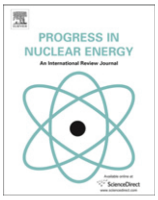
Progress in Nuclear Energy 53 (2011) 1181–1184

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene



Determination of a test section parameters for IRIS nuclear reactor pressurizer

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ARTICLE INFO

Article history:
Received 19 May 2010
Accepted 29 July 2011

Keywords:
Similarity
Fractional scaling
Dimensionless groups

ABSTRACT

An integral, modular and medium size nuclear reactor, known as IRIS, is being developed by Westinghouse and by research centers. IRIS is characterized by having most of its components inside the pressure vessel, eliminating the probability of accidents. Due to its integral configuration, there is no spray system for boron homogenization, which may cause power transients. Thus, boron mixing must be investigated. The aim of this paper is to establish the conditions under which a test section has to be built for boron dispersion analysis inside IRIS reactor pressurizer. Through Fractional Scaling Analysis, which is a new methodology of similarity, the main parameters for a test section are obtained. By combining Fractional Scaling Analysis with local scaling for the densimetric Froude number and a previously established volumetric scale factor, the values of recirculation orifices, inlet water temperature, time scale factor and recirculation flow for the test section (model) are determined so that boron distribution is well represented in IRIS reactor pressurizer (prototype). Analytical solutions were used to validate the adopted methodology and when the results simulated in the model are compared to those that characterize the prototype, the agreement for both systems is absolute. The thermal power also influences boron distribution inside the test section. This power is determined by condensation laws in the vapor region and by suitable correlations for free convection. The fractions for rising inlet recirculation water enthalpy and vapor formation are also considered.

1. Introduction

The pressurizer is an important component in PWRs, being responsible for pressure control in the cooling system. It maintains the core in a sub-cooled level, thus preventing the fuel from being exposed to hazardous situations. The cooling water level is also monitored by the pressurizer (Barroso and Baptista Filho, 2004), although there are situations in which this level must be determined directly (Wenran et al., 1998).

The pressurizer consists of a chamber in which vapor and liquid phases lie on the upper and lower portions, respectively. There is a spray nozzle in the top, while submerged heaters are located in the bottom. If there is a sudden rise in the coolant volume, promoting insurges in the pressurizer, the spray valves spread cold water to condense part of the vapor. On the other hand, if an outsurge takes place due to cooling events, heaters and natural flashing combine to rise the pressure to its normal value.

About twenty organizations from ten countries joined in a consortium-like organization, led by Westinghouse, to develop an integral, modular and medium size PWR. This reactor, known as IRIS, is characterized by having most of its components inside the pressure vessel, eliminating or minimizing the probability of accidents. Such a characteristic is known as ‘safety-by-deign’.

IRIS pressurizer is located in the upper portion of the pressure vessel. It consists of an insulated structure and acts as a divisor between the sub-cooled circulating coolant water and the saturated water inside the pressurizer. There are heaters and circulating orifices in the lower portion, and the latter are responsible for homogenizing boron concentration between primary coolant water and pressurizer saturated water, avoiding, thus, power transients in the case of outsurge events (Barroso et al., 2003).

The objective of this work is to obtain the main parameters for a low cost test section, in which experiments shall be performed to analyze boron dispersion between IRIS primary system and pressurizer.

2. Theory

2.1. IRIS pressurizer

The main parameter which is responsible for the adequate operation of a pressurizer is the ratio of vapor volume inside it and the reactor thermal power. Such a ratio indicates the capability of controlling pressure rises during heating transients. When

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0149-1970/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pnucene.2011.07.013

compared with conventional PWRs, this parameter is much greater in IRIS project. IRIS pressurizer also possesses a huge volume to accommodate liquid and vapor phases, providing a system pressure control without additional cost due to spray devices usually adopted in conventional pressurizers (Carelli et al., 2004).

The water inside IRIS pressurizer is separated from the subcooled primary water by an internal structure having an ‘inverted top hat’ shape. The mixing between these waters is accomplished by surge orifices appropriately positioned, providing necessary homogeneity of boron concentration.

The electrical heaters of IRIS pressurizer are designed to generate enough saturated water and vapor to prevent from pressure decrease during power rise in the turbine. Based on experimental data during transients in Shippingport reactor, Botelho et al. (2005) simulated outsurges with two and three volume models, obtaining nearly equal results independently of the adopted model. When applying such models to IRIS pressurizer, the same behavior was obtained, suggesting that IRIS pressurizer dynamics could be estimated when outsurge occurred.

2.2. Fractional scaling analysis (FSA)

A quantitative methodology was developed to scale time-dependent processes involving an aggregate of interacting modules, beyond organizing information to nuclear power plant design and safety analyses (Zuber et al., 2005). By applying FSA, it is possible to generate quantitative criteria for assessing the effects of design and operating parameters on thermal-hydraulics processes. This analysis is achieved at three levels: process, component and system and the validation was confirmed by using it in a LOCA (Loss of Coolant Accident).

To quantify the variation of a variable, δV, and considering a reference value, V_0, the fractional change or effect metric is defined by:

$$\Omega = \frac{\delta V}{V_0} \tag{1}$$

The effect metric can also be defined as the product of a fractional rate of change, ω, by the time interval, i.e.:

$$\Omega = \omega \cdot \delta t \tag{2}$$

Processes having the same effect metric are similar, inasmuch their variables undergo the same fractional change. When FSA is used, the similarity requires the equality of Ω values.

3. Methodology

The methodology of the present work is divided into five steps, namely:

a) Establishment of a physical model representing boron transfer inside the pressurizer;
b) Utilization of FSA to obtain the laws of scale;
c) Utilization of the densimetric Froude number to warrant local similarity;
d) Derivation of boron concentration equations to validate FSA;
e) Determination of thermal power for the model heater.

3.1. Establishment of a physical model for boron concentration transfer

The pressurizer is divided in three regions, as it is shown in Fig. 1. Surge orifices and heaters are located in the lower part of the pressurizer, named Region 1. The intermediate part, Region 2, is filled with saturated water, possessing recirculation orifices for boron homogenization. Region 3 is the upper part and it contains water vapor, condensate film and some droplets free of boron.

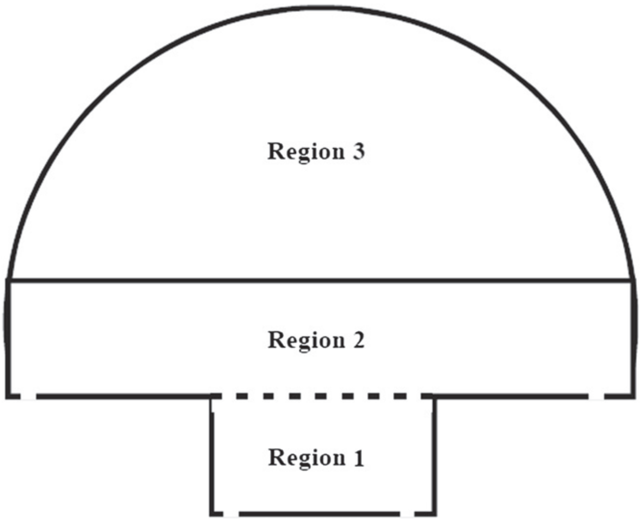

Fig. 1. Regions of IRIS pressurizer.

The bubbles generated in the heaters form an upstream flow that, when mixing with the entering jet, promote homogenization. Some bubbles cross Region 2, increasing the mass of vapor in Region 3. In the steady-state, the rate of vaporization in Region 1 is compensated by that of condensation in Region 3.

Although the water mass transfer between Regions 1 and 2 compensates, boron mass transfer does not: the bubbles from Region 1 that cross the border do not carry any boron, but the same mass rate from Region 2 brings borated water to Region 1. Water and boron mass balances are shown in Tables 1 and 2, in which C_1, C_2 and C_{in} represent the average concentrations in Region 1, 2 and primary circuit, respectively. During outsurges, the water leaving the pressurizer is not necessarily homogenized, being this the reason why at least two regions were considered.

Eqs. (3) and (4) represent the rates of boron mass in Regions 1 and 2, in which M_1 e M_2 symbolize water masses in Region 1 and 2, respectively.

$$\frac{d(M_1C_1)}{dt} = w_{circ}(C_{in} - C_1) + w_{cond}C_2 \tag{3}$$

$$\frac{d(M_2C_2)}{dt} = w_{circ}(C_1 - C_2) - w_{cond}C_2 \tag{4}$$

Table 1
Water and boron mass balance in Region 1.

Agent of variation	Water mass flow	Boron mass flow
Water inlet (w_{circ}) through surge orifice in Region 1	w_{circ}	$w_{circ} \cdot C_{in}$
Water inlet (w_{circ}) through surge orifice in Region 2	$-w_{circ}$	$-w_{circ} \cdot C_1$
Vapor outlet (w_{cond}) to Region 2	$-w_{cond}$	$-w_{cond} \cdot 0$
Water inlet (w_{cond}) from Region 2	w_{cond}	$w_{cond} \cdot C_2$
Balance	0 (zero)	$w_{circ} \cdot (C_{in} - C_1) + w_{cond} \cdot C_2$

Table 2
Water and boron mass balance in Region 2.

Agent of variation	Water mass flow	Boron mass flow
Water outlet (w_{circ}) through recirculation orifice in the bottom of Region 2	$-w_{circ}$	$-w_{circ}\cdot C_2$
Water inlet (w_{circ}) in Region 2	w_{circ}	$w_{circ}\cdot C_1$
Vapor inlet (w_{cond}) in Region 2	w_{cond}	$w_{cond}\cdot 0$
Vapor outlet (w_{cond}) to Region 3	$-w_{cond}$	$-w_{cond}\cdot 0$
Condensate inlet (w_{cond}) from Region 3	w_{cond}	$w_{cond}\cdot 0$
Water outlet (w_{cond}) to Region 1	$-w_{cond}$	$-w_{cond}\cdot C_2$
Balance	0 (zero)	$w_{circ}\cdot(C_1 - C_2)\cdot -w_{cond}\cdot C_2$

3.2. *Utilization of FSA to obtain the laws of scale*

During the startup or shutdown of a reactor, boron concentration must be changed by inserting another concentration in the primary circuit water. A homogeneous model is adopted for this concentration, as it is shown by Eqs.(5) and (6), in which C', M', w', C_E and C_0 represent, respectively, primary circuit boron concentration, primary circuit water mass, external water mass flow entering and leaving primary circuit, external reservoir boron concentration and initial primary circuit boron concentration.

$$C' = C_E + (C_0 - C_E)e^{-\alpha t} \tag{5}$$

$$\alpha = \frac{w'}{M'} \tag{6}$$

By applying FSA, boron concentrations are normalized by a maximum reference value, C_R. Eqs.(3) and (4) can be written as follows:

$$\frac{dC_1^\times}{dt} = \omega_1 \Phi_{in}^\times + \omega_1 \Phi_1^\times + \omega_2 \Phi_2^\times \tag{7}$$

$$\frac{dC_2^\times}{dt} = \omega_3 \Phi_3^\times + \omega_3 \Phi_4^\times + \omega_4 \Phi_5^\times \tag{8}$$

in which:

$$C_1^\times = \frac{C_1}{C_R} C_2^\times = \frac{C_2}{C_R} C_{in}^\times = \frac{C_{in}}{C_R} \tag{9}$$

$$\omega_1 = \frac{w_{circ}}{M_1} \omega_2 = \frac{w_{cond}}{M_1} \Phi_{in}^\times = C_{in}^\times \Phi_1^\times = -C_1^\times \Phi_2^\times = C_2^\times \tag{10}$$

$$\omega_3 = \frac{w_{circ}}{M_2} \omega_4 = \frac{w_{cond}}{M_2} \Phi_3^\times = C_1^\times \Phi_4^\times = -C_2^\times \Phi_5^\times = C_2^\times \tag{11}$$

Due to the homogeneous model used, the concentration entering the pressurizer, C_{in}, must have the same value of that one given by Eq.(5). The average fractional rate of change can be calculated by summing the individual fractional rates of change, each one multiplied by the respective agent of change signal, $\Phi^\times$, appearing in Eqs. (10) and (11).

$$\overline{\omega} = \omega_1 - \omega_1 + \omega_2 + \omega_3 - \omega_3 + \omega_4 = \omega_2 + \omega_4 \tag{12}$$

Since the average fractional rate of change is obtained, the effect metric of the whole system – the most important parameter according to FSA methodology – can be found by multiplying the term given by Eq. (12) by the related time:

$$\overline{\Omega} = \overline{\omega} t \tag{13}$$

FSA establishes also that each individual effect metric must have the same value so that similarity can be attained:

$$\Omega_j = \omega_j t \tag{14}$$

By applying Eq. (14) to ω_1 and ω_3 independently, one obtains the recirculation volumetric flow for the model, $Q_{in,m}$, as a function of physical properties of both systems (model and prototype), time (S_t) and volumetric (S_v) scales and prototype recirculation flow, $Q_{in,p}$. The terms ρ_m, ρ_p, $\rho_{in,m}$ and $\rho_{in,p}$ represent pressurizer water density for model, pressurizer water density for prototype, inlet water density for model and inlet water density for prototype, respectively.

$$Q_{in,m} = \frac{\rho_{in,p}}{\rho_{in,m}} \frac{\rho_m}{\rho_p} \frac{S_v}{S_t} Q_{in,p} \tag{15}$$

By using Eq. (14) to ω_2 and ω_4 independently, the condensation rate is obtained for the model, $w_{cond,m}$, and it is a function of physical properties of both systems, time and volumetric scales and prototype condensation rate, $w_{cond,p}$.

$$w_{cond,m} = \frac{\rho_m}{\rho_p} \frac{S_v}{S_t} w_{cond,p} \tag{16}$$

3.3. *Local similarity for the densimetric Froude number*

In a conventional pressurizer, homogenization is accomplished by spray lines that sprinkle cold water inside it. As there is no spray line in IRIS project, boron concentration will be homogenized by introducing recirculation (surge) orifices between primary circuit system and pressurizer.

Many authors who have studied mixing among fluids adopted a dimensionless parameter known as densimetric Froude number, given by Eq. (17), in which u_0, g, D, ρ_{in} and ρ represent inlet fluid speed, gravity acceleration, orifice diameter through which mixing occurs, inlet fluid density and environment fluid density, respectively.

$$Fr = \frac{u_0}{\sqrt{gD\left(\frac{\rho_{in} - \rho}{\rho}\right)}} \tag{17}$$

As homogenization is influenced by the inlet jet and this one depends on the densimetric Froude number, inlet water temperature and recirculation orifice must de combined so that both prototype and model must have nearly the same local densimetric Froude number in the orifice, since time similarity has been provided by FSA.

3.4. *Determination of the model heater thermal power*

The heater in the model must provide not only sensible and latent heats, but also supply thermal losses in the element representing the pressurizer. The portion of thermal power relative to sensible heat is given by Eq. (18), in which h_{sat} and h_{in} represent, respectively, the enthalpies of saturated and inlet water, while the other terms mean the same as ever mentioned.

$$\dot{Q}_1 = \rho_{in,m} Q_{in,m} (h_{sat} - h_{in}) \tag{18}$$

The portion of thermal power necessary to produce vapor is given by Eq. (19), in which w_{cond} and h_{lv} represent condensation

Table 3
Model variables.

Model parameter	Symbol	Value
Densimetric Froude number	Fr_m	0.1423
Inlet water temperature (K)	$T_{in,m}$	306.3
Time scale factor	S_t	0.196
Recirculation orifice (m)	D_m	0.0145

rate (equal to vaporization rate for steady-state condition) and vaporization enthalpy, respectively.

$$\dot{Q}_2 = w_{cond,m} h_{lv} \tag{19}$$

The term related to loss of energy, $\dot{Q}_3$, was accomplished by making a heat balance on the external wall of the element representing the pressurizer. Details for this procedure can be found in Silva (2008).

4. Results

4.1. Determination of the model variables for local similarity

Aiming to reducing costs, a 1:200 volumetric scale was adopted (under atmospheric pressure) for the model representing IRIS pressurizer. Since the parameters in IRIS are known, the densimetric Froude number at each recirculation orifice can be easily calculated by using Eq. (17). A program was developed to determine, considering economical aspects, the values for recirculation orifice diameter, inlet water temperature and time scale so that densimetric Froude number possesses the same value in the prototype and in the model, assuring local similarity. These model variables are shown in Table 3.

4.2. Determination of remaining parameters for the model

Since inlet and internal temperatures and time and volumetric scales were determined, Eqs. (15) and (16) were used to obtain, respectively, the recirculation flow and condensation rate for the element representing IRIS pressurizer.

$$Q_{in,m} = \frac{\rho_{in,p}}{\rho_{in,m}} \frac{\rho_m}{\rho_p} \frac{S_v}{S_t} Q_{in,p} = 1.367 \times 10^{-5} \mathrm{m}^3/\mathrm{s} \tag{20}$$

$$w_{cond,m} = \frac{\rho_m}{\rho_p} \frac{S_v}{S_t} w_{cond,p} = 4.069 \times 10^{-4} \mathrm{kg/s} \tag{21}$$

By applying Eqs. (10)-(13), the equality of average effect metric for prototype and model was confirmed as can be seen in Eqs. (22) and (23), although completely different operation conditions were specified for these systems, meaning that both have equal behavior.

$$\overline{\Omega_p} = \overline{\omega_p} t_p = 2.895 \times 10^{-6} t_p \tag{22}$$

$$\overline{\Omega_m} = \overline{\omega_m} t_m = \overline{\omega_m} S_t t_p = 2.895 \times 10^{-6} t_p \tag{23}$$

Table 4
Dimensionless fractional rates of change.

Dimensionless rate	Prototype	Model
$\hat{\omega}_1$	25.4676	25.4712
$\hat{\omega}_2$	0.7619	0.7621
$\hat{\omega}_3$	7.9585	7.9598
$\hat{\omega}_4$	0.2381	0.2381

Based on Eqs. (7)-(13), the dimensionless time rates of change for boron concentration in regions 1 and 2 were obtained, as can be seen in Eqs. (24) and (25), respectively.

$$\frac{\mathrm{d}C_1^\times}{\mathrm{d}t^\times} = \hat{\omega}_1 \Phi_{in}^\times + \hat{\omega}_1 \Phi_1^\times + \hat{\omega}_2 \Phi_2^\times \tag{24}$$

$$\frac{\mathrm{d}C_2^\times}{\mathrm{d}t^\times} = \hat{\omega}_3 \Phi_3^\times + \hat{\omega}_3 \Phi_4^\times + \hat{\omega}_4 \Phi_5^\times \tag{25}$$

in which:

$$\hat{\omega}_j = \frac{\omega_j}{\overline{\omega}} \tag{26}$$

with $j = 1–4$.

Since Eqs. (24) and (25) are dimensionless relative to concentration and time, both prototype and model should be described by the same equations. By comparing the values of terms given by Eq. (26) in Table 4, it can be seen that Eqs. (24) and (25) represent both systems with excellent accuracy. The validation of this methodology was also verified by Silva (2008) when the parameters of the model (obtained by FSA) were inserted in the analytical solution of Eqs. (24) and (25).

The thermal power in the model was evaluated by using Eqs. (18) and (19), considering also the loss term. It is intended to build a test section made of polycarbonate whose wall thickness is about 0.02 m. According to estimates done by Silva (2008), a thermal power equal to 5500 W is enough to maintain similarity between IRIS pressurizer and the test section described in this paper.

5. Conclusions

Through the combination of Fractional Scaling Analysis and local scaling, it was possible to determine the main parameters of a test section for boron dispersion analysis. This reduced scaled system provides many data which will help IRIS pressurizer construction. The results obtained by the above combination warrants similarity for the two systems with reduction in time and cost.

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