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ANALYSIS OF EXPERIMENTAL ROUTINES OF HIGH ENTHALPY STEAM DISCHARGE IN SUBCOOLED WATER

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ABSTRACT

The discharge of high enthalpy steam through safety release valves out from pressurizers in PWR´s needs to be condensed in order to allow the treatment of possibly present radwaste within. The Direct Contact Condensation is used in a relief tank to achieve the condensation. Care must be taken to avoid the bypass of the steam through the subcooled water, what would increase the peak of pressure and the necessity of structural reinforcement of the relief tank. An experiment to determine the optimal set up of the relief tank components and their characteristics (type of sprinkler, level of water, volume of tank, discharge direction, pressure in the pressurizer among others) was executed in 2000, in the CTE 150 facility, in CTMSP. In a total, 144 routines varying its components and characteristics were made, although no comprehensive analysis of its results were yet made, since the mass of data was too big to be readily analyzed. In order to comprehensively analyze it, a VBA program is being made to compile and graphically represent the mass of data. The current state of this program allowed conclusions over the peak pressure, adiabatic assumption of the experiment, and the quality of the steam generated due to the discharge.

1. INTRODUCTION

Pressurizers vessels are equipment with utility for Light Water Reactors. Particularly in PWR plants, pressurizers are connected to the primary circuit, and are responsible for controlling pressure transients. Pressurizers are the only primary components of a PWR having both and simultaneously a liquid and a steam phase of the coolant. The steam phase allows a limited expansion without significant pressure increase. Exhausted the accommodation capacity of enthalpy of the steam phase, the pressurizer may operate two devices which act antagonistically: in case of Reactor Coolant Boundary Pressure have a pressure reduction, the system enthalpy is increased through electrical resistances in the pressurizer vessel. Otherwise, in case of pressure increaseit is nee beyond the steam accommodation capacity, relief valve is opened to reduce the enthalpy of the primary loop through the outflow of coolant mass. When released by the relief valve, the wet steam contained in the pressurizer undergoes an adiabatic expansion becoming dry steam, potentially contaminated by tritium, corrosion products activated, and fission products. For this reason, it should be prevented from being directly discharged into the environment before an appropriate treatment, what begins with the containment of the steam outflow. First, it is necessary to reduce the enthalpy, so this steam mass is ejected in a sub-cooled water bath contained in a relief tank. Considering the differential pressure in the pressurizer and in the relief tank, and the necking of the expansion valve, this outflow usually undergoes in a shock wave. The injected steam takes on a plume shape, and condensation occurs on the interface layer with the bathwater. In [1], semi-empirical relationships for the length of steam plume depending on the injector nozzle diameter, mass flow, and the bath temperature, considering the open, two-phase water-steam. This interface has turbulent character, a fact that intensifies the heat exchange between the plume and bathing, considering the mass exchange between adjacent layers in a turbulent flow. [2] estimated the average heat transfer coefficients by condensation through the observation of the enthalpy flow and the area of the interface surface between steam and water, obtained from snapshots of the steam plume. The diameter of the steam plume is dependent on the pressure with which steam is injected. Subsequent theoretical development showed that the length of the plume is also dependent on the temperature difference between the bath and the temperature of the interface, as well as the speed at which the steam mass is injected. The transient regime of steam injection is characterized by formation of a reduced plume diameter and reduced length, since the initially large difference in temperature between the bath and the steam drives the latter to a rapid condensation. With time increase, the temperature difference is reduced, reducing the heat flux into the bath, allowing the plume length to extend, assuming a conical shape. Continuing with the injection, the temperature of the bath increases, approaching the end of subcooling range, when the cone-shaped plume starts to become unstable, and begins the bubble formation phenomenon. At this time, there are dynamic load peaks, which must be taken into consideration for the design of the tank. Continuing with steam injection, and with increasing temperature, the bubbles collapse reaching the water surface, then steam mass is released to the environment. If this tank does not communicate with the atmosphere, the released steam will increase the pressure inside the tank, taking it to the limit of its structural capacity.

1.1. Objectives

The immediate objective of this work is to present a platform to compile and compare a series of experiments of high enthalpy steam discharge in a subcooled bath. Each routine of discharge presents differences in the injector nozzle, time of discharge, direction of discharge, height of the nozzle within the subcooled bath, level of the water in the tank, tank diameter, tank orientation (vertical or tilted), pressure of discharge. None of this set of characteristics was found by the authors in the current literature. Besides, the injection of steam found in the literature is in the radial direction of the tank, while in this experiment, the injection of steam is axial, upwards or downwards, and the tank may be in the vertical or tilted position. For this, namely, the variety of steam injection conditions, and the direction of injection, this experiment may be considered singular.

This platform will allow to compare two different routines, for example, one with the tank in the vertical position, other with the tank in a tilted (45°) position. Also, this platform allows to compare two different parameters in a same routine, for example, the temperature of the water *versus* the steam pressure.

2. EXPERIMENTAL DESCRIPTION

In this section, a brief explanation of the experimental apparatus and the experimental routines will be given.

2.1. Experimental Apparatus - CTE 150

The CTE 150, *i.e.* Experimental Thermal-Hydraulic Circuit 150 bar is an experimental circuit for the simulation of thermal-hydraulic parameters of a primary and secondary loop of a nuclear power plant, located in Navy Technological Center in Sao Paulo. The heat generation of this loop is achieved by means of electrical resistance in the loop vessel reactor, simulating the generation of heat achieved by means of nuclear fuel. As a PWR plant, the loop has two circuits. Its primary circuit comprises a vessel where the electrical resistance is housed, which provides heat transfer to the coolant, in this case water. Also, the CTE-150 has Coolant Feed Pumps. A branch from the main primary circuit is made to connect the pressurizer, the single component of the primary loop that contains coolant in vaporous state. The over pressure of the pressurizer opens a Relief Valve to discharge steam in a Relief Tank in order to be collected, and treated before discharged. The interface between the primary and secondary circuit is performed by means of a heat exchanger of shell-and-tube type, said “Steam Generator”. The heat transferred from the side of Steam Generator tube to the shell side, vaporizes the secondary side water. This formed steam is conducted to a condenser where the steam returns to the liquid state, and through the action of extraction pumps, it is restored to the shell side of the steam generator.

2.2. Experimental Routines -Steam Discharge from Pressurizer in Relief Tank

The experimental procedure pressurizer steam discharges into a relief tank, conducted between May and September 2000 [3], consisted in the opening of an expansion valve that allows high enthalpy steam flow at 130 bar or 100 bar, from the pressurizer to the injection nozzle of the Relief Tank. The wet steam passing through an expansion in the pressurizer valve loses humidity and becomes dry, before to be injected into the undercooled water bath. For this, it is expected to obtain Direct Contact Condensation. In this situation, the condensation is accelerated because the heat transfer coefficient is maximized in the border region between the steamy plume and the water bath, since this interface forms a turbulent region, where the exchange of heat ends up being enhanced by the exchange of mass characteristic of this region. The steamy plume is a region characterized by two-phase flow, since it blends steam droplets of water that are drawn from the bath and water clusters which condensed from steam injected. The ideal condensation condition inside the tank occurs when all injected steam is condensed inside the water bath, with no escape. If the injected steam escape from the bath, it generates a thermo-dynamic imbalance condition corresponding to the pressure increase in the tank. The reasons giving rise to the escape of steam is to exceed the enthalpy absorption capacity of the bath, or steam injection too close of the vicinity of the liquid surface. Thus, during the experiment, it is expected increase in pressure and temperature of the water and the steam, and the steam leakage phenomenon may be identified if, when closing the injection valve immediately there is a pressure drop, corresponding to condensation of steam that ran out of the bath, generating a metastable steam accumulation.

Thus, for this experiment were considered 144 possible routines of two tanks with different diameters and same height, 8 different types of nozzles, two nozzle insertion heights, two initial

water levels inside the tank, two jet directions (upward and downward). Further, they considered two different pressures pressurizer (130 bar and 100 bar), two valve opening times (100 or 120 sec) and two tank gradient conditions (0° and 45°).
There were 8 continuous data taken over time, namely the temperature of the water tank, the steam temperature, the tank water level, also the pressure in the tank, the pressurizer water temperature, the temperature of the pressurizer, the pressurizer water level and pressure in the pressurizer.

3. DATA ANALYSIS

Because of the large number of routines, and the diversity of data collected so far it was not possible to proceed a comprehensive analysis of the experiment. This study aims to develop computer code that enables the analysis of the mass of data generated through the construction of graphics. Through this type of analysis, the steam discharge behavior may be defined. It is emphasized that this is a work in progress, whose current stage will be presented in the next section, and intentions for future development in the 5th section.

3.1. Computational Code Analysis

Through Microsoft Visual Basic for Applications, used in combination with Excel spreadsheets, it is in development a computer code to manipulate the data mass produced, equipped with graphical interface. At the present stage of development, water temperature charts, steam temperature and pressure in the tank versus the time elapsed after the opening of the expansion valve charts are produced. The graphical interface allows the choice of two different presentations:

• Two choices of parameters for the same experiment (Water Temperature, Steam Temperature, Water Pressure) versus time, as presented in fig.1;
• The same physical parameter for the choice of two different experiments, as presented in fig. 2.

A brief explanation of the interface templates is given, considering the index number inside each of the figures.

The first template (fig. 1) is chosen (option box 5) and allow us to choose, for one pre-chosen routine (option box 1), two different parameters (option box 2 and 3), which will be graphically represented (chart 6). As soon as the routine is chosen, its configuration are displayed in the template (display 4). A gray vertical line indicates the moment when the expansion valve is closed. This figure brings as example the temperature of the water and the pressure in the tank plotted against the time.

The second template (fig. 2) is chosen (option box 7) and allow us to choose, for two pre-chosen routine (option box 1 and 2), only one parameter (option box 3), which will be graphically represented (chart 8). As soon as both routine are chosen, their configuration are displayed in the template (display 4 and 5). Suggestions of experiments are displayed in the list box (6). This figure brings as example routines 1 and 2.

To create these charts, the user may select routines between 1 and 144, and the combination of parameters of the selected pattern are immediately presented the check boxes below the routine number box. In the case where the presentation of the same parameter for two different routines is selected, there is a combo box that displays suggestions for the second routine to be presented. This suggestion represents a routine where all, except one, of the first routine parameters are repeated. This way, the influence of one parameter is isolated, keeping all the rest the same.

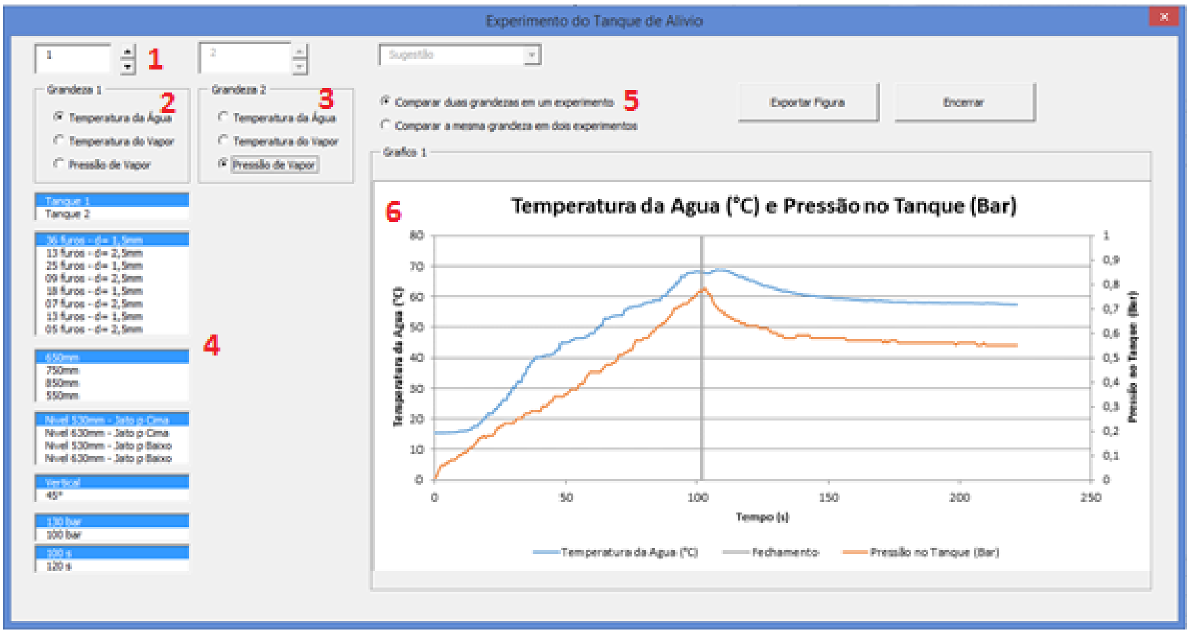

Figure 1: Same Routine for two parameters template
(Best Resolution Snapshot in Appendix)

Figure 2: Same Parameter for two different routines template
(Best Resolution Snapshot in Appendix)

4. RESULTS

In the current moment of this work, the results are limited to qualitative analysis of the produced charts. Along this research effort, the authors will proceed quantitative analysis in order to complement and support the qualitative results currently present.
The size of the tank has a major impact in the enthalpy accommodation, since a larger amount of coolant within the tank increases its thermos-hydraulic inertia. The larger tank T1 do not allow temperatures above 80°C, no matter what are the other conditions, while the smaller tank T2 frequently allow temperatures above 100°C. The behavior of the water temperature curve is very similar to the behavior of the steam pressure curve, so, it may be understood that the pressure in the tank is commanded by the temperature in the water. However, the steam temperature, once the expansion valve is closed, remains constant for a longer period of time. The system may not be considered adiabatic, mainly for routines where the steam is injected upwards, since the water temperature and the pressure have a reasonable drop after the valve is shut. When the steam is injected downwards, the behavior of the routine is similar to an adiabatic system, as seen in fig. 3.

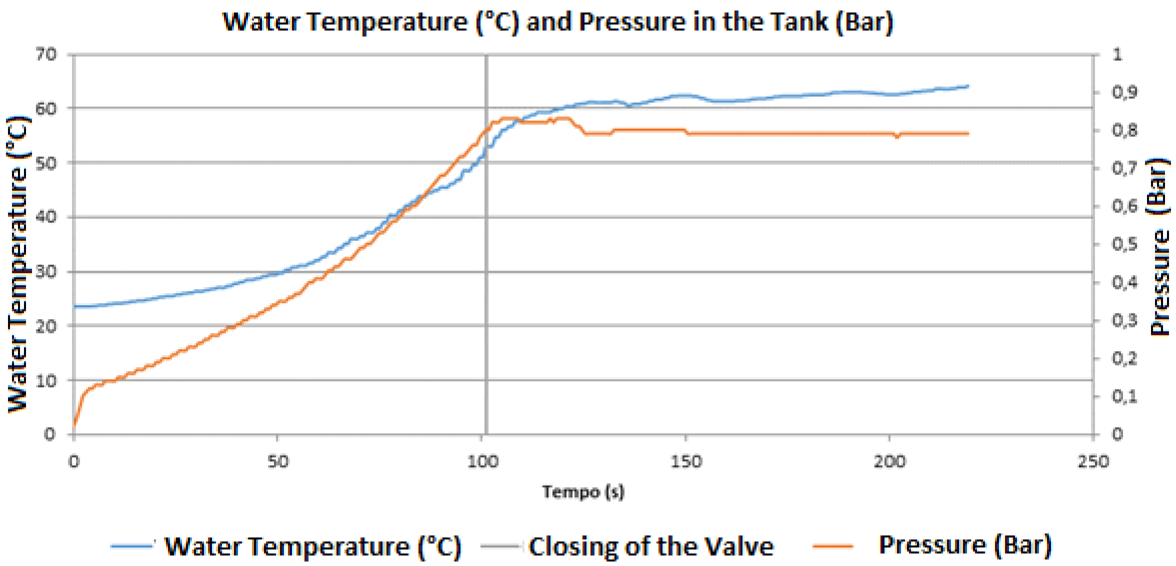

Figure 3: Water Temperature and Tank Pressure *vs.* time

A common behavior presented by the steam curve is a linear or slight parabolic increase, when the valve is open, followed by one of these two: (i) when the valve is closed, the steam curve remains constant, as presented in routine 41, fig. 4, or (ii) when the valve is closed, the steam curve drops immediately, as presented in routine 33, fig. 4. This behavior may be understood if we consider the steam discharge in the routine 33, as exceeding the enthalpy accommodation capacity of the coolant, so the energy is transfered out of the coolant, creating an unstable pressure over the liquid surface. As soon as the valve is closed, the system seeks for balance, transforming steam in water.

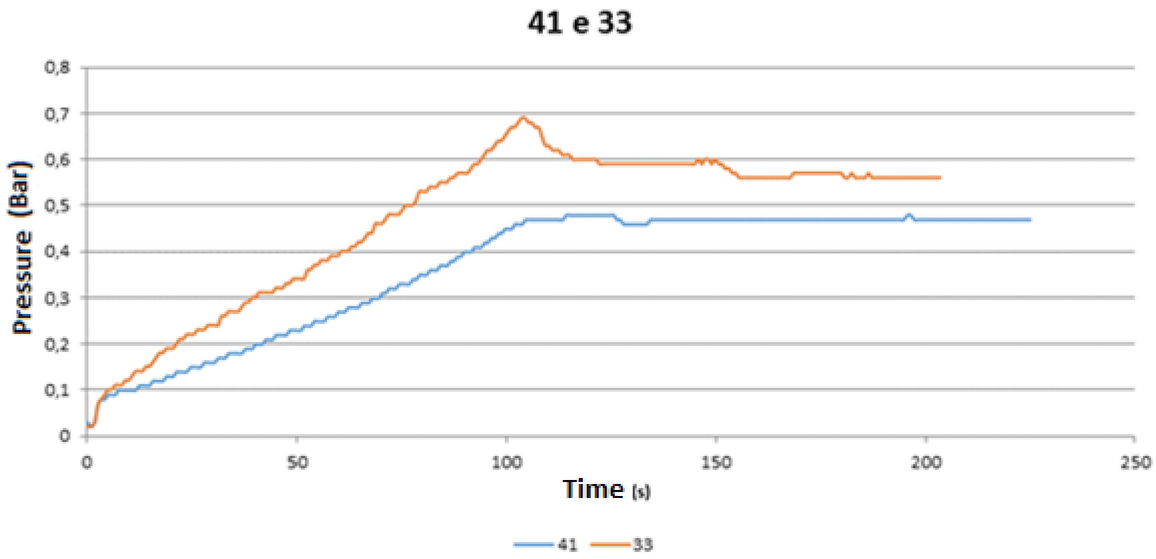

Figure 4: Routines 41 and 33 *vs.* time

The factors that take the routine 33 to a higher pressure are related to the smaller water level, and the smaller distance between the nozzle and the liquid surface, with the injection directed upwards, with all of the other factors remaining the same. As observed in the vast majority of routines, the upwards direction of the jet creates this unbalance condition, as long as, when directing the jet downwards, the closing valve transition smooths, and the inside pressure of the tank is stabilized, approaching to an adiabatic condition.

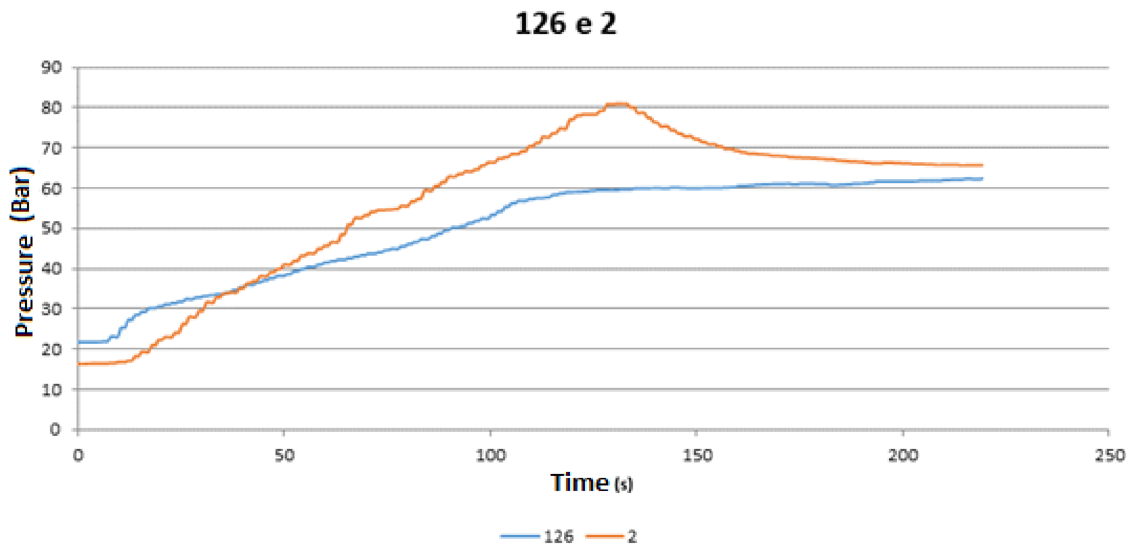

Figure 5: Routines 126 and 2 *vs.* time

No matter the high thermal inertia (higher coolant volume) of the tank T1, in routine 2, the temperature increase is similar to the tank T2, in routine 126. This behavior may be understood when it is considered the large discharge cross section (about three times) and the upward direction of the discharge in the routine 126. The cross section discharge area must be designed as a compromised between the necessity to quicly discharge the pressurizer, and the mechanical capacity of the relief tank to support the discharge.

5. CONCLUSIONS

No matter the early stage of this work still in progress, some qualitative conclusions may yet be drawn from the analysis of the sofware. (i) The amount of the coolant, and its effect in the thermos-hydraulic inertia is a major factor when considering the enthalpy accommodation capacity of a relief tank. (ii) The direction of discharge is highly influential, considering that the upward direction allows the creation of unstable thermos-hydraulic condition, creating a peak of pressure, simultaneously with the valve shut up. (iii) The pressure of the tank as a behavior linked to the water temperature, and dissociated to the water pressure. (iv) other major influential factor in the enthalpy accommodation capacity of the tank is the size of the cross section discharge area, which may be as influential as the volume of water in the tank.

5.1. Future Developments

As a preliminary work, useful features may be added: (i) the information of level of water in the tank, which would allow to infer the amount of injected steam. With this information, the amount of injected steam may be inferred, offering important information about the enthalpy injected; (ii) the chart presentation of temperature increase *vs.* the pressure increase, instead of time, would allow a different vision of the routines, and the development of a presentation considering the quality of the steam over the liquid surface, which would allow an analysis about the unbalance conditions created by the unabsorbed enthalpy in the subcooled water.
The main intention of the current work is to serve as preliminary analysis to a future CFD model, in order to model the steam plume created inside the relief tank. With this CFD model, considering the interface of the steamy plume turbulence and the inner two phase flow, this phenomenon would be closely studied.

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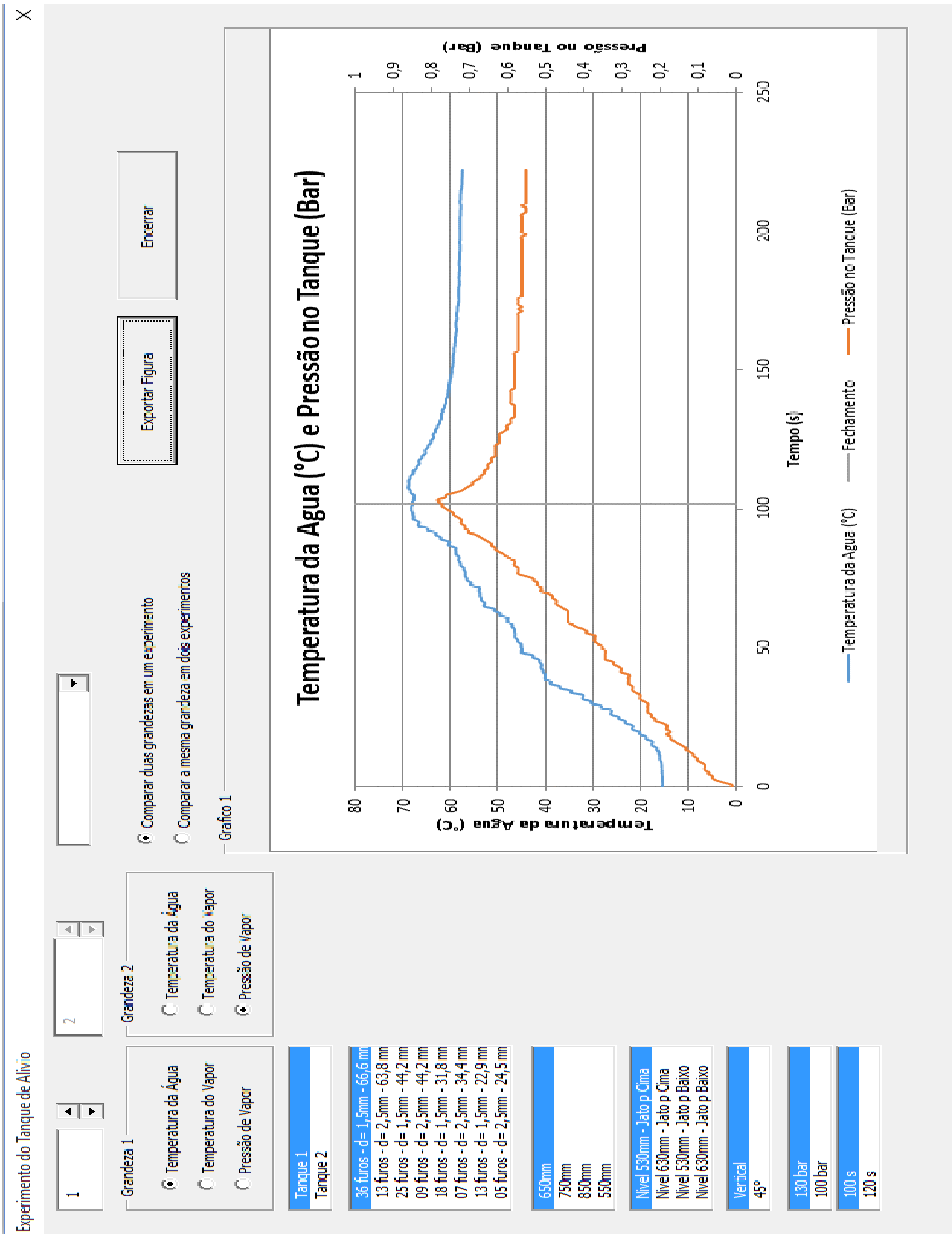
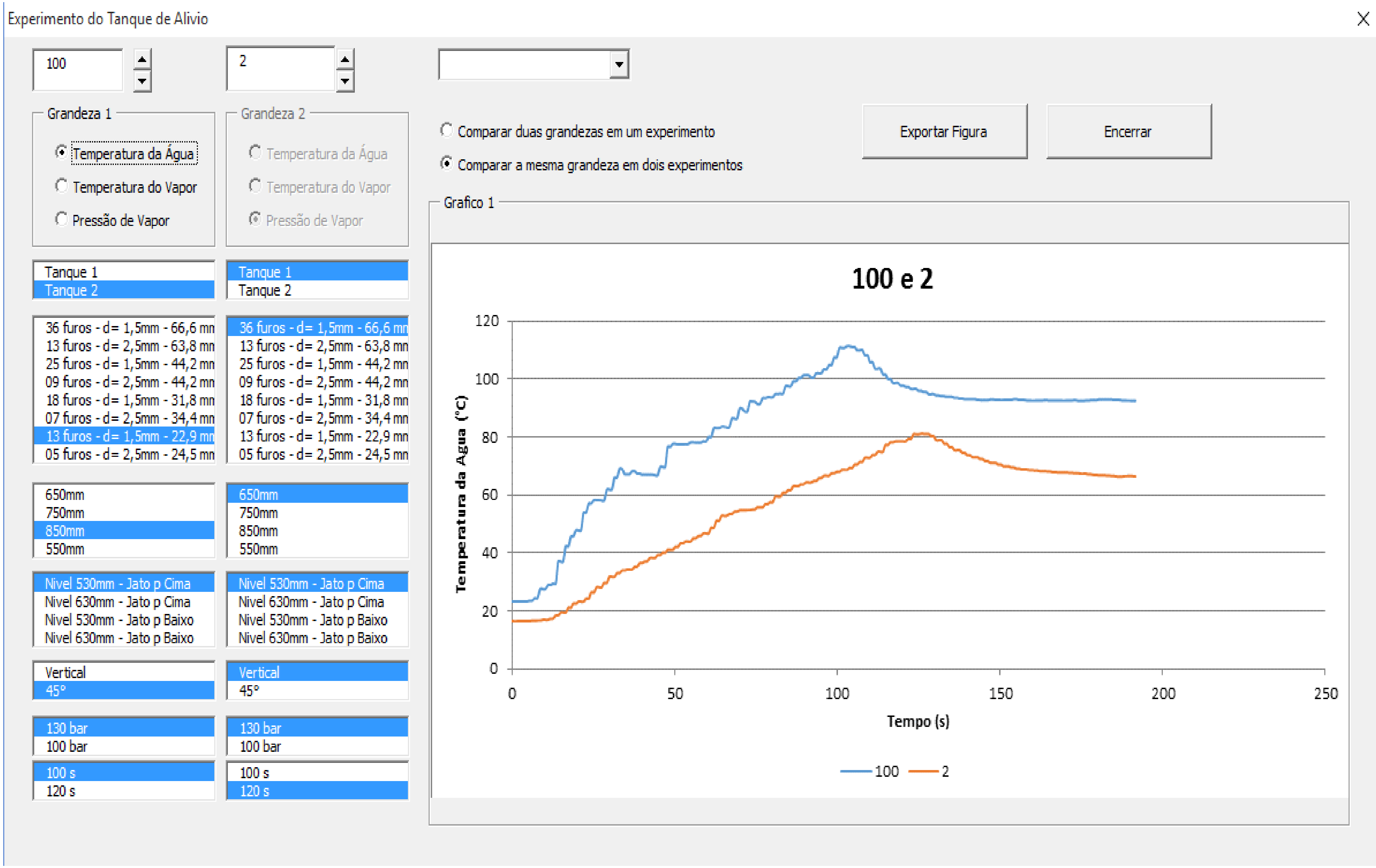
3. Bassel, W. S., “Experiment Relief Tank Primary - RP61-0104-5022-421-00”, CTMSP, São Paulo, Brazil (1993)

APPENDIX
INTERFACE SCREEN





Experimento do Tanque de Alivio
100
2
Grandeza 1
Temperatura da Água
Temperatura do Vapor
Pressão de Vapor
Grandeza 2
Temperatura da Água
Temperatura do Vapor
Pressão de Vapor
Comparar duas grandezas em um experimento
Comparar a mesma grandeza em dois experimentos
Exportar Figura
Encerrar
Tanque 1
Tanque 2
36 furos - d= 1,5mm - 66,6 mm
13 furos - d= 2,5mm - 63,8 mm
25 furos - d= 1,5mm - 44,2 mm
09 furos - d= 2,5mm - 44,2 mm
18 furos - d= 1,5mm - 31,8 mm
07 furos - d= 2,5mm - 34,4 mm
13 furos - d= 1,5mm - 22,9 mm
05 furos - d= 2,5mm - 24,5 mm
650mm
750mm
850mm
550mm
Nivel 530mm - Jato p Cima
Nivel 630mm - Jato p Cima
Nivel 530mm - Jato p Baixo
Nivel 630mm - Jato p Baixo
Vertical
45°
130 bar
100 bar
100 s
120 s
Grafico 1
100 e 2
Temperatura da Água (°C)
120
100
80
60
40
20
0
0
50
100
150
200
250
Tempo (s)
100
2