

DEVELOPMENT OF METHODS IN THE DESIGN OF A TEST SECTION FOR IRIS PRESSURIZER SIMULATION

Mário A. B. da Silva¹, Antonio C. de O. Barroso² and Carlos A. B. de O. Lira¹

¹ Universidade Federal de Pernambuco
Departamento de Energia Nuclear - CTG
Av. Prof. Luiz Freire, 1000 – Cid. Universitária
50740-540 Recife, PE
mabs250@yahoo.com.br
cabol@ufpe.br

² Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
barroso@ipen.br

ABSTRACT

In Pressurized Water Reactors, the pressurizer is responsible for regulating the pressure control in the cooling system. This component consists of a two-phase chamber. By a conveniently controlled action of spray and heaters, pressure is maintained within acceptable bounds.

The pressurizer conception in the innovative IRIS reactor is different when compared to a conventional PWR, giving rise to the need of additional analysis and experiments that may guarantee its performance. Nowadays, one of the important themes subjected to investigation is the homogenization of boron concentration in the circulating water between the primary and the pressurizer as a consequence of the new arrangement of the latter. The initial purpose of this work is to develop a set of conjugated methods that preserve the physical meanings of all mechanisms involved in the process, applying them in the design of a test section for carrying out experiments that simulate the conditions of the mixing of water from the primary circuit entering the IRIS pressurizer.

Simplified equations based upon Plume Model will be used for dispersion analysis, taking into account temperature and boron concentration differences between the primary circuit water and that of the pressurizer. Fractional Scaling Analysis will be utilized to provide the conditions of similarity for the most relevant processes, which will help develop a reduced scale test section.

1. INTRODUCTION

The achievement of experimental tests in many engineering projects utilizing structures having real dimensions demands high costs, difficulting the accomplishment of such tests. Thus, the use of models subjected to loads and dimensions that are different from those encountered in prototypes became an efficient way for analyzing structural problems.

The understanding of a phenomenon together with dimensional analysis make the generalization of experimental data possible, describing the phenomenon as a whole without being restricted to a specific experiment [1].

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 vessel, eliminating or minimizing the probability of severe accidents.

In the case of conventional pressurizers, there is a small continuous flow of primary water through the spray, which is compensated by another equal flow that goes out through the surge line, allowing a circulation between the reactor coolant system and the pressurizer water, warranting acceptable limits for occasional differences in boron concentrations. There are neither surge lines nor spray in IRIS pressurizer, but surge and circulation orifices that promote a circulation between the two media.

Through the use of Plume Model and Fractional Scaling Analysis, some conditions of operation have been obtained so as to design a test section preserving similarity between model and prototype. A test section shall be built based upon the preceding combination, providing experimental data which will help construct IRIS pressurizer.

2. THEORY

2.1. Theory for Dispersion of Jets and Plumes

The simplest case of turbulent jet flows is a simple momentum jet surrounded by a fluid of equal (or very close) density. If there is a density difference between the jet and the surrounding environment, then buoyant effects must be considered. Density stratification is also a very important point. For instance, in a stably stratified ocean, it is possible to prevent rising sewage jets from reaching the surface through induced mixing between the jets and the surrounding water [2].

The similarity of linear expansion of the nominal jet boundaries was shown experimentally, i.e., the jet width is proportional to its distance from the source [3]. The velocity distribution was shown to follow a Gaussian profile. The central longitudinal velocity was found to be inversely proportional to the distance from the source, and the volume flux over a cross section increased linearly with the distance from the source.

The equations of conservation of volume, momentum and density deficiency for a jet are, respectively [4]:

$$\frac{\partial}{\partial z}(b^2 w) = 2 \alpha b w \quad (1)$$

$$\frac{\partial}{\partial z}(b^2 w^2) = 2 \lambda^2 b^2 \Delta \quad (2)$$

$$\frac{\partial}{\partial z}(b^2 w \Delta) = \left(1 + \frac{1}{\lambda^2}\right) b^2 w \frac{\partial \Delta_a}{\partial z} \quad (3)$$

In Eq(1), (2) and (3), b represents the effective jet radius, w is the axial jet velocity evaluated on the jet axis; α is the empirical entrainment constant, λ is an empirical constant for density profile, Δ is the stratification evaluated on the jet axis, and Δ_a represents the tank stratification, given by:

$$\Delta_a = g \left(\frac{\rho_a - \rho_0}{\rho_0} \right) \quad (4)$$

where g is the gravity acceleration, ρ_0 is a reference density and ρ_a is the density profile of the tank.

By using vertical jets with water and salt, it was shown [5] that when a jet was penetrating a denser ambient, its velocity decreased down to zero, after which the plume fell over the original jet and formed a stationary profile as it is displayed in Fig. (1).

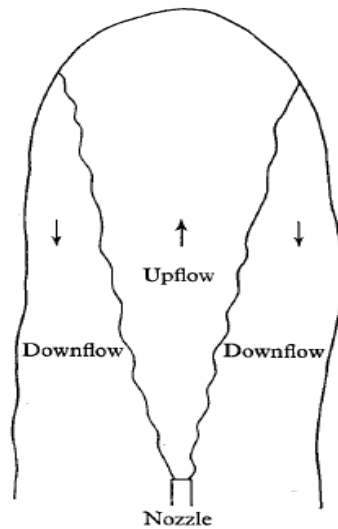


Figure 1 – Submersed jet profile in a lighter stagnant ambient

2.2. Fractional Scaling Analysis

A quantitative methodology was developed so as to scale time-dependent processes involving an aggregate of interacting modules, beyond organizing information to Nuclear Power Plant design and safety analyses [6]. Through Fractional Scaling Analysis (FSA), it is possible to generate quantitative criteria for assessing the effects of design and operating parameters on thermal-hydraulic processes. This analysis is achieved at three levels: process, component and system and its 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:

$$\Omega = \frac{\delta V}{V_0} \quad (5)$$

Processes having the same effect metric value are similar, inasmuch their variables undergo the same fractional change. When FSA is used, the similarity requires only the equality of Ω values [7].

3. METHODOLOGY

Initially, the first task was to determine a relation between the flow in the prototype, Q^p , and in the model, Q^m . Applying FSA to the equations of mass and boron concentrations and admitting that the total fractional rate of change is due to an entering jet (recalling that a flow exists even for steady-state condition), the following relations are found for the prototype and model:

$$Q_{in}^m = \frac{T_s}{V_s} \frac{(\rho' Q)_{in}^p \rho^m}{\rho^p \rho'^m} \quad (6)$$

$$\left(\frac{V_j}{V_{BL}} \right)_p = \left(\frac{V_j}{V_{BL}} \right)_m \quad (7)$$

In Eq(6), ρ' and ρ represent the entering and environment fluid density, respectively. V_s and T_s represent the inverse scale factors for volume and time, respectively; the subscript *in* refers to fluid entering the pressurizer. In Eq.(7), V_{BL} and V_j represent the bulk liquid and jet volume, respectively.

The next step was to make a discretization for Eq.(1) up to (3) by using Euler's Method [8], leading to equations (8), (9) and (10), respectively:

$$b_{i+1} = b_i + \left[2\alpha - \frac{g \lambda^2 b_i}{w_i^2} \left(\frac{\rho_a - \rho_i}{\rho_i} \right) \right] \Delta z \quad (8)$$

$$w_{i+1} = w_i + \left(\frac{2 \Delta z}{b_i w_i} \right) \left[g \lambda^2 b_i \left(\frac{\rho_a - \rho_i}{\rho_i} \right) - \alpha w_i^2 \right] \quad (9)$$

$$\rho_{i+1} = \frac{I}{b_i^2 w_i} \left[b_i^2 (\rho_a - \rho_i) w_{i+1} + 2 b_i w_i (\rho_a - \rho_i) b_{i+1} + b_i^2 w_i (4 \rho_a - 3 \rho_i) \right] \quad (10)$$

A code was developed by varying IRIS pressurizer surge orifice diameter from 3.0 cm up to 7.0 cm, once this value is not well defined yet, but will be probably inside this range. For each of these diameters, dimensionless group numbers were obtained varying the temperature of operation from 50°C up to 90°C and the test section surge orifice diameter varied from 10% up to 80% of the corresponding IRIS surge orifice diameter.

The volume scale factor was arbitrarily chosen as 1:200 and the inverse time scale factor varied from 4 to 6 for each condition cited above. Each dimensionless group was formed by three dimensionless numbers: the first one, R_{sc} , was the relation between the quotient of jet volume to the bulk liquid volume in the model to the corresponding in the prototype, that is:

$$R_{sc} = \frac{\left(\frac{V_j}{V_{BL}} \right)_m}{\left(\frac{V_j}{V_{BL}} \right)_p} \quad (11)$$

The jet was considered to have a conical shape whose height was calculated when the central jet velocity vanished. The second and third dimensionless parameters, Rs_{Re} and Rs_{Fr} were fixed as the quotient of Reynolds and Froude numbers in the model to the prototype, respectively, both calculated in the orifice conditions:

$$Rs_{Re} = \frac{Re_m}{Re_p} \quad (12)$$

$$Rs_{Fr} = \frac{Fr_m}{Fr_p} \quad (13)$$

For the complete similarity between the prototype and model, the three dimensionless parameters should equal one, but due to the quantity and complexity of the phenomena involved, the preservation of all parameters is not possible in the test section.

4. RESULTS

As the preservation of all dimensionless parameters is impossible, a fraction of each was considered by taking into account its relevance. The parameter defined in Eq.(12), obtained from FSA, had the greatest weight, a . The Reynolds number does not have a significant importance in mixing phenomena, receiving, thus, the least weight, b . The Froude number is currently taken into account in the mixing literature, having an intermediate weight, c .

A new dimensionless parameter, Obj , was defined as a function of Rsc , Rs_{Re} , Rs_{Fr} and of their respective weights; the Obj minimum value corresponded to the best test section conditions for similarity, leading to an optimization process:

$$Obj = abs(a.Rsc + b.Rs_{Re} + c.Rs_{Fr} - 1) \quad (14)$$

Fixing a scale for volume, the operation conditions for the test section were obtained through the data generated by the code. The data obtained after optimization are shown in Table 1, where Tot, Dot and 1/Ts represent the optimized values for temperature, surge diameter and inverse volume scale factor, respectively; RSCa represents the jet concentration ratio in the model to the prototype, while RSRea and RSFra represent the Reynolds and Froude ratios in the model to the prototype, respectively. For instance, for a 3.0 cm surge orifice diameter in the IRIS, the operation temperature, the surge orifice diameter and the inverse time scale for the test section were equal to 56.5°C, 1.92 cm and 4.72, respectively.

Table 1 – Optimized values for the test section parameters

D _{IRIS} (cm)	a	b	c	Tot (°C)	Dot (cm)	1/Ts	RSCa	RSRea	RSFra
3	0.9	0	0.1	56.5	1.92	4.72	1.094	0.0099	0.154
4	0.9	0	0.1	55.76	2.64	4.62	1.096	0.0093	0.139
5	0.9	0	0.1	55.84	3.26	4.65	1.095	0.0094	0.144
6	0.9	0	0.1	55.71	3.94	4.64	1.095	0.0094	0.141
7	0.9	0	0.1	55.8	4.66	4.51	1.096	0.009	0.132

Using Eq.(6), a value equal to 1.6 ml/s was obtained through this survey. A very close value (1.5 ml/s) was obtained when the same scaled parameters were used with another methodology [9].

5. CONCLUSIONS

A computer code based on jet dispersion and Fractional Scaling Analysis was developed to design a test section that will simulate power transients due to boron concentration change. The whole analysis was grounded in simple calculations. Depending on which parameter one wishes to preserve, the operation conditions for the test section were successfully obtained, supplying reliability for prototype construction.

REFERENCES

1. V. L. Streeter, E. B. Wylie, *Mecânica dos fluidos*, McGraw-Hill, São Paulo, Brasil (1980).
2. L. Fan, *Turbulent buoyant jets into stratified or flowing ambients fluids KH-R-15*, W.M. Keck Lab. of Hydraulics and Water Resources, Calif. Inst. Tech. Rep., United States (1967).
3. M. L. Albertson, Y. B. Dai, R. A. Jensen, H. Rouse, “Diffusion of submerged jets”, *Transactions of American Civil Engineering*, **115**, pp.639-697 (1950).
4. A. E. Germeles, “Forced plumes and mixing of liquids in tanks”, *Journal of Fluid Mechanics*, **71**, pp.601-623 (1975).
5. J. S. Turner, “Jets and plumes with negative or reversing buoyancy”, *Journal of Fluid Mechanics*, **26**, p.779-792 (1966).
6. N. Zuber, W. Wulff, U. S. Rohatgi, I. Catton, “Application of fractional scaling analysis (FSA) to loss of coolant accidents (LOCA) – Part 1”, *Proceeding of the 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11)*, Avignon, France (2005).
7. N. Zuber “The effects of complexity, of simplicity and of scaling in thermal-hydraulics”, *Nuclear Engineering Design*, **204**, pp.1-27 (2001).
8. D. Greenspan, V. Casulli, *Numerical Analysis for Applied Mathematics, Science and Engineering*, Addison-Wesley Publishing Company, United States (1988).
9. P. F. Peterson, V. E. Schrock, R. Greif, “Scaling for integral simulation of mixing in large, stratified volumes”, *Nuclear Engineering and Design*, **186**, pp.213-224 (1998).