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# Development of a Computer Code, PZRTR, for the Thermal Hydraulic Analysis of a Multi-Cavity Cold Gas Pressurizer for Integral Reactor

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## Abstract

Development of the conceptual design of integral reactor, SMART (System-integrated Modular Advanced ReacTor), has been completed. The concept of cold gas pressurizer is applied to the SMART: Pressurizer is maintained at cold temperature of less than about 100 ℃, which is realized with coolers installed in and with wet thermal insulators installed on one of cavities located inside hot reactor vessel, to minimize the contribution of steam partial pressure and is filled with nitrogen gas as pressure-absorbing medium. The working medium and working temperature of cold gas pressurizer is totally different from that of hot steam pressurizer of commercial PWR. In addition, the gas pressurizer is intended to be designed to meet pressure transient during normal power operation (by its gas volume capacity) without using active control system and during plant heatup/cooldown operation with using active gas control system. Therefore in order to evaluate the feasibility of the concept of cold gas pressurizer and its intended design goal, thermal hydraulic behaviors and controllability of the cold gas pressurizer during transients especially heatup/cooldown operation must be analyzed. In this study, thermal hydraulic transient analysis computer code for Reactor Coolant System of integral reactor composed of a multi-cavity cold gas pressurizer, modular once-through steam generator, core and primary circuit, PZRTR, is developed. The pressurizer module of the PZRTR code is based on a two-fluid, nonhomogeneous, nonequilibrium model for the two-phase system behavior and the steam generator module is based on a homogeneous equilibrium model of two-phase flow process. The core module is simply based on axial power distributions and primary circuit is based on temperature distributions. The PZRTR code is currently dedicated to simulate the thermal hydraulic behavior of cold gas pressurizer during heatup operation. The mathematical models of complex thermal hydraulic phenomena of fluid mediums expected in the multi-cavity gas pressurizer are developed and are detailed. Using the developed code PZRTR, transient behavior of cold gas pressurizer during heatup operation is simulated and calculated results are discussed. The results show that the concept and design goal of cold gas pressurizer can be achieved under the condition of properly posed operational limit of heatup rate and the development of relevant operational procedures.

# 1. Introduction

The concept of cold gas pressurizer is applied to the SMART: Pressurizer is maintained at cold temperature of less than about 100 ℃, which is realized with coolers installed in and with wet thermal insulators installed on one of cavities located inside hot reactor vessel, to minimize the contribution of steam partial pressure and is filled with nitrogen gas as pressure-absorbing medium. The working medium and working temperature of cold gas pressurizer is totally different from that of hot steam pressurizer of commercial PWR. In addition, the gas pressurizer is intended to be designed to meet pressure transient during normal power operation without using active control system and during plant heatup/cooldown operation with using active gas control system. Therefore in order to evaluate the feasibility of the concept of cold gas pressurizer and its intended design goal, thermal hydraulic behaviors and controllability of the cold gas pressurizer during transients especially heatup/cooldown operation must be analyzed. In this study, thermal hydraulic transient analysis computer code for Reactor Coolant System of integral reactor composed of a multi-cavity cold gas pressurizer, modular once-through steam generator, core and primary circuit, PZRTR, is developed. The pressurizer module of the PZRTR code is based on a two-fluid, nonhomogeneous, nonequilibrium model for the two-phase system behavior and the steam generator module is based on a homogeneous equilibrium model of two-phase flow process. The core module is simply based on axial power distributions and primary circuit is based on temperature distributions. The PZRTR code is currently dedicated to simulate the thermal hydraulic behavior of cold gas pressurizer during heatup operation. The mathematical models of complex thermal hydraulic phenomena of fluid mediums expected in the multi-cavity gas pressurizer are developed.

# 2. Description of the Key Components

The major components of the SMART such as a multi-cavity gas pressurizer, modular once-through steam generator, main circulation pumps are integrated in a reactor vessel. Figure 1 shows an analytical schematic view of the SMART reactor system.

## 2.1 A Multi-cavity Cold Gas Pressurizer

The pressurizer system includes in-vessel pressurizer and out-of-vessel gas cylinders holding gas supply and connected with the reactor via piping with valves. On-load operation gas cylinders are connected from the in-vessel pressurizer by means of remotely controlled valves. Nitrogen is used as a working medium in the pressurizer system.

The in-vessel pressurizer is designed as a leaktight vessel and the system of pipelines consisting of a cover, which is a load-bearing structural component (being under the primary pressure and, at the same time, functions as a central cover of the reactor), cylindrical barrel and bottom. Inner space of the pressurizer is divided by a cylindrical partition into two cavities: end cavity (EC) placed in the center and intermediate annular cavity - at its periphery.

Lower part of the pressurizer intermediate cavity (IC) is connected via a pipeline to main reactor space, whereas its upper part is connected to lower part of the end cavity.

Heat transfer area of a single-row helical heat-exchanger/cooler is placed around the cylindrical partition in the intermediate cavity. The cooler maintains preset temperature mode under operation. Via threaded-soldered titanium-steel joints modules are grouped in 2 distributing and 2 collecting external headers (having 5 tubes each) placed on the pressurizer cover. The headers are connected to component cooling pipelines. Each pair of headers forms an independent section of the cooler which can be isolated from the system by valves.

One section of the cooler is constantly in operation. The second section is used during heatup operation and isolated at the end of heatup by valves for standby for the case of possible failure of the first one. Heat transfer area of each section is designed so as 4 out of 5 modules are sufficient to maintain temperature mode in the pressurizer.

Inner surface of cylindrical barrel and bottom of the pressurizer are coated with a multi-layer insulation (consisting of 20 layers) made of titanium sheets of about 0.2 mm thick. Gaps between the layers are filled with water. Design thickness of insulation is 20 mm. Figure 2 shows an analytical schematic view of the multi-cavity pressurizing system of the SMART; Top view shows the state of pressurizer at normal operation while bottom view shows the situations during heatup operation. The high-pressure nitrogen system is connected to gas cylinder and is used to supply a nitrogen gas to gas cylinder at the time required for increasing the system pressure during heatup operation.

### 2.2 A Once-Through Steam Generators

The steam generator (SG) for the SMART is included into the integral reactor and intended for generation of superheated steam during plant operation and for transfer of heat from the primary circuit during cooldown. The steam generator consists of a tube system (tubing), steam and feedwater pipelines located inside the reactor vessel, steam and water headers placed on the side wall of reactor vessel and outside steam and feedwater pipelines with isolation valves.

Figure 3 shows analytical schematic view of the SG tube (nodalized region of helical once-through steam generator tube). The SG heat transfer surface is placed in an annular gap between outer diameter and inner diameter which is constituted by inner surface of the vessel and outer surface of the core barrel. The SG heat transfer surface of a helical type is made of tubes and arranged in the form of twelve cassettes cylindrical in transverse section.

A heating coolant (primary circuit) flows outside the tubes. A heated one (secondary circuit) - feedwater, steam-water mixture, superheated steam – flows inside the tubes. Coolant flows in primary and secondary circuits are counter-current: The tube bundle of the SG heat transfer surface is flown over by the primary circuit coolant in transverse direction as it moves downwards. A general direction of the secondary coolant movement is from the bottom to the top.

## 3. The Mathematical Models of Quasi-steady Analysis of Primary Coolant Heatup

### 3.1 Models for A Multi-cavity Cold Gas Pressurizer

- Water Temperature in the Pressurizer

This mathematical model realized in PZRTR code is intended for analysis of slow processes in NSSS with in-vessel cooled pressurizer. The model allows to determine variations of temperature and pressure in the pressurizer during reactor coolant heatup from cold state to nominal parameters. The analytical scheme consists of two parts, i.e. the pressurizer scheme shown in Figure 2 and the scheme of the primary circuit which is modeled by three volumes with hot, cold and average temperatures of primary coolant shown in Figure 1.

The reactor can be heated with preset rate using control system of the core. Ideal operation of control system has been assumed for the analysis and therefore primary coolant temperature change rate was taken to be constant and preset, i.e. 40 °C/h.

During primary coolant heating, some portion of water is expelled to the pressurizer because of density change. As a consequence, steam-gas mixture volume is reduced, while primary pressure rises. Flow rate of water displaced to the pressurizer can be found as

$$G_{HP-U} = -\left[ V_{hp} \frac{\partial \rho_{hp}}{\partial T} \frac{\partial T_{hp}}{\partial \tau} + V_{cp} \frac{\partial \rho_{cp}}{\partial T} \frac{\partial T_{cp}}{\partial \tau} + V_{core} \frac{\partial \rho_{core}}{\partial T} \frac{\partial T_{core}}{\partial \tau} + V_{sg} \frac{\partial \rho_{sg}}{\partial T} \frac{\partial T_{sg}}{\partial \tau} \right]$$

where

$V_i$ = volume of a given section;

$\rho_i$ = average water density in this section;

$T_i$ = water temperature in this section.

Heatup proceeds in three successive stages, with the following cavities being filled during which of these stages: filling of upper annular cavity; filling intermediate cavity of the pressurizer; filling of end cavity of the pressurizer. At all stages all cavities exchange heat with each other and hot leg of the primary circuit. In addition, coolant displaced from the primary circuit contributes some amount of heat at each stage.

At the first stage displaced water with hot part enthalpy $h_{hp}$ enters upper annular cavity, fills it and raise temperature therein. During this time the other cavities receive heat only due to heat exchange between them and the primary circuit.

$$\begin{cases} \dfrac{dh_U}{d\tau} = \left[ G_{HP-U} \left( h_{hp} - h_U \right) + Q_{HP-U} + Q_{U-SL} - Q_{U-FWL} - Q_{U-I} \right] \dfrac{v_U}{V_{WU}} \\ \dfrac{dh_I}{d\tau} = \dfrac{Q_{HP-I} + Q_{U-I} + Q_{E-I} - Q_{HE}}{M_{WI}^{\min}} \\ \dfrac{dh_E}{d\tau} = \dfrac{Q_{HP-E} - Q_{E-I}}{M_{WE}^{\min}} \end{cases}$$

where

$V_{Wi}$ = water volume in $i$*'th* cavity

$v_i$ = specific water volume in $i$*'th* cavity

$M_{Wi}^{\min}$ = minimum water mass in $i$*'th* cavity.

Minimum water masses are entered in input data for calculations. It means minimum amount of water which may contain in upper annular cavity and pressurizer cavities after filling of the primary circuit. All heat fluxes are calculated by static correlations.

At the second stage intermediate cavity of the pressurizer is filled with water which enters there having enthalpy of water in upper annular cavity. As filling continues, cooler in the pressurizer starts to remove heat from intermediate cavity.

$$\begin{cases} \dfrac{dh_U}{d\tau} = \left[G_{HP-U}\left(h_{hp} - h_U\right) + G_U\left(h_{hp} - h_U\right) + Q_{HP-U} + Q_{U-SL} - Q_{U-FWL} - Q_{U-I}\right]\dfrac{v_U}{V_{WU}} \\ \dfrac{dh_I}{d\tau} = \left[G_{HP-U}\left(h_U - h_I\right) + Q_{HP-I} + Q_{U-I} + Q_{E-I} - Q_{HE}\right]\dfrac{v_I}{V_{WI}} \\ \dfrac{dh_E}{d\tau} = \dfrac{Q_{HP-E} - Q_{E-I}}{M_{WE}^{\min}} \end{cases}$$

where $G_U$ = coolant flow rate through upper annular cavity which is produced by MCP operation.

At the third stage end cavity of the pressurizer will be filled with water displaced from interim cavity.

$$\begin{cases} \dfrac{dh_U}{d\tau} = \left[G_{HP-U}\left(h_{hp} - h_U\right) + G_U\left(h_{hp} - h_U\right) + Q_{HP-U} + Q_{U-SL} - Q_{U-FWL} - Q_{U-I}\right]\dfrac{v_U}{V_{WU}} \\ \dfrac{dh_I}{d\tau} = \left[G_{HP-U}\left(h_U - h_I\right) + Q_{HP-I} + Q_{U-I} + Q_{E-I} - Q_{HE}\right]\dfrac{v_I}{V_{WI}} \\ \dfrac{dh_E}{d\tau} = \left[G_{HP-U}\left(h_I - h_E\right) + Q_{HP-E} - Q_{E-I}\right]\dfrac{v_E}{V_{WE}} \end{cases}$$

Water volume in upper annular cavity and pressurizer cavities is determined based on condition of water mass conservation in the primary circuit.

$$\sum_i \frac{V_{Wi}}{v_i} = M_{W\Sigma}$$

- Primary Pressure in the Pressurizer

Primary pressure is determined based on condition of gas mass conservation in the primary circuit.

$$M_{GU} + M_{GI} + M_{GE} + M_{GRB} = M_{G\Sigma}$$

where

$$M_{Gi} = \frac{P_{Gi}V_{Gi}}{RZ_{Gi}\left(T_i + 273\right)}$$

$P_{Gi} = P - P_S\left(T_i\right)$ = partial gas pressure in *i'th* cavity, [Pa]; Steam partial pressure is assumed to be at 100% humidity on gas temperature

$R$ = 296.93 = gas constant for nitrogen, [J/kmole·°C]

$Z_{Gi}$ = nitrogen compressibility coefficient

$T_i$ = temperature in *i'th* cavity, [°C].

- Gas Temperature in the Pressurizer

$$\frac{dE_j}{d\tau} = G_{jin}h_{in} - G_{jout}h_{out} + \dot{Q}_j + \dot{W}_j$$

where

$E_j$ = internal energy of gas mass in cavity j

$\dot{Q}_j$ = net heat transfer to the gas dome j from all sources.

$\dot{W}_j$ = work done to gas mass in cavity j by volume expansion/contraction.

Energy transport by convective heat transfer to the gas dome from the walls and fluid surface is modeled using an empirical Newton cooling law formulation. When the cavity is in its stagnant initial condition or at very slow transient state, the gas dome is saturated with water vapor. However, as the reactor coolant is heated up during heatup operation, there is vaporization at the liquid-gas interface. This mechanism transports a large amount of energy to the gas as a result of the heat of vaporization of the water. Assuming that the process can be approximated by a quasi-steady formulation, then for diffusion in a stagnant gas, the mass transfer for the process can be written as

$$\dot{M}_{vap} = -\zeta A_i \frac{dC}{dx}$$

where

$\dot{M}_{vap}$ = rate of vapor diffusion

$\zeta$ = diffusion coefficient

$A_i$ = surface area of the liquid-gas interface

$\frac{dC}{dx}$ = vapor concentration gradient.

Formulation and discussion on the concentration can be detailed in Reference [1].

Since the energy transported to the gas dome by the vaporization process must come from the liquid and since the energy per unit mass require for vaporization is $h_{fg}$, then the rate of energy transport to the gas dome by vaporization is

$$\dot{Q}_{vap} = \dot{M}_{vap} h_g (T_f)$$

3.2 Steady-State Models for A Once-through Steam Generator.

Modular steam generator with helical heat transfer surface consists of several cassettes connected in parallel and placed in the reactor vessel. In this analysis it was assumed that primary and secondary coolants are distributed uniformly in the cassettes.

The analysis involves integration of the following parameters along the length of a SG tube:

- primary coolant enthalpy $h_1$
- secondary coolant enthalpy $h_2$
- thermal power of one cassette $N_{12}$
- friction resistance in the secondary side $P_2$.

$$\begin{cases} \dfrac{dh_1}{dl} = \dfrac{k_l \cdot (T_1 - T_2)}{G_1^{cas}} \cdot N_t \cdot k_u \\ \dfrac{dh_2}{dl} = \dfrac{k_l \cdot (T_1 - T_2)}{G_2^{cas}} \cdot N_t \cdot k_u \\ \dfrac{dN_{12}}{dl} = k_l \cdot (T_1 - T_2) \cdot N_t \cdot k_u \\ \dfrac{dP_2}{dl} = -\zeta \cdot \dfrac{(G_2^{cas})^2 \cdot \upsilon_{f2}}{2 \cdot S_{2cas}^2} \end{cases}$$

where

$k_l$ –linear heat transfer coefficient,

$$\boldsymbol{k}_l = \frac{\pi}{\dfrac{1}{\alpha_1 \boldsymbol{d_o}} + \dfrac{1}{2\lambda} \mathbf{ln} \dfrac{\boldsymbol{d_o}}{\boldsymbol{d_i}} + \dfrac{1}{\alpha_2 \boldsymbol{d_i}}} \text{ [W/m]}$$

$\alpha_1$ and $\alpha_2$ – heat transfer coefficients in primary and secondary circuits, respectively
$d_o$ and $d_i$ – OD and ID of SG tube, [m]
$\lambda$ – thermal conductivity of tube metal, [W/m]
$T_1$ –primary coolant temperature, [°C]
$T_2$ –secondary coolant temperature, [°C]
$N_t$ – number of tubes in SG cassette
$k_u$ – heat transfer area utilization factor
$G_1^{cas}$ – primary coolant flow rate per one cassette, [kg/s]
$G_2^{cas}$ – secondary coolant flow rate per one cassette, [kg/s].

Depending on secondary coolant enthalpy, SG tube can be divided axially into the following parts: economizer part; evaporation part; steam superheating part. At each part heat transfer is calculated by its own correlations recommended by SG designer [2]. Heat equations are solved together with hydraulic path equation for the secondary coolant. Variation of secondary coolant pressure along SG tube is found from the following correlation

$$\frac{\boldsymbol{dP}_2}{\boldsymbol{dl}} = -\zeta \cdot \frac{(\boldsymbol{G}_2^{\boldsymbol{cas}})^2 \cdot \upsilon_{f2}}{2 \cdot \boldsymbol{S}_{2\boldsymbol{cas}}^2}$$

where $\zeta$ = hydraulic resistance coefficient composed of friction resistance and correction for flow spinning.

## 4. Numerical Solution Method

Numerical solution algorithm is shown in Figure 4.

## 5. Results and Discussion

Using the developed code PZRTR, transient behavior of cold gas pressurizer during heatup operation is simulated. In analysis, initial pressure and temperature of reactor system is 20 ℃ and 2 Mpa, respectively. When the reactor coolant temperature reaches 140 ℃ during heatup operation, gas filling system is initiated to supply a nitrogen gas up to the preset required mass. At this stage of gas filling operation, heatup operation is suspended. During gas filling operation, temperature and pressure of gas in a multi-cavity pressurizer increase continuously due to the flow work of insurged gas flow. After gas filling operation is completed, heatup operation is resumed until the core exit temperature reaches the zero power temperature of 301 ℃. At 40000 sec, one train of cooler is isolated and put into to normal standby position. Figures 5 shows temperature behaivior during heatup operation. Gas temperature of water in end cavity is around 72 ℃ and that of nitrogen is around 69 ℃, which are consistent to those of steady-state results and shows the feasibility of the realization method of the concept of cold pressurizer. Figure 6 shows water level and pressure behavior during heatup. The maximum peak pressure during heatup is about 16 MPa at 30000 sec (at the time that core exit temperature first reaches the target temperature of 301 ℃). Figure 7 shows the behavior N2 gas mass in cavities of pressurizer. At the end of heatup operation, the most portion of total N2 mass is in gas cylinder, which means that pressure buffering during transient is done mostly by the gas volume of gas cylinder. Figure 8 shows N2 gas flowrate through connecting surge lines between cavities. In general, the calculated results show that the concept and design goal of cold gas pressurizer can be achieved under the condition of properly posed operational limit of heatup rate and the development of relevant operational procedures.

## 6. References

6.1 RELAP5/MOD 3 code manual volume 1
6.2 SKBK: Steam generator with helically coiled heat transfer area, analytical method(IZH ER.500609.001)

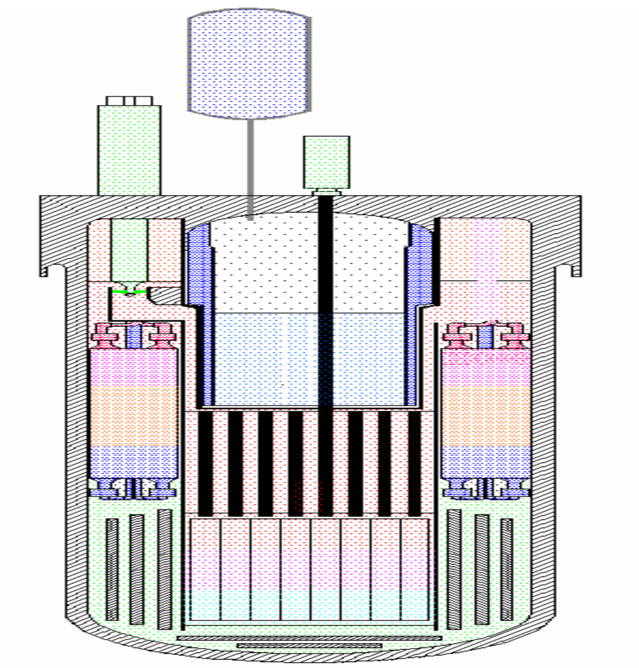

Figure 1  Reactor System of the SMART

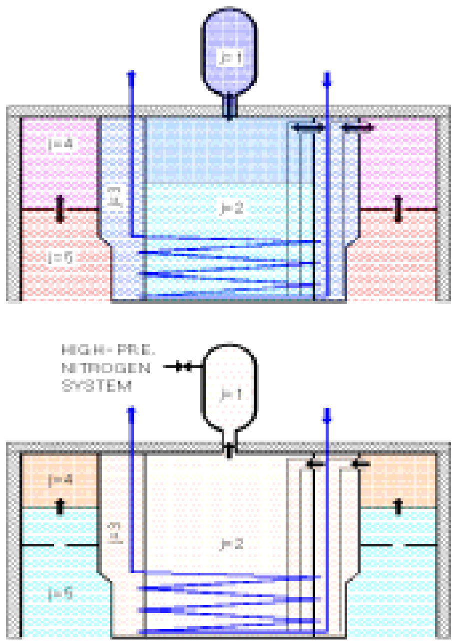


Figure 2  Multi-cavity Gas Pressurizer
(Top : normal / Bottom : heatup)

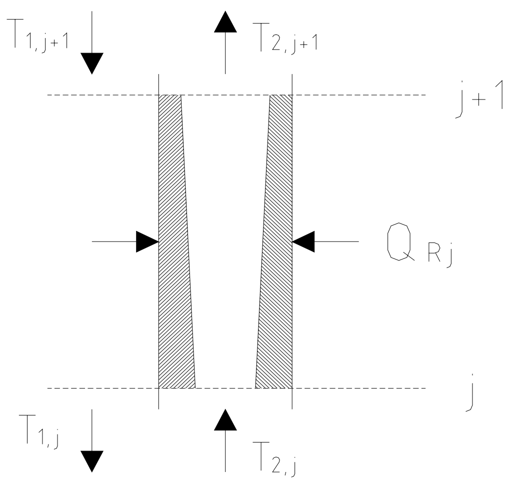


Figure 3  Nodalization of Helical Once-through Steam Generator

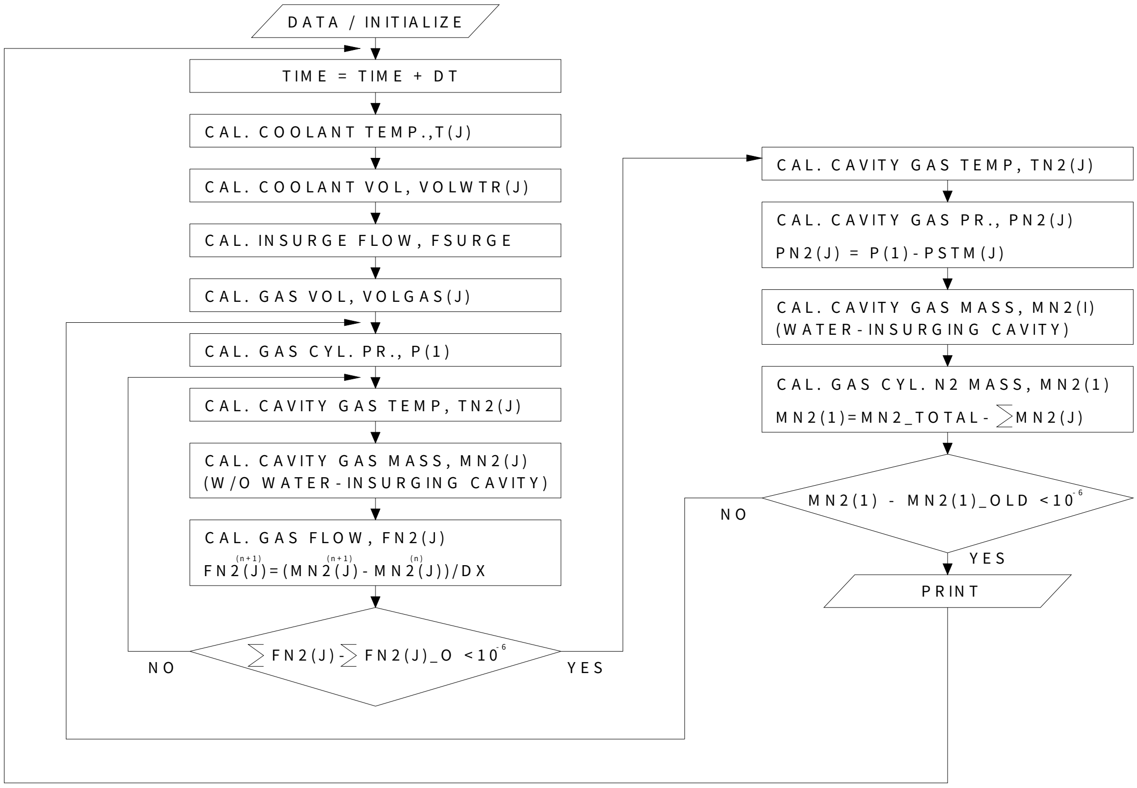


Figure 4 Numerical Solution Algorithm of PZRTR

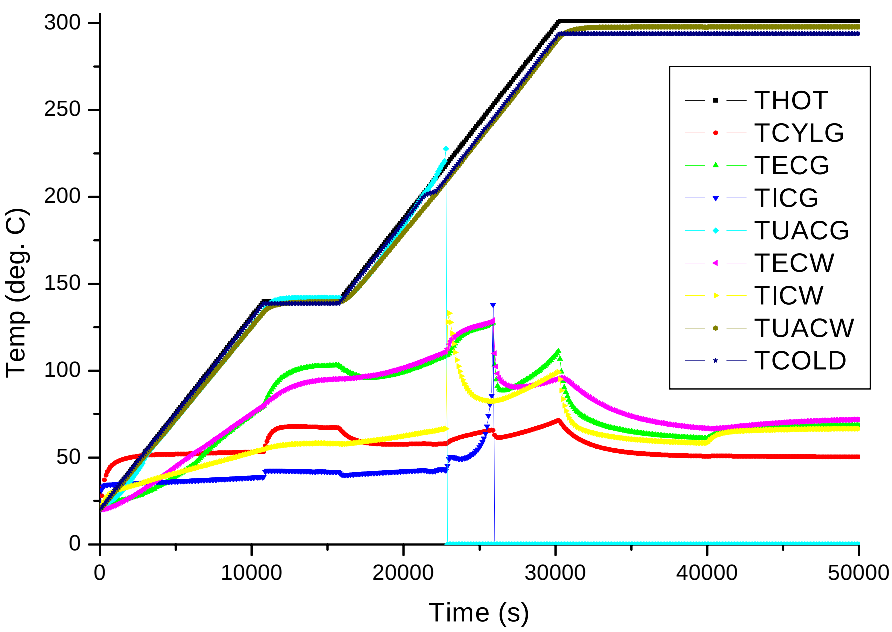


Figure 5 Temperature Behavior during Heatup Operation

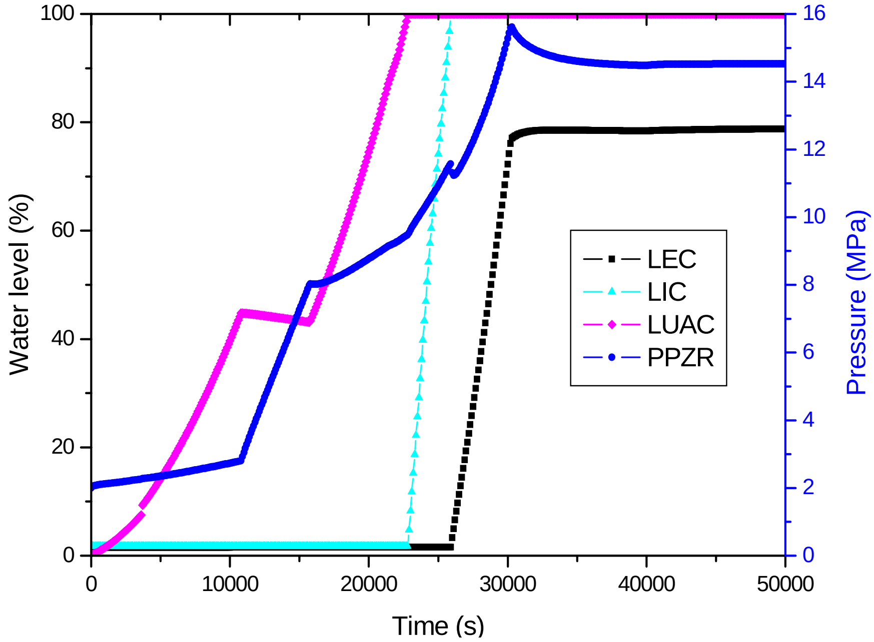


Figure 6 Water Level and Pressure Behavior during Heatup Operation

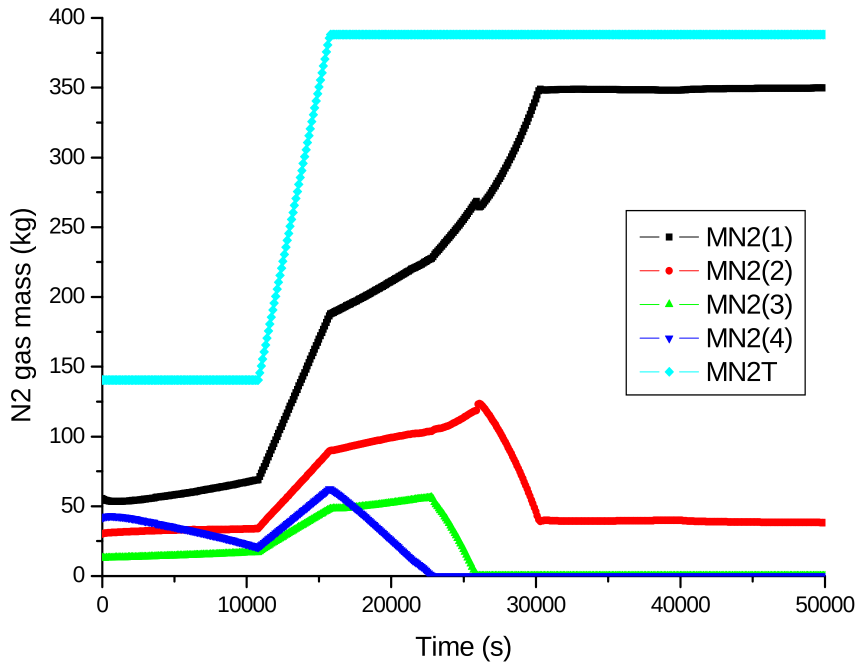


Figure 7 N2 Gas Mass Behavior during Heatup Operation

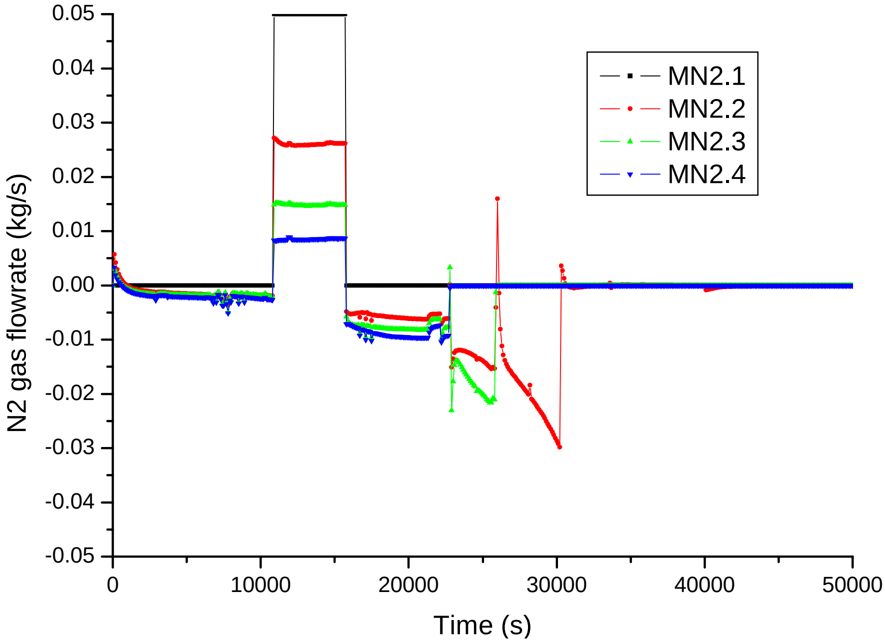


Figure 8 N2 Gas Flowrate Behavior during Heatup Operation