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Analysis of single-phase natural circulation experiments by system codes

Mario Misale [a]*, Monica Frogheri [a], Francesco D'Auria [b], Emanuele Fontani [b], Alicia Garcia [c]

[a] *DITEC, University of Genova, via All'Opera Pia 15/A, 16145 Genova, Italy*

[b] *DCMC, University of Pisa, via Diotisalvi 2, 56126 Pisa, Italy*

[c] *CNEA, Argentina*

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Abstract — In this paper, the results of simulations of natural circulation loop performance, obtained by Cathare and Relap codes, are reported. Both series of results are analyzed and compared with experimental data gathered in the MTT-1 loop, a rectangular natural circulation loop realized by DITEC at the University of Genova. Both Cathare and Relap codes, in absolute terms, show poor agreement with experimental data. At low power, the Cathare code shows a good capability to predict the steady state quantities, after the initial transient. On the other hand, no unstable behavior is predicted at each analyzed power level. The Relap code is able to show oscillating quantities, but not at the same power levels as in the experiments. © 1999 Éditions scientifiques et médicales Elsevier SAS

natural circulation / single-phase / instability / thermalhydraulic codes

1. INTRODUCTION

Natural circulation in single-phase conditions is of great interest in heat transfer applications, including solar energy conversion and Passive Nuclear Reactor cooling. The single-phase natural circulation loops (thermosyphon) are systems in which the fluid removes heat from a source and transports it to a higher elevation sink. The fluid flow is due to the density gradient between the hot and the cold section.

The analysis of these systems, under various thermal conditions, has shown that they can exhibit instability phenomena, such as flow reversal and flow stagnation. This behavior is relevant in engineering applications, since it can bring about undesirable conditions like flow, power and temperature excursions. In particular, in Passive Nuclear Reactor cooling, it has to be demonstrated that the passive mechanism to remove heat during an accident preserves the safety functions and that instabilities can not occur.

The instability phenomenon has been analyzed by various authors [1–4], utilizing analytical models and comparing the results with experimental data, but, up to today, there is not a theory applicable to all complex systems.

In the context of a wider research program, finalized to the analysis of complex geometrical systems, the MTT-1 loop has been designed and operated by DITEC at the University of Genova. The experimental data have shown the presence of a power threshold for the instability occurrence.

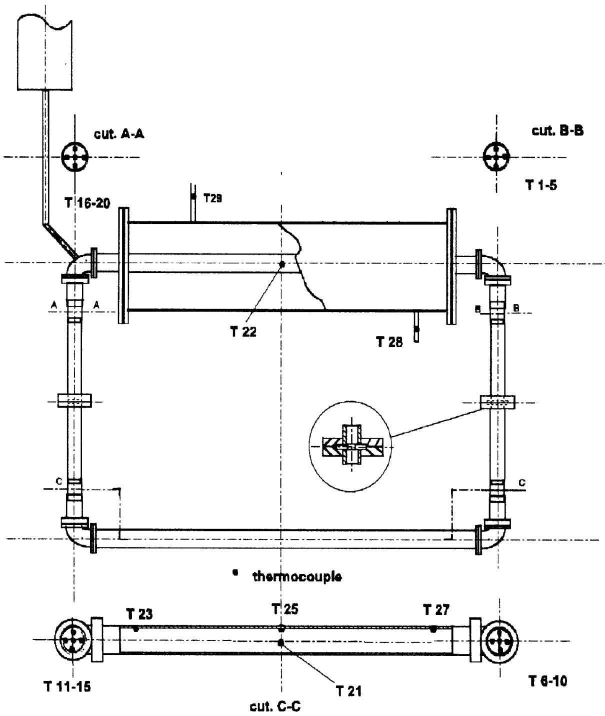
In this paper, two system codes designed for the geometry and features of Nuclear Power Plants, Cathare and Relap, are used for predicting the instability condition. The calculated results are compared with experimental data in the attempt to draw conclusions about the capabilities of the codes.

2. OVERVIEW OF THE EXPERIMENTS

2.1. The MTT-1 loop

The circuit (shown in *figure 1*) consists of two copper horizontal tubes (heat transfer sections) and two plexiglas

* Correspondence and reprints.
misale@ditec.unige.it



Loop height	637
Loop width	782
Loop inner diameter	20
Heating section length	720
Cooling section length	600
Cooler inner diameter	142
Expansion tank height	668
Expansion tank diameter	50

Figure 1. Sketch of the MTT-1 loop (dimensions in mm).

vertical tubes (adiabatic legs), connected through four 90° bends. The diameter of the piping constituting the loop is 0.02 m, constant all over the length, and axis lengths are 0.637 and 0.782 m for the horizontal and the vertical parts, respectively. An expansion tank open to the atmosphere is installed at the uppermost elevation of the loop, to allow the volumetric expansion of the fluid.

The lower heating section is equipped with an electrical heating cable wired on the outside of the copper tube. The upper heat extraction system is a coaxial cylindrical heat exchanger with water flowing into 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 second condition can be achieved by adopting a high value of water flow rate, minimizing the temperature differences between the inlet and the outlet of water.

The loop is equipped with 30 calibrated ($\pm 0.1\,°\mathrm{C}$) T-thermocouples (0.5 mm in diameter): 20 of them are distributed in 4 measurement sections at the inlet and the outlet of the heater and the cooler, in which there are 1 thermocouple on the axis of the tube and 4 others distant $0.25D$ from the center, and at 90° one from the other; the other thermocouples are located at the wall of the heated (4) and the cooled (4) sections and at the inlet and the outlet of the cooling jacket (2).

The loop instrumentation includes one differential pressure gauge; the high speed data acquisition system National Instruments (Lab PC+, SCXI-1102, SCXI-1303) is also part of the system.

2.2. Main results

Only one series of experiments is considered here (for details on the other experiments see [5, 6]). Each experiment starts with the primary loop full of degassed water at ambient temperature (16 °C). The heat exchanger is full of tap flowing water at imposed temperature and mass flow rate. These quantities remain constant during the test. In these conditions, at time “0” the power of the heater is switched on and reaches the design value in 2 s.

This work considers several series of experiments with a constant power, ranging from 100 to 900 W. In this way, it is possible to investigate the behavior of the natural circulation loop at different power levels.

For each test, the difference between the inlet (thermocouple T10) and the outlet temperature of the heater (thermocouple T15) is analyzed. This value (ΔT) is easy to measure and it is correlated to the value of the mass flow rate in the primary loop.

The experimental results show the presence of a threshold at about 500 W. Below this value, the difference ΔT, after an initial oscillation transient, reaches a stationary value and instabilities are not present. Over 500 W, the loop shows a typical unstable behavior: repetitive flow reversals occur and the frequency of the oscillations increases with the power. Moreover, the frequency of the flow reversal becomes irregular at higher powers.

3. CODE SIMULATIONS

In order to simulate the experimental behavior of the MTT-1 loop, two system codes, Cathare2 V1.3u [7] and

Relap5/Mod3.2 [8], have been utilized. These codes are designed to simulate complex geometry in thermalhydraulic conditions, typical of Nuclear Power Plants.

Therefore this application is outside the original design boundaries of the codes. In fact the MTT-1 loop works at low pressure and very low mass flow rate; these features may be not present in Nuclear Power Plants. Materials utilized for the structures of MTT-1 (as copper and plexiglas) are not present in the codes' library; in the case of Relap, relative properties are added by the user (this has not been done in the case of Cathare, owing to compiler difficulties).

The two nodalizations have similar features, and in each one of them a particular trick is used. Experimental data show that the temperature in the pressurizer is not constant during the test, determining a delay in the primary loop temperature rise. For this reason, in the simulation it is necessary to establish a natural circulation between the primary loop and the pressurizer. Two tubes, connected with the primary loop at different heights, allow fluid circulation due to a different density.

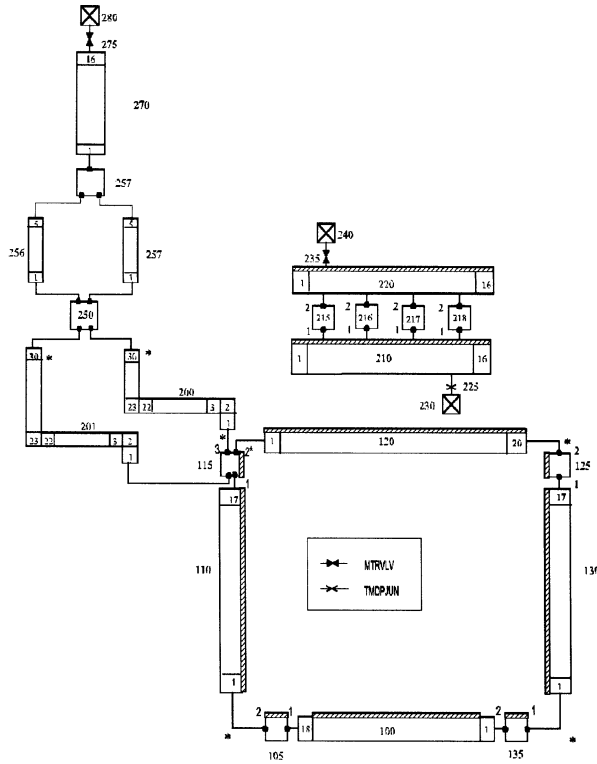


Figure 2. Nodalization of MTT-1 loop for Relap5/Mod3.2 code.

3.1. Simulation of MTT-1 experiments with Relap code

The Relap5 code (Reactor Leak and Analyses Programme) is based on a non-homogeneous and non-equilibrium model for two-phase systems solved by a fast, partially implicit numerical scheme.

In *figure 2* the developed nodalization of the MTT-1 loop is shown. The primary loop is simulated by 4 pipes and 4 branches. For the 4 pipes, 36 nodes of length 0.035 m are utilized. There is no difference in the node quantity between the heat transfer sections (horizontal tubes) and the adiabatic legs.

The heat structures are used to simulate the heat losses to the environment. For the specific heat and thermal conductivity of the structures, exact values dependent on temperature are utilized.

In order to realize the expansion tank and the related connecting pipe with the primary loop 47 nodes are used. The connection between the tank and the primary loop is realized with two pipes to allow natural circulation. Care is taken to achieve an acceptable mass flow rate in this connection by tuning the pressure drops.

3.2. Simulation of MTT-1 experiments with Cathare code

Cathare (Code avancé de thermo-hydraulique pour les accidents des reacteurs à eau) has been developed at the Centre d'études nucleaires de Grenoble (CENG), in order to perform best estimate calculation of PWR accidents. The models utilized by the code are based on six balance equations (conservation of mass, energy and momentum for both phases) which are solved by a completely implicit method.

The primary loop (see *figure 3*) is simulated by 4 axial elements. For the adiabatic legs 2 axial elements (LVP and RVP) are utilized where, in order to minimize numerical errors, the element is divided in 17 meshes. For single-phase thermosyphon loops the prediction of instability conditions is better if the number of the nodes in the legs is high.

The horizontal tubes are simulated with 2 axial elements as well as the four bends. In each bend a singular pressure drop is considered (a K coefficient of 0.1 for steady and reverse flow is used).

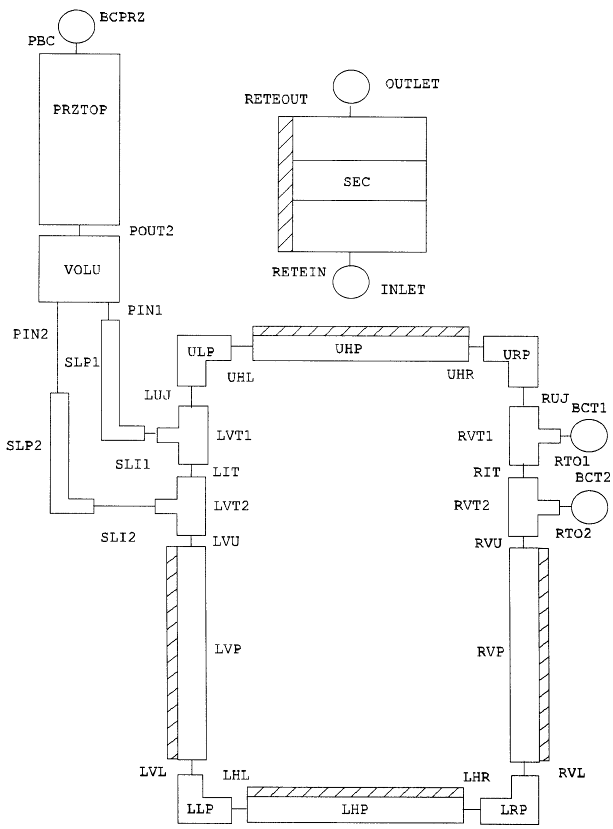


Figure 3. Nodalization of MTT-1 loop for Cathare code.

For the heat exchanger in the secondary side an axial element is utilized. In order to simulate the different densities of the fluid, the element is vertical. The total volume of the element is equal to the real exchanger volume.

4. COMPARISON OF RELAP AND CATHARE CALCULATIONS

The comparison between Cathare and Relap results and experimental data is shown in *figures 4–9*, where, at different power levels, the temperature difference between the inlet and the outlet of the heater is analyzed. The main results, in terms of ΔT, average temperature in the loop and flow rate, are presented in the *table*. These quantities are sufficient to display the behavior of the loop and to qualify the nodalization used. In fact, the first step of this work is a partial qualification of both input decks by comparing the value of the temperature difference across the heater.

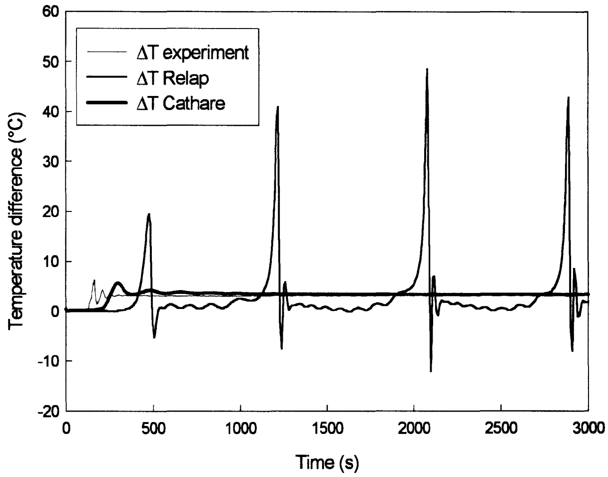


Figure 4. Temperature difference between inlet and outlet of the heater (power = 100 W).

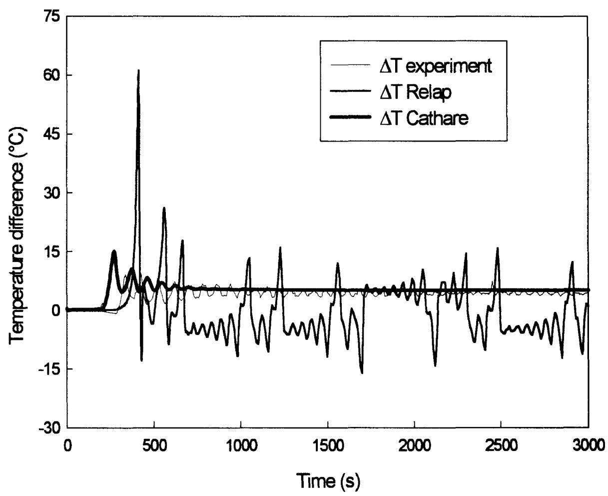


Figure 5. Temperature difference between inlet and outlet of the heater (power = 400 W).

At low power levels, the Cathare code produces a good agreement with experimental data. The difference between calculated and measured steady state temperature after the transient is less than 0.2 °C (see *figure 4*). There is also a good agreement for the temperature at the inlet and the outlet of the heater. On the other hand, the Relap code exhibits temperature oscillations at low power levels which are not observed in the test.

As power is increased, the Cathare code results depart from experimental data. Below 500 W the agreement with the tests is good but the temperature error at the steady state increases with power (*figure 5*).

TABLE
Main results of simulations in comparison with experimental data.

Case	ΔT (°C) at 3 000 s	T_m (°C) at 3 000 s	G (kg·s^{-1}) primary loop at 3 000 s	Presence of oscillations at 3 000 s
Experiment 100 W	3.1	19.2	–	No
Cathare 100 W	3.3	19.2	0.0059	No
Relap 100 W	14.5	27.2	0.0006	Yes
Experiment 200 W	3.2	23.5	–	No
Cathare 200 W	4.1	24.0	0.0096	No
Relap 200 W	−2.6	19.4	0.0056	Yes
Experiment 300 W	4.8	29.2	–	No
Cathare 300 W	4.6	27.5	0.0130	No
Relap 300 W	5.0	28.1	−0.0022	Yes
Experiment 400 W	4.3	34.7	–	No
Cathare 400 W	5.1	30.8	0.0158	No
Relap 400 W	4.1	30.7	–	Yes
Experiment 500 W	3.9	39.8	–	No
Cathare 500 W	5.7	34.0	0.0178	No
Relap 500 W	8.3	34.0	0.0268	Yes
Experiment 600 W	10.7	42.0	–	Yes
Cathare 600 W	6.2	37.0	0.0196	No
Relap 600 W	−5.4	39.4	−0.0232	No
Experiment 700 W	−1.2	47.9	–	Yes
Cathare 700 W	6.6	39.7	0.0213	No
Relap 700 W	6.1	44.2	0.0239	No
Experiment 800 W	−1.2	54.2	–	Yes
Cathare 800 W	7.1	42.4	0.0229	No
Relap 800 W	6.7	49.1	0.0245	No
Experiment 900 W	−5.1	54.8	–	Yes
Cathare 900 W	7.5	44.8	0.0244	No
Relap 900 W	−2.8	53.2	−0.0278	Yes

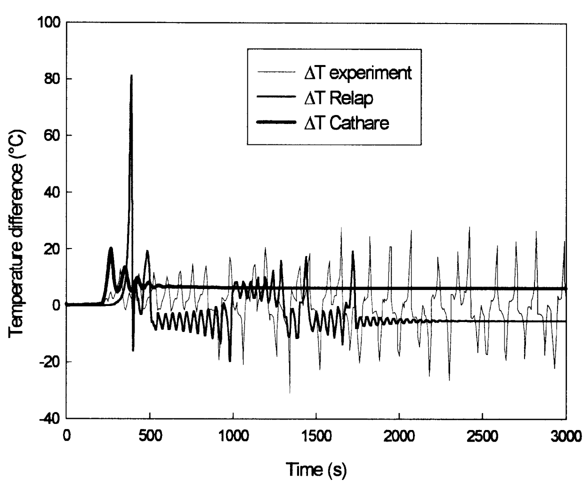


Figure 6. Temperature difference between inlet and outlet of the heater (power = 600 W).

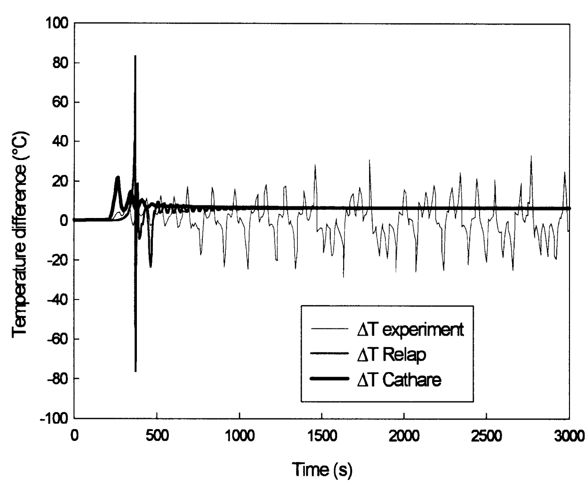


Figure 7. Temperature difference between inlet and outlet of the heater (power = 700 W).

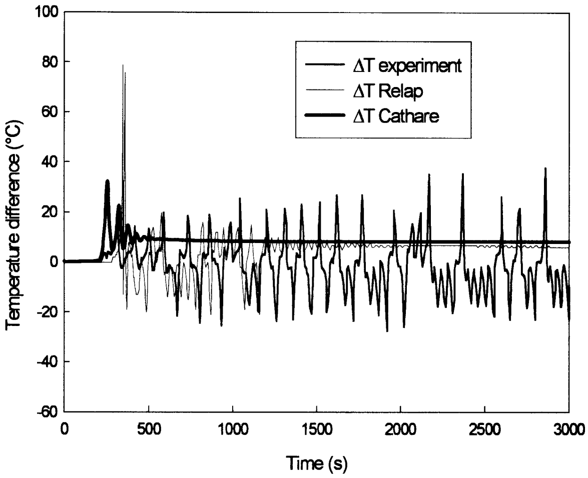


Figure 8. Temperature difference between inlet and outlet of the heater (power = 800 W).

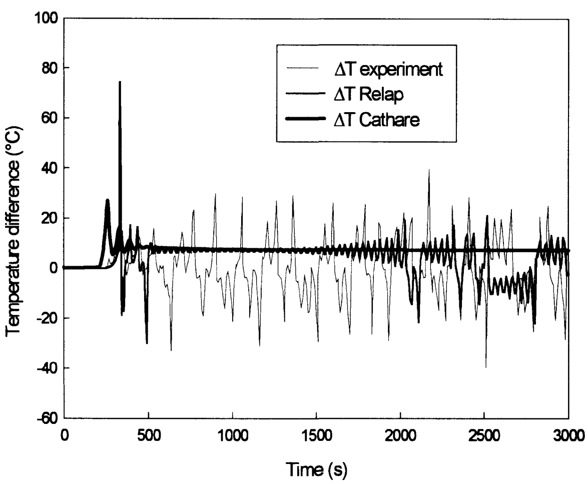


Figure 9. Temperature difference between inlet and outlet of the heater (power = 900 W).

Above 500 W, when the real system becomes unstable, the code shows a stable behavior again (*figure 6*).

In this range of power, the Relap code shows always an unstable behavior. There are high temperature excursions. At 400 W (see *figure 5*) the temperature difference reaches about 77 °C.

Above 500 W the real loop is unstable and the temperature oscillates with a frequency which increases with power. In the case of simulation, on the contrary, it is possible to see, by comparing *figure 6* and *figure 9*, that the flow reversals have higher frequencies at 600 rather than at 900 W.

The Cathare code does not exhibit oscillations at any power level. After a high peak the temperature reaches the steady state value in about 500 s.

The Relap code, above 500 W, shows a particular behavior. At 700 and 800 W (see *figures 7* and *8*) the loop model is stable in contrast with the experimental data. In both cases the steady state value of the temperature and the mass flow rate is about the same that obtained with the Cathare code.

In *figure 9* (above 2 000 s) it is shown that the Relap code predicts an oscillatory behavior, with amplitude and frequency that are comparable with the experimental ones.

The discrepancies revealed by the comparison between experimental and calculated results, can be related to the one dimensional structure of the codes used. During the experimental campaigns, in fact, multi-dimensional effects have been measured [10]. In particular, the analysis of the experimental data lead us to discover fluid temperature variations in a given measurement section (differences up to 4 K on the same cross section have been measured), not depending on the adopted power level; moreover, the multi-dimensional structure changed inside the loop during the same test.

5. CONCLUSIONS

This work shows the deficiency of the actual system thermalhydraulic codes in predicting the instability of a single-phase natural circulation loop having a simple geometry. The stability map derived with these codes is not consistent with the experimental stability map.

The calculations exhibit the following features:

– in the case of the Cathare code the behavior at low power levels can be predicted with acceptable accuracy;

– in the case of the Relap code the qualitative behavior of the loop when the system is unstable is actually simulated; however, the dependence of oscillation amplitude and frequency upon supplied power is not calculated; at maximum power level tolerable for the loop (900 W) Relap results show frequency and amplitude comparable with experimental data.

Reasons for the above mentioned codes discrepancies can be related to multi-dimensional effects, identified and characterized during the experimental campaigns.

The use of thermalhydraulic codes, as Cathare and Relap, allows the consideration of system effects, like periodic heat transfer between liquid and walls, local and distributed pressure drop, heat losses to the environment. These phenomena cannot be taken into account by simplified models. Owing to this, we still encourage the use of these codes in this area.

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