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TEST FACILITY FOR REFLOODING EXPERIMENTS AT NUCLEAR TECHNOLOGY DEVELOPMENT CENTER (CDTN)

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Abstract. *A test facility for rewetting experiments (ITR - Instalação de Testes de Remolhamento) has been constructed at the Thermal Hydraulics Laboratory of Nuclear Technology Development Center (CDTN), with the objective of performing investigation on basic phenomena that occur during the reflood phase of a Loss-of-Coolant Accident (LOCA), in a Pressurized Water Reactor (PWR), using tubular and annular test section. This paper present the design aspects of the facility, and the current stage of the works. The mechanical aspects of the installation as its power supply system and instrumentation are described. The instrumentation calibration results, and the description of one typical test performed are presented. A comparison with theoretical calculations using computer code is also presented. The computer code used is being updated to a most recent computational language.*

Keywords: *Thermal Hydraulic, LOCA, nuclear fuel rods, rewetting.*

1. INTRODUCTION

One of the fundamental subject in nuclear reactor safety analysis, which is still under investigation, is rewetting of reactor core after the postulated Loss-of-Coolant Accident (LOCA) in Light Water Reactor (LWR). Following the blow-down phase of LOCA in a LWR, the fuel clad temperature may rise quickly to a high value (around 930ºC at PWR), so that the injected water from emergency core cooling system (ECCS) during reflooding phase may not wet the clad immediately on coming into contact due to its sudden evaporation. As fuel cladding temperature decreases, the water could wet the surface and moves on. Then, quenching the clad is essential for effective heat removal by the emergency coolant; the situation will be worst by resulting on core melt down due to degradation on heat removal from the very hot fuels (Todreas and Kazimi, 2012) (Mulua *et al*., 2005).

Rewetting is the re-establishment liquid in contact with hot solid surface. The process can be called reflooding, quenching or refilling. It has different industrial applications such as steam generators, metallurgical treatment, jet of rockets, start-up of liquefied natural gas pipe lines, and filling of vessels with cryogenic liquids at room temperature.

A great effort has been taken to study rewetting phenomena during the last two decades. These efforts include both experimental and analytical works. Through the Accident Analysis techniques, it simulates the course of the accident using computer codes for verification of the nuclear reactor safety conditions. Older computer code, used in the Accident Analysis, used very conservative assumptions and thermal-hydraulics models to compensate the lack of knowledge for phenomena involved. With this, is underestimated the central safety margins, which forced the use of very large safety factors in the same project.

The codes developed more recently, within an international effort to allow the reduction of the high costs involved in building nuclear power plants, are able to more realistically describe the behavior of these plants. The Nuclear Technology Development Center (CDTN) is developing a program to allow Brazil to become independent in the field of reactor safety analysis. This program includes:

- adaptation and implementation of advanced computer codes;
- participation in international work for codes evaluation;
- conducting experimental research and support.

The experimental work necessary for the development, and evaluation of computer codes, that describe the behavior of a nuclear power plant in case of accident, can be divide into three categories:

- tests for the development of models that provide information on basic physical processes and lead â design models;
- tests to the development of models, which provide information on the basic physical processes and carry to the design models;
- tests separate effects which reproduce the conditions into components or small groups of components which allow the establishment of correlations to be employed in the codes; and

- integral-tests, which provide information on system behavior as a whole, forming the basis for the verification of codes, which are performed on a large test facility, which simulates all the primary circuit of a PWR reactor and contain substantially all the important system components.

The Nuclear Technology Development Center (CDTN) has a long lasting program to study experimentally and numerically several phenomena that affect reactor safety. Several conditions have and are being studied including the rewetting phenomena. In the past decade at CDTN a new group of codes have been used to study reactor safety. These are Computational Fluid Dynamics – CFD codes that solve the 3D flow and require validation so they can be properly used for accident analysis and licensing purposes. Although there are experimental data on several phenomena, the results obtained in the past emphasized information that could lead to average behavior empirical correlations. For modern 3D code validation, a new set of more detailed measurements are required. Therefore there is a necessity to perform new experiments. This work describes the existing system for the experimental evaluation of rewetting in a PWR reactor and the improvements being performed.

2. TEST FACILITY FOR REWETTING (ITR)

It was designed and is assembled in the thermal hydraulics laboratory of Nuclear Technology Development Center (CDTN), a test facility capable of simulating the conditions that occur in reflooding phase of a LOCA in a pressurized water reactor. The facility using tubular and annular test sections, was named Test Facility for Rewetting (ITR) The ITR enables testing varying the wall initial temperature, the injected cooling water temperature and velocity, the heat flow dissipated in the testing section and the system pressure (Lee *et al.*, 2001).

Table 1 provides the variation ranges of each parameter. The maximum design pressure 6 bar corresponds approximately to the predicted value for the pressure in the primary circuit of a PWR type Angra II, during rewetting phase of a LOCA due to a major disruption. The injected water temperature ranges and velocity, and heat flow in the test section also correspond to the expected in that case. The initial temperature of maximum expected wall is 600 °C, due to limitations with the thermocouple welding to the test section wall. ITR is now being recovered to simulate the LOCA reflooding phase with more detail so that its data can be used to validate complex 3D CFD code simulation.

Table 1. Range of variables of the Test Facility for Rewetting (ITR) (Rezende, 1985)

Parameter	Range	Step
Wall Initial Temperature	300 to 600 ºC	50 ºC
Injection Water Temperature	40 to 100 ºC	20 ºC
Injection Velocity	2 to 12 cm/s	2 cm/s
Heat Flux through Test Section Internal Surface	2 to 6 W/cm^2	1 W/cm^2
System Pressure	2 to 6 bar	1 bar

The ITR enables testing with upward or downward injection of water. Figure 1 shows an installation photograph and Fig. 2 shows its diagram.

Figure 1. Test Facility for Rewetting (ITR)

The ITR is divided into three distinct segments (Fig. 2):
- the water injection line;
- the pressurization line;
- the measuring line of the water carried out by the steam.

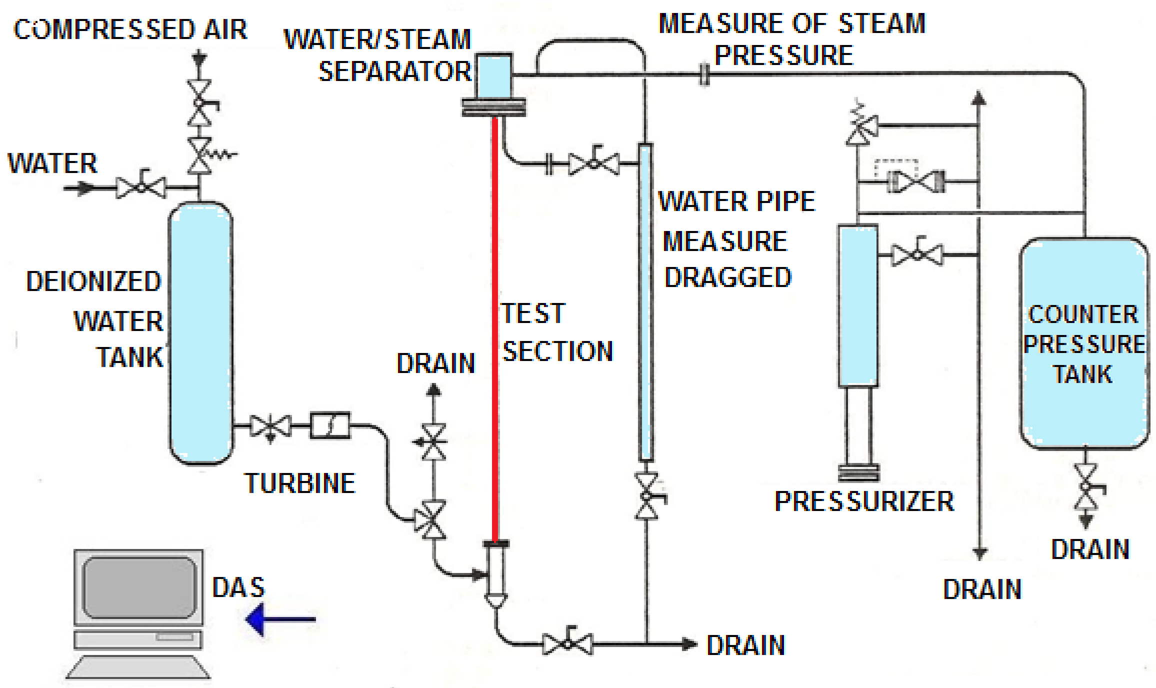

Figure 2. Diagram of the Test Facility for Rewetting (ITR)

2.1 Description of the Test Facility for Rewetting (ITR)

The water injection line consists of the piping section from the demineralized water tank to the entrance of the test section. This is a stainless steel AISI 316 piping, 50 mm in diameter, serial 40. The injection turbine flow meter and a globe valve for adjusting the flow are located in this line. After the turbine a three-way valve allow to direct the injection flow to the test section or to a draining piping. An experiment starts up by turning on these three-way valve to direct the flow to the test section. The draining piping has another globe valve for adjusting the upstream pressure at about the experimental pressure set up for the test section, so that after turning on the three-way valve the flow rate does not presents significant changes.

The pressurization line consists of the whole piping from the steam/water separator to the pressurizer. The piping is also in stainless steel AISI 316, 25mm in diameter. Close to the pressurizer there is a counter pressure tank to stabilize the system pressure. A relief valve installed over the pressurizer maintains the set up pressure. The safety valve has a higher set point (9 bar). The pressurizer has a set of resistors with an electrical power of 11 kW. A protective thermocouple welded at the top end of the resistance triggers the shutdown of them if they come to find out, thus preventing its burning. The volume of water above the resistors at the tests beginning allows carrying a complete test without the resistors becoming dry.

The measuring line of the water carried out by the steam consists of the water/steam separator, two vertical tubes for collecting and measuring the water carried out by the steam and precipitated in the separator and the collecting ducts. The water/steam separator is a camera above the test section where the entrained water precipitated due to the steam expansion. The steam leaving the test section undergoes an expansion upon entering the separator, causing it to precipitate the water droplets entrained in the steam. A piece of a tube 80mm in diameter, positioned within the separator, is another cause of the precipitation of entrained droplets of water, either by forcing the steam to make a sudden change in direction as to impact the tube. As the flood front is moving in the testing section increases the volume of water carried out. Thus, when the first tube is full, the second filling starts. The second tube a greater diameter and is able to contain a greater volume of water. A differential pressure transducer measures the volume of the precipitated water collected in the vertical tubes.

The ITR test sections were built with commercial tubes, but with hydraulic diameter close to Angra II fuel elements. It consists of an AISI 316 stainless steel tube 13,72mm external diameter and 9.24mm internal diameter. The tube has a total length of 4040mm: 3900 mm of heated length and 140mm upstream to get a fully developed flow. The test section is heated directly by Joule effect, using the tube itself as the heating resistance. The electric supply lower connection is directly on the test section tube, 140mm over the lower flange. The upper electric connection is on the test section upper flange.

At its upper portion the test section go through the flange of the water/steam separator ending 50mm above it to prevent the precipitate water to flow back into the test section (Fig. 3).

An outer tube, larger in diameter and wall thickness, makes the connection between the test section end and the flange.

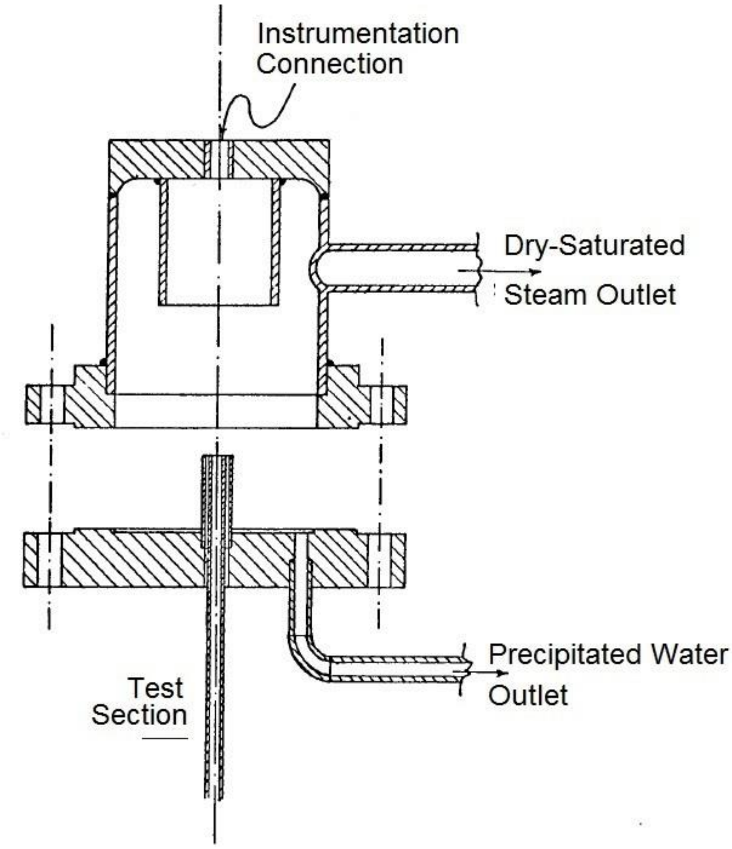

Figure 3. The Upper End of the Test Section and the Water/Steam Separator

2.2 The Electric Power Supply

The ITR power supply is derived from the substation of CDTN Thermal Hydraulic Laboratory through 112.5 kVA transformer, through the Auxiliary Services Panel (PSA). PSA it goes to its own distribution panel, from where it takes the power supply to all units of the ITR. The feed system of the test section, into direct current, consists of a 220V to 60V transformer, 45 kVA and a rectifier assembly 20 kW. The preheater supply consists of a rectifier assembly of the same type of the previous, but with a power of 6 kW. The pump and the pressurizer have three-phase power.

2.3 The Instrumentation

It was performed measurements of temperature, pressure, level, and flow along the test facility. In addition to these points still perform wall-temperature measurements in 10 positions along the test section, and the measure of electric power dissipated in the test section.

For safety reasons and because of the number of simultaneous measures, which often involve the immediate operator action, these values are recorded and displayed remotely. The measured values are sent to a Data Acquisition System (DAS) installed in the control room.

The wall temperature in the test section is measured by **t**en thermocouple type K (cromel-alumel) 1.5 mm in diameter with mineral insulation and stainless steel cladding, monitor the wall temperature along the test section (Fig. 4). These thermocouples were embedded in small slots in the wall of test section, and soldiers using silver solder. Each thermocouple is radially phased of 60° of the previous thermocouple, so as to obtain a spiral distribution.

The water temperature at the pump suction is measured by a thermo-resistor. The temperature range is 0 °C to 100 °C. The pressures in the suction and the discharge of the pump and the pressure in the pipe which returns the valve to the tank is measured via Bourdon pressure gauge.

The measure of steam flow, to the outlet of the separator, is performed by means of an orifice plate and differential pressure transmitter. The hole diameter is 7.97mm, it was dimensioned according to Burton (1965) to a maximum pressure difference across the plate equivalent to 2500 mm water column and the maximum expected flow steam 11.5m/h for the 2 bar of pressure.

The methodology used to evaluate the propagation of uncertainty in the results was done based on the pioneering article of Kline and McClintock (1953), with the propagation of uncertainties based on the specification of uncertainties in various primary measurements. Suppose a set of measurements is made and the uncertainty in each measurement is estimated. Then, these measurements are used to calculate some desired result for the experiments. We wish to estimate the uncertainty in the calculated result on the basis of the uncertainties in the primary measurements. The result R is a given function of the independent variables $x_1, x_2, x_3, ..., x_n$. Thus,

$$R = R(x_1, x_2, x_3, ...x_n) \quad (1)$$

Let U_R be the uncertainty in the result and $U_1, U_2, U_3, ..., U_n$ be the uncertainties in the independent variables. The uncertainty in the result is given as:

$$U_R = \left[\left(\frac{\partial R}{\partial x_1}U_1\right)^2 + \left(\frac{\partial R}{\partial x_2}U_2\right)^2 + ... + \left(\frac{\partial R}{\partial x_n}U_n\right)^2\right]^{1/2} \quad (2)$$

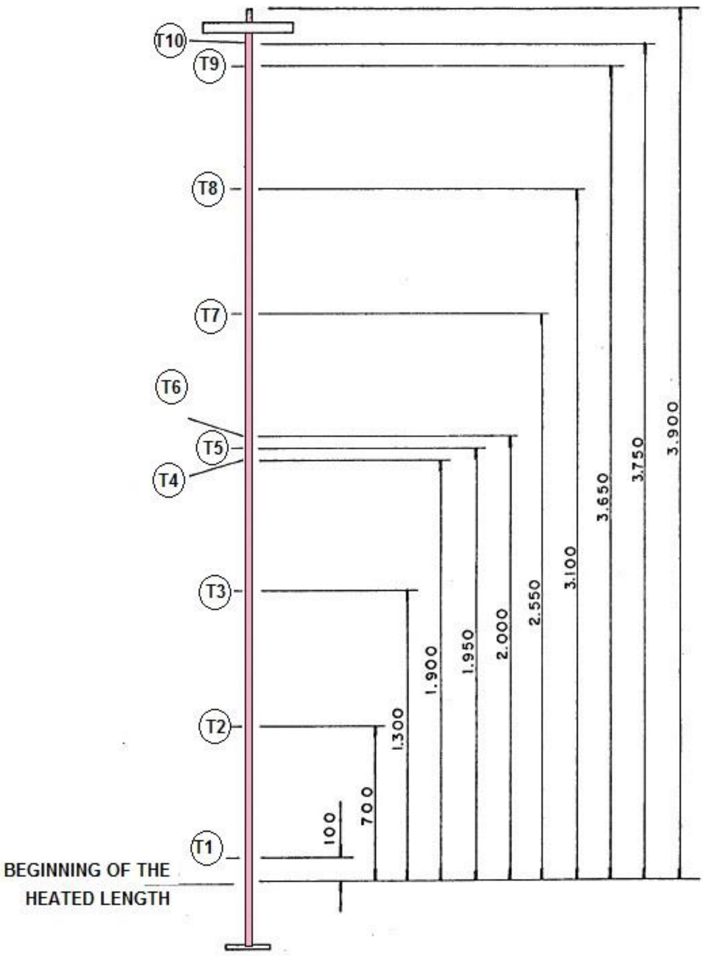

Figure 3. Thermocouple Distribution along the Test Section

3. TYPICAL TEST

There were two tests for proof of performance conditions of the ITR. Table 2 shows the values of input parameters imposed for each test. The Figuras9 to 19 show the results of these tests, whereas Figures 20 and 29 compare the results with the results predicted by the German computer code Hydroflut (Kühler, 1979) (Hein, 1980).

Table 2. Values of parameters for tests performed

Parameter	Test 1	Test 2
Pressure	4 bar	1 bar
Injection Velocity	6.2 cm/s	6.2 cm/s
Water Injection Temperature	400 ºC	400 ºC

4. RESULTS

Figures 4 and Fig. 5 show the evolution of the wall temperature in the quotas of the thermocouple the test section. In Figure 9, which relates to Test No. 1, only curves appear thermocouple T3 to TIO. This was due to that the positions of thermocouples TI and T2 have found is flooded at the beginning of the test, and there was not such heating position above the Leidenfrost temperature (Colier, 1972). The water present in the test section, before the start of the test, originated from steam condensation during pressurization of the system. For the No. 1 test, measures were taken so that this condensate was withdrawn before starting the test.

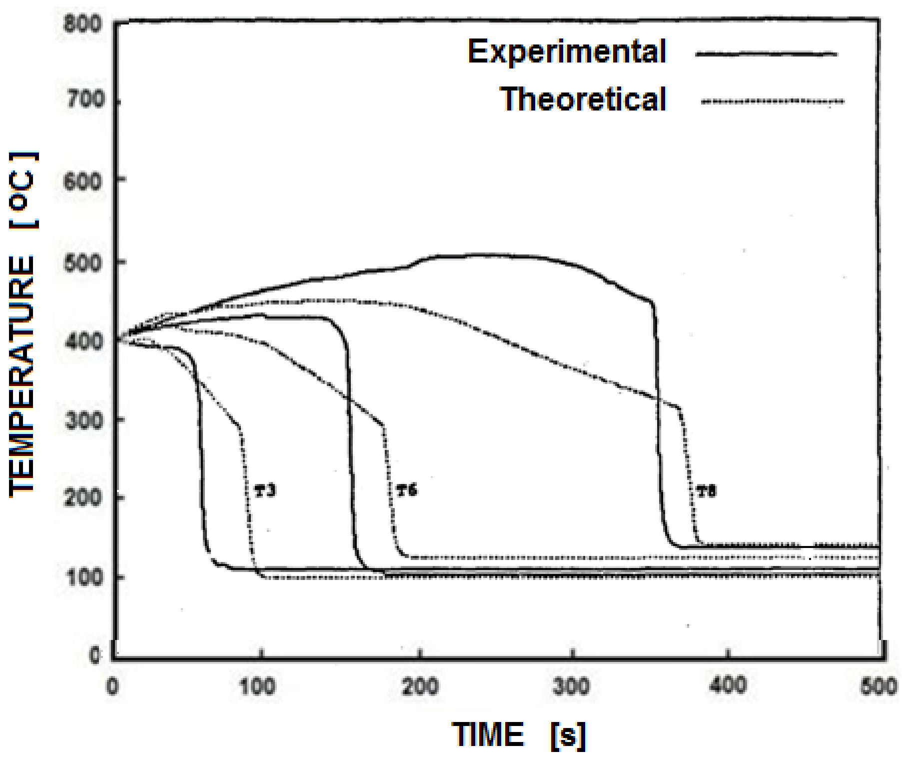

Figure 4. Experimental and calculated evolution of wall temperature in Test 1

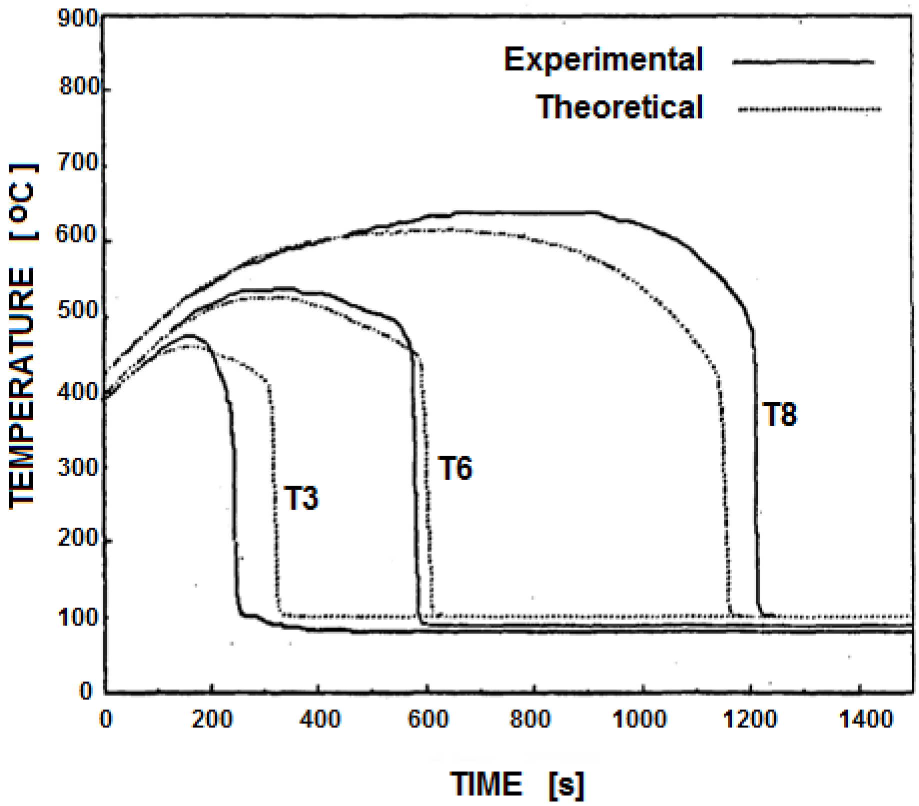

Figure 5. Experimental and calculated evolution of wall temperature in Test 2

3. CONCLUSIONS

From tests carried out to evaluate the performance conditions of the Test Facility for Rewetting (ITR), it can conclude that this has good operating conditions. The pressure control system based on pneumatic controller and the relief valve, kept at constant pressure at desired levels without any detectable oscillation. The water injection conditions by means of a centrifugal pump were also satisfactory. Also the pressurizer and the preheater, subject to individual performance testing, showed good operating condition.

The calibration of the instrumentation shown that most of the systems is suitable for accuracy. Nevertheless, some improvements may be made to the injection flow measurement systems, the volume of water dragged by the steam flow of the steam out of the test section and the power dissipated in the test section.

The orifice plate for measurement of steam flow has been designed considering the maximum flow expected steam during a test at atmospheric pressure, with the maximum initial temperature wall, the maximum flow injection and a maximum power dissipated in section tests. These conditions lead to the expected maximum flow. However, for a test in opposite conditions, steam flow was found to be very small, thereby compromising the accuracy of the measuring system used. As the orifice plate has a hole with a diameter close to the minimum recommended by the standard, it is not advisable to simply replacing the board. What is suggested is the use of one or more flow meters installed in parallel.

The power dissipated in the test section could be recorded during a test, from the voltage and current values, setting up a current meter (shunt), and an electronic multiplier circuit. This procedure, besides being more accurate, eliminate the calculations that are currently needed to obtain power.

The codes used to date in rewetting experiments are of the years 80s. The main code used, the Hydroflut (in Fortran 77 language) was used in this experiments (Rust *et al.*, 1976). At the time this program is being updated to a most recent computational programming language, as the Python software (PSF, 2015). Work is being performed to update the test section and increase instrumentation and lower uncertainty of the results. These efforts are being made so that a new experimental campaign can be performed to obtain results for complex 3D code validation, as CFD (Ansys, 2012).

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