EXPERIMENTAL INVESTIGATION OF NATURAL CIRCULATION INSTABILITY IN A BWR-TYPE SMALL MODULAR REACTOR

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Abstract

The Purdue NMR (Novel Modular Reactor) represents a BWR-type small modular reactor with a significantly reduced reactor pressure vessel (RPV). Specifically, the NMR is one third the height and area of a conventional BWR RPV with an electrical output of 50 MWe. Experiments are performed in a well-scaled test facility to investigate the thermal hydraulic flow instabilities during the startup transients for the NMR. The scaling analysis for the design of natural circulation test facility uses a three-level scaling methodology. Scaling criteria are derived from

non-dimensional field and constitutive equations. Important thermal hydraulic parameters, e.g. system pressure, inlet coolant flow velocity and local void fraction, are analyzed for slow and fast normal startup transients. Flashing instability and density wave oscillation are the main flow instabilities observed when system pressure is below 0.5 MPa. And the flashing instability and density wave oscillation show different type of oscillations in void fraction profile. Finally, the pressurized startup procedure is recommended and tested in current research to effectively eliminate the flow instabilities during the NMR startup transients.

Keywords

Flow instability, NMR, Natural circulation test facility, Startup tests, Pressurized startup procedures

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Nomenclature

Latin Letters

A	Cross-sectional area [m^2]
a	Flow area [m^2]
C_p	Heat capacity [$\text{J/kg-}^\circ\text{C}$]
d	Diameter [m]
D	Hydraulic diameter [m]
f	Friction factor or Frequency [s^{-1}]

g	Gravitational acceleration [m/s^2]
k	Conductivity [$\text{W/m}^\circ\text{C}$]
K	Orifice coefficient [-]
l	Axial length scale [m]
l_o	Axial length of heated section [m]
$\dot{m}$	Mass flow rate [kg/s]
$\dot{m}_o$	Mass flow rate of heated section [kg/s]
N_f	Friction number [-]
N_{Fr}	Froude number [-]
N_o	Orifice number [-]
N_{sub}	Subcooling number [-]
N_{th}	Thermal inertial ratio number [-]
N_{zu}	Zuber (phase change) number [-]
$\dot{Q}$	Total heat transfer rate [W]
T^*	Characteristic time ratio [-]
x	Vapor quality [-]
v	Circulation rate [m/s]
V	Volume [m^3]

Greek Letters

α	Thermal diffusivity [m^2/s]
β	Volumetric thermal expansion coefficient [K^{-1}]
δ	Conduction thickness [m]
Δ	Difference [-]
Δi_{fg}	Latent heat [J/kg]
Δi_{sub}	Subcooling in terms of enthalpy [J/kg]
ρ	Mass density [kg/m^3]
τ	Time scale [s]

μ Dynamic viscosity of liquid [kg/m-s]

Subscripts

f Liquid

g Gas

h Heated section

i i th component

o Reference point/component (heated section)

R Ratio of model over prototype

S Solid

1. Introduction

With the continuous increasing demands for energy worldwide in the next decades, small modular reactors (SMR) can provide electricity in many countries and regions which lack advanced transportation systems and infrastructure. Compared to traditional nuclear reactors, SMR designs can be much safer, more economical, easier to construct, and simpler to operate. Some SMR designs, such as the Mitsubishi's Integral Modular Reactor (IMR) (Hibi et al., 2004), the Purdue University's Novel Modular Reactor (NMR) (Ishii et al., 2015), and the NuScale Power Reactor (Ingersoll, 2009) etc., have simplified the reactor system and integrated the passive safety systems by removing the primary coolant pumps. These SMRs are designed to operate and manage Design Basis Accidents (DBAs) under natural circulation cooling instead of traditional forced circulation cooling. Under such natural circulation conditions the system is prone to instabilities in system pressure, flow rate, core power, and cooling capability. The flow instabilities in a nuclear reactor can cause mechanical vibrations that challenge the structure integrity and even control difficulties that can result in a power excursion.

Density wave oscillation (DWO) is the most common dynamic instability (Boure et al., 1973) which occurs in natural circulation systems. Ishii (1971) concluded that DWO is caused by kinematic-wave (density wave) propagation, which is often called thermally induced flow instability. The mixture density and flow rate in two-phase flow are strongly coupled. DWO is also a low frequency oscillation with the wave propagation velocity close to flow velocity. Small perturbation methods (Ishii, 1971) can be utilized to derive the system transfer functions to obtain the stability map, which is widely used in stability analysis.

Flashing instability is another kind of dynamic instability and commonly observed in the system with a long riser. Lee and Ishii (1988) studied the flashing instability using Freon-113 as coolant in a test loop, which simulates the B&W light water reactor, after the Three-mile Island (TMI) accident. They found that the flashing in the riser section induced large amplitude oscillations and can last for several hours during tests. Other instabilities such as DWO still existed after the flashing instability. Flashing instability can be frequently seen during natural circulation boiling water reactor (NCBWR) startup. The saturated coolant leaves the core and becomes vapor due to the decrease of hydrostatic head in the adiabatic chimney. Aritomi et al. (1992) investigated the natural circulation instability induced by hydrostatic head in a test loop

with parallel channels. The oscillation periods became shorter with an increase in vaporization rate. Furuya et al. (2005) conducted experiments in a boiling natural circulation loop (SIRIUS-N) at low pressure. The flashing induced density wave oscillations were found in the chimney based on the passing time of single-phase liquid.

Condensation induced instability, which is called geysering instability by some scholars, is another kind of instability that can occur during the startup of boiling water reactor. Aritomi et al. (1992, 1993) explained this instability mechanism by studying the startup procedure for NCBWR. Geysering instability is induced by condensation and dependent on both inlet velocity and subcooled conditions. They found that the period of geysering instability is determined by the delay time for boiling of subcooled coolant at the channel inlet.

The objective of this study is to experimentally study thermal hydraulic flow instabilities that may occur in the NMR during reactor initial startup in a new natural circulation test facility, which is built based on the three-level scaling methodology (Ishii et al., 1996). Section 2 describes the NMR-50 design, test facility scaling and instrumentation. The experimental results and analyses are presented in Section 3. And the key conclusions of this research are summarized in Section 4.

2. Experimental approaches

2.1 Prototype description

The preliminary conceptual design of the NMR-50 is developed at Purdue Thermal Hydraulic and Reactor Safety Laboratory (TRSL) (Ishii et al., 2013; Ishii et al., 2015). Selected design parameters of the RPV are shown in Fig. 1 and Table 1. The Reactor Pressure Vessel (RPV) is 8.5 m in height and 3.6 m in inner diameter. Inside the reactor vessel, feedwater (FW) mixed with recirculated coolant flows through the downcomer to the core and then is heated. The steam-water mixture flows upward through the chimney, separator and dryer. The separated vapor leaves the steam dome through main steam line (MSL) and goes into the turbine.

2.2 Test facility scaling

For the scaling of a complex system such as nuclear reactor, a good scaling methodology is not only convenient to use but able to keep the most similarity between prototype and model. Ishii et al. (1996) developed a three-level scaling methodology for the design of Purdue

University Multi-dimensional Integral Test Assembly (PUMA). The scaling criteria come from series of dimensionless numbers, which are derived from dimensionless transfer functions based on the small perturbation technique and considering the whole system response. The important dimensionless numbers that govern the scaling of NMR-50 are summarized as follows:

The Zuber number, which is also phase change number, is used to scale the power level of the system.

$$N_{Zu} = \frac{\dot{Q}}{\dot{m}_o} \frac{\Delta\rho}{\rho_g \Delta i_{fg}} \propto \frac{\text{core enthalpy rise}}{\text{latent heat}} \quad (1)$$

The subcooling number scales the inlet subcooling of the heated section.

$$N_{sub} = \Delta i_{sub} \frac{\Delta\rho}{\rho_g \Delta i_{fg}} \propto \frac{\text{core inlet subcooling}}{\text{latent heat}} \quad (2)$$

The Froude number is required to scale the ratio of gravity and the inertia in both single-phase flow and two-phase flow.

$$N_{Fr} \equiv \frac{gl_o}{v_o^2} = \frac{\text{gravity}}{\text{inertia}} \quad (3)$$

The time ratio number scales the heat conduction inside the solid.

$$T^* \equiv \frac{\alpha_s l_o}{\delta_s^2 v_o} = \frac{\text{transport time}}{\text{conduction time}} \quad (4)$$

The thermal inertial number scales the energy storage in the solid structure, which is important in the transient analysis.

$$N_{th} \equiv \frac{\rho_s c_{ps} A_s}{\rho_f c_{pf} A_o} = \frac{\text{solid heat capacity}}{\text{liquid heat capacity}} \quad (5)$$

The Friction number for two-phase flow is required to scale the inlet flow resistance.

$$N_f = \left(\frac{fl}{d} \right)_i \left[\frac{1 + x(\Delta\rho / \rho_g)}{(1 + x\Delta\mu / \mu_g)^{0.25}} \right] / \left(\frac{a_i}{a_o} \right)^2 \quad (6)$$

The orifice number is required to scale the orifice flow resistance.

$$N_o = K_i \left[1 + x^{3/2} (\Delta\rho / \rho_g) \right] / \left(\frac{a_i}{a_o} \right)^2 \quad (7)$$

The similarity criteria between two different systems can be obtained from detailed consideration of the above dimensionless numbers. In the following analysis, subscript R denotes the ratio between the model and the prototype. Thus,

$$\psi_R \equiv \frac{\psi_m}{\psi_p} = \frac{\psi \text{ in the model}}{\psi \text{ in the prototype}} \quad (8)$$

Based on the three-level scaling method, the design of the Ideally Scaled Facility (ISF) for BWR-type SMR is firstly performed as a reference for the test facility without considering any engineering limitations. The ISF design is strictly scaled from NMR-50 with the same fluid and under the same full pressure, i.e. constant pressure scaling. Thus all the fluid properties can be considered identical between the prototype and the model:

$$\rho_{fR} = \rho_{gR} = \beta_{fR} = C_{pfR} = k_{fR} = \mu_{fR} = \mu_{gR} = \Delta i_{fgR} = 1 \quad (9)$$

The similarity criteria based on dimensionless numbers is

$$(N_{Zu})_R = (N_{sub})_R = (N_{Fr})_R = (N_{th})_R = (N_f)_R = (N_o)_R = 1 \quad (10)$$

In using these dimensionless parameters to scale the test facility, the length and area of the test facility for geometrical scaling have been determined based on a previous design of a simulated reactor core (Dixit, 2010; Dixit et al., 2013). Given these parameters for both the test facility and prototype, the natural circulation rate (velocity scale) ratio can be derived from the Froude number. From the phase change number, the power ratio has the same value as the mass flow rate ratio. The mass flow rate ratio is easy to determine from the flow area, fluid properties, and velocity ratio. Another important ratio is the hydraulic diameter ratio, which is derived from the time ratio number. Under these scaling ratios, the time scale of events is shortened in the scaled-down ISF by a factor of $l_{o,R}^{1/2}$. The ratios for the ISF prototypic pressure scaling are given in Table 2. The scaling analysis can be verified with RELAP5 code simulation (Siefken et al., 2001). Using the power curve scaled from that of GE's SBWR (Cheng et al., 1998) in Fig. 2, the startup transients can be simulated for the NMR-50 and the ISF. As can be seen in Fig. 3, the pressure responses in the NMR-50 and the ISF (before 20000 s) have a discrepancy of less than 0.1 %. The pressure spikes after 15000 seconds are due to the water level control inside RPV.

The natural circulation instability test facility, which is also defined as the Engineering Scaled Facility (ESF), is built based on the design of ISF. However, in this case engineering

limits such as the available pipe sizes must be considered. The important geometrical parameters for the test facility are given in Table 3. As can be seen, the height of the test facility is close to that of the NMR-50, but the core flow area is significantly scaled down at a ratio of 1/1164 by using a three-inch pipe. The scaling distortions between the ISF and the ESF are carefully examined and properly compensated. Table 4 shows the initial water mass and structure mass of the ESF for comparison with the ISF. For current research, the heat lost to the additional required metal components in the ESF is compensated separately through flexible electrical heaters wrapped around stainless steel flanges in the test loop.

In the RELAP5 analysis for the ESF startup transient, the power ramp used is identical to that for the ISF. The pressure during startup for both the ISF and ESF is shown in Fig. 4. As can be seen, the pressure is lower in the ESF than in the ISF due to larger initial water inventory and additional structural mass. An analysis of the total energy inventory of the ISF and ESF, based on the heat capacity of the coolant and structure and the masses given in Table 4, shows an expected discrepancy of 13% at $t = 17000$ seconds. This is due to reduced production of steam in the ESF, as more energy is required to reach saturation conditions due to the additional mass. The actual discrepancy is 14%, indicating that other scaling distortions have minimal effect.

2.3 Test facility configuration

A new natural circulation test facility was constructed based on the main geometrical parameters given in Table 3. The detailed schematics of the facility for the startup transients and quasi-steady tests are shown in Fig. 5. This test facility includes similar structures as the NMR-50 such as:

1. Lower plenum housing the unheated section of electrical heater rods,
2. Heated section (red part) simulating the core,
3. Chimney section (riser),
4. Separator and steam dome section, and
5. Downcomer (simplified by using pipes).

The core section has four cartridge heaters and has a layout of 2×2 . The overall length of the heater is 1.3 m and has a 19.05 mm O.D. The heated length of the electrical heater rod is 1.13 m. The maximum power of the heater rods is 20 kW. It is powered with a three-phase 480 VAC

source and controlled by Watlow SCR power controller with an accuracy of $\pm 0.5\%$ of the power output. The time constant difference between the reactor fuel rods and electrical heater rods is not important in the thermal hydraulic flow instability analysis (Woo, 2008). As shown in Fig. 5, the test facility has two heat exchangers in a secondary path. This alternate path is used for the degassing process and steam condensation during steady-state tests, however is isolated and unused during startup transient experiments.

2.4 Test facility instrumentation

The test facility is equipped with home-made impedance void meters, pressure transducers, thermocouples and magnetic flow meters. Seven instrument ports are installed in the core and chimney to measure different thermal-hydraulic parameters. Two Honeywell absolute pressure (AP) transducers are installed at the bottom of the inlet and top of the steam dome. Three differential pressure (DP) transducers are installed to measure the pressure differences for the following purposes: DP1 measures the inlet loss between the bottom of the downcomer and the core inlet; DP2 measures the pressure difference between the core inlet and core exit; DP3 measures the pressure difference between the chimney inlet and the steam dome. All the Honeywell ST3000 Smart Pressure Transmitters 100 series can offer an accuracy of $\pm 0.0375\%$ of the span. One Honeywell MagneW 3000 Plus Smart electromagnetic flow meters are installed in the downcomer section to measure the single phase natural circulation rate with an accuracy of $\pm 0.5\%$ of the readings. Several T-type thermocouples are embedded in the test section to measure the temperatures at different locations with an uncertainty of $1\text{ }^{\circ}\text{C}$. The impedance void meter is a key instrument for void fraction measurements. It can provide the void fraction by measuring the electrical impedance of two-phase flow. There are three impedance probes (IMP01 - IMP03) in the core section, and four (IMP04 - IMP07) in the chimney section. The calibration is performed by using differential pressure transducer to measure the density difference between single-phase liquid and two-phase mixture. And the compressed air is injected uniformly at the bottom of core inlet to generate two-phase mixture in the core section and chimney section. The calibration data for impedance probe 01 is shown in Fig. 6. A third order polynomial is used to determine the impedance void meter calibration. The accuracy of the impedance probes used to measure void fraction can reach 0.5% in absolute value for low void fraction measurement.

3. Test results

3.1. Normal startup transients

The normal startup transient experiments are performed at two different power ramp rates. The initial conditions can be seen in Table 5. The normal startup transient tests start from partially vacuum pressure, which can be obtained from cooling down the test loop after degassing procedure. The initial water level for startup transient is set at 5.85 m. Two linear power curves in Fig. 7 are selected to test slow heat-up and fast heat-up startup transients.

3.1.1. Slow heat-up startup transients

The steam dome pressure, temperature profile, and natural circulation rate for the slow startup transients are shown from Fig. 8 - 10. The total test time is about 220 minutes and the temperature increases at about 25°C/hr. The startup transient tested can be divided into four phases, i.e. single phase natural circulation (0-50 minutes), periodic flashing in chimney (50-100 minutes), core net vapor generation (100-160 minutes), and two-phase natural circulation (160-220 minutes). Figure 11 shows three pressure drop profiles at different locations of the test facility. The pressure drop at the core inlet (DP1) depends on the natural circulation rate and inlet flow resistance, so its profile is similar to that of the natural circulation rate. The pressure drop in the core section (DP2) is mainly caused by the flow regime in the core, so higher value means bigger void fraction. And the pressure drop in the chimney section (DP3) is largely determined by the flow regime and water level during the transients. The time traces of void fraction from the core exit to the chimney outlet are shown in Fig. 12 - 15. Among them, Figure 13 shows two sets of detailed void fraction (IMP03) at the core exit.

The coolant inside the loop is stagnant at the beginning. It takes several minutes to heat the coolant in the core to initiate the single phase natural circulation. And the first phase does not last very long and ends with the occurrence of flashing in the chimney. The system pressure and core inlet temperature start to increase after 50 minutes. Then the natural circulation rate oscillates intermittently due to the periodic occurrence of flashing at the top of the chimney, which can be seen from the void fraction profile (IMP07) between 50 and 100 minutes. The oscillation amplitude of natural circulation rate becomes much smaller at about 100 minutes. After that, the startup transients go into the phase of net vapor generation in the core section.

In the net vapor generation phase, more bubbles in the core can be generated due to decreasing of the core inlet subcooling and increasing power density. This period characterizes the fluctuating chimney inlet subcooling. As can be seen in Figs. 10 and 13, oscillations in natural circulation rate, which is defined as the single-phase velocity at the core inlet, can be observed with a period of around 6 minutes. By tracking the axial void fraction profiles in this period, it oscillates in an intermittent style. The void fraction becomes smaller at the chimney inlet (IMP04) due to condensation and grows bigger near the outlet of chimney (IMP07) due to flashing. Similar flashing phenomenon was also found by Lee and Ishii (1988) in their Freon-113 loop. They also pointed out that the period of flashing becomes shorter with higher power density, which is also observed during this test.

After 160 minutes the oscillations caused by flashing are damped and flow is stabilized due to less inlet subcooling and increasing system pressure. The two-phase natural circulation rate grows smoothly with increasing power density and void fraction. Density wave oscillations are observed from 170 minutes to 185 minutes, which can be recognized from the detailed void fraction profile shown in Fig. 13. The oscillation is continuous and close to sinusoidal wave, which is different from the intermittent flashing instability. However, density wave oscillations observed are in small amplitude and diminish with the rising system pressure and power density. No instabilities occur at pressure larger than 0.5 MPa, which is also confirmed by Woo (2008).

3.1.2. Fast heat-up startup transients

The steam dome pressure, temperature, and natural circulation rate for the fast startup transients are shown in Fig. 16-18. The axial void fraction profiles are shown in Fig. 19-22. The time used to raise the steam dome pressure to 0.8 MPa is about half of that in the slow heat-up. As can be seen in Fig. 18, similar flow fluctuation pattern occurs in fast startup transients and the period of flashing is shorter due to higher power density.

For the fast startup transients before 60 minutes, higher power density is beneficial for the development of single phase natural circulation. In the phase of core net vapor generation, the effect of power density on the flashing instability is not very obvious. However, flashing instability does not last long due to increasing power density and pressure and show similar intermittent oscillations in the void fraction as that of slow transients. The core power during this

phase is mainly used to remove the system subcooling before the generation of two-phase natural circulation.

In the two-phase natural circulation, density wave oscillations are observed from 80 minutes to 95 minutes. Figure 20 shows the detailed void fraction profile at the core exit. The magnitude of density wave oscillation observed in the fast startup transient is much larger than that in the slow startup transients. Natural circulation rate becomes stable again at the end of this phase.

3.2. Pressurized startup transients

The experimental results in above sections show that flow instabilities exist under different power ramp rates. The flashing instability occurs frequently during the transition to the two-phase natural circulation. The reason for the flashing instability in the chimney is that the decreasing hydrostatic head along the axial elevation is pretty sensitive to the system pressure. The solution to eliminate the flashing instability turns naturally to the pressurized startup procedure. The initial conditions for the pressurized startup procedures can be seen in Table 6. Same power curves shown in Fig. 7 are used for the pressurized startup transients. The key process in the pressurized startup procedures are to increase the pressure to 0.3 MPa at the beginning and vent when the pressure reaches 0.5 MPa. The non-condensable gas, i.e. nitrogen, can be used to pressurize the test facility after the degassing procedure. The two pressure limits are chose based on the test experiences and test facility itself. After the venting process at 0.5 MPa, the venting valve is closed and the startup transients continue until the pressure reaches operating pressure. This procedure can be used for both slow startup transient and fast startup transients. Here only the experimental results for fast pressurized startup transients are presented.

The experimental results for the fast pressurized startup transients are shown in Fig. 23 -24. The fast pressurized startup transients observed can also be divided into four phases, i.e. stable single phase natural circulation (0-90 minutes), net vapor generation (90-105 minutes), coolant evaporation (105-115 minutes), and two-phase natural circulation (after 115 minutes). The system pressure shown in Fig. 23 increases slowly in the single phase natural circulation phase and then rises almost exponentially after boiling begins at around 90 minutes. The two void fraction profiles in Fig. 25 and Fig. 26 do not show any void fraction signals at core exit and chimney exit before 90 minutes. And the flashing does not occur in chimney even when bubbles

are largely generated in the core part until 105 minutes. The system pressure drops slightly at about 105 minutes when the venting process starts. And the vapor evaporation at the top of the chimney is different from those during flashing instability. The natural circulation rate in Fig. 24 increases from 4 cm/s to 8 cm/s during the venting process. After the venting, the velocity decreases to 6 cm/s, which is the typical value for the two-phase natural circulation rate in this test facility. The stable two-phase natural circulation phase is not too long because the test stops at 0.8 MPa.

4. Conclusions

This paper studies the thermal-hydraulic flow instabilities during the NMR-50 startup transients. Two kinds of flow instabilities, i.e., flashing instability and density wave oscillations, are observed at different phases during the normal startup transients. Flashing instability occurs immediately after the development of single phase natural circulation. Flashing causes intermittent oscillations in the void fraction profile at the top of the chimney. After the flashing instability, the density wave oscillations can be observed at the beginning of the two-phase natural circulation but diminish with increasing system pressure. No flow instabilities can be observed in this test facility when pressure is over 0.5 MPa. The flow instabilities are not significantly affected by using different power ramp rates.

The pressurized startup procedure is investigated to eliminate the flashing instability during the startup transients for the NMR-50. The tests show that stable two-phase natural circulation can be successfully developed immediately after the loop vaporization during the venting process. And both periodic flashing instability and density wave oscillations do not occur during the whole pressurized startup transients.

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Caption of Figures

Fig. 1. NMR-50 RPV design parameters.

Fig. 2. Startup power ramp.

Fig. 3. RELAP5 prediction of pressure during startup for the NMR-50 and the ISF.

Fig. 4. RELAP5 prediction of pressure during startup for the ESF and the ISF.

Fig. 5. Schematic diagram of experimental loop.

Fig. 6. Calibration of impedance probe 01.

Fig. 7. Power curves for normal startup transients.

Fig. 8. Steam dome pressure for the slow normal startup transients.

Fig. 9. Core inlet temperature for the slow normal startup transients.

Fig. 10. Natural circulation rate for the slow normal startup transients.

Fig. 11. Differential pressures for the slow normal startup transients.

Fig. 12. Void fraction (IMP03) at the core exit for the slow normal startup transients.

Fig. 13. Detailed void fraction at the core exit (IMP03) for the slow normal startup transients.

Fig. 14. Void fraction (IMP04) at the chimney inlet for the slow normal startup transients.

Fig. 15. Void fraction (IMP07) at the chimney outlet for the slow normal startup transients.

Fig. 16. Steam dome pressure for the fast normal startup transients.

Fig. 17. Core inlet temperature for the fast normal startup transients.

Fig. 18. Natural circulation rate for the fast normal startup transients.

Fig. 19. Void fraction (IMP03) at the core exit for the fast normal startup transients.

Fig. 20. Detailed void fraction at the core exit (IMP03) for the fast normal startup transients.

Fig. 21. Void fraction (IMP04) at the chimney inlet for the fast normal startup transients.

Fig. 22. Void fraction (IMP07) at the chimney outlet for the fast normal startup transients.

Fig. 23. Steam dome pressure for the fast pressurized startup transients.

Fig. 24. Natural circulation rate for the fast pressurized startup transients.

Fig. 25. Void fraction (IMP03) at the core exit for the fast pressurized startup transients.

Fig. 26. Void fraction (IMP07) at the chimney outlet for the fast pressurized startup transients.

Caption of Tables

Table 1 RPV preliminary design parameters.

Table 2 Summary of derived ISF scaling ratios.

Table 3 Geometrical design parameters of test facility.

Table 4 Comparison of initial water mass and structure mass (Unit: kg).

Table 5 Initial conditions for the normal startup transients.

Table 6 Initial conditions for the pressurized startup transients.

Table 1 RPV preliminary design parameters

Component	Specification	NMR-50
RPV	Total height (mm)	8500
	I.D. (mm)	3600
	Wall materials	Low alloy steel
	Wall thickness (mm)	90
	Top of active fuel (TAF) elevation (mm)	2367
	Top of chimney (mm)	6386
	Top of separator tubes (mm)	7228
	Top of dryer skirt (mm)	7969
Core	Active fuel length (mm)	1372
	Core shroud I.D. (mm)	2950
	Core shroud wall thickness (mm)	50
Chimney	Chimney shroud I.D. (mm)	2861
	Chimney wall thickness (mm)	50
Separator	Separator tube diameter (mm)	93
	Separator tube thickness (mm)	3.08
	Number of separators	211
Dryer	Dryer skirt I. D. (mm)	2862
	Dryer skirt O. D. (mm)	2876

Table 2 Summary of derived ISF scaling ratios

Component	Scaled by
Length	$l_{o,R} = l_{h,R}$
Area	$a_{o,R}$
Volume	$V_{o,R} = a_{o,R} \times l_{o,R}$
Natural circulation rate	$v_{o,R} = \sqrt{l_{o,R}}$
Mass flow rate	$\dot{m}_{o,R} = \rho_{fR} v_{o,R} a_{o,R}$
Power	$\dot{Q}_R = \dot{m}_{o,R}$
Core hydraulic diameter	$D_{o,R} = \sqrt{l_{o,R}} / \sqrt{v_{o,R}}$
Time scale	$\tau_R = l_{o,R}^{1/2}$

Table 3 Geometrical design parameters of test facility

Component	Specification	Test facility
RPV	Total height (mm)	7000
	Wall materials	304 Stainless steel
	Wall thickness (mm)	3.0
	TAF elevation (mm)	1950
	Top of chimney (mm)	5260
	Top of separator tubes (mm)	5950
Core	Active fuel length (mm)	1130
	Hydraulic diameter (mm)	23.0
	Inner diameter (mm)	82.8
	Wall thickness (mm)	3.05
Chimney	Inner diameter (mm)	82.8
	Wall thickness (mm)	3.05
Downcomer	Inner diameter (mm)	54.8
	Wall thickness (mm)	2.77

Table 4 Comparison of initial water mass and structure mass (Unit: kg)

	ESF	ISF
Initial water inventory	54	52
Structure (except fuel assembly and flanges)	84	79
Fuel	15	23

Table 5 Initial conditions for the normal startup transients.

Pressure	Coolant temperature	Coolant level	Core inlet subcooling
(kPa)	(°C)	(m)	(°C)
55	84	5.85	18

Table 6 Initial conditions for the pressurized startup transients

Pressure	Coolant temperature	Coolant level	Core inlet subcooling
(kPa)	(°C)	(m)	(°C)
300	85	5.85	53

Fig. 1. NMR-50 RPV design parameters.

Fig. 2. Startup power ramp.

Fig. 3. RELAP5 prediction of pressure during startup for the NMR-50 and the ISF.

Fig. 4. RELAP5 prediction of pressure during startup for the ESF and the ISF.

Fig. 5. Schematic diagram of experimental loop.

Fig. 6. Calibration of impedance probe 01.

Fig. 7. Power curves for normal startup transients.

Fig. 8. Steam dome pressure for the slow normal startup transients.

Fig. 9. Core inlet temperature for the slow normal startup transients.

Fig. 10. Natural circulation rate for the slow normal startup transients.

Fig. 11. Differential pressures for the slow normal startup transients.

Fig. 12. Void fraction (IMP03) at the core exit for the slow normal startup transients.

Fig. 13. Detailed void fraction at the core exit (IMP03) for the slow normal startup transients.

Fig. 14. Void fraction (IMP04) at the chimney inlet for the slow normal startup transients.

Fig. 15. Void fraction (IMP07) at the chimney outlet for the slow normal startup transients.

Fig. 16. Steam dome pressure for the fast normal startup transients.

Fig. 17. Core inlet temperature for the fast normal startup transients.

Fig. 18. Natural circulation rate for the fast normal startup transients.

Fig. 19. Void fraction (IMP03) at the core exit for the fast normal startup transients.

Fig. 20. Detailed void fraction at the core exit (IMP03) for the fast normal startup transients.

Fig. 21. Void fraction (IMP04) at the chimney inlet for the fast normal startup transients.

Fig. 22. Void fraction (IMP07) at the chimney outlet for the fast normal startup transients.

Fig. 23. Steam dome pressure for the fast pressurized startup transients.

Fig. 24. Natural circulation rate for the fast pressurized startup transients.

Fig. 25. Void fraction (IMP03) at the core exit for the fast pressurized startup transients.

Fig. 26. Void fraction (IMP07) at the chimney outlet for the fast pressurized startup transients.