17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0829
THERMAL ANALYSIS OF TUBES TAMPONING IN CONDENSERS OF A PWR NUCLEAR POWER PLANT

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Abstract. *In nuclear power plants, Condensers are heat exchangers responsible to turn all the steam exhausted from turbines into saturated liquid, due to the sea water heat transfer, which occurs inside of these equipment. During the operation, could be needed the tamponing of Condensers damaged tubes, avoiding contamination of the secondary fluid with salt water. The objective of this work is performing a thermal analysis of PWR nuclear power plant Condensers and identify the negative aspects of the tamponing a part of its tubes. For this, a bibliographic review was carried out contemplating some concepts of thermodynamics, heat transfer and fluid mechanics. Then, was considered and analyzed the Brazilian nuclear power plants. For Angra 1, the average fluid enthalpy was identified as 1,820.49 kJ/kg at Condenser inlet and 160.76 kJ/kg at the outlet. For Angra 2, the average fluid enthalpy was identified as 2,258.50 kJ/kg at Condenser inlet and 169.09 kJ/kg at the outlet. After initial calculations, the thermal power of secondary circuit, after tamponing, was analyzed. The tubes tamponing decreases the heat transferred along the condenser, increasing the pressure inside the equipment. This causes a reduction of the general efficiency of the power plant.*

Keywords: *Nuclear Power Plant, Secondary Circuit, Condenser, Tubes Analysis, Tamponing.*

1. INTRODUCTION

A Pressurized Water Reactor (PWR) plant has two independent, closed cooling circuits. In the first, water is responsible for cooling the reactor core that is in constant nuclear fission and is highly radioactive. In the second, the water operates similarly to the Rankine Cycle and its main purpose is absorbing heat from the primary circuit, generating energy. There is also a third open circuit, which may be the sea or river. A simplified PWR power plant is shown in Fig.1.

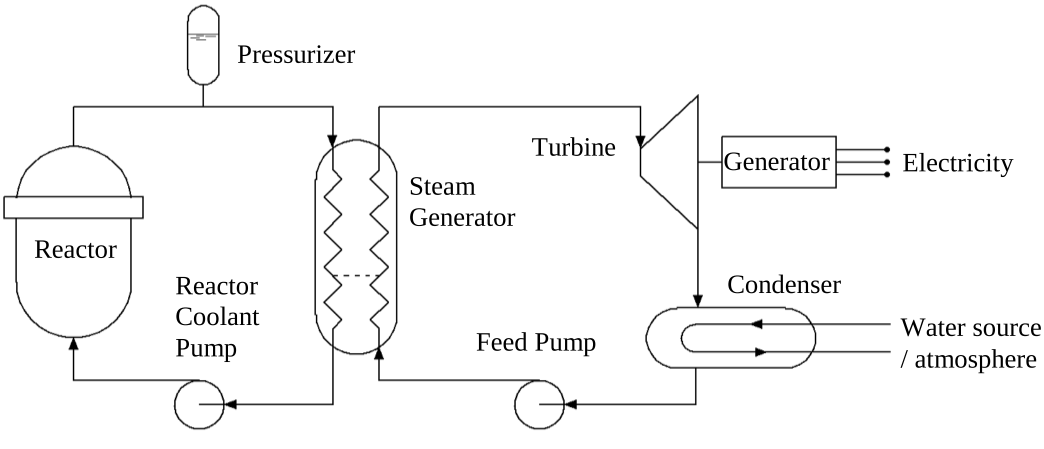

Figure 1: Simplified PWR Power Plant
Adapted from Todreas, 2015

The secondary circuit of a PWR nuclear power plant consists of four main components, as shown in Fig.1: Feed Pump, Steam Generator, Turbine and Condenser. In this last equipment, the heat transfer between the water of the secondary circuit and the sea water occurs, thus maintaining the system parameters acceptable for a good performance.

In general, the Condensers used in nuclear power plants are large size equipment, horizontal, consisting of shell and tube. In the Condenser shell, the saturated steam, arising from the Turbine, flows vertically. Inside the horizontal tubes flows sea water which absorbs the heat from the steam.

During the construction and operation of these Condensers, much care must be taken, as the equipment works under manometric negative pressure. According to Canalini (1985), among the main predictive tests applied, the watertightness test is essential to guarantee a good maintenance and operation of these equipments. The tubes failed in this test are either tamponed or plugged in such a way that no more seawater flows through them.

Knowing that the tamponade of a damaged tubes is essential so that there is no contact of the sea water with the secondary circuit (which could cause corrosion in the equipment due to the high presence of minerals in the sea water), it is necessary to analyze the negative impacts of this practice and also the tamponed pipes limit for a Condenser outlet temperature acceptable, without impair the circuit efficiency.

Brazilian nuclear power plants, Angra 1 and Angra 2, operate with PWR reactors and contributed, in 2016, with 2.6% of country electric matrix, according to EPE (2018). In this context, NUCLEP was created to attends the Brazilian Nuclear Program, and was responsible for supply some equipment for nuclear power plants. Angra 3 will be the third nuclear power plant in the Central Nuclear Almirante Álvaro Alberto (CNAAA) and its Condensers are being built in NUCLEP.

In February 2015, a few months before the programed refueling stop, Angra 1 was turned off due to failures in Condensers tubes, which could affect the Steam Generators.

2. METHODOLOGY

2.1 Proceding of Analysis

Some steps have been taken in this work. Firstly, the conditions for analyzes were defined. After, the operation of a Condenser was analyzed in terms of thermodynamics and heat transfer. Considering the data obtained from Angra 1 and Angra 2, the operation of the Condenser in the secondary circuit was analyzed. Then, heat transferred was simulated for a perfect Condenser of Angra 1 and Angra 2 (no tamponing) and was verified the critical areas for tamponing.

2.2 Physical Formulation

For the analysis of this volume control the mass conservation is considered, which occurs in steady state condition. Considering the First Law of Thermodynamic, we have to:

$$ {}_1^2Q = U_2 - U_1 + \frac{m\left(u_2^2 - u_1^2\right)}{2} + mg\,(Z_2 - Z_1) + {}_1^2W \tag{1} $$

Where Q, U, m, u, g, Z and W are, respectively, the transferred heat, internal energy, mass, velocity, gravity, height and work. The subscripts 1 and 2 are, respectively, the initial and final points. Applying the First Law in a PWR nuclear power plant, in which the kinetic and potential energies can be neglected, and knowing that the relation between internal energy, pressure and volume results in enthalpy, we have to:

$$ {}_1^2W = p\int_1^2 dV = p(V_2 - V_1) \tag{2} $$

$$ {}_1^2Q = \left(U_2 + p_2V_2\right) - \left(U_1 + p_1V_1\right) = h_2 - h_1 \tag{3} $$

Where h, V and p are, respectively, the enthalpy, volume and pressure. Applying these concepts in a control volume, we have to:

$$ \sum\left(\dot{Q}_{vc} - \dot{W}_{vc}\right) + \sum\left(\dot{m}_e h_e - \dot{m}_s h_s\right) = 0 \tag{4} $$

Considering the secondary circuit of a PWR nuclear power plant as a Rankine Cycle, presented in Fig.2, the properties of points 4 to 1, which represent the condensation process, can be defined using a thermodynamic table.

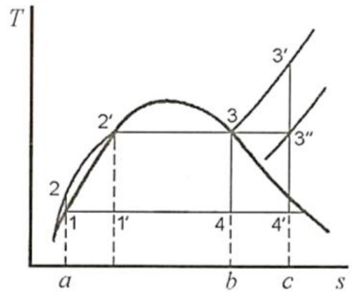

Figure 2: Operation of a simple circuit according to the Rankine cycle
Adapted from Sonntag & Borgnakke (2009)

Analyzing the Rankine graphic, the cycle efficiency is given by:

$$\eta = \frac{w_{liq}}{q_{hot}} = \frac{w_T - w_B}{h_3 - h_2} = \frac{(h_3 - h_4) - \int_2^1 v\, dp}{h_3 - h_2} \tag{5}$$

Where v is specific volume; w_{liq}, q_{hot}, w_T and w_B are, respectively, the liquid work, heat from hot source, turbine work and pump work. Considering that the Condenser tubes are organized in a layout, according to Fig. 3, some concepts of heat transfer can be used to find the thermal power dissipated in each tube.

According to Incropera (2008), the thermal capacity of heat transfer of a specific fluid condition is given by Eq. (6). This thermal capacity depends on the flow mass $\dot{m}$ and the fluid specific heat c_p.

$$C_{th} = \dot{m}.c_p \tag{6}$$

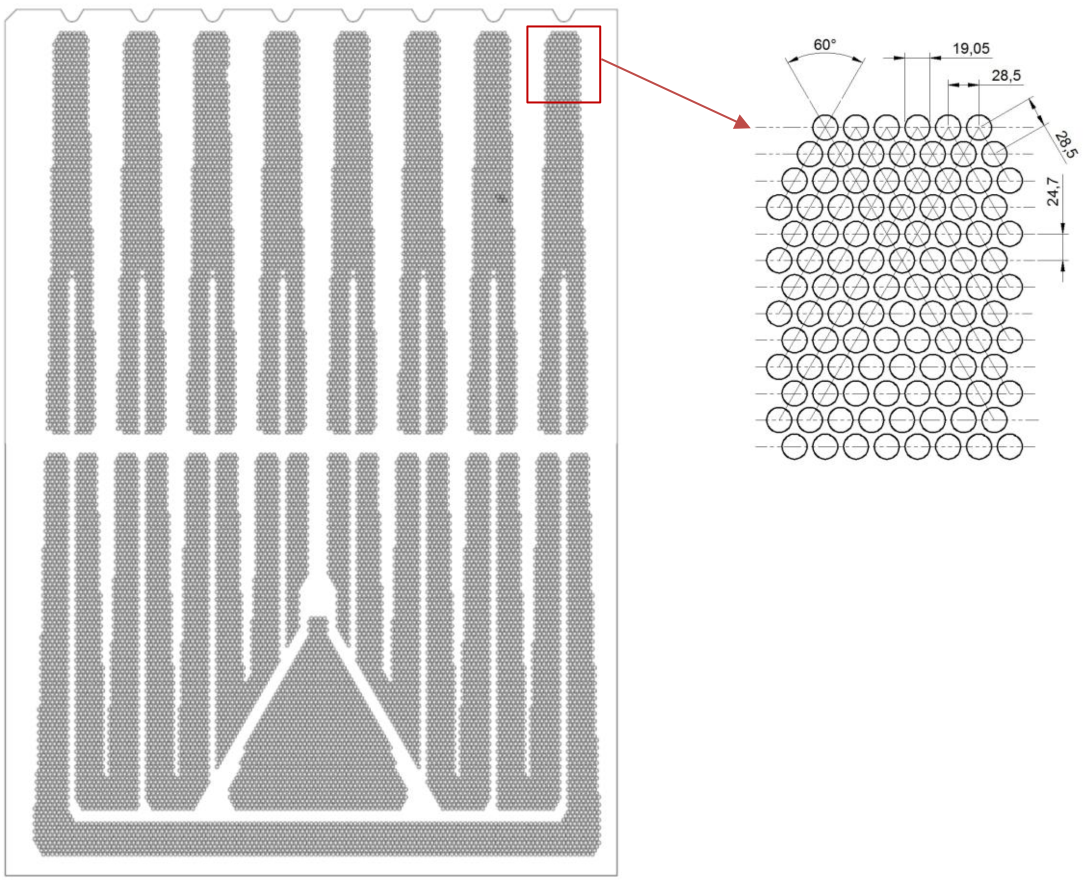

Figure 3: Typical tubes layout on the Condenser tubesheet (dimensions in mm)
Adapted from Eletronuclear (2014)

2.3 Angra 1 Nuclear Power Plant

The first Brazilian nuclear power plant went into operation in 1985 and the reactor system supplier is WESTINGHOUSE. Angra 1, located at Nuclear Central Almirante Álvaro Alberto (CNAA), in Angra dos Reis (RJ), produces 640 MW and generates sufficient energy to feed one city with 1 million people. According to Eletronuclear (2018), the Angra 1 Condenser material is ASTM A-285C, their tubes is made of Titanium (ASME B-338 Gr.02) and the sea water flow is 38.53 m³/s. The Tab. 1 presents the main parameters of Angra 1 nuclear power plant.

Table 1: Angra 1 Condenser flow properties, with the nuclear power plant in 100% of power
Adapted from Souza (2017)

Variables	Flow [kg/s]	Pressure [bar]	Temperature [ºC]	Enthalpy [kJ/kg]
Flow inlet after LP turbine	553.30	0.068	-	2,232.51
Heaters drains	159.70	-	44.94	188.43
Condensed - RSU turn	10.17	0.21	60.67	254.00
Steam - RSU turn	4.25	0.21	60.67	2,435.50
CVS drains	0.59	-	99.06	414.90
Replacement water	4.90	-	-	84.07
Feed water outlet	733.60	0.068	38.40	160.76

2.4 Angra 2 Nuclear Power Plant

The second Brazilian nuclear power plant went into operation in 2001 and the reactor system supplier is SIEMENS/KWU. Angra 2, located at Nuclear Central Almirante Álvaro Alberto (CNAA), in Angra dos Reis (RJ), produces 1,350 MW and generates sufficient energy to feed one city with 2 million people. According to Eletronuclear (2018), the Angra 2 Condenser material is ASTM A-36, their tubes is made of Titanium (Gr.02) and the sea water flow is 74.40 m³/s. The Tab. 2 presents the main parameters of Angra 2 nuclear power plant.

Table 2: Angra 2 Condenser flow properties, with the nuclear power plant in 100% of power
Adapted from Siqueira (2016)

Variables	Flow [kg/s]	Pressure [bar]	Temperature [ºC]	Enthalpy [kJ/kg]
Flow inlet after LP turbine	1,139.90	0.050	32.88	2,258.00
Heaters drains	179.20	0.11	46.90	196.20
Condensed - RSU turn	-	-	-	-
Steam - RSU turn	-	-	-	-
CVS drains	0.80	0.97	98.90	414.50
Replacement water	-	-	-	-
Feed water outlet	1,319.80	0.070	39.40	169.09

For this work, it was considered smooth tubes (no fins) and isobaric process in Condensers. According to Eletronuclear (2018), the total number of tubes in group of Condensers is 48,000. According to Souza (2017), the negative pressure inside the Condenser is due to the fluid condensation itself. Thus, a less heat transfer causes a less pressure drop, affecting the overall plant efficiency.

Considering the representation of Condenser operation, Fig. 4, heat transfer occurs through regions, line by line of the tubes assembly, from the top to the bottom of the tubesheet. As the saturated steam goes down and touches the lines of tubes, it causes the decrease of the liquid-steam mixture enthalpy, increasing a liquid portion on this mixture.

During the phase change, where the salt water goes into all the tubes with the same temperature, the consideration of a constant decreasing of the enthalpy along the tubesheet provides good approximations. Knowing this, in this study, a constant variation of the mixture enthalpy was considered.

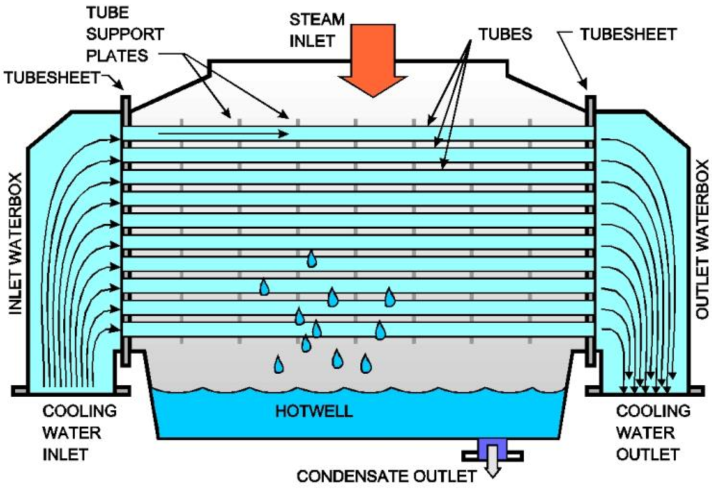

Figure 4: Condenser operation diagram

3. RESULTS AND DISCUSSION

The Condenser receives saturated steam from Turbine and heaters drains. By performing a weighted average of enthalpy of input fluids in the Angra 1 Condenser, an average enthalpy of 1,820.49 kJ/kg was found for the outflow (733.60 kg/s). Considering that the rejected heat in Condenser is transferred totally to Circulation Water System (SAC), which is the sea water, and that condensate enthalpy is 160.76 kJ/kg, we assuming that enthalpy variation is constant along the 212 tubes lines.

Using the Eq. (4) and Tab. 1, it was possible to calculate the total heat rejected in Angra 1 Condenser, as following:

$$\dot{Q}_{cond.} = 553.30*2{,}332.51+159.70*188.43+10.17*254.00+4.25*2{,}435.5+0.59*414.90+4.90*84.07-733.60*170.48$$

$$\dot{Q}_{cond.} = 1{,}209.20MW$$

Knowing the heat which shall be rejected, considering the salt water temperature at Angra 1 Condenser inlet with 27 °C and the flow mass with 38.53 kg/s, according to Souza (2017), the salt water enthalpy can be find using the Eq. (4), as following:

$$h_o = \frac{\dot{Q}_{cond.}}{\dot{m}_{salt}} + h_i = \frac{1209200}{38530} + 113.28 = \mathbf{144.66\ kJ/kg}$$

Using the same procedure, by performing a weighted average of enthalpy of input fluids in the Angra 2 Condenser, an average enthalpy of 1,956.49 kJ/kg was found for the outflow (1,139.90 kg/s). Considering that the rejected heat in Condenser is transferred totally to Circulation Water System (SAC), which is the sea water, and that condensate enthalpy is 169.09 kJ/kg, we assuming that enthalpy variation is constant along the 212 tubes lines.

Using the Eq. (4) and Tab. 1, it was possible to calculate the total heat rejected in Angra 1 Condenser, as following:

$$\dot{Q}_{cond.} = 1{,}139.90*2{,}258.5+192.20*196.2+0.80*414.50-1{,}319.80*165.1$$

$$\dot{Q}_{cond.} = 2{,}392.05MW$$

Knowing the heat which shall be rejected, considering the salt water temperature at Angra 2 Condenser inlet with 27 °C and the flow mass with 74.40 kg/s, according to Souza (2017), the salt water enthalpy can be find using the Eq. (4), as following:

$$h_o = \frac{\dot{Q}_{cond.}}{\dot{m}_{salt}} + h_i = \frac{2392050}{74400} + 113.28 = \mathbf{145.45\ kJ/kg}$$

According to thermodynamics tables, the encountered enthalpies refer to salt water temperatures at third circuit outlet of 34.50 °C for Angra 1 and 34.69 °C for Angra 2. Applying the Eq. (1) to (4), Eq. (6) and Tab. 1, it was possible to determine the behavior of enthalpy and heat transferred inside the Condensers. This behavior can be seen in Fig. 5:

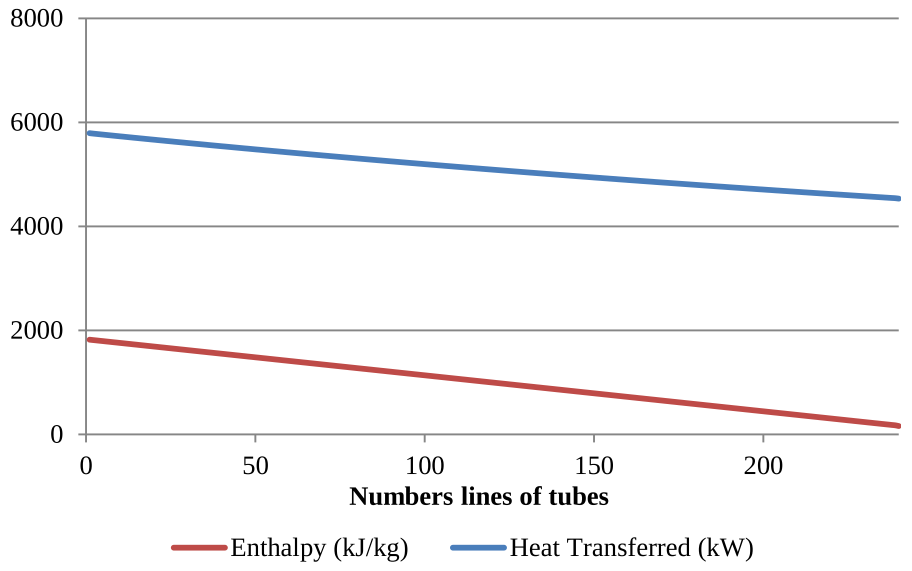

Figure 5: Enthalpy and heat transferred along Condenser tubes

Although the fluid enthalpy presents higher value on the firsts lines of tubes, through the Eq. (6) it is possible to note that the thermal capacity is lower as more steam presents on the fluid, due to the low specific heat of steam compared with liquid water. This causes a quasi-linear behavior on the heat transferred and the enthalpy, as can be seen on Fig. 5.

Knowing that the Condenser vacuum is generated by the condensation itself, due to decreasing of specific volume, it was analyzed whether the tamponing of the pipes would have an impact on the efficiency of the secondary circuit and, consequently, the entire plant. The result is shown in Fig. 6.

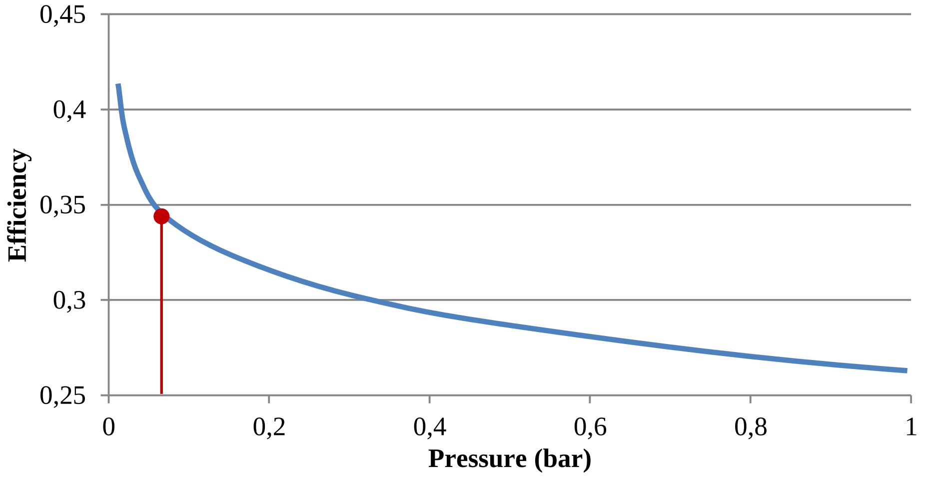

Figure 6: Efficiency of a nuclear power plant and pressure decreases in Condenser

It is important to note that the steam quality on LP turbines is an important limit value when the objective is the increase of the plant efficiency, causing more pressure drop inside the Condensers. This condition can be observed in Fig. 7.

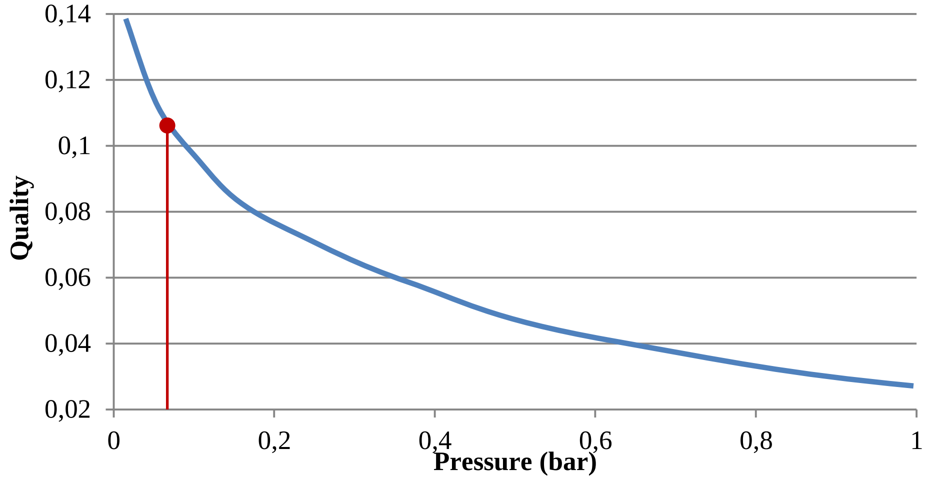

Figure 7: Steam quality behavior in function of pressure inside the Condensers

Looking to Fig. 7, it is possible to note that the steam quality is already on the recommended limit. Therefore, it is not possible to increase the plant efficiency through the decreasing on Condenser pressure without considering the increase of liquid on the steam mixture inside the LP turbines, condition which harms its work, due to possibility of corrosion inserted by the friction between the droplets and blades.

4. CONCLUSIONS

It was found that the tubes located in the upper regions of the Condenser transfer a little bit more heat, because they have a higher enthalpy of the saturated steam. However, the heat transferred on the upper regions is not so high as could be, because the low thermal capacity due to the low specific heat of steam compared to the liquid water.

It has also been observed that the tamponing of the tubes (from any region) causes a lower thermal exchange and, consequently, a lower vacuum generation, which impacts negatively the yield of the plant.

Therefore, two important situations can be highlighted. The first is that the indiscriminate tamponade of the tubes is harmful and, if carried out in large quantity in any regions of the Condenser, can cause a critical situation of less heat transfer from steam coming from turbines, harming the pressure drop inside the Condensers. The second situation is the harming of the pressure drop inside the Condensers causes directly influence on the plant efficiency.

It was also observed that it is not possible to increase the plant efficiency through the indiscriminate decreasing on Condenser pressure without considering the possibility of liquid increasing on the steam mixture inside the LP turbines, condition which harms its work, due to possibility of erosion inserted by the friction between the droplets and blades.

5. REFERENCES

Canalini, A. & Carvalho, N. C., 1985. *Testes de prevenção e detecção de vazamentos em tubos Condensadores e Geradores de Vapor de uma Usina Nuclear do tipo PWR. VI Seminário Nacional de Ensaios Não Destrutivos.* Belo Horizonte, Brazil.

Chaves, L. C., 2017. *Análise Termodinâmica do Circuito Primário de um Submarino Nuclear Utilizando Parâmetros Pré-Definidos da Usina Nuclear de Angra 1. Bachelor's Dissertation,* CEFET/RJ.

ELETRONUCLEAR. 2014. *Nuclear Power Plant Basic Systems,* Eletrobras Termonuclear SA, Rio de Janeiro, Brazil.

ELETRONUCLEAR. 2018. *Eletrobras Termonuclear S.A - Eletronuclear. http://www.eletronuclear.gov.br*

Incropera, F. P., 2008. *Fundamentos de Transferência de Calor e Massa. Ed. 6ª.*

Siqueira, D. S., 2016. *Análise Energética e Exergética de uma Usina Nuclear com Reator PWR.* Master's Dissertation. Itajubá, Brazil.

Sonntag, R. & Borgnakke, C., 2009. *Fundamentos da Termodinâmica. Ed. 7ª.*

Souza, Y. L., 2017. *Análise Termodinâmica e Modelagem Computacional com Otimização de Parâmetros do Sistema Secundário da Usina Nuclear de Angra 1. Bachelor's Dissertation,* CEFET/RJ.

Todreas, N. E., 2015. *Nuclear Systems: Thermalhydraulic Fundamentals.*

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