EFFECTS OF POWER PUMP VARIATIONS IN THE THERMALHYDRAULICS BEHAVIOR OF A TEST SECTION DURING A CRITICAL HEAT FLUX EXPERIMENT

Pedro Carajilescov
Instituto de Energia, Pontifícia Universidade Católica do Rio de Janeiro
pcarajilescov@hotmail.com

Eloi Fernandez y Fernandez
Mechanical Engineering Dept., Pontifícia Universidade Católica do Rio de Janeiro
eloi@mec.puc-rio.br

Flávio da Costa Almeida
Mechanical Engineering Dept., Universidade Federal Fluminense
flaengmec@ig.com.br

Abstract. *Critical heat flux represents one of the major thermalhydraulics limits of PWR reactors. Usually empirical correlations of experimental data are used to verify the occurrence of this limit. To validate a design correlation, experimental data, obtained with test sections similar to the actual fuel elements, are required. In the development of the INAP-11, it has been considered to perform critical heat flux measurements utilizing the Experimental Thermal Loop, CTE-150, with a deviation where the test section would be installed. In such situation, the main flow that crosses the circulation pump would be divided in two parts, with the major part flowing through the original section of the loop while a small part would cross the test section. The present work analyses the effect of variations in the power pump in the transient flow in the test section.*

Keywords: *critical heat flux, transient flow, safety of nuclear reactor.*

1. Introduction

In PWR nuclear reactors, one of the major thermal hydraulic limits is represented by the occurrence of critical heat flux (CHF). In order to prevent its occurrence, the designer develops shut down curves based on empirical correlations of experimental data obtained in test sections that simulate the geometry and operational conditions of the reactor under consideration. The most important correlations adopted by the nuclear industry are the W-3 correlation (Tong, 1967) and the EPRI correlation (Reddy and Fighetti, 1983). In the case of the INAP-11, being developed by the CTM/SP, an analysis performed with experimental data available in the open literature has demonstrated that the EPRI correlation would yield better results than the W-3 correlation (Carajilescov, 1996). However, for licensing purposes, validation of the selected correlation is required, through comparison with experimental data obtained for the same geometry and operation conditions of the reactor INAP-11. So, it has considered performing CHF experiments utilizing the Experimental Thermal Loop, CTE-150, installed in the CTM/SP. Two main activities are required: (a) modification of the CTE-150 to accommodate the test section in a branch of the circuit, parallel to the original line, and (b) development of a test section with characteristics similar to the INAP-11 fuel elements.

The modification of the CTE-150 can be observed, schematically in Figure 1.

Regarding the test section, it has been considered to perform the experiment with a square test section, named S-1 test section, with 3 x 3 electrically heated rods, as shown in Figure 2.

The occurrence of critical heat flux or, as many authors prefer, “boiling crisis” is characterized by a sudden drop in the heat transfer coefficient due to a change in the boiling mechanism, leading to a temperature excursion of the heated wall. Considering the low thermal capacity of the electrically heated rods, such situation, even for short periods of time, might provoke large damages in the rods and, consequently, considerable money losses due to the replacement costs.

On the other hand, this kind of experiment is characterized by gradual increase of the electrical power been dissipated by the rods until the desired conditions are reached. During this process, several factor can affect the flow in the test section. One of these factors is related to the change in flow regime in the test section due to power increase (Carajilescov and Fernandez, 2005).

The present work analyses the thermalhydraulics behavior of the transient flow in the test section due to power variations in the circulation pump, which will yield a reduction in the pump pressure difference.

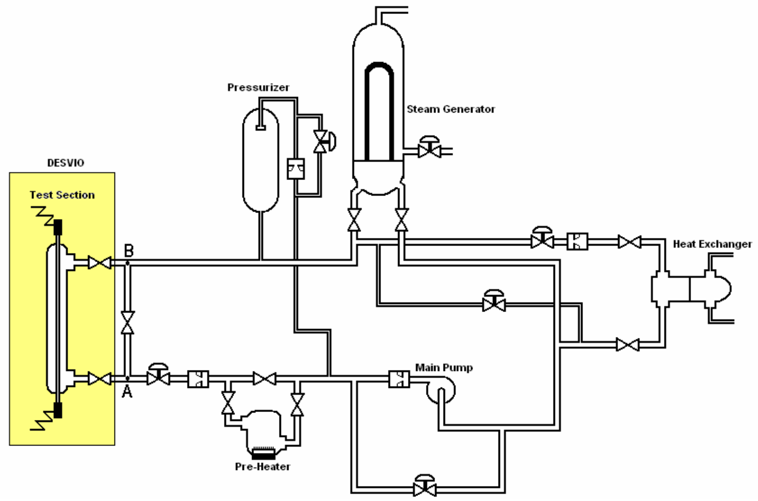

Figure 1. Experimental Thermal Loop CTE-150 with deviation for the test section.

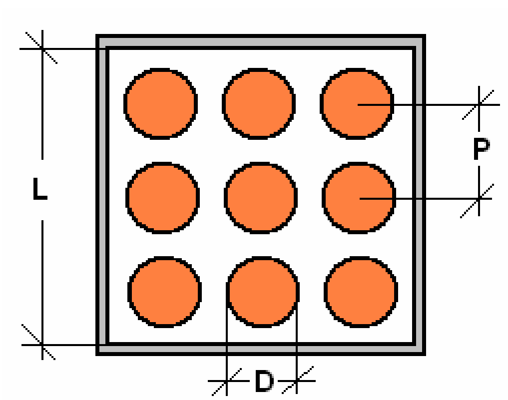

Figure 2. Cross section of the S-1 test section.

2. Theoretical modelling

Considering that the CTE-150 is a loop of large capacity, its flow can be taken as single phase, except in the deviation part, and can be represented by (Hirdes and Carajilescov, 1988):

$$\frac{L_T}{A}\frac{d\dot{m}_T}{dt} = \Delta P_B - \Delta P_T^F \tag{1}$$

where L_T and A represent the total length and cross sectional area of the ducts. In this equation, the first term in the right side represents the pump pressure difference, while the second one is the total frictional pressure drop of the loop.

The flow in the bypass is described by the equation:

$$\frac{L_{BP}}{A_{BP}}\frac{d\dot{m}_{BP}}{dt} = \Delta P_{AB} - \Delta P_{BP}^F - \rho_0 g H_{AB} \tag{2}$$

In this equation, H_{AB} represents the height of the AB section, as shown in Figure 1, ΔP_{AB} and ΔP_{BP}^F are, respectively, the total pressure drop, between points A and B, and the frictional pressure drop in the bypass. Obviously, $A_{BP} = A$.

In the deviation, where the test section is placed, the flow equation is given as:

$$\frac{L_{DESV}}{A_{DESV}}\frac{d\dot{m}_{ST}}{dt} = \Delta P_{AB} - (\Delta P_{DESV}^F + \Delta P_{DESV}^G + \Delta P_{DESV}^A) \tag{3}$$

The pressure drop terms, in the right side, represent the frictional, gravitational and acceleration pressure drops, respectively.

Considering that $\dot{m}_T = \dot{m}_{BP} + \dot{m}_{ST}$, equations (1-3) can be combined, resulting:

$$\frac{d\dot{m}_{ST}}{dt} = -\frac{a_{21}\phi_1 - a_{11}\phi_2}{a_{11}a_{22} - a_{12}a_{21}} \tag{4}$$

and

$$\frac{d\dot{m}_T}{dt} = \frac{a_{22}\phi_1 - a_{12}\phi_2}{a_{11}a_{22} - a_{12}a_{21}}, \tag{5}$$

where:

$a_{11} = -a_{22} = r\frac{L_T}{A}$, $a_{21} = \frac{L_T}{A}$ and $a_{12} = -\left(r\frac{L_T}{A} + \frac{L_{DESV}}{A_{DESV}}\right)$.

with **r** being given by $r = \frac{L_{BP}}{L_T}$. Obviously, $r \le 1$.

$$\phi_1 = (\Delta P^F_{DESV} + \Delta P^G_{DESV} + \Delta P^A_{DESV}) - (\Delta P^F_{BP} + \rho_0 g H_{AB})$$
$$\phi_2 = \Delta P_B - (\Delta P^F_{BA} + \Delta P^F_{BP}).$$

In order to obtain the pressure drop in the deviation, that section was divided in three parts, with the first one representing the entrance region, the second, the heated length of the test section and the last one being the exit region.

Since the frictional pressure drop, in any part of the loop, was considered to be given by:

$$\Delta P^F = K \bullet \dot{m}^2_{ST}, \tag{6}$$

the frictional pressure drop, in the deviation, can be represented by:

$$\Delta P^F_{DESV} = \left[K_E + K_{ST}\left(\frac{h_{sat}}{H}\right) + K_{ST}\left(1 - \frac{h_{sat}}{H}\right)\frac{\rho_0}{\left(\frac{\rho_0 + \rho_S}{2}\right)} + K_S\left(\frac{\rho_0}{\rho_S}\right)\right] \bullet \dot{m}^2_{ST} \tag{7}$$

where the indexes E and S correspond to the entrance and exit regions.. In this expression, h_{sat} represents the saturation height of the heated length of the rods

The gravitational pressure drop, in the deviation, is given by:

$$\Delta P^G_{DESV} = \rho_0 g H_E + \rho_0 g h_{sat} + \left(\frac{\rho_0 + \rho_S}{2}\right) g (H - h_{sat}) + \rho_S g H_S \tag{8}$$

Finally, the acceleration pressure drop can be written as:

$$\Delta P^A_{DESV} = \frac{1}{A^2_{ST}}\left(\frac{1}{\rho_S} - \frac{1}{\rho_0}\right) \bullet \dot{m}^2_{ST}. \tag{9}$$

Equations (4) and (5) were solved by the forth-order Runge-Kutta method.

For parametrization, it was adopted the following relationships:

(a) $r = \frac{L_{BP}}{L_T}$, representing the ratio between the bypass length and the circuit total length.

(b) $\gamma = \frac{K_{BP}}{K_T}$, which gives the ratio between the frictional pressure drop factor for the bypass and the whole loop. It should be observed that these factors include the duct and all localized obstacles in the loop, such as valves, bends, contractions and expansions and so on.

Obviously, the factors **r** and γ will vary between zero and the unity, depending on the localization of the deviation for the test section and of the obstacles in the circuit, particularly in the bypass section.

The pressure drop by friction, in the test section, was calculated utilizing the overall friction factor that includes the rods and the grids, given by (Franco and Carajilescov, 2000):

$$\mathbf{f}^{*} = 0.90 \bullet \mathbf{Re}^{-0.25}. \tag{10}$$

From the thermal point of view, the flow analysis, along the heated length of the test section, was performed by finite differences, dividing the region in control volumes, according to Figure 3

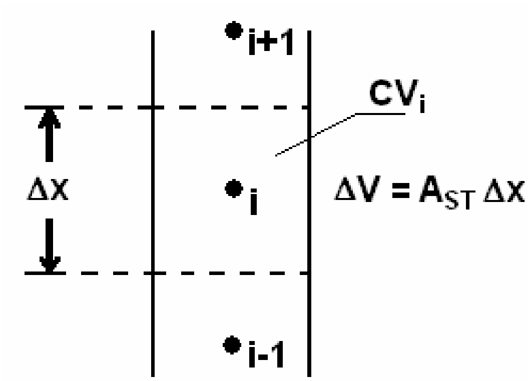

Figure 3. Control volume.

Let $\dot{m}_{i,n}$ be the flow crossing the border between control volumes **i** and **i+1**, in the time step **n**. The mass and energy balances, in the control volume CV_i give:

$$\dot{m}_{i,n+1} = \dot{m}_{i-1,n+1} - \frac{\Delta V}{\Delta t}\left(\rho_{i,n+1} - \rho_{i,n}\right) \quad \text{and} \tag{11}$$

$$h_{i,n+1} = \frac{\left(\rho_{i,n}\Delta V + \dot{m}_{i-1,n+1}\Delta t\right)}{\left(\rho_{i,n+1}\Delta V + \dot{m}_{i,n+1}\Delta t\right)} h_{i-1,n+1} + \frac{p_w \Delta x \Delta t}{\left(\rho_{i,n+1}\Delta V + \dot{m}_{i,n+1}\Delta t\right)} q''_{i,n+1} \tag{12}$$

In equation (12), h represents the fluid enthalpy, p_w is the wetted perimeter and q" is the local heat flux.

In the solution of these equations, it was adopted:

$$\rho_i = \alpha_i \rho_g + (1 - \alpha_i)\rho_f \ ,$$

where α_i is the void fraction in the control volume. Assuming the non-sliping condition, the void fraction is given by:

$$\alpha_i = \frac{1}{1 + \left(\frac{1 - x_i}{x_i}\right)\left(\frac{\rho_g}{\rho_f}\right)} \ ,$$

with the flow quality given by $x_i = \frac{h_i - h_f}{h_g - h_f}$

For prediction of occurrence of critical heat flux, the EPRI correlation was utilized.

3. Results

The developed model was applied considering the design parameter of the loop and test section as presented in Table 1.

Table 1. Design parameter of loop and test section.

PARAMETER	UNITY	VALUE
EXPERIMETAL LOOP		
Nominal diameter of piping	in	4
Inside diameter of piping	m	0.0873
Estimated length of piping	m	35
Deviation heigth	m	3.5
TEST SECTION		
Rod diameter	m	0.010
Array pitch	m	0.0133
Heated length	m	1.00
Number of rods		9
Lateral length of test section duct	m	0.0399
Axial power distribution		uniform
Radial power distribution		uniform

The initial conditions of simulation are presented in Table 2.

Table 2. Initial operational conditions for simulations.

PARAMETER	UNITY	VALUE
DP of main pump	bar	16
Total flow rate	Kg/s	21
Flow rate in test section	Kg/s	0,6
Pressure in pressurizer	bar	130
Inlet temperature in test section	degrees C	265
Initial heat flux	Mw/m2	1,20

The tests were performed considering a decrease of **5%** in the pressure difference of the main pump, after a period of **0.5 s** after the beginning of the experimental run, for the situations presented in Table 3.

Table 3. Simulated cases.

	Case 1	Case 2
factor r	0,10	0,10
factor γ	0,02	0,20

Figure 4 shows the total and bypass flow rates as function of time. It can be observed the factors **r** and γ do not affect the bypass and total flow rates. However, tests have shown that the factor γ has a strong effect on the test section flow rate while the factor **r** will produce only minor changes. So, the variations observed in Figure 5 can be attributed only the variation of the factor γ. Since, in case 1, there is only a small flow resistance in series with the test section, the flow rate responds promptly to the reduction in the pressure difference, recovering part of the flow after the response of the loop. So, a new steady flow is reached about 1.0 s after the beginning of the transient.

Due to the test section flow rate variation, depending on the initial heat flow, boiling crisis will occur as shown in Figure 6. The parameter MDNBR (minimum departure from nucleate boiling ratio) represents the ratio between the local and the critical heat fluxes, given by the EPRI correlation, at exit section of the test section.

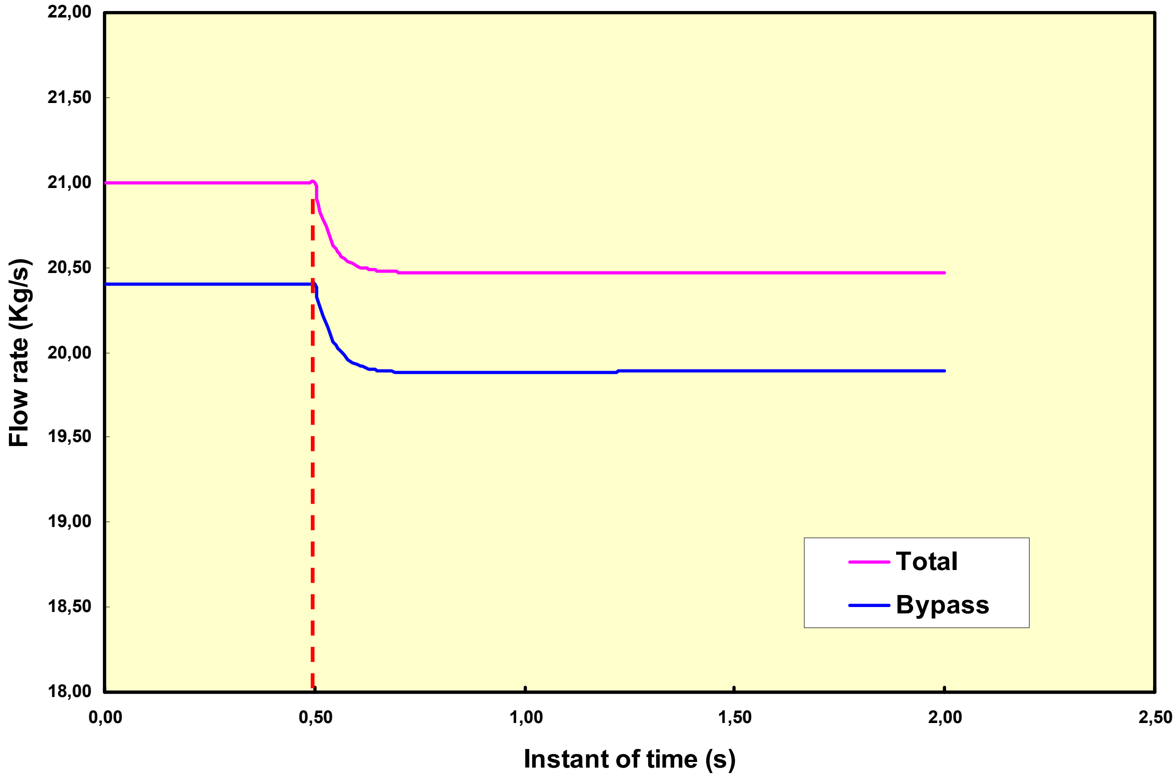

Figure 4. Bypass and total flow rates as function of time.

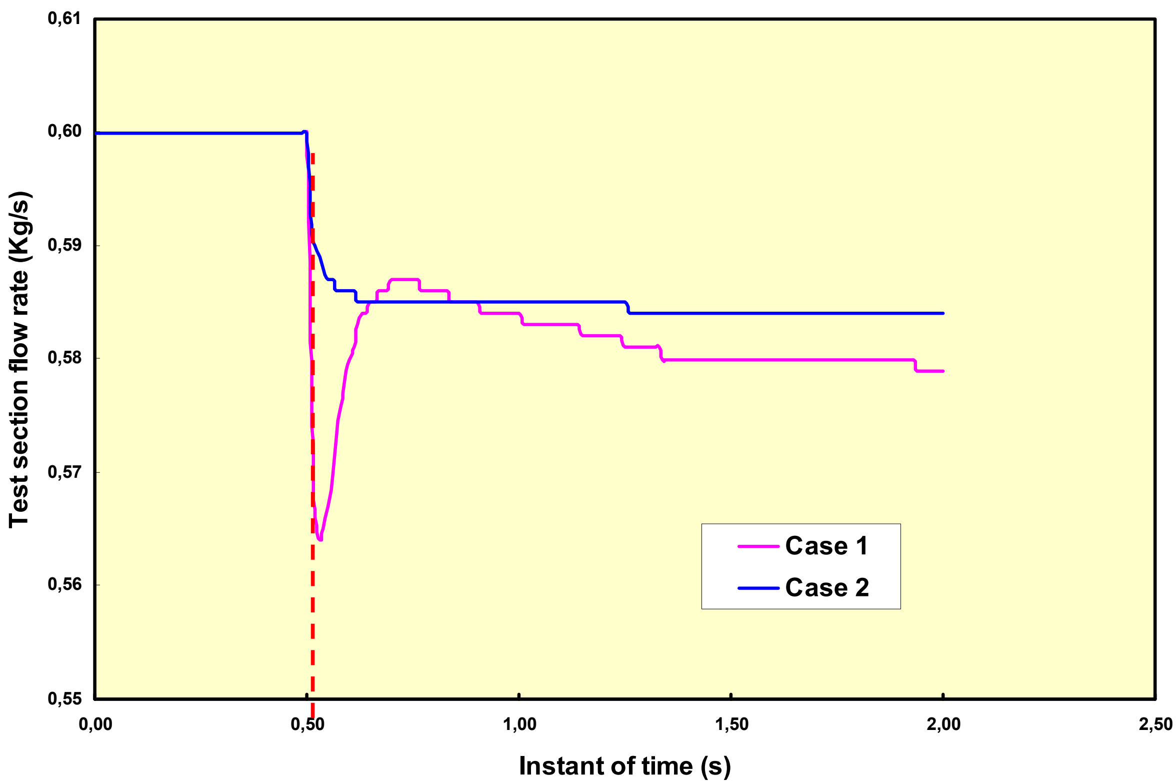

Figure 5. Time variations of the test section flow rate.

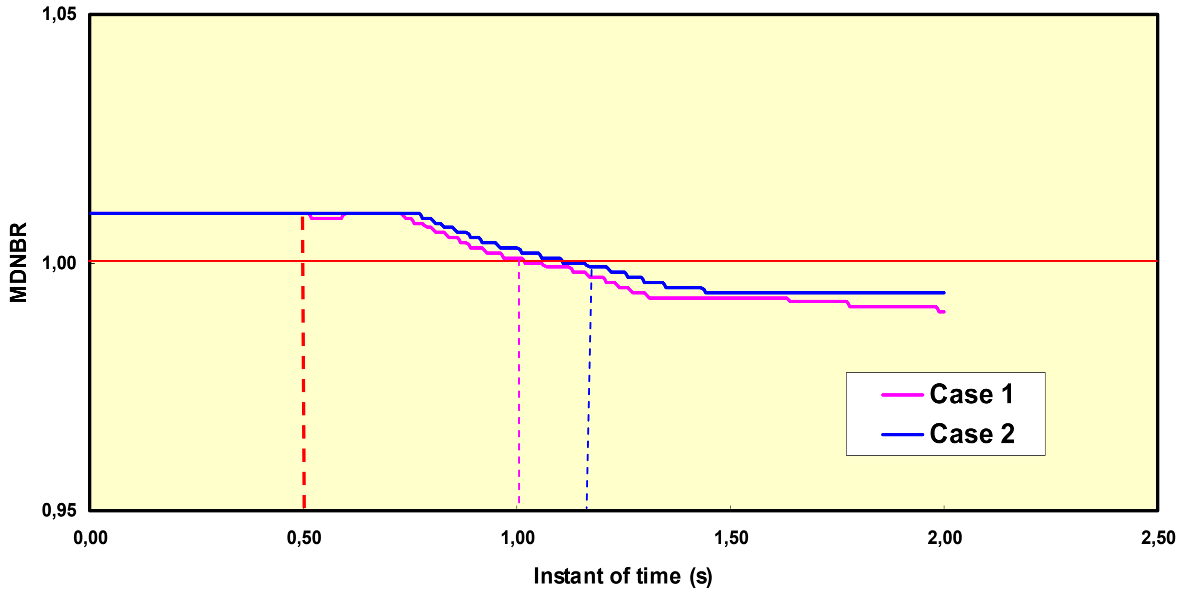

Figure 6. Minimum DNB ratio as function of time.

It can be observed that the boiling crisis will occur after 0.5s e 0.7s after the variation in the pump pressure, for cases 1 and 2, respectively. So, the situation will be more critical for case 1 than for case 2, since the operator will have less time to disconnect the rod power, before permanent damages occur.

4. Conclusions

Measurements of critical heat flux require a precise knowledge of the local flow conditions, such as flow rate, quality and void fraction to be utilized in the development or validation of design correlations. As shown, such conditions are very difficult to be obtained, since the occurrence of CHF will take place during a transient flow regime. The situation will be aggravated in those cases when the pressure drop in test section represents a considerable part of the total pressure drop in the deviation, as in case 1.

Since the electrically heated rods have small thermal capacity, the occurrence of boling crisis will provoke an immediate degradation of the heat exchange conditions, yielding a fast temperature excursion that might provoke irreparable damages to the rods and, consequently, elevated cost of reposition.

Finally, experiments of this kind require the utilization of very precise instruments and very short time of reaction to any change of the operational parameters.

5. References

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6. Responsibility notice

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