the characteristic aspects of the phenomenon.

Figure 2 shows some examples of such models with particular emphasis to their applications in the fields of solar, nuclear, and geothermal energy and cooling of electronic equipment.

The solar heating plant show in Fig. 2-a is made up of a lower collector, connecting pipes and an upper storage tank. This system was studied in a preliminary work [69] in which the efficiency and the daily variations of flow rate and temperature values inside the various components were evaluated by theoretical and experimental procedures. A further refinement of the numerical method has been proposed in [70] while numerous experimental results are reported in [59]. These studies confirmed that natural circulation solar heaters offer stable flows within a wide range of working parameters.

Figure 2-b shows a model, first proposed in [6], which was designed to point out both theoretically and experimentally that different solutions are possible under the same imposed thermal conditions [71, 72]. Significant functional instabilities with the possibility of flow reversal in some of the parallel channels were observed in [52, 53]. Finally, in [32], the

Mario Misale
Full professor
University of Genoa – Italy
Dept. of Mecahnical Engineering DIME
Thermal Division
Via Opera Pia 15-a (I) 16145 Genova
mario.misale@unige.it

combinations of flow rate and imposed heat fluxes, which lead to unstable behavior in a simple loop (made up of only two parallel channels with rectangular section) were experimentally determined.

Figure 2-c represents a model similar to that studied in [3]; such model is well suited to the analysis of the heat transfer conditions which bring about fluid motion in the loop from the rest state. Further studies regarding geological applications are reported in [61, 68].

From the examples mentioned so far it follows that four different aspects of the analysis of natural circulation loops may be developed: a) the onset of motion from the rest state and subsequent transient; b) the steady-state; c) instability of the steady-state with oscillations and flow reversals; d) multiple steady-state solutions.

The models shown in Figs. 2-d and 2-e are the most exhaustively studied today, following some theoretical and experimental works which provided correct definitions of the main variables for the analysis of single-phase natural circulation loop behavior [9, 13, 14, 28, 31, 64, 67].

The model in Fig. 2-d consists of a lower heat exchanger (point heat source), capable of providing a finite heat flux and a cooler located at higher elevation (point heat sink), which cools the fluid. The two parallels pipes that connect the lower heat source to the upper heat sink are, for the sake of simplicity, considered adiabatic.

Figure 2-e shows a toroidal loop consisting of a heated lower semicircular portion and an upper one cooled by means of external jacketing with constant wall temperature.

Finally, Fig. 2-f may be interpreted as a generalization of the loop depicted in Fig. 2-d: the heat sources have been replaced by pipes of finite length, imposing different heat boundary conditions (imposed temperature at the cooler T_c, imposed temperature at the heater T_h or imposed heat flux).

II. Thermo-hydraulic behaviour of NCLs

Natural circulation systems are susceptible to several kinds of instability. Although instabilities are common to both forced and natural circulation systems, the latter is inherently more unstable than forced circulation systems due to the nonlinear nature of the natural convection process and its low driving force. Because of the not in phase between the buoyancy and friction forces of the natural circulation process, any disturbance in the driving force will affect the flow which in turn will influence the driving force, leading to an oscillatory behaviour even in cases where eventually a steady state is expected. In other words, due to the strong coupling between the flow and the driving force, a regenerative feedback is inherent in the mechanism which causes NCL flow. As a result, single-phase natural circulation systems often exhibit instability

Four thermal-hydraulic behaviours could appear in a single-phase natural circulation loop: stable (Fig. 3a) (steady temperature difference across the heat sinks), neutral stable (Figs. 3b) (oscillations of the temperature differences across the heat sinks without amplification but characterised by the same sign), neutral unstable (Fig. 3c) (oscillations of the temperature differences across the heat sinks without amplification but characterised by positive and negative sign),

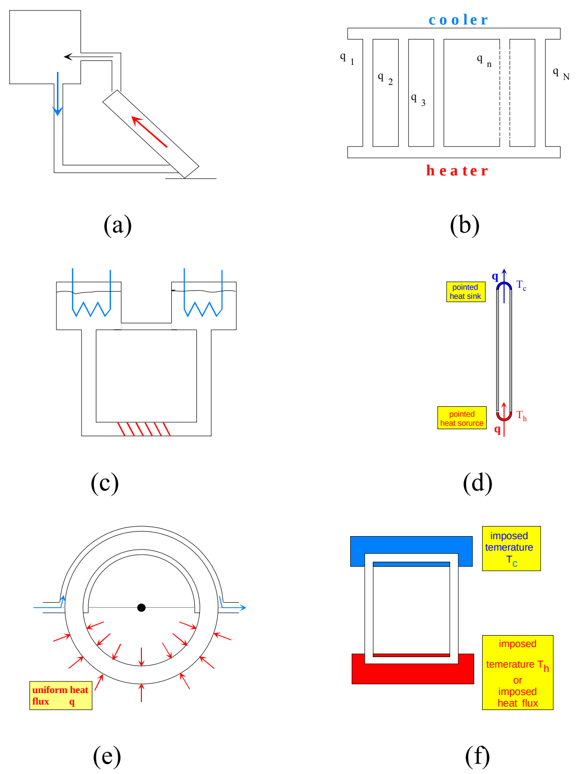
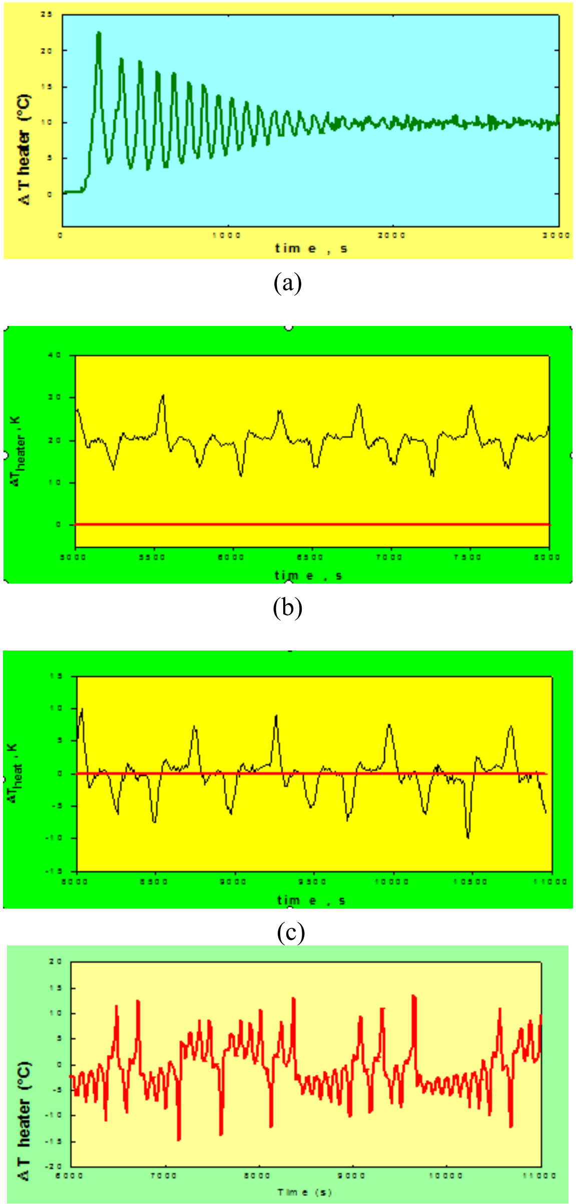


Fig. 2. Single-phase Natural Circulation Loops: applications (a, b, c) and models (d, e, f)

and unstable (Fig. 3d) (amplification of the oscillations of the temperature differences across the heat sinks and flow reversals).

As well known the instability depends on the interaction between the buoyancy force generated by density difference and the friction along the loop. However, only in [67] a physical explanation of the instability is reported. In steady motion, viscous and thermal dissipation seem to oppose any change in the flow rate. In fact, any increase in flow rate would cause and increase in friction and a decrease in total buoyancy. These two restraining effects may not be in phase and an overshooting can then occur, eventually producing growing oscillations.

According the Welander's model, a hot pocket of fluid, due to any thermal disturbance of the system, may emerge from the heated section slightly hotter than its normal steady state temperature. This hot pocket accelerates the flow while ascending along the hot leg because of larger buoyancy force thus created, and is not completely cooled at the heat sink because of the lower residence time due to larger velocity. Thus the hot pocket emerges from the cooler at a higher temperature than its normal steady state temperature. An opposite phenomena occurs if a cold pocket emerges from the heater. As the cold pocket ascends along the hot leg and the hot pocket descends along the cold leg, the flow gets decelerated with the result that the hot pocket emerges hotter



(a)

(b)

(c)

(d)

Fig. 3. Thermo-hydraulic behaviour of NCL: (a) stable, (b) neutral stable, (c) neutral unstable, and (d) unstable.

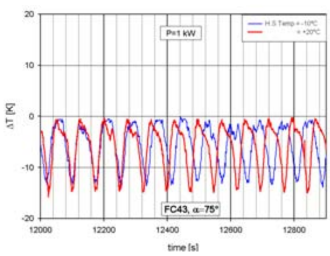


Fig. 4. Unidirectional pulsing oscillations

from the heater and the cold pocket emerges colder from the cooler with every passing cycle. This amplification process continues until the buoyancy force experiences a reversal in sign causing the flow to reverse. The amplification process above described then continues in the reverse direction, causing the flow to change its direction repeatedly from clockwise to anticlockwise and vice- versa. Thus, the flow oscillations are mainly due to creation of hot and cold density pockets which get amplified with time in the system.

A different type of flow oscillation is defined as unidirectional pulsing. The temperature differences at the heater and cooler of a rectangular loop are drawn in Fig. 4. The unidirectional pulsing is characterised by the same sign of the temperature differences but more regular trend of the neutral stable. These type of oscillations appear in the case of reduced buoyancy force or increased friction, typically in the case of very low heat flux or high value of loop inclination (reduced gravity).

III. Experimental aspects investigated

The thermo-hydraulic behaviour of a single-phase natural circulation loop depends by a numerous parameters such as:

1. Influence of wall thermal conductivity
2. Influence of power and loop inclinations
3. Effect of heater and cooler orientations
4. Stabilisation of the loop by localised pressure drops or nanofluids (?)
5. Influence of geometrical dimensions (mini-loop)

The above parameters are now shortly discussed.

III. 1. Influence of wall thermal conductivity

In many NCL models the thermal conductivity of the tubes is negligible. Only a first attempt to understand the influence of this parameter was reported in [74] where a 1D model analysed the different behaviours of a rectangular loop where the vertical legs was made by cooper or pirex. The presence of higher thermal conductivity shows reduction of amplitude oscillations.

Recently, a systematic study was made on the influence of thermal conductivity of the material employed in the assembly of the loop [26]. The authors constructed three toroidal loops under the same boundary conditions; the first one was made of a copper tube (Loop 1), the second one was fabricated with a top cooper half and a bottom glass half (Loop 2), and the third one was made of a glass tube (Loop 3). In Tab. 1 reports the characteristics of the three loops.

Tab. 1. Characteristics of the three loops

	Upper half	Lower half
Loop 1	Copper	Copper
Loop 2	Copper	Glass
Loop 3	Glass	Glass

A simply scheme of the toroidal loop is shown in Fig. 5.

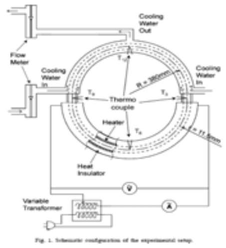


Fig. 5. Schematic configuration of the toroidal loop.

The liquid flow along the loop is driven by buoyancy due to the negative vertical temperature gradient formed by heating from below and cooling from above.

The influence of the pipe thermal conductivity is depicted in Fig. 6. The Loop 3 is the only NCL that shows unstable flow; moreover, its upper limit of heat flux is lower (about 400 W) than the others two loops

Since the properties of the two fluids are different, the power dissipated at the heater is lower in the case of FC43 than water. Moreover, the loop inclinations start from vertical (0°) and varied at 30°, 60°, and very close to 90° (quite horizontal).

Two different results were observed for the two liquids used during the experiments. The water runs showed stable or unstable behaviour (Figs. 7,8), whereas the FC-43 runs always showed unstable behaviour (Figs. 9,10). In particular, when the fluid was water and 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

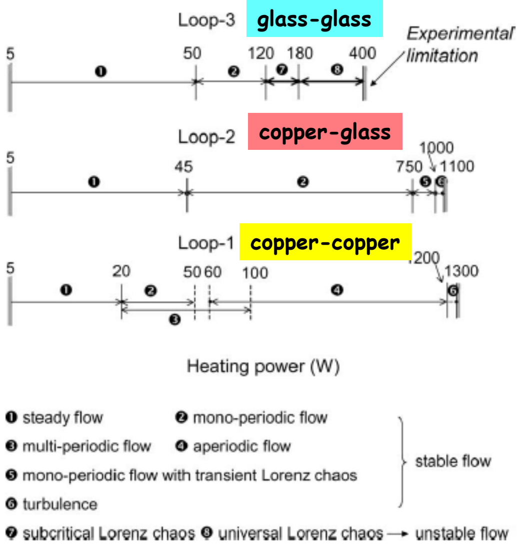


Fig. 6. Heating power range for the different behaviours observed for the three loops.

III. 2. Influence of power and loop inclinations

In this paragraph the influence of the power transferred to the liquid as well as the loop inclination are reported [46]. In particular, different combinations between the working liquid and tube materials were investigated in a rectangular single-phase natural circulation loop. . Two different working fluids are considered, i.e., water and FC43 [75].

The thermo-physical properties of these fluids are reported in Tab. 2.

Tab. 2. Thermo-physical properties of water and FC43.

	WATER	FC43	FC43/WATER
ρ [kg/m3]	997.1	1859	1.86
μ [kg/ms]	8.9e-4	5.4e-3	6.08
β [1/K]	2.5e-4	1.2e-3	4.8
c_p [J/kgK]	4183	1042	0.25
Pr	6.3	85	13.6

the power was increased. At the beginning of the experiment, thermal conduction through the vertical legs probably plays an important role: when the power is increased, the amount of heat conducted through the pipes 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 vertical pipes should be coupled with the proprieties of the liquid used in the experiments. These results confirm that the thermal conductivity of pipes can not be neglected both in the theoretical models and in numerical simulations.

Indeed, loop behaviour was always unstable when FC-43 was utilized, also in the case of pipes made of stainless steel. Only for the loop inclination close to 90° (horizontal) the results obtained for water were similar to those measured for FC-43. When the loop is almost horizontal, the buoyancy force is at its minimum, and the friction force always induces stability in the loop independently on the liquid/pipe material combinations.

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 (Fig. 19).

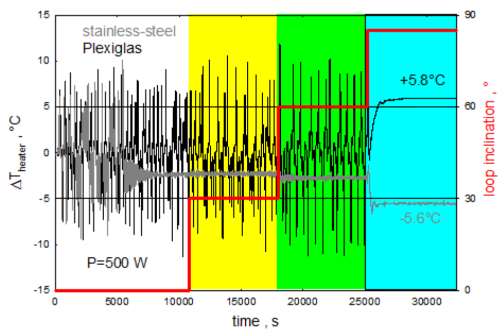


Fig. 7. Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=500 W, H_2O).

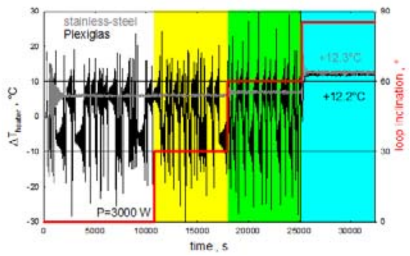


Fig. 8. Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=3000 W, H_2O).

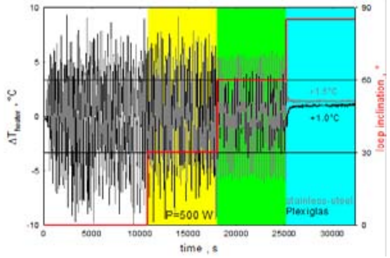


Fig. 9. Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=500 W, FC43).

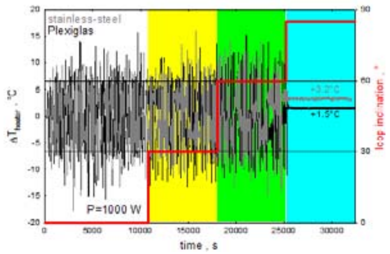


Fig. 10. Temperature difference across the heater ΔT_{heater} vs. time for two connecting materials, colours background correspond to different loop inclinations. (P=1000 W, FC43).

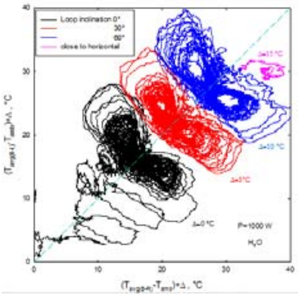


Fig. 11 Trajectories of average temperature difference bottom left vs. average temperature difference bottom right (P=1000 W, H_2O).

Figure 11 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 the temperature differences between the average temperature at the bottom right and the ambient one are reported, whereas on the y-axis the temperature differences between the average temperature at the bottom left and the ambient one are reported. In order to better represent the data at inclination of 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 it can be deduced from Fig. 11, the trajectories are those typical of chaos. In particular, after the extinction of the initial transient, the graphs show the typical chaotic attractors, in case of 0° (vertical), 30°, and 60°, whereas when the loop is almost horizontal (pink line) the oscillations in the flow disappear

III. 3. Effect of heater and cooler orientations

A deeper study on the effect of heater and cooler orientations is reported in [66]. Four heater-cooler combinations have been considered.

HHHC ➪ Horizontal Heater – Horizontal Cooler
HHVC ➪ Horizontal Heater – Vertical Cooler
VHHC ➪ Vertical Heater – Horizontal Cooler
VHVC ➪ Vertical Heater – Vertical Cooler

In Fig. 12 and in Tab. 3 the four scheme and their geometrical quotations are reported, respectively.

The HHHC loop was considered as a symmetric loop, whereas the HHVC, VHHC, VHVC was considered asymmetric loop.

Tab. 3. Geometrical dimensions of the HHHC, HHVC, VHHC, and VHVC loops.

Length scales for various orientations of the test loop

Orientation	Flow direction	Length scales of the loop (m)					
		L_1	L_2	L_3	L_4	L_h	L_c
HHHC	Clockwise	0.41	0.31	0.305	0.385	0.62	0.8
HHVC	Clockwise	0.41	0.22	1.18	0.385	0.62	0.8
VHHC	Clockwise	1.12	0.31	0.305	0.35	0.73	0.8
VHVC	Clockwise	1.12	0.22	1.18	0.35	0.73	0.8
HHVC	Anticlockwise	0.385	1.18	0.22	0.41	0.62	0.8

Reading the quotations reported in Tab. 3, it is possible observe that only in the strictly geometrical sense the HHHC loop is symmetric, because, L1 and L2 should have the same dimension as well as L3 and L4, or in other words the four dimension must be equal to assure the exactly vertical symmetry.

It is our opinion that, even if the difference among the four lengths are very small, some particular kind of flow oscillations could depend on these small geometrical asymmetry.

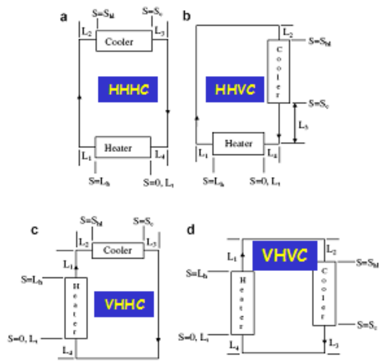


Fig. 12. Different heater and cooler orientations.

Typical flow initial transients observed with different orientations are shown in Fig 13. With horizontal heater, flow beginning is more oscillatory than that with vertical heater (compare Fig. 13a to with d) and a stagnant period is also observed before initiation of flow. Flow was found to start either in the clockwise or anticlockwise direction with horizontal heater. Stable steady state flow in both directions was only possible for the orientation with both horizontal heater and cooler. With horizontal heater and vertical cooler, stable flow was obtained only in the clockwise direction. For this orientation, even if the flow initiated in the anticlockwise direction, it was found to reverse automatically leading to steady flow only in the clockwise direction (Fig. 13).

Only HHHC loop showed an unstable behaviour. In particular different types of oscillations were observed. In Figure 14 these oscillatory modes are reported. The predominant oscillatory modes are unidirectional pulsing (UDP) and bi-directional pulsing (BDP), both of which are nearly periodic. Between these two, an oscillatory mode with chaotic switching (CS) between unidirectional and bi-directional pulsing (intermittency) is observed (Fig. 14a and b). UDP is characterised by periodic high flow pulses in the same direction followed by a period of near stagnant flow and is observed only at low powers (see Fig. 14c). Bidirectional pulsing (BDP) is characterized by the occurrence of alternate clockwise and anticlockwise flow pulses (Fig. 14c).

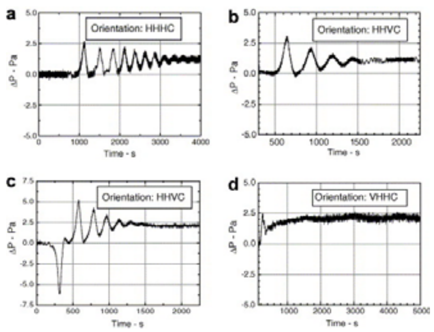


Fig. 13. Flow initiation for different orientations. (a) Flow initiation in the anticlockwise direction at 102 W, (b) flow initiation in the anticlockwise direction at 128 W, (c) auto flow reversal in case of initiation in the clockwise direction at 257 W and (d) flow initiation in the anticlockwise direction at 530 W.

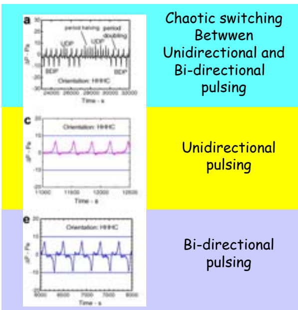


Fig. 14. Various unstable oscillatory modes observed with change in operating conditions for the HHHC orientation.

The steady-state data could be analysed adopting an analytical correlation developed by Vijayan [66].

In case of stable flow, 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:

$$Re_{ss} = \frac{w \cdot D}{\nu} \tag{6}$$

$$Gr_m = \frac{D^3 \cdot \rho^2 \cdot P \cdot H}{A \cdot \mu^3 \cdot c_p} \cdot \beta \cdot g \tag{7}$$

For brevity the analytical method is not reported. The final correlations are respectively:

$$Re_{ss} = 0.1768 \left[\frac{Gr_m}{N_G} \right]^{0.5} \text{(for laminar flow)} \tag{8}$$

$$Re_{ss} = 1.96 \left[\frac{Gr_m}{N_G} \right]^{0.364} \text{(for turbulent flow)} \tag{9}$$

where N_G is a geometrical parameter related to the total length and the internal diameter of the loop.

$$N_G = \left(\frac{L_{tot}}{D} + \frac{k}{f} \right) \tag{10}$$

The data in term of Re_{ss} and Gr_m are reported in Fig. 15.

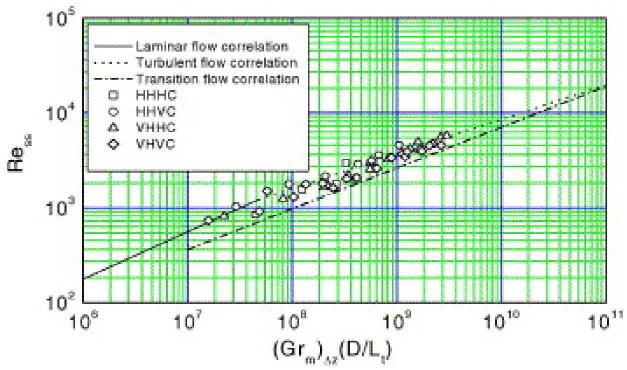


Fig. 15. Steady state natural circulation data

Even if in [66] the effect of heater and cooler orientations was studied analytically and experimentally, another possible thermal boundary condition is the imposed temperatures at the heater and at the cooler. Usually, the thermal boundary conditions are uniform heat flux at the heater and imposed temperature at the cooler. The latter condition was achieved using tap water; only recently in [49], the temperature of the cooler was controlled by a cryostat (temperature range –20°C,+30°C).

A different approach was proposed in a theoretical study [7] adopting, for a rectangular loop, both constant temperature at the heater and constant temperature at the cooler. The simply scheme of the model is drawn in Fig. 16.

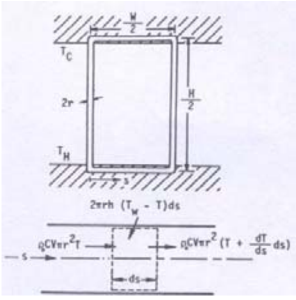


Fig. 16. Rectangular natural circulation loop: T_H (heater temperature) and T_C (cooler temperature).

The main quantities considered were:

the modified Grashof number

$$G_m = \frac{4 \cdot g \cdot \beta \cdot (T_H - T_C) \cdot r^{1+b} \cdot V_{ref}^{b-2}}{a \cdot \nu^b \cdot (1+A)} \tag{11}$$

the friction parameter

$$F = \frac{a \cdot W \cdot \nu^b}{r^{1+b} \cdot V_{ref}^b \cdot (1+A)} \tag{12}$$

the aspect ratio

$$A = \frac{W}{H} \tag{13}$$

the friction coefficient

$$f = \frac{a}{Re^b} \tag{14}$$

Different aspect ratios were considered: A=1, 10 or 1/10, 5 or 1/5. For each value a neutral stability curve was calculated for laminar or turbulent flow.

In Fig. 17 the neutral stability curves are depicted. As it can be seen, the worst aspect ratio value is A=1, as it corresponds to the greater unstable zone both for laminar and turbulent flow. Some considerations could be done for A=10 or 1/10 and A=5 or 1/5.

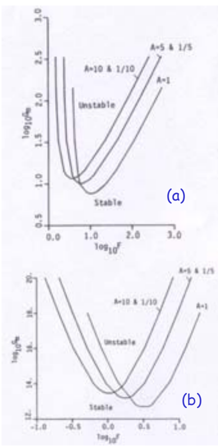


Fig. 17. Neutral stability curves in F, G_m coordinates: (a) laminar flow; (b) turbulent flow.

Even if the friction along a loop characterised by A=10 or 1/10 is almost the same, the buoyancy force in the case of a taller loop (A=1/10) should be higher than in case A=10. For this reason it is very strange that the neutral curves for A=10 or 1/10 are the identical. The same consideration can be applied for A=5 or 1/5.

II. 4. Stabilisation of the loop by localised pressure drops or nanofluids (?)

The aim of the researchers involved in the study of single-phase natural circulation loop is that to achieve the stabilisation of the loop or at least to reduce the flow instabilities without reducing the mass low rate.

In this paragraph two different techniques are illustrated:

a) localised pressure drop [40]
b) utilisation of nanofluids [in press ETFS]

Experiments were focused on the behaviour of a rectangular loop with localized pressure drops realized by two sharp-edged orifices located in the middle of the vertical legs. It is necessary to localise two orifices, one for each vertical leg, because the vertical symmetry of the rectangular loop must be maintained. The scheme of this experimental apparatus as well as its geometrical dimensions are reported in Fig. 18 and Tab. 4, respectively.

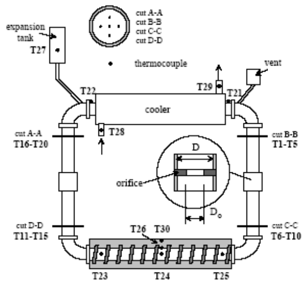


Fig. 18. Sketch of the rectangular loop. The localized pressure drops (orifices of different diameter) are placed in the middle of vertical legs.

Tab. 4. Geometrical dimensions of the rectangular loop used in this study and those of MTT1 loop (dimensions in mm).

	LOOP #1
Loop height	1245
Loop width	1480
Loop inner diameter	40
Heating section length	1400
Cooling section length	1200
Cooler inner diameter	200
Expansion tank height	668
Expansion tank diameter	50
Loop total length	5616
Length - diameter ratio	140.4

During the experiments, the internal diameter of the orifices was increased from 10 mm up to 36 mm and the input power was varied from 500 W up to 3400 W.

The main conclusions can be summarized as follows (Figs. 19, 20):

⇒ the pressure drops could stabilize the loop behaviour; the smallest orifice diameters D_0=10 mm and 22 mm stabilize the loop, while the orifice diameters D_0=26 mm, 30 mm and 36 mm are not able to induce the stabilization of the loop. However, the oscillations observed with D_0=26 mm are quite different from those measured with D_0=30 mm and D_0=36 mm: no flow amplification was detected during each test, whereas the amplitude and the frequency increase when the power level increases

⇒ during the initial transient, in case of the 10 mm orifices, after a single peak (overshoot), there is an increasing trend of the temperature up to the stationary level temperature difference, while in the other configurations the temperature oscillates around the steady-state value;

⇒ the amplitude of oscillations in the initial transient decreases with the increase of pressure drops, as well as the time needed for their damping.

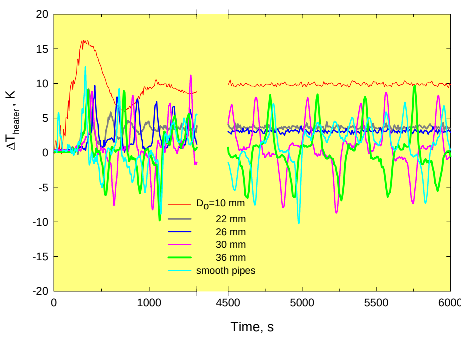


Fig. 19. Comparison between tests with smooth pipes and pipes with orifices (P=500 W).

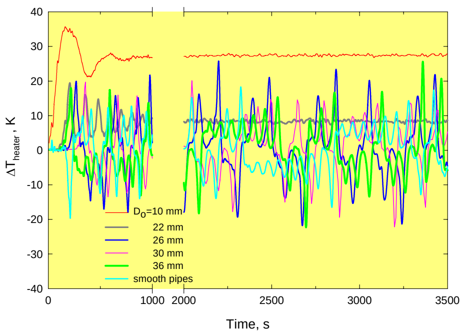
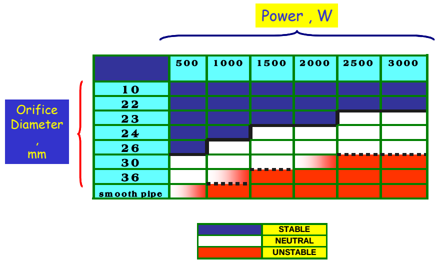


Fig. 20. Comparison between tests with smooth pipes and pipes with orifices (P=2500 W).

In Figs. 19 and 20 the temperature differences at the heater are depicted in case of presence of localised pressure drops. It is important to remember that the maximum fluid temperature is an important parameter that should be controlled . The presence of the orifice could cause the stabilisation of the loop, but the temperature of the fluid increases up to the transition temperature between single and two phase flow. Finally, in Tab. 5 are represented the different combinations between power and orifice diameters.

Tab. 5. Thermo-hydraulic behaviour of LOOP#1 as function of power level and orifice diameter.



A new technique to stabilise the flow in a NCL is the addiction of *nanofluids* in the liquid [76]. As well known, the presence of nanofluids (Al_2O_3, CuO) causes the increment of some thermo-physical properties such as density, thermal conductivity, and viscosity [77].

The nanofluids are engineered colloids made of a base fluid and nanoparticles (1-100 nm). Nanofluids have higher single-phase heat transfer coefficients than their base fluids. In particular, the heat transfer coefficient increases the mere thermal-conductivity effect, and cannot be predicted by traditional pure-fluid correlations such as Dittus-Bolter’s. In nanofluid literature this behaviour is generally attributed to thermal dispersion and intensified turbulence, brought about by nanoparticle motion.

In [76] have considered seven slip mechanisms that can produce a relatively velocity between the nanoparticles and the base fluid. These are inertia, Brownian diffusion, thermophoresis, diffusophoresis, Magnus effect, fluid drainage, and gravity. The main conclusion is that of the seven, only Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids.

The classic rectangular loop depicted in Fig. 21, is filled with nanofluids (Al_2O_3) at different concentrations (0.3-2 % by wt. , particle size 40-80nm).

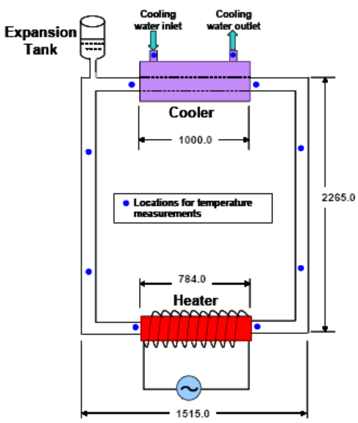


Fig. 21. Schematic of experimental facility.

In Fig. 22 the steady-state flows in the loop are shown. As it can be easily observed, the presence of nanofluids cause an increase of mass flow rate between 20 and 35 % depending on the concentration of nano powder and operating condition.

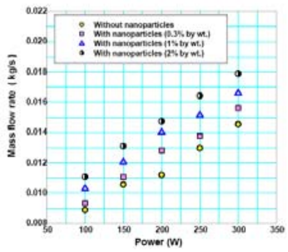


Fig. 22. Variation of steady state flow rate with different concentration of nanoparticles.

It is still more interesting the results showed in Fig. 23, where the tests performed without nanoparticles are compared with those performed with nanoparticles, for the same thermal conditions. The most significant finding was that the flow instabilities are suppressed even with a low concentration of 0.3 % by weight of Al_2O_3 nano powder.

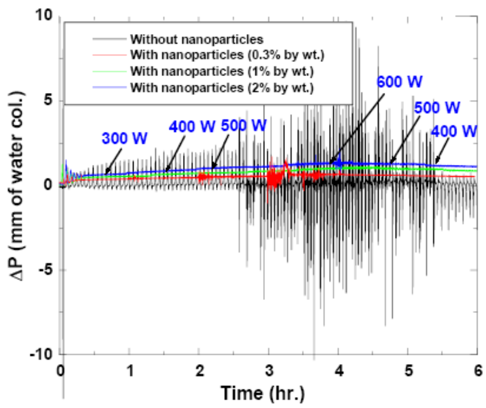


Fig. 23. Suppression of flow instability with nanofluids during power raising and set back process.

III. 5. Influence geometrical dimensions (mini-loop)

Another parameter which influences the dynamic of NCL is the dimension of the loop. Most researchers focused their attention on large scale systems, with particular consideration to performance optimization and stability analysis, while there are only a few studies about natural circulation inside small scale devices, which were studied until now only in case of two-phase flow, particularly for computer cooling applications.

Two preliminary papers considered the thermo-hydraulic behaviour of a single-phase natural circulation mini-loops [17, 48].

The experimental set up consists of two rectangular single phase natural circulation mini-loops (ML1, ML2). Fig. 24 shows a scheme of the mini-loops, whereas the geometrical dimensions of ML1 and ML2 are summarised in Tab. 6.

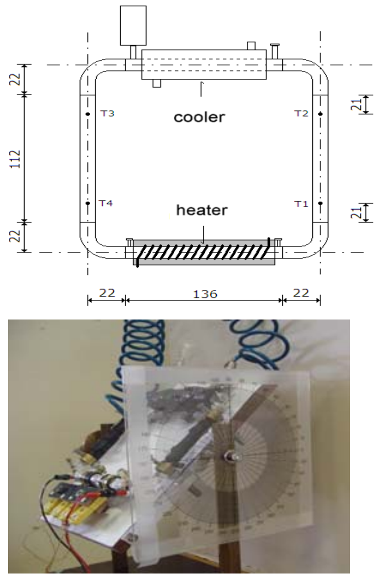


Fig. 24. Scheme of the mini-loops

Tab. 6. Geometrical dimensions [mm] and characteristics of the mini-loops.

	ML1	ML2
D	4	4
W	180	180
H	151	264
L_h=L_c	100	100
L_{tot}	662	888
L_{tot} /D	166	222
H/W	0.84	1.47

Particular attention must be devoted to the instrumentation used to measure the fluid temperature. In case of mini-loops, the fluid temperatures were measured by four shielded thermocouples (O.D. of 0.2 mm), placed in the vertical legs in the middle of the cross sections at a distance of 40 mm from the horizontal tubes axis (Fig.34). The presence of thermocouples inside the tube reduces the cross sectional area of 3.2%. This value is sufficiently small to neglect the consequent increase in pressure losses [40].

For each mini-loop two parameters were studied: the power transferred to the fluid and the mini-loop inclination. In Tab. 9 as example the first experimental campaign is described.

The mini-loop thermo-hydraulic behaviour was 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 [49].

In the Figs. 25-27 the transient behaviours of ΔT_h data, for the three mini-loop inclinations, are compared together.

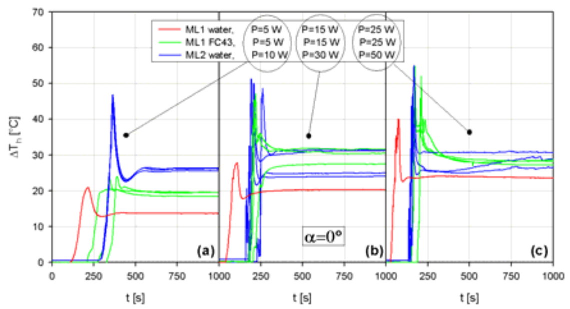


Fig. 25. Transient behaviours of ΔT_h for α=0°.

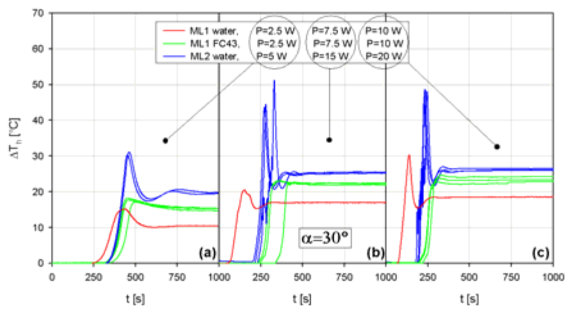


Fig. 26. Transient behaviours of ΔT_h for α=30°.

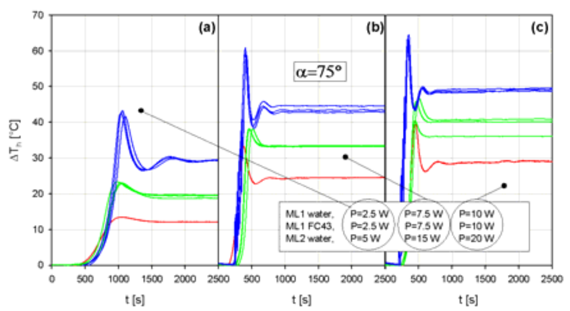


Fig. 27. Transient behaviours of ΔT_h for α=75°.

Since all data are stable, they were analysed with the Vijayan's model [66] developed for large scale natural circulation loops. The parameters involved are just introduced above (see ***III. 3. Effect of heater and cooler orientations*** section), and they were applied to the mini-loop. The corrective parameter cos(α) term is introduced in Gr_m (see Eq. 7) to take into account the reduction in buoyancy forces due to the mini-loop inclination α:

$$Gr_m = \frac{D^3 \cdot \rho^2 \cdot P \cdot H}{A \cdot \mu^3 \cdot c_p} \cdot \beta \cdot g \cdot \cos(\alpha) \qquad (14)$$

All data regarding both mini-loops and two different fluids (water or FC43) are depicted in Fig. 28.

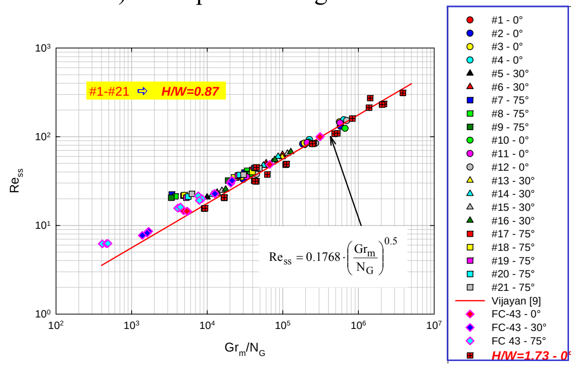


Fig. 28. Comparison between experimental data and Vijayan's correlation

The same analysis developed with water and FC43 was conducted filling the ML2 mini-loop with Al_2O_3 nanofluid [78]. The experiments were conducted varying both the volumetric concentration of nanofluid (0.5 % and 3 %). And the heat sink temperature. In [78] are reported the formulas used to evaluate the thermo-physical properties of the nanofluid. The representation of the experimental data are depicted in Fig. 29.

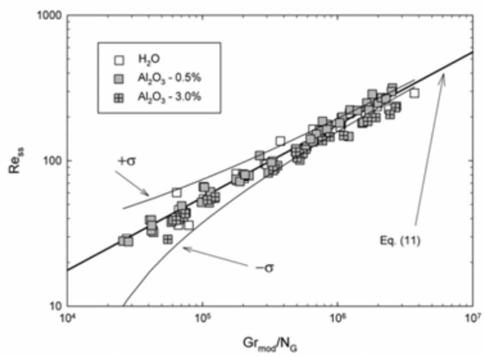


Fig. 29. Comparison between experimental data and Vijayan's correlation.

IV. Final Remarks

OPEN QUESTIONS

The main open questions in the study of single-phase NCLs are:

The instrumentation should be able to measure the velocity and the temperature of the fluid without disturbance on the measurements:

⇒ *Magnetic flow meter*
⇒ *Ultrasound Pulsed Doppler Velocimetry*
⇒ *Liquid crystal*

The thermo-hydraulic behaviour of a single-phase natural circulation loop depends on:

⇒ *Interaction between the fluid properties and material utilised to construct the loop (pipe material)*

Thermal performance of complex loop:

⇒ Heaters and coolers displacement and numbers

⇒ Horizontal parallel channels (new nuclear reactors)

Thermal performance of mini-loop

Stability map able to take into account the pipe materials, loop inclination

Numerical simulation

Acknowledgment

This research was supported by MIUR under the funding scheme of National Research Projects PRIN and Italian Space Agency.

References

1. Acosta R., Sen M., and Ramos E., Single-phase natural circulation square loop, Wärma-und Sfoffübertragung, vol. 21, pp- 269-275, 1987
2. Ambrosini, W, and Ferrei J.C., Stability analysis of single-phase thermosyphon loops by finite-difference numerical methods, Nuclear Eng. and Design, vol. 201 (1), pp. 11-23, 2000.
3. Bau, H. H., and Torrance, K.E., Transient and steady behaviour of an open symmetrically-heated free convection loop, Int. J. Heat and Mass Transfer, vol. 24 (4), 597-609, 1981.
4. Cammarata, G., Fichera, A., Frogheri, M., Misale, M., and Pagano, A., Confronto del comportamento dinamico di circuiti a circolazione naturale, 18th UIT Conference, Cernobbio, Italy, 271-282 (in Italian), 2000.
5. Wang, Y., Singer, J., and Bau, H.H., Controlling chaos in a thermal convection loop, Fluid Mechanics, vol. 37, pp. 479-498, 1992
6. Chato, J. C., Natural convection flows in parallel channel systems, J. of Heat Transfer, vol. 85, pp. 339-345, 1963.
7. Chen K., On the oscillatory instability of closed-loop thermosyphons, J. of Heat Transfer, vol. 107, pp. 826-832., 1985.
8. Chen W.L., Wang S.B., Twu S.S. Chung C.R., and Pan C., Hysteresis effect in a double channel natural circulation loop, Int. J. of Multiphase Flow, vol. 27, pp. 171-187, 2001.
9. Crevelin, H. F., De Paz, J. F., Baladi, J. Y., and Schoenhals, R. J., Stability characteristics of a single-phase free convection loop, J. Fluid Mechanics, 67 (1), 65-84, 1975.
10. Damerell P.S. and Schoenhals R.J.: Flow in a toroidal thermoyphon with angular displacement of heated and cooled sections, J. of Heat Transfer, vol. 101, pp. 672-676, 1979.
11. Ehrhard P., and Muller U., Dynamical behavior of natural convection in a single-phase loop, J. Fluid Mech, vol. 217, pp. 487-518, 1990.
12. Ehrhard P., Karcher, Ch. and Muller U., Dynamical behavior of natural convection in a double-loop system, Exp. Heat Mass Transfer, vol. 2, pp. 12-26, 1989.
13. Ferreri, J. C., Single-phase natural circulation in simple circuits: reflections on its numerical simulation, Eurotherm Seminar No. 63, Single and Two-Phase Natural Circulation, Eds. M. Misale and F. Mayinger, 17-30, 1999.
14. Ferreri J. C., and Ambrosini, W., Sensitivity to parameters in single-phase natural circulation via automatic differentiation of Fortran codes, Eurotherm Seminar No. 63, Single and Two-Phase Natural Circulation, Eds. M. Misale and F. Mayinger, 397-406, 1999.
15. Frogheri M., Misale M., Bertucci M., D'Auria F., and Cicchini G., Preliminary stability results obtained from the operation of a simple natural circulation loop, Proc. of ICONE5, 5th Int. Conference on Nuclear Engineering, Nice (F), May 26-30, 1997.
16. Frogheri M., Misale M., and D'Auria F., Experiments in single-phase natural circulation", Proc. of 15th UIT National Conference, 305-316, 1997.
17. Garibaldi P. and Misale M., Experiments in single-phase natural circulation mini-loops with different working fluids and geometries, Accepted for publication in Journal of Heat Transfer.
18. Garibaldi P., 2008, single-phase natural circulation loops: effects of geometry and heat sink temperature on dynamic behaviour and stability, PhD Thesis, Genoa, Italy.
19. Gorman M, and Widmann P.J., Nonlinear dynamic of a convection loop: A quantitative comparison of experiment with theory, Physica vol. 19D, pp. 255-267, 1986.
20. Greif, R., Natural Circulation Loops, J. of Heat Transfer, vol. 110, pp. 1243-1258, 1988
21. Hallinan K.P., and Viskanta R., Heat transfer from a vertical tube bundle under natural circulation conditions, Int. J. Heat Fluid Flow, vol. 6, pp- 256-264, 1985.
22. Hart J.E., Observation of complex oscillations in a closed thermosyphon, J. of Heat Transfer, vol. 107, pp. 883-839, 1985.
23. Haware S.K., Grover R.B., and Venkat Raj V., Experimental investigation into natural convection heat transfer in a open loop thermosyphon with horizontal tubes, 7th National Heat Transfer and Mass Transfer Conference, Indian Institute of Technology, Kharagpur, paper #HMT-D2-83, 1983.
24. Huang B.J., and Zelaya R., heat transfer behavior of a rectangular thermosyphon loop, J. of Heat Transfer, vol. 110, pp. 487-493, 1988.
25. Japikse D, Jallouk P.A., and Winter E.R.F., Single-phase transport in the closed thermosyphon, Int. J. of Heat and Mass Transfer, vol. 14, pp. 869-887, 1971.
26. Jiang Y.Y., and Shoji M., Flow stability in a natural circulation loop: influence of wall thermal conductivity, Nuclear Eng. And Design, vol. 222 (1), pp. 16-28, 2003.
27. Jiang Y.Y., and Shoji M., Spatial and Temporal Stabilities of Flow in a Natural Circulation Loop: Influences of Thermal Boundary Condition, J. of Heat Transfer, vol. 125 (4), pp. 612-623, 2003.
28. Keller, J. B., Periodic oscillations in a model of thermal convection, J. Fluid Mechanics, 26 (3), 599-606, 1966
29. Kim, J.-H., Kim T.-W., Lee S.-M., and Park G.-C., Study on the natural circulation characteristics of the integral type reactor for vertical and inclined conditions, Nuclear Eng. Design, vol. 207, pp. 21-31, 2001
30. Kukita Y., and Tasaka K., Single-phase natural circulation in pressurized water recator under degraded secondary cooling conditions, HTD-Vol. 115, Natural Circulation in Single-Phase and Two-Phase Flow, Eds. F.B. Cheung and M. S. El-Genk, pp. 77-83, Book. No. H00518, 1989.
31. Lapin, Yu. D., Heat transfer in communication channels under conditions of free convection, Teploenergetika, vol. 16 (9), pp. 59-61, 1969
32. Malkin, S. D., Khabenskii, V. B., Migrov, Yu. A., and Efimov, V. K., Aperiodic instability of a single-phase flow in a system of parallel channels at low velocities of circulation common to whole loop, Thermal Engineering, vol. 31 (11), pp. 20-24, 1984.
33. Mertol, A., Place, W., Webster, T., Greif, R., Detailed loop model (DLM) analysis of liquid solar thermosyphon with heat exchangers, Solar Energy, vol. 27, pp. 367-386, 1981.
34. Mertol A., and Grief R., A review of natural circulation loops, In: Kakac S, Aung W., and Viskanta R. (Eds), Natural Convection: Fundamentals and Applications, Hemisphere, New York, pp. 1033-1071, 1985.
35. Misale, M., Tagliafico, L., and Tanda, G., Experiments in a free convection rectangular loop, Proc. of the 4th International Symposium on Transport Phenomena in Heat and Mass Transfer, Sydney (Australia), pp. 203-211, 1991.
36. Misale, M., D'Auria, F., Frogheri, M., and Ruffino, P., Steady-state and stability behavior of a single-phase natural circulation loop, 11th International Heat Transfer Conference, pp. 385-390, 1998.
37. Misale, M., D'Auria, F., Frogheri, M., Fontani, E., and Garcia, A., Analysis of single-phase natural circulation experiment by system codes, Int. J. Thermal Sciences, vol. 38, pp. 977-983, 1999.
38. Misale, M., and Frogheri, M., Multidimensional aspects in single-phase natural circulation, Industrial Heat Engineering, vol. 21, pp. 41-47, 1999.
39. Misale, M., Frogheri, M., and D'Auria, F., Experiments in natural circulation: influence of scale factor on the stability behavior, Eurotherm

Seminar No. 63, Single and Two-Phase Natural Circulation, eds. M. Misale and F. Mayinger, pp. 109-116, 1999.

40. Misale, M., and Frogheri, M., Stabilization of a single-phase natural circulation loop by pressure drops, Experimental Thermal and Fluid Sciences, Vol. 25 (5), pp. 277-282, 2001.

41. Misale, M., D'Auria, F., and Petruzzi, A., 2002, Single-phase natural circulation in a rectangular loop in micro-gravity condition, Space technology and Applications International Forum – STAIF 2002, paper no. 104, Editor M. S. El-Genk, Albuquerque, New Mexico, 3-6 February, Albuquerque, New Mexico.

42. Misale, M., Cavallero, D., and Devia, F., 2002, Influence of loop inclination on thermal-hydraulic behavior of a single-phase natural circulation, EQUIFASE, paper no. EQ-11, 12-16 Ottobre, Foz de Iguazú (Brazil)

43. Misale, M., Marasso, M., and Devia, F., 2003, Numerical simulation of a single-phase natural circulation loop for different gravitational fields, UIT Conference, paper no. UIT03-324, Udine (Italy).

44. Misale, M., Mousavian, S.K., D'Auria, F., and Salehi, M.A., 2004, Transient and stability analysis in single-phase natural circulation loop, Annals of Nuclear Energy, vol. 31, pp. 1177-1198

45. Misale, M., Devia, F., Fichera, A., and Pagano, A., 2004, On the dynamical behaviour of inclined rectangular circulation loops, 22nd UIT Conference, pp. 113-117, Genova (Italy).

46. Misale, M. and Devia, F., 2004, Experiments in a single-phase natural circulation loops: effects of interaction between the wall tube and fluids properties, 6th International Symposium on Heat Transfer, Beijing, China, June 15-19, 09-07 paper, pp. 697-704.

47. Misale, M., Bruzzone, A.G, Devia, F., and Viazzo, S., 2005, Prediction of dynamic behviour of a single-phase rectangular natural circulation loop, 16th IASTED International Conference, Modelling and Simulation, Cancun (Mexico), May 18-20, pp. 452-457, paper # 459-125, ISBN: 088986-498-5

48. Misale, M., Garibaldi, P., Passos, J.C., and Ghisi de Bitencourt, G., 2007, Experiments in a single-phase natural circulation mini-loop, Experimental Thermal and Fluid Science, vol. 31 (8), pp. 1111-1120

49. Misale, M., and Garibaldi, P., 2007, Influence of thermal boundary conditions on the thermo-hydraulic behaviour of a rectangular single-phase natural circulation loop, Advance in Heat Transfer. 5th Baltic Heat Transfer Conference, September 19-21. (vol. 2, pp. 200-206). ISBN/ISSN: 5-7422-1592-4. ST. Petersburg: (Russian Federation).

50. Nishihara, T., Oscillatory instability of a single-phase natural circulation loop, 8th International Topical Meeting on Nuclear Reactor ThermoHydraulics, Kyoto, Japan, 839-847, 1997.

51. Ong, K. S., A finite-difference method to evaluate the thermal performance of a solar water heater, Solar Energy, vol. 16, pp. 137-147, 1974

52. Proshutinskii, A. P., and, Lobachev, A. G., Aperiodic instability of down-coming flow coolant in a system of parallel channels, Thermal Engineering, 27 (10), 18-21, 1980.

53. Proshutinskii, A. P., and Trofimova, N. N., Prediction of circulation in a channels with downcoming flow of coolant, Thermal Engineering, vol. 29 (12), pp. 18-21, 1982.

54. Rao N.M., Maiti B., and Das P.K., Steady State Performance of a Single Phase Natural Circulation Loop With End Heat Exchangers, J. of Heat Transfer, vol. 130 (8), August 2008.

55. Satoh, A., Okamoto, K., and Madarame, H., Instability of Single-phase Natural Circulation Under Double Loop System, Chaos, Solitons & Fractals, vol 8 (9), pp. 1575-1585, 1998.

56. Satou A., Madarame H., and Okamoto K., Unstable behaviour of single-phase natural circulation under closed loop with connecting tube, Experimental Thermal and Fluid Science, vol. 25, pp. 429-435, 2001.

57. Sen, M., Ramos, E., and Treviño, C., The toroidal thermosyphon with known heat flux, Int. J. Heat Mass Transfer, 28 (2), 219-233, 1985.

58. Sen, M., Ramos, E., and Treviño, C., On the steady-state velocity of the inclined toroidal thermosyphon, J. of Heat Transfer, vol. 107, pp. 974-977, 1985.

59. Shitzer, A., Kalmanoviz, D., Zvirin, Y., and Grossman, G., Experimental with a flat plate solar water heating system in thermosyphonic flow, Solar Energy, vol. 22, pp. 27-35, 1979.

60. Suda, F., The steady-state, transient and stability behavior of a rectangular natural circulation loop – experiments and one-dimensional model, Experimental Heat transfer, Fluid Mechanics and Thermodynamics, Eds. M. Giot, F. Mayinger, and G.P. Celata, 2191-2198, 1997.

61. Torrance, K. E., Open-loop thermosyphons with geological application, J. of Heat Transfer, vol. 101, pp. 112-117, 1979.

62. Vijayan P.K.and Austregesilo H.: Scaling laws for single-phase natural circulation loops, Nucl. Eng. Design, vol. 152, pp. 331-334, 1994.

63. Vijayan, P.K., Nayak, A.K., Pilkhwal, D.S., Saha, D., and Verkat Raj,. V, Effect of loop diameter on the stability of single-phase natural circulation in rectangular loops, Nureth 5, 261-267, 1992.

64. Vijayan, P. K., Experimental observations on the general trends of the steady state and stability behaviour of single-phase natural circulation loops, Eurotherm Seminar No. 63, Single and Two-Phase Natural Circulation, Eds. M. Misale and F. Mayinger, pp. 3-16, 1999.

65. Vijayan , P.K., Badè, M.H., Saha, D., Sinha; R.K., and Venkat Raj, V., A generalised correlation for the steady state flow in single-phase natural circulation loop, Report BARC/2000/E/021, Bhabha Atomic Research Centre, Mumbai, India, 2000.

66. Vijayan P.K., Sharma M., and Saha,D., Steady state and stability characteristincs of single-phase natural circulation in a rectangular loop with different heater and cooler orientations, Exp. Thermal and Fluid Science, vol. 31 (8), pp. 925-945, 2007.

67. Welander, P., On the oscillatory instability of a differentially heat fluid loop, J. Fluid Mechanics, vol. 29 (1), pp. 17-30, 1967.

68. Zhou, Kun-Ying, and Bau, H.H., On the stability and flow reversal of pressure-driven flow in an asymmetrically heated U-shaped tube, J. of Heat Transfer, vol. 107, pp. 125-136, 1984.

69. Zvirin, Y., Shitzer, A., and G. Grossman, The natural circulation solar heater-models with linear and non-linear temperature distribution, Int. J. Heat Mass Transfer, vol. 20, pp. 997-999, 1977.

70. Zvirin, Y., Shitzer, A., and Bartal-Bornstein, A., On the stability of the natural circulation solar heater, Proc. 6th Int. heat transfer Conference, Toronto, Canada, vol. 2, pp. 141-145, 1978.

71. Zvirin, Y., and Rabinoviz, Y., On the behavior of natural circulation with parallel channels, Proc. 7th Int. Heat transfer Conference, Munchen, Germany, vol. 2, pp. 299-304, 1982.

72. Zvirin, Y., Natural circulation loops with parallel channels: transient behavior, Nuclear Engineering Design, vol. 84, pp. 73-81, 1985.

73. Zvirin, Y., A review of N. C. loops in PWR and other systems, Nuclear Engineering and Design, vol. 67, pp. 203-225, 1981.

74. Misale, M. and Tagliafico, L., 1987, The transient and stability behavior of single-phase natural circulation loops, Heat and Technology,Vol. 5, N° 1-2, pp. 101-116.

75. 3M[TM] NOVECTM Engineered Fluids, 3M Center, St. Paul, Minnesota.

76. Nayak, A.K., Gartia, M.R., and Vijayan, P.K., An experimental investigation of single-phase natural circulation behavior in a rectangular loop with Al_2O_3 nanofluids, Experimental Thermal Fluid Sciences, Vol. 3, 184-189, 2008.

77. Buongiorno, J., Convective transport in nanofluids, ASME Journal of Heat Transfer, vol. 128, pp. 240-250, 2006.

78. Misale, M., Devia, F., and Garibaldi, P., Experiments with Al_2O_3 nanofluid in a single-phase natural circulation mini-loop: preliminary results, Applied Thermal Engineering, Vol. 40, 64-70, 2012.

About Author (s):

Prof. Mario Misale, full professor at University of Genoa Italy.
Scientific researches: heat transfer, single and two-phase thermo-fluid-dynamics, characterization of dielectric fluids and nanofluids. Authors of more than 120 papers