Journal of the Korean Nuclear Society
Volume 15, Number 3, September, 1983

《**Original**》

A Simplified Fast Running System Code Development to Simulate the Loop Transients

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(Received July 9, 1983)

회로의 과도 현상을 모사하기 위한 간단한 Fast-Running System Code의 개발

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(1983. 7. 9 접수)

Abstract

A simplified fast-running system code is developed to simulate loop transients such as pump coastdown, loop failures and natural circulation. Special emphasis is put on the numerical investigation of the natural circulation system with multiloop. For this purpose, 5 governing equations are derived, and they are discretized by the space-time integration technique. The developed computer program is applied to three sample problems; transition from 2-loop to 1-loop operation, transition from 1-loop to 2-loop operation, and the transient behavior with decay power in the case of 2-loop operation.

요 약

펌프의 coastdown이나 회로의 고장 또는 자연 순환같은 회로 내의 과도 현상을 모사하기 위해 간단한 fast-running computer code가 개발되었다. 본 논문에서는 특히 다회로의 자연 순환계에 관한 수치 해석적 연구에 중점을 두었으며, 이를 위해 5개의 지배 방정식이 유도되고, space-time 적분 방법에 의해 discretization되었다. 개발된 전산 프로그램은 몇가지 예제에 적용되었는데, 이는 2-회로 유동에서 1-회로 유동으로의 과도 현상, 1-회로 유동에서 2-회로 유동으로의 과도 현상, 그리고 2-회로의 열교환기가 작동할 때 decay power에서의 과도 현상 등이다.

Nomenclature

A	: area
(BF)	: buoyancy force term
c	: specific heat
D	: diameter or equivalent diameter
(FF)	: friction force term
f	: (Darcy or Moody) friction factor
g	: gravitational acceleration
H	: height
H_p	: pump head

h : heat transfer coefficient
K : hydraulic loss coefficient
k : thermal conductivity
L : length
N : total number of loops
P : core thermal power
p : pressure
Q : volumetric flowrate
R : overall friction factor
r : radius
s : space variable
T : temperature
t : time
U : overall heat transfer coefficient
u : velocity
β : thermal expansion coefficient
ρ : density

Subscripts

a : loop-A
b : loop-B
c, cl : cold leg
dc : downcomer
h, hl : hot leg
i : inlet or inner side
l : loop
lp : lower plenum
lm : log-mean
$n, n+1$: time steps
o : outlet or outer side
r : core
s : heat exchanger
up : upper plenum
v : vessel
1 : primary side
2 : secondary side

I. Introduction

When the primary pump is tripped in a pressurized water reactor, the only mechanism of core cooling is the natural circulation of the primary coolant. Therefore, natural circulation is one of the most important aspects in consideration of nuclear reactor safety. Natural circulation is the buoyancy-driven flow induced by the density difference due to temperature variations along the loop.

There are several system codes to simulate the transient behavior of the light water reactors, but most of them are intended to obtain highly detailed results and time-consuming. The present work is a simplified numerical investigation of a single-phase natural circulation system with 2-parallel once-through heat exchangers. N-loop system is generally treated assuming that (N-1) loops have the same behavior. If heat loss into the atmosphere through the leg walls is neglected, 5 governing equations for 5 unknowns can be derived from the laws of momentum and energy conservations.

These equations are discretized by using the space-time integration techniques, and simplified computer program to solve those discretized governing equations is developed. Then sample calculation is carried out to examine the performance of the program. It should be said that this work is intended to study the feasibility of the experimental loop and the real-time calculation of transients.

Although it leaves much room for improvement, the program seems to be not bad in simulation of the transient behavior of the natural circulation system.

Some parts are not described in detail in this article because they are presented already in others. This article puts emphasis on the numerical analysis.

II. Theoretical Analysis

II. 1. System Simulation

Schematic diagram of the simulated system is depicted in Fig. 1 as a block diagram. It consists of core, hot and cold legs, 2 once-through

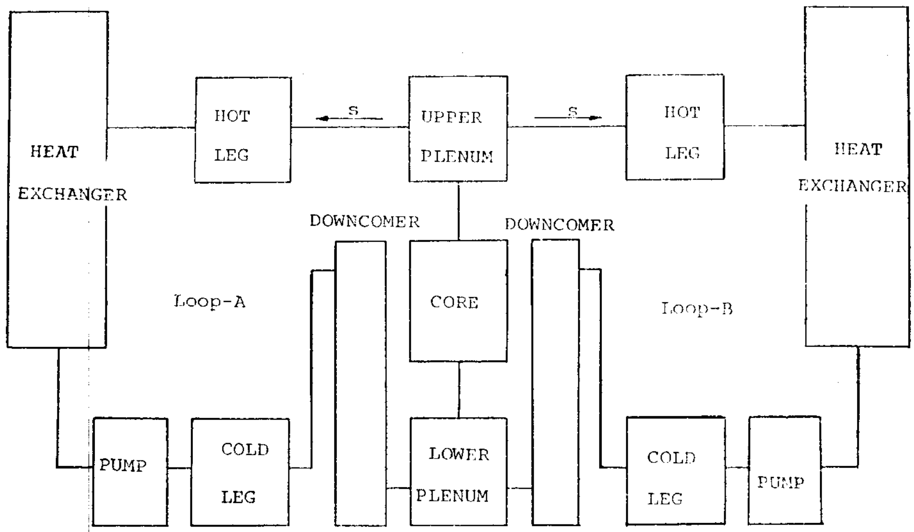

Fig. 1. Simulated System

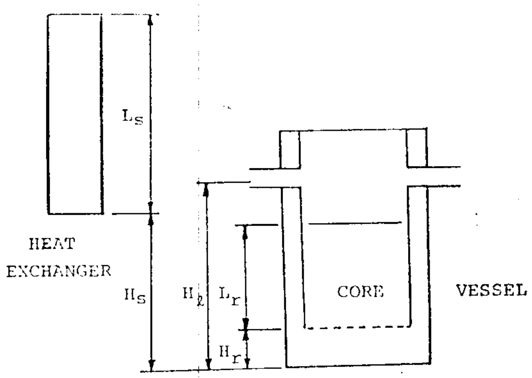

Fig. 2. Several Notations

heat exchangers, downcomer, upper and lower plenums, primary pumps, and other connections.

Governing equations are derived to represent N-loop system, one loop (A) of which behaves unlike other (N-1) loops. With many assumptions, they are reduced to five nonlinear partial differential equations. The important assumptions made in this study are as follows:

i) One-dimensional approach can represent the system behavior appropriately.

ii) Boussinesq approximation is valid (single phase).

iii) Pressure is sustained at atmospheric level.

iv) Heat loss into the atmosphere through hot and cold leg walls is negligible.

v) Complete mixing is achieved at the entrance of downcomer.

vi) Temperature distributions of the primary coolant in core and heat exchangers are linear.

vii) All loops have the same geometry.

Other assumptions will be mentioned in subsequent sections whenever needed. Some notations are shown in Fig. 2 for the convenience of representation.

II. 2. Derivation of the Governing Equations

II. 2. 1. Momentum equations

Momentum equation can be represented as the pressure drop relation. Because the sum of the pressure drops around any closed loop of channels must be zero (Kirchhoff's law), following relationships can be written.

$$\Delta P_{ah}+\Delta P_{as}+\Delta P_{ac}+\Delta P_{dc}+\Delta_{lp}+\Delta P_{r}+\Delta P_{up}=0. \quad (1)$$

$$\Delta P_{bh}+\Delta P_{bs}+\Delta P_{bc}+\Delta P_{dc}+P_{lp}+\Delta P_{r}+\Delta P_{up}=0. \quad (2)$$

And, pressure drop due to single-phase flow in the tube with constant flow area can be written as follows (ref. 3):

$$\Delta P=\left(\frac{L}{A}\right)\rho_0\frac{dQ}{dt}+R\cdot\frac{1}{2}\rho_0 Q^2$$

$$+g\int_{\Delta z}\rho dz-g\rho_0\ H_p(t) \tag{3}$$

where

$$R=R_{fr}+R_{\rm form}$$

$$=\sum_{i\ \rm tubes}f_i\frac{L_i}{D_iA_i^2}+\sum_{j\ \rm forms}\frac{K_j}{A_j^2} \tag{4}$$

Then following equation is obtained from eqs(1) and (3).

$$\left(\frac{L}{A}\right)_l\rho_0\frac{dQ_a}{dt}+\left(\frac{L}{A}\right)_v\rho_0\frac{dQ}{dt}+\frac{1}{2}\rho_0R_aQ_a^2$$

$$+\frac{1}{2}\rho_0R_vQ^2+g\oint\rho dz-\rho_0gH_{pa}(t)=0. \tag{5}$$

where

$$\left(\frac{L}{A}\right)_l=\left(\frac{L}{A}\right)_h+\left(\frac{L}{A}\right)_s+\left(\frac{L}{A}\right)_c \tag{6a}$$

$$\left(\frac{L}{A}\right)_v=\left(\frac{L}{A}\right)_{dc}+\left(\frac{L}{A}\right)_{lp}+\left(\frac{L}{A}\right)_r$$

$$+\left(\frac{L}{A}\right)_{up} \tag{6b}$$

$$R_a=R_{ah}+R_{as}+R_{ac} \tag{6c}$$

$$R_v=R_{dc}+R_{lp}+R_r+R_{up} \tag{6d}$$

Q=total flowrate

$$=Q_a+(N-1)Q_b \tag{7}$$

Buoyancy term can be represented as another form by the following procedure.

$$g\oint\rho dz=g\oint\rho_0\left[1-\beta(T-T_0)\right]dz$$

$$=g\oint\rho_0dz-\beta g\rho_0\oint Tdz+\beta g\rho_0T_0\oint dz$$

$$=-\beta g\rho_0\oint Tdz \tag{8}$$

And

$$\oint_{\rm loop-A}Tdz=\int_r Tdz+\int_{up+hl}Tdz$$

$$+\int_s Tdz+\int_{cl}Tdz+\int_{dc+lp}Tdz$$

$$=\frac{1}{2}(T_h+T_c)L_r+T_h\left[H_s+L_s-(H_r+L_r)\right]$$

$$-\frac{1}{2}L_s(T_h+T_{ac})$$

$$+T_{ac}(H_l-H_s)+T_c(H_r-H_l)$$

$$=\left[\frac{1}{2}(L_s-L_r)+H_s-H_r\right]T_h+\left(\frac{1}{2}L_r+H_r\right.$$

$$\left.-H_l\right)T_c+\left(H_l-\frac{1}{2}L_s-H_s\right)T_{ac} \tag{9}$$

Here, the difference between T_c and T_{ac} should be noted. For convenience sake, let

$$\beta g\rho\oint Tdz=(BF),$$

then the pressure drop relations for loops A and B become as follows:

$$\left(\frac{L}{A}\right)_l\rho\frac{dQ_a}{dt}+\left(\frac{L}{A}\right)_v\rho\frac{dQ}{dt}+(FF)_a$$

$$+(FF)_v-(BF)_a-\rho gH_{pa}=0. \tag{10}$$

$$\left(\frac{L}{A}\right)_l\rho\frac{dQ_b}{dt}+\left(\frac{L}{A}\right)_v\rho\frac{dQ}{dt}+(FF)_b$$

$$+(FF)_v-(BF)_b-\rho gH_{pb}=0. \tag{11}$$

where

$$(FF)_a=\frac{1}{2}R_a\rho Q_a^2 \tag{12a}$$

$$(FF)_b=\frac{1}{2}R_b\rho Q_b^2 \tag{12b}$$

$$(FF)_v=\frac{1}{2}R_v\rho Q^2 \tag{12c}$$

$$(BF)_a=\beta g\rho\oint_{\rm loop-A}Tdz \tag{13a}$$

$$(BF)_b=\beta g\rho\oint_{\rm loop-B}Tdz \tag{13b}$$

In the above equations, ρ replaces the reference density (ρ_0).

II. 2. 2. Energy equations

Since heat loss through the cold and hot leg walls is ignored, energy equations should be established for core and heat exchangers.

For the heated section (core),

$$\rho cA_r\frac{\partial T}{\partial t}+\rho cQ\frac{\partial T}{\partial s}=\frac{P}{L_r} \tag{14}$$

And for the heat exchangers,

$$\rho cA_s\frac{\partial T}{\partial t}+\rho cQ_a\frac{\partial T}{\partial s}=-U\pi D_s(T-T_{a2}) \tag{15}$$

$$\rho cA_s\frac{\partial T}{\partial t}+\rho cQ_b\frac{\partial T}{\partial s}=-U\pi D_s(T-T_{b2}) \tag{16}$$

In the above equations, U denotes the overall heat transfer coefficient of the heat exchanger.

Eqs (10), (11), (14), (15) and (16) govern the system behavior with the aid of state equations. Continuity equation is already introduced into above equations. For numerical analysis above equations should be discretized by using some appropriate techniques.

III. Numerical Analysis

III. 1. Discretization of the Governing Equations

III. 1. 1. Momentum Equations

Integrating eqs (10) and (11) with time, t, from t_n to t_{n+1} leads to:

$$\left[\left(\frac{L}{A}\right)_l+\left(\frac{L}{A}\right)_v\right]\rho Q_{a,n+1}+\left(\frac{L}{A}\right)_v \rho(N-1)Q_{b,n+1}$$
$$=\left(\frac{L}{A}\right)_l\rho Q_{a,n}+\left(\frac{L}{A}\right)_v\rho Q_n-\left[(FF)_{a,n+1}+(FF)_{v,n+1}-(BF)_{a,n+1}-gH_{pa,n+1}\right]\Delta t \quad (17)$$

$$\left(\frac{L}{A}\right)_v\rho Q_{a,n+1}+\left[\left(\frac{L}{A}\right)_l+(N-1)\left(\frac{L}{A}\right)_v\right]\rho Q_{b,n+1}$$
$$=\left(\frac{L}{A}\right)_l\rho Q_{b,n}+\left(\frac{L}{A}\right)_v\rho Q_n-\left[(FF)_{b,n+1}+(FF)_{v,n+1}-(BF)_{b,n+1}-gH_{pb,n+1}\right]\Delta t \quad (18)$$

where

$$Q_n=Q_{a,n}+(N-1)Q_{b,n} \quad (19)$$

III. 1. 2. Energy Equations

Energy equation for the heat exchanger of loop-A can be discretized as follows:

$$\int_{t_n}^{t_{n+1}}dt\int_0^{L_s}ds\left[\rho cA_s\frac{\partial T}{\partial t}+\rho cQ_a\frac{\partial T}{\partial s}=-U\pi D_s\Delta T\right]:$$

$$\int_0^{L_s}\rho cA_s(T_{n+1}-T_n)ds+\int_{t_n}^{t_{n+1}}\rho cQ_a(T_{ac}-T_h)dt=-\int_{t_n}^{t_{n+1}}\pi U_a D_s L_s\Delta T_{a,lm}dt$$

Because the temperature distribution in the heated section is assumed to be linear,

$$\rho cA_s\left(\frac{T_{h,n+1}+T_{ac,n+1}}{2}-\frac{T_{h,n}+T_{ac,n}}{2}\right)L_s+\rho cQ_{a,n+1}(T_{ac,n+1}-T_{h,n+1})\Delta t=-\pi D_s L_s(U\Delta T_{lm})_{a,n+1}\Delta t$$

By rearranging above equation, following equation can be obtained.

$$\left[1-\frac{2Q_{a,n+1}\Delta t}{A_sL_s}\right]T_{h,n+1}+\left[1+\frac{2Q_{a,n+1}\Delta t}{A_sL_s}\right]T_{ac,n+1}=T_{h,n}+T_{ac,n}-\frac{2\pi D_s\Delta t}{\rho cA_s}(U\Delta T_{lm})_{a,n+1} \quad (20)$$

where

$$\Delta T_{lm}=\frac{\Delta T_2-\Delta T_1}{\ln(\Delta T_2/\Delta T_1)} \quad (21)$$

$$\Delta T_1=T_h-T_{2,o} \quad (22a)$$

$$\Delta T_2=T_c-T_{2,i} \quad (22b)$$

For an once-through heat exchanger, U is given by the following expression.

$$U_i=\frac{1}{\frac{1}{h_i}+R_{f,i}+\frac{r_i}{k}\ln\left(\frac{r_o}{r_i}\right)+\left(\frac{r_i}{r_o}\right)R_{f,o}+\left(\frac{r_i}{r_o}\right)\frac{1}{h_o}} \quad (23)$$

where

h_i, h_o : heat transfer coefficients of inner and outer sides

k : thermal conductivity of wall

$R_{f,i}, R_{f,o}$: fouling factors

If $T_{2,i}$ is given, $T_{2,o}$ can be obtained from the heat balance equation.

$$(\rho cQ)_1(T_h-T_c)=(\rho cQ)_2(T_{2,o}-T_{2,i})$$

$$T_{2,o}=\frac{(\rho cQ)_1}{(\rho cQ)_2}(T_h-T_c)+T_{2,i} \quad (24)$$

By the similar procedure,

$$\left[1-\frac{2Q_{b,n+1}\Delta t}{A_sL_s}\right]T_{h,n+1}+\left[1+\frac{2Q_{b,n+1}\Delta t}{A_sL_s}\right]T_{bc,n+1}=T_{h,n}+T_{bc,n}-\frac{2\pi D_s\Delta t}{\rho cA_s}(U\Delta T_{lm})_{b,n+1} \quad (25)$$

Energy equation for the heated section(core) is also discretized as follows:

$$\int_0^{L_r}ds\int_{t_n}^{t_{n+1}}dt\left[\rho cA_r\frac{\partial T}{\partial t}+\rho cQ\frac{\partial T}{\partial s}=\frac{P}{L_r}\right]$$

$$\left[1+\frac{2Q_{n+1}\Delta t}{A_rL_r}\right]T_{h,n+1}+\left[1-\frac{2Q_{n+1}\Delta t}{A_rL_r}\right]\frac{Q_{a,n+1}}{Q_{n+1}}T_{ac,n+1}+\left[1-\frac{2Q_{n+1}\Delta t}{A_rL_r}\right]\frac{(N-1)Q_{b,n+1}}{Q_{n+1}}T_{bc,n+1}=T_{c,n}+T_{h,n}+\frac{2P_{n+1}\Delta t}{\rho cA_rL_r} \quad (26)$$

III. 2. Numerical Scheme

Eqs (17), (18), (20), (25) and (26) constitute 5 discretized governing equations for 5 unknowns—Q_a,Q_b, T_h, T_{ac} and T_{bc}. These equations are nonlinear, so that direct matrix manipulation is impossible and iteration should be performed at each time step.

Two-step procedure is taken in the iteration. For each time step $(n+1)$, $Q^1_{a,n+1}$ and $Q^1_{b,n+1}$ are to be found from eqs (17) and (18) using n-time step values for other terms at first. Next $Q^1_{a,n+1}$ and $Q^1_{b,n+1}$ are used to calculate $T^1_{h,n+1}$, $T^1_{ac,n+1}$ and $T^1_{bc,n+1}$ from eqs (20), (25) and (26). Then they are used to obtain $Q^2_{a,n+1}$ and $Q^2_{b,n+1}$ from eqs (17) and (18). And $Q^2_{a,n+1}$ and $Q^2_{b,n+1}$ are used again to find T^2_{n+1}'s.

This procedure should be repeated until convergence appears, that is$|(T^i_{h,n+1}-T^{i-1}_{h,n+1})/T^i_{h,n+1}|\ll 1$, etc. Then $Q^i_{a,n+1}$, $Q^i_{b,n+1}$, $T^i_{h,n+1}$, $T^i_{ac,n+1}$, and $T^i_{bc,n+1}$ represent the $(n+1)$ time step values, and iteration begins for $(n+2)$ time step.

Above discussions are shown as a flow chart in Fig. 3.

III. 3. Computer Program

Computer program, SIMFARS, is developed to simulate the natural circulation phenomena in a multiloop system. It consists of 1 main program and 4 subprograms—ITERAT, TIMESU, CALCU1 and CALCU2. Interconnections

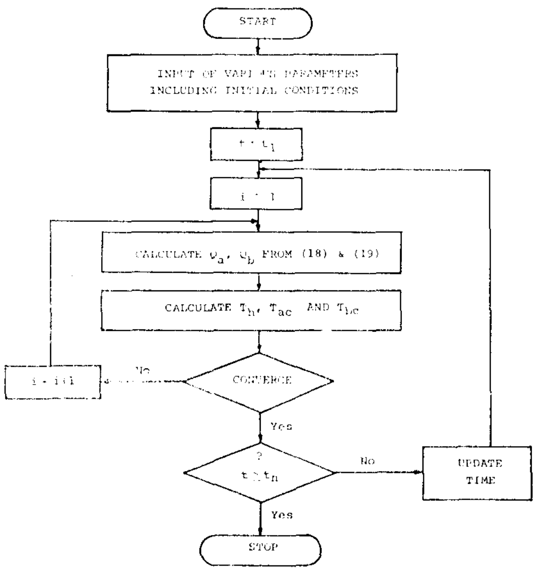

Fig. 3. Flow Chart for Iteration

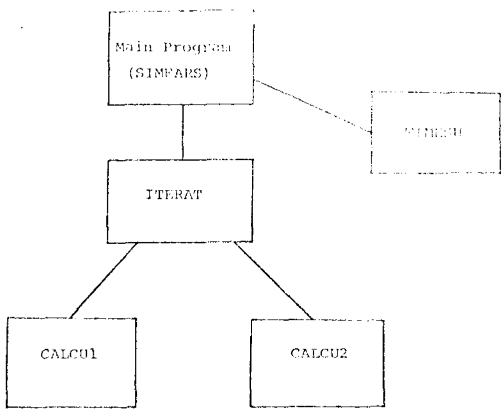

Fig. 4. Interconnections between Subprograms

Table 1. Brief Descriptions of Subprograms

Name	Functions
Main Program (SIMFARS)	Input of various parameters including loop dimensions, initial conditions, etc. Update time and call TIMESU, ITERAT. Print of results
ITERAT	Execute iteration at each time step and find Q_a, Q_b, T_{ac}, T_{bc} and T_h.
TIMESU	Input of various parameters varying with time only —power, pump head, secondary loop condition, etc.
CALCU 1	Calculate friction and buoyancy term —$(FF)_a$, $(FF)_b$, $(FF)_v$, $(BF)_a$ and (BF_b)
CALCU 2	Calculate the heat transfer characteristics —$(U\Delta T_{lm})_a$ and $(U\ \Delta T_{lm})_b$.

between these subprograms are shown in Fig. 4. And Table 1 describes the subprograms briefly.

Many fluid properties varying with temperature are introduced as quadratic functions of temperature into our program.

IV. Sample Calculations

In order to examine the performance of the computer program, some sample problems are treated. Because experiments have not been carried out by the present author and it is impossible to find appropriate data, only the general trend can be examined. Input data, shown in Table 2, are based on the experimental system which is being fabricated by the author.

Three examples are treated in this article:

i) Transition from 2-loop to 1-loop operation.

ii) Transition from 1-loop to 2-loop operation.

iii) The transient behavior with decay power in the case of 2-loop operation.

Here, 1-loop operation means that the heat exchanger of loop-A is disordered and lost its cooling capability as a result.

Through the numerical experiments, it was found out that suitable values of the time interval, Δt, lie between 0.3 and 1.0 second. Attention should be paid in the selection of time interval, and it is taken as 0.5 second in the present calculations.

Computational results are shown in Figs. 5, 6 and 7. Neglecting small oscillations in the beginning of transients, which are believed to be numerical oscillations, it seems that the program simulate the general trend well. Comparing Fig. 6 with ref. 1 makes this conclusions sure.

It can be said from Fig. 5 that, although 1 heat exchanger is disordered, considerable flow still exists in that disordered loop and total flowrate is almost the same as that of 2-loop operation. But temperatures are higher in 1-loop operation. Fig. 7 shows that both the core

Table 2. Input Parameters for Sample Calculations

Parameters	Input values	Parameters	Input values
Loop dimensions		Secondary flow	
A_k	0.00173m^2	flowrate	1.0×10^{-3} m^3/s
A_c	0.000935	inlet temperature	13.0 °C
A_h	0.00173	Others	
A_r	0.0439	$R_{form,l}$	1.0×10^7
A_{dc}	0.0230	$R_{form,v}$	2.6×10^3
A_{lp}	0.0439	number of loops	2
A_{up}	0.0439	fouling factors	1.0×10^{-4}m^2-°C/W
A_2	0.00337	power	2.0 kW
L_h	2.80 m	time interval	0.5 s
L_c	1.70	iteration limits	
L_s	1.30	(error bound)	
L_r	0.26	flowrate	10^{-5}
L_{dc}	0.55	temperature	10^{-5}
L_{lp}	0.10		
L_{up}	0.30		
H_s	0.25		
H_r	0.10		
H_l	0.55		

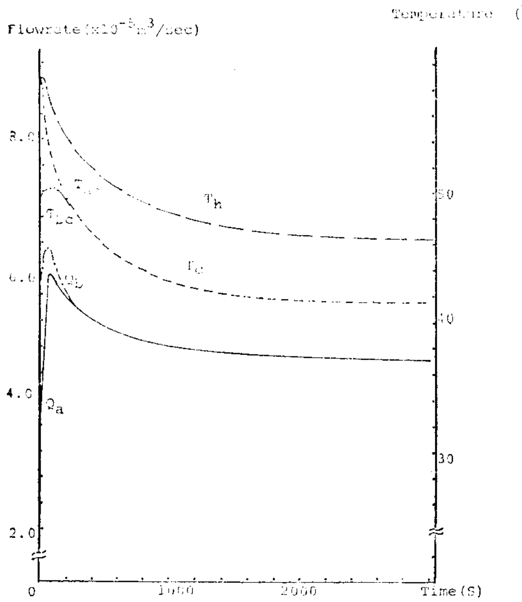

Fig. 5. Transition from 2-Loop to 1-Loop Operation

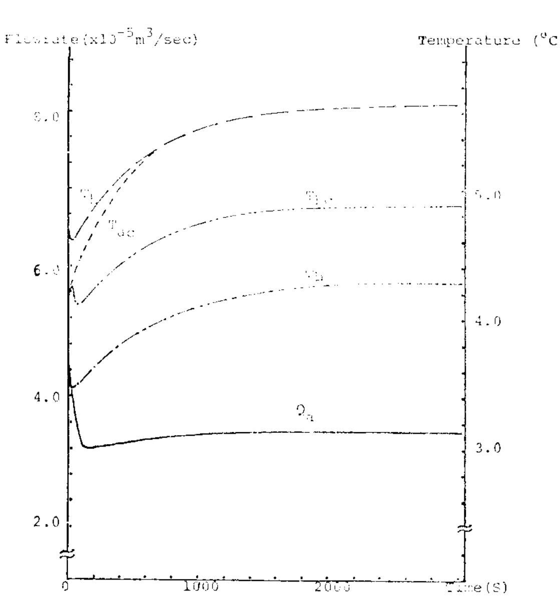

Fig. 6. Transient from 1-Loop to 2-Loop Operation

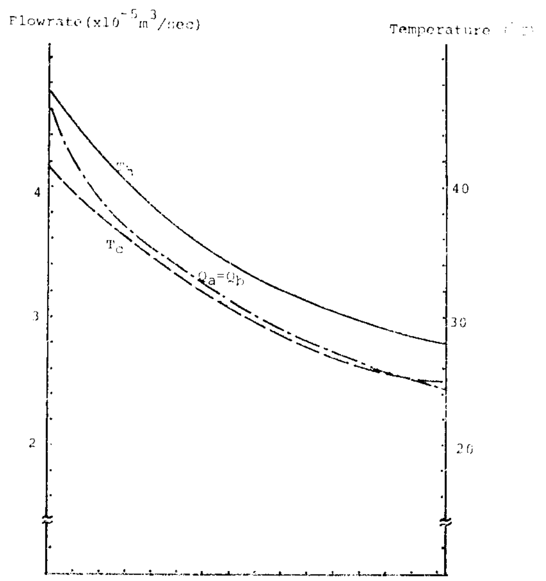

Fig. 7. Transient Behavior with Decay Power in the Case 2-Loop Operation

flowrate and temperatures are decreasing with decreasing power. It takes about 90 seconds in PRIME(~20 seconds in CYBER) to simulate 5000 second transient.

V. Discussion and Conclusions

Derivation and discussion of the governing equations, computer program and sample calculations are treated in previous sections. This work has some aspects to be improved although it is not bad in the simulation of the general behavior.

Some problems are as follows:

i) The program cannot describe the local behavior in the case of highly unusual transients.

ii) There is no reliable method to describe the heat transfer coefficient and friction factors in the transition region from laminar to turbulent flow.

iii) Flow in the vessel is not 1-dimensional.

iv) Complete mixing of the coolant does not occur at the entrance of downcomer.

v) Reasonable modelling of the heat exchanger and pressurizer are not contained.

Many other problems are involved, but most of them can be ignored in return for fast running.

Though above items may cause considerable errors in the computational results, those errors can be reduced by adequate modifications. And because it is intended to develop a fast running code, small errors are expected and permitted.

The assumption that the system is sustained at atmospheric level was made to introduce the various fluid properties as functions of temperature, and it does not have a great effect on the thermohydraulic behavior for the single-phase flow. For the application to PWR loss of flow accident analysis, the pressurizer model should be incorporated with this program. In that case, various properties should be introduced as functions of pressure and temperature through the simple modification. And the more experimental data are available, the more properly this program can be improved.

SIMFARS can be used for several purposes. Since it is not a detailed system code and fast-running, it can be applied to the operational transient analysis as well as safety analysis for the real-time computation. It is applicable to low pressure, low power reactors such as experimental reactors, LMFBRs and district heating reactors, and also applicable to the loss of flow accidents of various reactors with some modifications. It can be also said that the present program is a good starting point for the advanced fast-running system code development.

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