CIRNAT- A CODE FOR ONE AND TWO-PHASE NATURAL CIRCULATION

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SUMMARY

This paper presents the CIRNAT code developed for one and two-phase natural circulation analysis. An one-dimensional approach of the conservation equations was adopted with an homogeneous model for the two-phase flow representation. Several heat transfer regimes were included as subcooled boiling, condensation, laminar and turbulent one-phase liquid and vapor, pool boiling, nucleate boiling, etc... The results of two studies are presented: transient behavior of a boiling/condensing system and a "Loss of Flow Accident" in a pool research reactor core.

INTRODUCTION

Termosyphon is an opened or closed loop with a heat source, at a lower level, connected to a heat sink by tubes (Huang and Zelaya, 1988). These devices transport heat by the natural convection mechanism and are widely used in solar systems, geothermal energy, cooling of electronic components, nuclear reactors, boiler design, etc...

The fluid flow, for a single phase termosyphon, is generated by the density differential due to the thermal expansion of the working fluid (Zvirin et alii, 1981). In boiling systems, the difference in density between the liquid and vapor phases provides the driving force for the fluid circulation (Lee, 1990). In both cases heat is added to the fluid at the heat source and extracted at the heat sink.

To analyse the performance of natural circulation systems operating in one and two-phase flows, a code, CIRNAT, based on a one-dimensional formulation of the conservation laws is in development. The Homogeneous approach of the two-phase flow was implemented and different heat transfer regimes are considered: laminar / turbulent liquid and vapor flows, pool boiling, flow boiling and condensation. Thermal properties of water and vapor are estimated by correlations in a wide range of temperatures and pressions. Features like parallel loops, variable boundary conditions, reversal flows give to this code the capability to treat a large variety of systems.

In order to validate the code, experiments, for one phase flow, were held, first at a simple square loop (Lavrador at al, 1994) and afterwards in an integral test facility (Bastos, 1993) which simulates the primary circuit of a pressurised water reactor. The agreement between numerical and experimental results were good. Two phase flow analysis in a boiling/condensing system were performed recently. A closed square glass circuit was built at the Chemical Engineering Departament of USP, and several experiments were held with different heat source levels and cooling flow rates. The results were also encouraging although the simplicity of the two phase model adopted.

This work is a description of the code and presents some results obtained for the IEA-R1, a nuclear research reactor from IPEN and the boiling/condensing system mentioned in the previous paragraph.

CONSERVATION EQUATIONS

The code is based on the "Finite Volume Technique" and the conservation equations are considered as one-dimensional. Two equations, momentum and energy, are associated to the fluid nodes and one equation, heat balance, to the structural nodes.

The integrated energy conservation equation for the fluid, has the form:

$$C_p\frac{\partial h_p}{\partial t}=Gf(h_s-hp)+Gc_1(c_pT_{w1}-h_p)+Gc_2(c_pT_{w2}-h_p)+S \quad (1)$$

where:

Cp is the thermal capacitance of node P,

$$C_p=\rho c_p v \quad (2)$$

Gf is the the enthalpy transport conductance,

$$Gf=M c_p \quad (3)$$

Gc1 and Gc2 are the thermal conductances,

$$Gc_i=\frac{Gcond\,Gconv}{Gcond+Gconv} \quad (4)$$

Gcond and Gconv are the conduction and convection conductances respectively;

The energy added to node P is placed at the source term S. This energy can be the heat flux dissipated by an external device (electrical heater, nuclear rod, etc...), generated by chemical reaction or due to the connection of node P to a surge line node.

Figure 1 shows a scheme of the heat flux exchanges between node P and it's neighbours where "S" is the preceding fluid node which depends on the flow direction, and "W1" and "W2" are structural nodes.

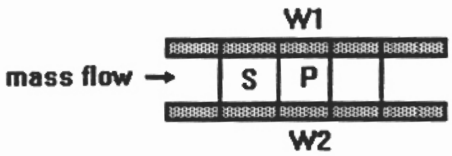

Figure 1 - Schematic Nodal Representation

Notice that the thermal capacitance and the conductances are not constant but they depend on the enthalpy of node P due to the variation of the thermal properties. In this way, equation (1) is non linear requiring an iterative procedure to be solved.

Integrating the momentum equation around the loop, equation (5) is obtained:

$$\frac{dM}{dt}=\frac{1}{\Gamma}\left[-\Delta p-\frac{1}{2}\frac{M^2 R}{\rho}+g\xi-\frac{1}{2}\frac{M^2\eta}{\rho}-\frac{1}{2}\frac{M_c^2 R_c}{\rho}-\Gamma_c\frac{dM_c}{dt}\right] \quad (5)$$

in this equation,

$$\Gamma=\sum_{i=1}^{n}\frac{z2(i)-z1(i)}{A(i)} \quad (6),$$

where z2(i) and z1(i) are the final and initial spatial co-ordinates and A(i) the cross sectional area;

$$\Delta P = P_{out} - P_{in} \quad (7)$$

P_{out} and P_{in} are the outlet and inlet pressures for an opened loop, for a closed loop this term vanishes;

$$R=\sum_{i=1}^{n}\left(f\frac{z2(i)-z1(i)}{d(i)A^2(i)}+\frac{K(i)}{A^2(i)}\right) \quad (8)$$

where f is the friction factor, K(i) the form loss coefficient and d(i) the diameter ;

$$\xi=\sum_{i=1}^{n}\rho(i)\vec{e}_z\vec{e}_g\left(z2(i)-z1(i)\right) \quad (9)$$

$$\eta=\frac{1}{A_{out}^2-A_{in}^2} \quad (10)$$

A_{out} and A_{in} are the outlet and inlet flow areas for an opened loop, and is null for a closed loop.

The last two terms are related to parallel loops. The parameters with the subscript "c" represent the portion of the loop belonging to more than one loop:

$$M_c=\sum_{j=1}^{l}M_j \quad (11)$$

M_j is the mass flow rate for the j loop.

The heat balance equation for the structure nodes is shown in (12).

$$C_I\frac{dT_I}{dt}=Gc1\left(T_K-T_I\right)+Gc2\left(T_L-T_I\right)+Q \quad (12)$$

In this equation nodes "K" and "L" are structural or fluid nodes in the radial direction. If "K" is a structural node, Gc1 is a simple conduction conductance. If it is a fluid node Gc1 is a conduction/convection conductance.

In two-phase flows the fluid presents high volume variations entraining pressure changes as it expands or contracts. To consider this effect, an expansion tank model was developed. An expansion tank is an reservoir connected to the loop by a surge line. The flow rate at the surge line is estimated by the continuity equation:

$$M_S=-V\frac{d\bar{\rho}}{dt} \quad (13)$$

where M_S is the mass flow at the surge line, V the total volume of the loop and $\bar{\rho}$ the volume average density of the loop fluid. So, if $d\bar{\rho}/dt$ is negative (M_S>0), the fluid at the loop is contracting and there is a fluid flow from the expansion tank to the loop. On the other side, if $d\bar{\rho}/dt$ is positive there is a fluid flow from the loop to the expansion tank. The energy conservation equation (1) is also valid for the surge line nodes and reservoir nodes.

In natural circulation the driving force for the flow is the density variation. This force, $g\xi$, is a function of the temperature field. On the other side, the temperature field depend on the flow velocity and the structure temperatures. It is clear that equations (1), (5), (12) and (13) must be solved simultaneously.

TWO-PHASE MODEL

As a first approach a simple homogeneous model was adopted. The idea of the homogeneous model is to replace the two-phase fluid by a one phase pseudo-fluid. The physical properties of the pseudo-fluid are estimated as an average of the liquid and vapor properties.

Considering both phases at the same velocity and in thermodynamic equilibrium, *expression (13) gives the quality* of the mixture.

$$x=\frac{h-h_L}{h_{LG}} \quad (13)$$

where h is the enthalpy of the two-phase mixture, h_L the enthalpy of the saturated liquid and h_{LG} the heat of vaporisation. The density is estimated by expression (14).

$$\frac{1}{\rho}=\frac{x}{\rho_v}-\frac{1-x}{\rho_L} \quad (14)$$

The void fraction and other properties as viscosity, specific heat and thermal conductivity are calculated by expressions (15) to (18)

$$\alpha=\frac{x\rho}{\rho_V} \quad (15)$$

$$\frac{1}{\mu} = \frac{x}{\mu_V} + \frac{1-x}{\mu_L} \tag{16}$$

$$cp = \alpha cp_V + (1-\alpha) cp_L \tag{17}$$

$$K = \alpha K_V + (1-\alpha) K_L \tag{18}$$

The second term on the right hand side of equation (5), $-\frac{1}{2}\frac{M^2 R}{\rho}$, represent the frictional pressure drop. R is called "Hydraulic Resistance" and is calculated by expression (8) as a function of the friction factor and the form losses. For a one-phase flow the friction factor is estimated by the Churchill correlation (Churchill, 1977) for laminar and turbulent flows. For a two-phase flow, a multiplier factor is used:

$$f = \phi^2_{LO} f_{OP} \tag{19}$$

where f_{OP} is the one phase friction factor and ϕ^2_{LO} is estimated by expression (20).

$$\phi^2_{LO} = \left[1 + x\left(\frac{\rho_L - \rho_V}{\rho_V}\right)\right]\left[1 + x\left(\frac{\mu_L - \mu_V}{\mu_V}\right)\right]^{-1/4} \tag{20}$$

The conservation equations involve certain thermodynamic properties of the fluid. In CIRNAT, these properties are estimated by the ASME formulation. The subroutines are those of the International Association for the Properties of Water and Steam (IAPWS).

HEAT TRANSFER REGIMES

A wide range of heat transfer regimes may be encountered in a natural circulation system with phase change. The logic for selecting the heat transfer regimes is shown in Figure 2. Initially some numerical problems, related to a sudden variation of the heat transfer coefficients were detected. This problem was treated estimating, for a certain regime, the heat transfer coefficient with different correlations and taking the largest among them. The condensing regime has three correlations: laminar film condensation in inclined surfaces, film condensation in tubes with stratified flow and turbulent film condensation in tubes. For the one phase liquid or vapor different correlations are available, figure 3. The adimensional Gr/Re^2 evaluates if the heat transfer regime is mainly a forced convection regime or a natural convection regime.

GENERAL CODE STRUCTURE

CIRNAT was developed in FORTRAN77 for SUN workstations and PC computers using a structured philosophy of programming. Three programs constitutes the heart of the code:

PREPRO - is the pre-processor for the geometric and nodal description. The connectivity table and boundary conditions are automatically generated with a small number of instructions;

LOOP - is the integrator of the coupled algebro-differential equations. A semi-implicit procedure (Crank-Nicholson) was implemented with automatic adjustable time step to reduce time consuming;

INTHG - generates files for common use graphic programs.

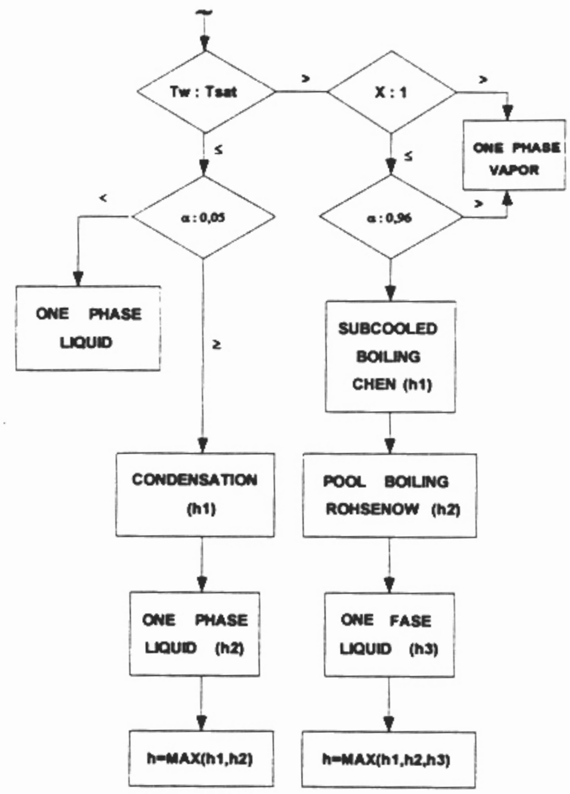

Figure 2 - Heat Transfer Regimes

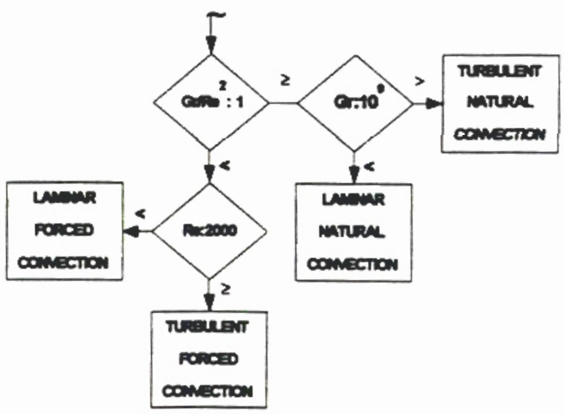

Figure 3 - One Phase Liquid or Vapor

To simulate a complex system like a multi loop nuclear reactor, different entities helps the geometric description:

Node - the smallest entity of a model. There are two kinds of nodes: fluid and solid. They are classified as "diffusive nodes", associated to the conservation equations, and "boundary nodes";

Bloc - is a group of nodes with a common geometric characteristic. There are solid and fluid blocs. This entity was created to reduce the number of instructions for the geometric description in the pre-processing phase;

Loop - is an opened or closed path for the fluid flow and it is formed by a series of fluid blocs;

Component - is a series of blocs (nodes) associated to special equations like a pressuriser or an expansion tank;

System - is formed by all loops and components of a model.

ANALYSIS OF A BOILING/CONDENSING SYSTEM

To generate data for the code validation, a series of experiments were held at a boiling/condensing loop built in Pyrex. Since the interest is a parametrical analysis, a small rectangular glass loop was designed with an electrical heat source and a coil cooler. The main dimensions of the circuit are indicated in figure 4. The heater is a 75 mm cylindrical glass tube with two resistances. The power applied is controlled in the range of 0 to 7000 W. The cooler is all made in glass with 33 mm internal diameter, 610 mm high and 2 parallel coils. The coolant is tap water at ambient temperature. An expansion tank is connected to the loop at the horizontal section of the cold leg to prevent vâpor entrainement.

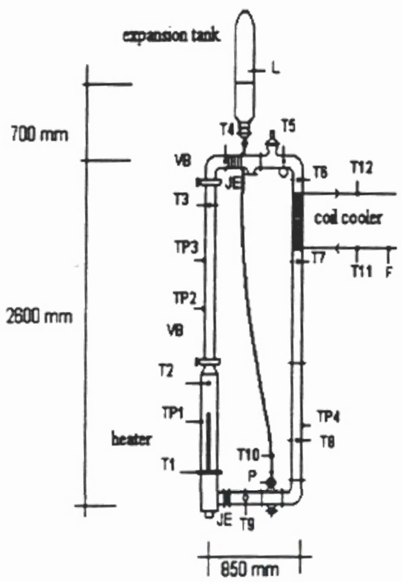

Figure 4 - Schematic View of the Loop

The experiment starts with the primary circuit filled with water at rest and the heater turned off. The fluid temperature is completely homogeneous and equal to the ambient temperature all along the loop. The heater is turned on with a constant heating power. The flow rate and the inlet temperature at the coil cooler are also kept constant. The nodal description of the system is presented in figure 5. The coil cooler was divided in 30 slices of the same size. Figure 6 shows the results for the hot and cold legs. At the beginning of the transient, from 0 to 1000 s, there is no phase change. For this part of the experiment, the model presents very good results for both temperatures. The hot leg temperature is very well estimated and the cold leg is slightly overestimated. At the phase change region, the loop presents a very complex thermal-hydraulic behavior with sustained oscillations due to chugging instabilities observed at the heater. The model is not able to predict the cyclic behavior of the system but the variables are "macroscopically" well estimated. It seems that the pressure, which is constant at the model, play an important role in the prediction of the oscillations.

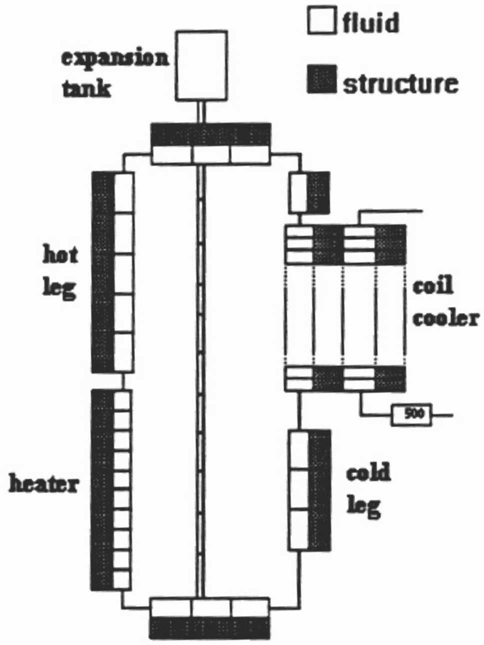

Figure 5 - Nodal Description of the Circuit

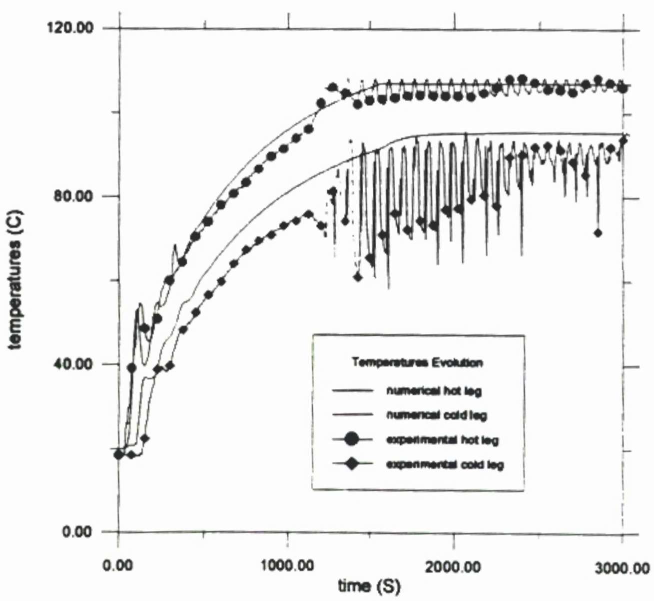

Figure 6 - Hot and Colg Leg Temperatures Evolution

ANALYSIS OF THE IEA-R1 RESEARCH REACTOR

In nuclear reactors, the understanding of natural circulation is one of the major steps in designing more reliable systems to maintain the integrity of the core in accidental conditions. The reactor shall be conceived in such a way that natural circulation remains cooling the core, removing the residual heat generated by the decay products. The analysis presented here is a loss of flow accident for the IEA-R1 research reactor.

IEA-R1 is a pool nuclear research reactor built at IPEN in 1957. The analysis presented here is part of the project to increase the power of the reactor from 2 to 5 MW. The reactor core is an assembly of fuel and control elements. Figure 7 presents a typical control element with 12 fuel plates and 2 neutron absorber plates. In normal conditions, the refrigerant flows from top to bottom through the channels formed by the fuel plates, region C. All elements are fixed at a matrix plate which is connected to the primary pump by a natural convection valve, "header". This study postulates the loss of the pump energy supply and as a consequence the loss of the flow rate through the core. Figure 8 shows the time variation of the normalised flow rate obtained experimentally. Due to the inertial disk coupled to the rotor axis, the flow rate varies from its nominal value to 0.20 in 27 seconds. After that time, the header is decoupled and the fuel elements are no longer connected to the primary pump and tubes. At this stage the only way to refrigerate the fuel plates is by natural convection.

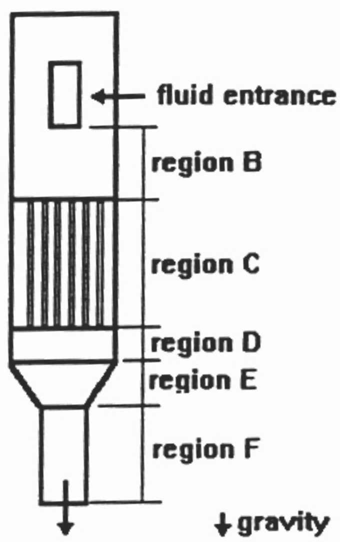

Figure 7 - Control Element Geometry

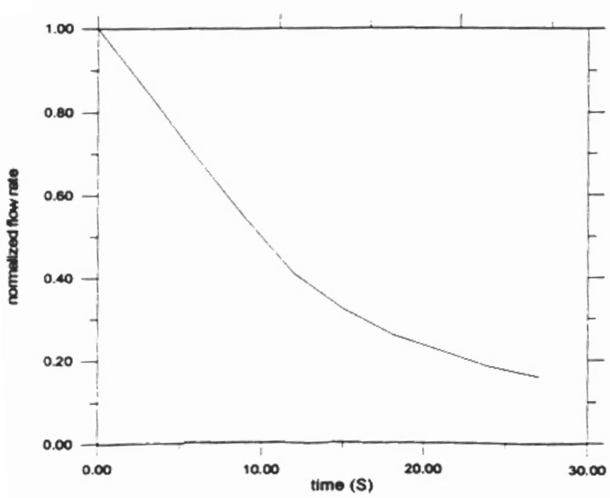

Figure 8 - Flow Rate Time Variation

Figure 9 presents the evolution of the heat flux generated by the decay of the fission products and figure 10 the nodal description of the control element. The fuel elements region is divided in 30 slices of the same dimensions. The notion of "equivalent nodes" was used to represent the 12 plates and 13 channels by a singular equivalent plate and channel.

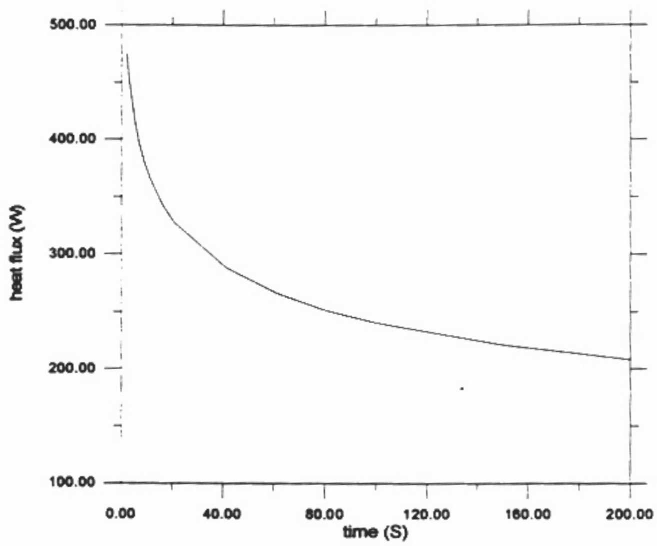

Figure 9- Decay Heat Flux Evolution

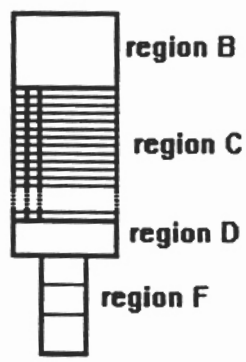

Figure 10 - Control Element Nodal Description

Figure 11 shows the temperatures and the mass flow rate evolution. The temperatures at the top and bottom of the control element is presented due to the flow reversal. The first part of the transient is a forced flow problem with a decreasing mass flow rate. It is observed that, at the beginning, the temperature at the bottom of the element increases but there is no phase change. At time t=27 s, the header decouples the core from the primary circuit and a natural circulation regime starts. At t=30 s there is a flow reversal and the temperature at the top of the element rises gradually to 57 C approximately. After 60 seconds temperature and mass flow rate are nearly in equilibrium.

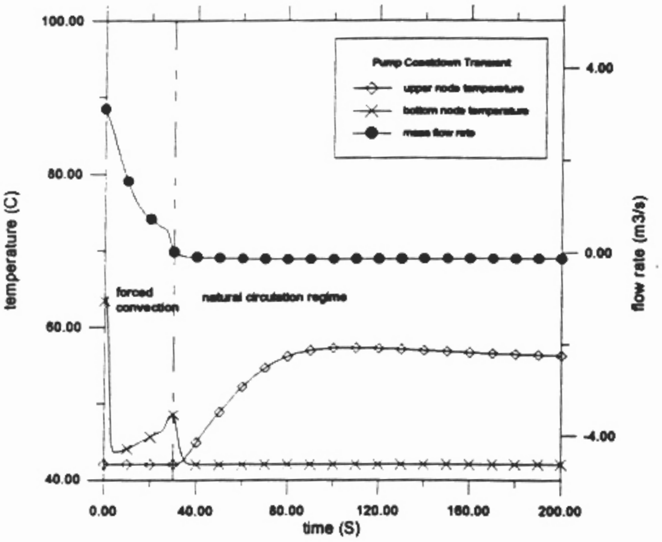

Figure 11 - Temperature and Mass Flow Rate Evolution

CONCLUSION

CIRNAT, a one-dimensional code for natural circulation analysis, was described. The homogeneous approach was adopted for the two-phase flow regime and different heat transfer regimes were considered. The code was exhaustively tested for one-phase flow systems. For two phase flows a boiling/condensing system was simulated. The results are qualitatively correct but the oscillations observed at the system were not captured by the model. Other two-phase flow tests must be done to show the limits of the homogeneous approach before the introduction of a more complex model.

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