TRANSIENT ANALYSIS OF NATURAL CIRCULATION IN PARALLEL LOOPS

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SUMMARY

This paper presents a comparison between experimental and numerical solutions of a circuit with parallel loops in one phase natural circulation. The experimental facility is a four-loop U-tube heat exchanger similar to a PWR power plant with four steam generators. The mathematical model is based on a one-dimensional approximation of the conservation equations. The results, for the transient regime have shown a good agreement.

INTRODUCTION

Modern nuclear reactors are designed to remove heat from the core, in normal and accidental conditions, by passive operation modes like natural circulation. These reactors are safer and simpler to operate due to the reduced number of components envolved. In order to get an insight in this area, a developing program started at IPEN/COPESP in 1991. As part of this program a numerical tool to analyse transient natural circulation has been developed. Comparisons with experimental data from CTE-150, the first Brazilian integral test facility, have been done showing a good agreement (Bastos, 1993). The geometry of CTE-150, however, is significantly different from the most pressurized water reactors (PWR). Therefore, the information obtained is not directly applicable to natural circulation in PWR's.

This paper presents an analysis of a small-scale facility with four parallel loops that resembles a four-loop U-tube steam generator PWR. The experimental facility developed at EPRI in 1981 consisted of an electrical heater in an aluminum vessel simulating the reactor core. Each of the four loops have an U-tube heat exchanger simulating a steam generator as the heat sink.

The data generated by the experiment is compared with a mathematical model based on a one-dimensional finite volume formulation.

MATHEMATICAL MODEL

The analysis is based on a one-dimensional formulation of the conservation laws. Viscous dissipation, axial conduction and heat losses to the surroundings are neglected. The Boussinesq approximation for the driving force term is adopted. The momentum equation then becomes

$$\rho\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial s}\right)=-\frac{\partial p}{\partial s}-\frac{\partial \tau}{\partial s}+\rho g\,\bar{e}_s\bar{e}_g \qquad (1)$$

Where ρ is the density, v the velocity at the fluid flow direction, t the time, s the spatial coordinate, p the pressure, τ the shear stress and g the gravitational acceleration.

The energy balance equation for the fluid flow is

$$\rho c_p\left(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial s}\right)=q''' \qquad (2)$$

Where T is the temperature, cp the specific heat and q''' the volumetric heat flux.

The heat conduction equation for the tubes has the form

$$\rho c_p\frac{\partial T_w}{\partial s}=k\left(\frac{\partial^2 T_w}{\partial r^2}+\frac{1}{r}\frac{\partial T_w}{\partial r}\right)+q''' \qquad (3)$$

With T_w as the tube wall temperature and k the thermal conductivity.

Correlations to estimate pressure losses and heat transfer coefficients are necessary due to the one-dimensional approach of the conservation laws. Classical forced flow correlations are adopted for the friction factor (Churchill 1977) and the form friction factor (Idel'Cik 1960). Natural and forced convection heat transfer correlations were implemented in the code (Bejan 1993) and the adimensional parameter Gr/Re^2 is used to decide the appropriate correlation .

The flow and heat transfer are governed by equations (1), (2) and (3). These equations are coupled and must be solved simultaneously. In addition to the usual free convection coupling, there is a coupling between
- structure and fluid and
- momentum equations of parallel loops.

In this way, the procedure of advancing in time follow the steps:

1. solution of the fluid energy and momentum equations for all loops,

2. solution of the heat balance equation for the structure.

The code is based on a "Finite Volume Technique" and as the fluid is considered incompressible, the "integral

Momentum Method" is adopted for the momentum equation. A semi-implicit procedure is used to integrate the final algebro-differential system of equations.

EXPERIMENTAL FACILITY AND PROCEDURE

Experimental Facility Description: The facility was developed to have the same physical processes as a full-scale PWR. One process proved to be the important factor: the flow in the facility needed to be turbulent.

Estimates showed that in PWR during natural circulation (0,2% power), the Reynolds number, Re,in the hot leg would be about 2x10^{6} and 2x10^{4} in heat exchanger tubes. It was decided that the model should operate in the turbulent regime for two reasons . First, the heat transfer mechanism in the steam generator would be closer to the prototipe. Second, the pressure drop to flow rate relationship would follow the same power law.

Preliminar calculations showed that geometric scalling would not produce turbulent flow and the exact geometric scalling was relaxed. A practical limit for the maximum power set at 12 kW and a maximum Δz =0.9 m was set between the heat source and the heat sink.

Table 1. Dimensions and Parameters of Model Facility

Number of loops	4
Maximum power input	12 kW
Operating pressure	101 kPa
Maximum design temperature	88 °C
Total primary volume	0.093 m3
VESSEL	
Material	Aluminum and Pyrex glass
Height	914 mm
Inside diameter	305 mm
DOWNCOMER	
Material	Pirex glass
Length	806.5 mm
Inside diameter	229 mm
Outside diameter	249 mm
HEATER	
Diameter	127mm
Length	531.9mm
LEGS	
Material	type L cooper tube
Inside diameter	50.42 mm
HEAT EXCHANGERS	
Type	12 U-tube
Number of active tubes	6(6 blocked)
TUBE	
Material	Cooper
Inside diameter	17 mm
Outside diameter	19 mm
Length (heigth)	910 mm
Heat transfer area (12 tubes-inside diam.)	1.18 m2
Maximum designed secondary flow rate	0.0001267m3/s(7.6 l/min)
Shell inside diameter	154.1 mm

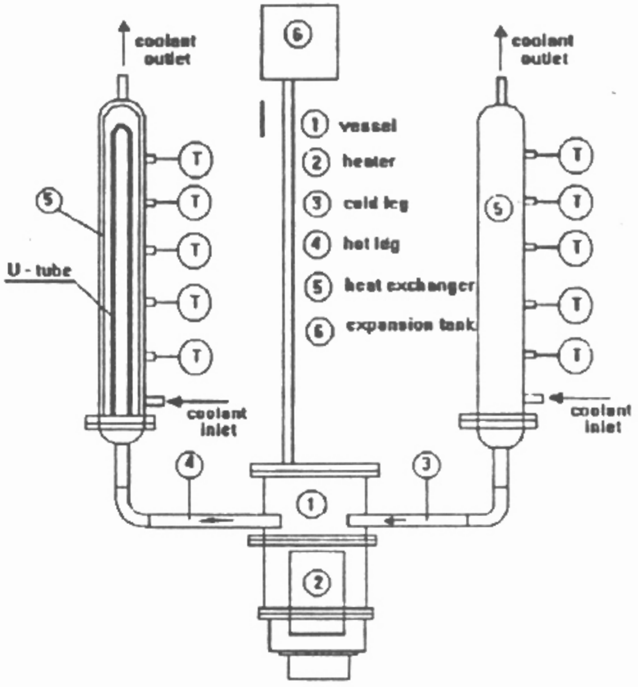

Figure.1. Natural Circulation Facility Elevation

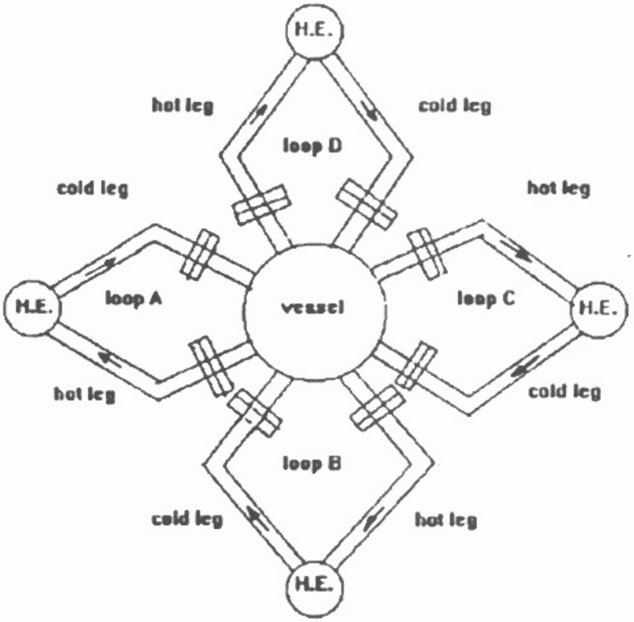

Figure. 2 Natural Circulation Facility Plan View

The facility was constructed to operate at atmospheric pressure and an expansion tank is installed to allow for specific volume changes of the water during heatup and cooldown.

The schematic geometry of the facility is given in figures (1) and (2) ; most of the important parameters are summarized in table (1).

Experimental Procedure

Initially the primary and secondary systems are at rest with homogeneous temperature of 20 °C at all loops and the heater turned off.

The transient starts turning on and maintaining the heater with 12.1 kW. The variable parameter of the experiment is the number of heat exchangers operating. From the beginning of the experiment to 240 min (14400 s) only the secondary side of Loop A is active. The cooling water flows at 5.7 l/min and the temperature at the entrance is 20 °C. At time 240 min, the secondary side of Loop B is activated with the same flow rate and entrance temperature of Loop A. With two active loops the transient proceeds to 380 min when the Loop C is activated also with the same flow rate of loops A and B. During all the test, the secondary side of Loop D is inactive.

The main parameter of interest during these tests was temperature. To measure this, 26 type E thermocouples were installed in the facility. A PDP 11/34 computer is the data acquisition system was used. When taking data, the program scans the multiplexer ten times in about 4s. More information about the experiment can be found in Jeuck III, P. (1981).

RESULTS

The model's nodal discretisation, for one loop, is presented in figure 3.

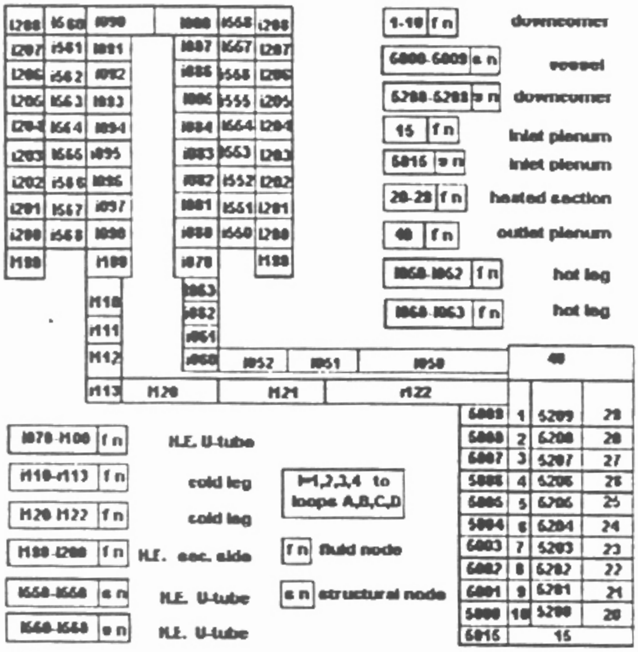

Figure 3. Nodal Discretisation

Each primary loop is represented by 56 fluid nodes and 39 structural nodes. The vessel region has:

- 10 fluid nodes for the downcomer region
- 10 fluid nodes for the heater region
- 11 structural nodes representing the vessel wall
- 10 structural nodes representig the downcomer wall
- 1 fluid node for the inlet plenum
- 1 fluid node for the outlet plenum

The nodes at the vessel region are common to all loops.

The U-tube heat exchanger has 20 fluid nodes at the primary side and 18 structural nodes representing the tubes walls. The secondary side is represened by 10 nodes.

The hot and cold legs have 7 fluid nodes each.

It's observed that, in general, the model predicts well the time evolution of the temperatures. The numerical results are slightly above the experimental ones for all the simulation. Nevertheless the temperature difference between the hot and cold legs are well predicted.

For the first part of the experiment - just loop A active - the temperatures of all loops present high frequency oscillations compared with the time constant of the transient. These oscillations are observed at the model results but with higher amplitudes. A more realistic behavior of the phenomenum would be obtained if structural nodes for the hot and cold legs and the heat exchangers shells were considered at the model. However, the increase in the number of nodes

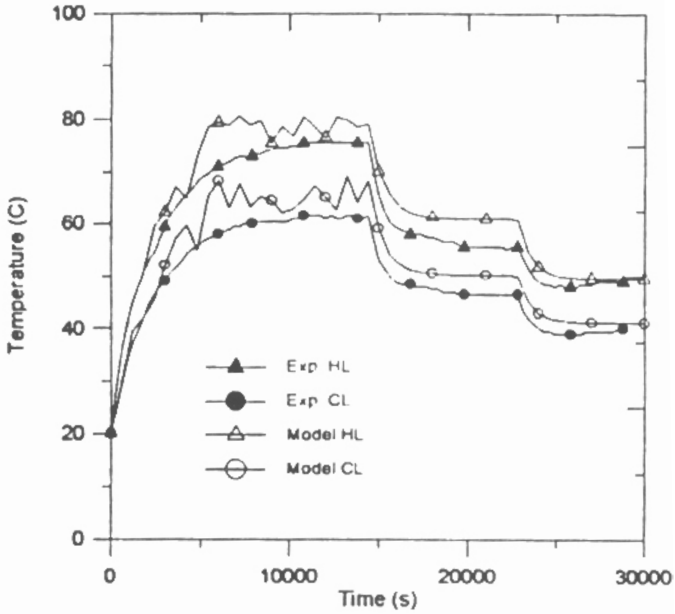

Figure 4. Hot and Cold Legs Evolution - LOOP A

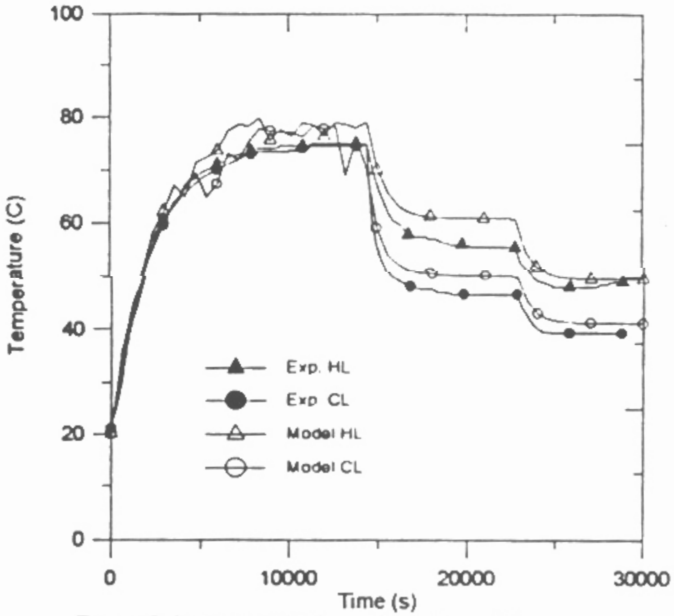

Figure 5. Hot and Cold Legs Evolution - LOOP B

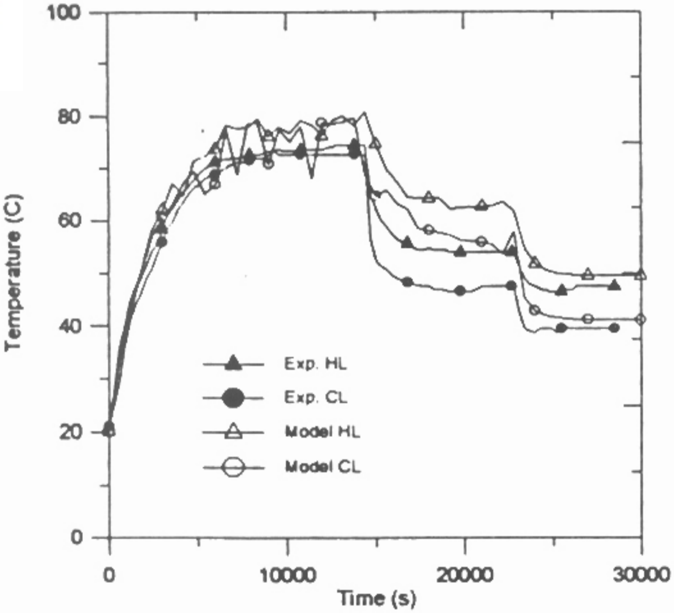

Figure 6. Hot and Cold Legs Evolution - LOOP C

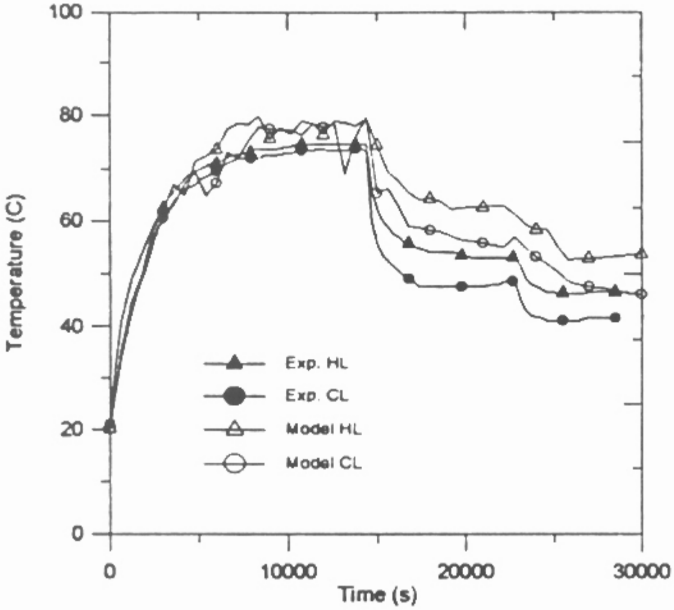

Figure 7. Hot and Cold Legs Evolution - LOOP D

would imply in a increase in the time of processing which is already around 24 hours in a Sun SPARC-10.

Loops B, C and D at the first part of the transient present a residual flow rate induced by loop A. This experimental observation is also obtained by the model as shown figure 8. Notice that when loop B is activated (T=14400 s) flow reversal is observed in loop C. The same happens in loop D and this inversion in the flow rate direction is caused by the temperature reduction of the hot leg due to the increase in the reactor flow rate.

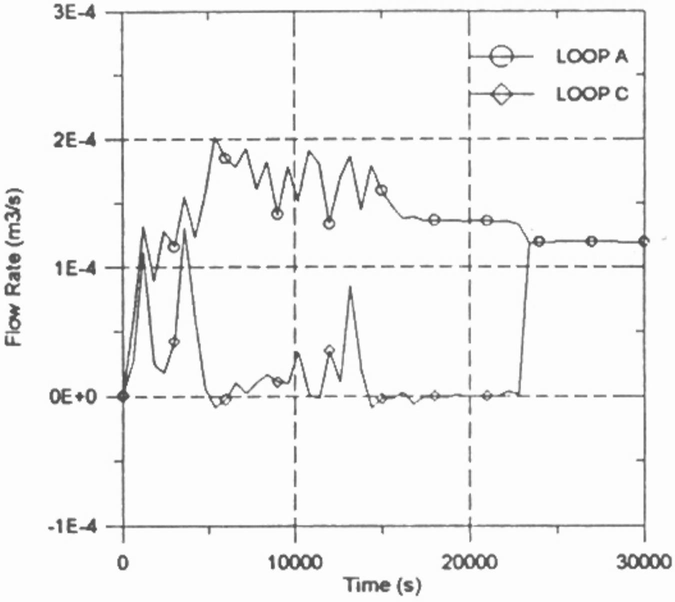

Figure 8. Flow Rate Evolution - Loops A and C

CONCLUSION

This work presents a comparison between experimental and numerical results for a one phase natural circulation problem. The experimental facility is similar to a PWR with four U-tube steam generators in turbulent flow. The variable parameter of the experiment is the number of active loops - the loops that have a secondary cooling water fluid flow.

A good agreement is observed between experimental and numerical results. The most relevant characteristics of the experiment have also been detected by the model. The inaccuracies of the model are due to the correlations for the heat transfer and friction factor coefficients.

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