DESIGN OF MODIFIED THROTTLING CALORIMETER FOR LOW STEAM QUALITY MEASUREMENTS

Alan Rabelo de Souza Moura, alan.moura@itec.ufpa.br
Hussein Felix Gazel, husseingazel@yahoo.com.br
ManoelF. M. Nogueira, mfmn@ufpa.br
Grupo de Energia, Biomassa&MeioAmbiente, Faculty of Mechanical Engineering, Federal University of Pará, Belém, Pará, Brazil, zip code 66075-110

Abstract. *On the Amazon, the Pará state stands out as the one who has more intensively utilized its bases of timber. One alternative for more efficient waste use is its combustion in cyclone boilers, converting chemical energy into power or process steam. The accurate measurement of this steam energy plays a key role on the enterprise energy management. On this scenario, the project developed by the group Energy, Biomass and Environment, EBMA, at Mechanical Engineering School, UFPA, made possible the construction of a cyclonic combustion boiler at laboratory scale and producing wet steam at low pressure (8 kgf/cm²). To determine the efficiency of the boiler using the direct method demands to know the produced steam enthalpy. Since the boiler does not possess super-heater, evaluation of the steam quality is required to quantify steam enthalpy. A technique for doing this involves the throttling calorimeter. However, they are not effective for low steam quality values like the ones expected for the EBMA boiler. The effectiveness of this device is limited by the throttling capacity to convert the mixture liquid-vapor in superheated steam. In this context, a modified throttling calorimeter was developed capable to determine low values of steam quality. In this device, electric heaters adds heat to the stream in a controlled flux and the stream velocity which passes through it is measured using the thermal mass flow meter operating principles. For the sizing of the throttling and the heaters, a steam flow analyses was made based on forecasts for the boiler steam quality. For this device was developed an appropriate instrumentation, which allowed the computer assisted instantaneous steam quality measurement. This device can be used in any range of steam quality, by adding the appropriate amount of heat to the steam and has an uncertainty of 7%.*

Keywords*: throttling calorimeter, steam quality, cyclone boilers, instrumentation.*

1. NOMENCLATURE

B	Orifice pressure drop coefficient	v	Specific volume
C_c	Contraction coefficient	h	Specific enthalpy
CV	Control volume	x	Steam Quality
g	Gravity acceleration	T_s	Surface temperature
$\dot{Q}$	Heat transfer rate	T	Temperature
z	Height	T_∞	Temperature of lowing fluid
l	Liquid	C_{cap}	Thermal capacity
$\dot{m}$	Mass flow rate	R_t	Thermal resistence
G	Mass velocity	D	Tube diameter
d	Orifice diameter	δ	Uncertainty
P	Pressure	v	Vapor
Δp	Pressure drop	h_{lv}	Vaporization enthalpy
ΔP_{l0}	Pressure drop for all flow as liquid	V	Velocity
r	Radial	K_0	Velocity ratio
T_{Sat}	Saturation temperature	$\dot{W}$	Work transfer rate

2. INTRODUCTION

2.1 Motivation

On the Amazon, the Pará state stands out as the one who has more intensively utilized its bases of timber. The supply chain of this sector presents large waste generations as sawdust and shavings. One alternative for more efficient waste use is its combustion in cyclone boilers, converting chemical energy into power or process steam. Steam is an important secondary energy. It can be used to produce energy because of its heat energy or working capacity. Due to its environmental friendly nature, and the high energy efficiency, steam is widely used in industrial production. The accurate measurement of steam energy plays a key role to the current domestic energy consumption and improvement of enterprise energy management level (Tao et al., 2008).

On this scenario, the project developed by the group Energy, Biomass and Environment, EBMA, at Mechanical Engineering School, UFPA, made possible the construction of a cyclonic combustion boiler at laboratory scale and producing wet steam at low pressure (8 kgf/cm²). The determination of the efficiency of the boiler using the direct method demands to know the energy of the produced steam. When boilers operate without super-heater, as the UFPA boiler, the steam produced is at the saturation temperature, consequently two-phases, liquid and vapor, are present at saturate conditions, this is called wet steam.

To know the wet steam energy first is necessary to determine the state of the two-phase liquid–vapor mixture, thus the pressure and the quality of the substance should be known. However, there are no effective means to directly measure the quality or other properties of the saturated mixture such as specific volume, enthalpy or internal energy (Dorfman and Fridman, 2006).

2.2 Background

2.2.1 Barrel Calorimeter

Rathore (2010) presents in his work the working principle of the barrel calorimeter. A know mass of steam at a pressure, P is condensed in the presence of a known quantity of water filled in a barrel calorimeter. As steam condenses, the mass and temperature of water increase. The amount of heat lost by wet steam and amount of heat received by water on the calorimeter are equated to obtain the dryness fraction of wet steam: $m_v[(xh_{lv}) + C_{pwater}(T_{sat} - T_2)] = (C_{cap} + m_{water}C_{pwater})(T_2 - T_1)$. The barrel calorimeter is show in Fig. 1.

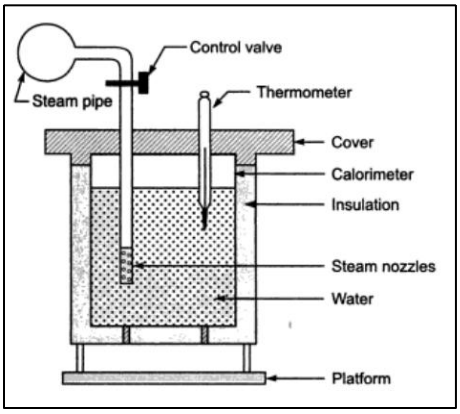


Figure 1. Barrel Calorimeter.

The value of the steam quality obtained by this method involves considerable error, since the heat losses due to convection and radiation are not taken into account.

2.2.2 Separating Calorimeter

The separating calorimeter separates water particles from wet steam mechanically by centrifugal action. The steam passing into the calorimeter is forced to change its direction of motion by means of a perforated cup. The water particles due to their greater moment of energy (being heavier) tend to move away and get separated from the mixture as shown in Fig. 2.

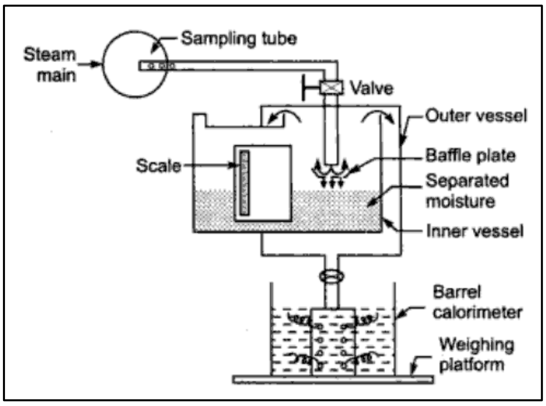


Figure 2. Separating calorimeter.

Some quantity of moisture drains through the perforated cup, some quantity falls as large droplets and some quantity sticks with the wall of the separator. The condensate is collected in the separator and its quantity is measured by a glass tube. The dry steam is passed through a small condenser, where it condenses and its mass is measured (Rathore, 2010). The dryness fraction x is determined as: $x = m_v/(m_l + m_v)$. It is noticed that the steam quality obtained from such experimentation is not accurate, but it is just a close approximation.

2.2.3 Throttling calorimeter

A sample of wet steam at a pressure $P_1$is taken from the steam line. The wet steam is then throttled, through an orifice or a restricted valve, to a pressure P_2 and a temperature T_2 in such a way that the steam reaches the superheated region (Figure 3). During the throttling process, the enthalpy of steam remains constant (Singh, Bhavikatti e Chandra, 2006 and Rathore, 2010).

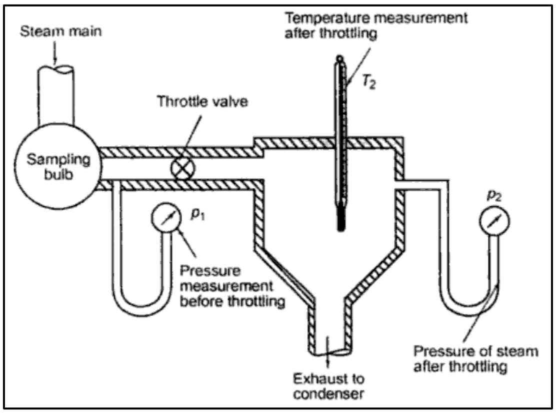


Figure 3. Throttling calorimeter.

The state 1 is defined by pressure P_1 and dryness fraction x_1, while the state 2, in superheated region after throttling can be defined by the pressure P_2 and temperature T_2. Using properties of wet steam at P_1 and superheated steam at P_2 and T_2, we get:$x_1=(h_2-h_1)/h_{lv1}$.

After throttling the pressure drop must be enough to transform the wet steam in superheated steam with its temperature T_2 above the saturation temperature, T_{sat} by 5°C, to guarantee a good approximation of the real steam quality. However, the pressure P_2 that the steam will get must be bigger than the atmospheric pressure; otherwise, the steam will not flow through the calorimeter. Therefore, if the steam quality is too low, the pressure drop may not be enough to make the steam reaches the necessary temperature.

Taking as an example, the steam line where the pressure is P_1=784.53 kPa(8 kgf/cm²) minimum pressure that the steam can assume which guarantees its flow through the calorimeter is P_2=151.99 (1.5 atm). The minimum temperature that steam must get is $T_2=T_{sat}+5°C=116.7°C$. Since temperature and the pressure at state 2 are known is possible to find the enthalpy, which is h_2=2404 kJ/kg. Since the pressure P_1 is known and the enthalpy at state 2 is equal to enthalpy at state 1 the minimum quality that can be determined using a throttling calorimeter for this case is x_1=0.969. Since the maximum steam quality is 1.0 this is a very restricted range to work with.

2.2.4 Electrical calorimeter

Singh, Bhavikatti e Chandra (2006) describes the working principle of the electrical calorimeter in their work. The working principle employed in this apparatus is similar to that of throttling calorimeter. Here also wet mixture is brought to the superheated state, by heating and no by throttling. For known amount of heat added and the final enthalpy for superheated steam being known, one can find the initial enthalpy. Figure 4 shown the electrical calorimeter.

For a wet steam mass flow rate $\dot{m}$, heat added by the heater $\dot{Q}_{add}$, and the enthalpies before and after heating being h_1 and h_2, stead flow energy equation considering no heat loss may be written as: $\dot{m}h_1 + \dot{Q}_{add} = \dot{m}h_2$. Rearranging the equation and using the relation between steam quality and enthalpy we get: $x = [h_2 - (h_{l1} + \dot{Q}_{add}/\dot{m})]/(h_{v1} - h_{l1})$.

The bigger disadvantage of this calorimeter is, that depending on how low the quality of the steam that is to be determined is, the power added by heater may be high.

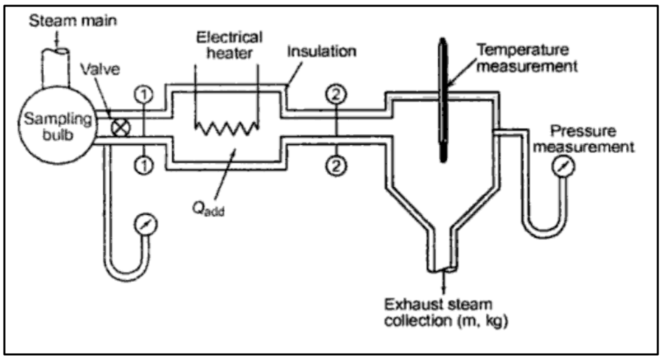


Figure 4. Electrical calorimeter.

2.3 Objective

The determination of thermodynamics properties of steam has a very important paper on the industrial plants energy efficiency studies. When the considered steam is wet steam the steam quality determination is crucial. However, today, the industry does not count with an apparatus sufficiently trustable to determine this property.

In this context, this paper presents a modified throttling calorimeter which combines the working principle of the throttling calorimeter with the electrical calorimeter. The proposed calorimeter must be capable of determine instantaneous the quality of steam in a wide range of quality.

3. WORKING PRINCIPLE

Figure 5 presents the temperature x entropy diagram, for the proposed calorimeter, for states 1 to 3.The initial throttling is dimensioned to cause an initial rise on the steam quality by reducing the pressure from P_1 to P_2, what makes part of liquid to evaporate. As mentioned, if the steam quality is not high, the pressure drop may not be enough to get superheated steam, and additional heat must be add until it reaches the superheated state or state 3.

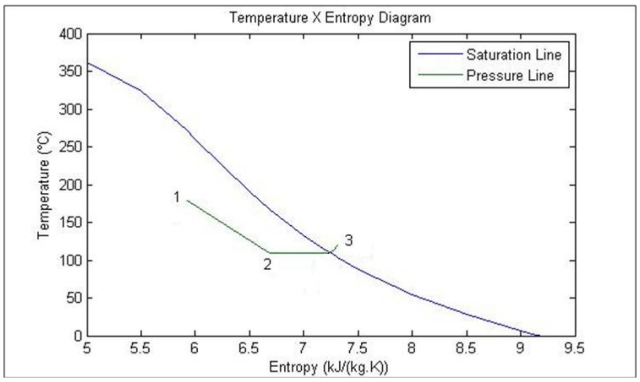


Figure 5. Temperature x entropy diagram for the modified throttling calorimeter

The proposed calorimeter is designed with a 1 inch and a 2 inch tubes connected by a plate with an throttling orifice. Two electrical heaters, one to superheat the steam and other to determine its mass flow rate, are used to add heat and thermal isolation layer is applied to avoid heat loss to surrounds. The calorimeter can be represented as shown in Fig. 6h where the numbers 1, 2 and 3 represents the states of Fig. 5.

The energy balance equation for a control volume between points one and three for the calorimeter in steady state is show below (Moran and Shapiro, 2009):

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}[(h_1 - h_3) + \frac{(v_1^2 - v_3^2)}{2} + g(z_1 - z_3)] \qquad (1)$$

Since there is no external work applied to the system, there is no change in height and in general the variation of kinetic energy is negligible, Eq. (1) becomes:

$$0 = \dot{Q}_{2-3} + \dot{m}(h_1 - h_3) \qquad (2)$$

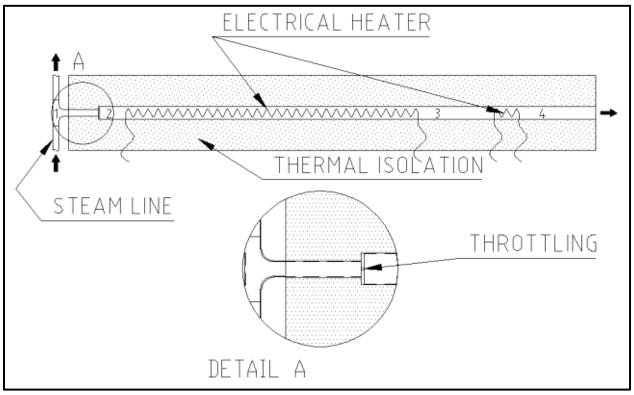


Figure 5. Modified throttling calorimeter.

Once h_3 is the specific enthalpy of superheated steam, it can be determined by measuring the pressure and temperature on that region.

The steam quality can be given by the following expression:

$$x = \frac{h_1 - h_{l_1}}{h_{v_1} - h_{l_1}} \tag{3}$$

Where h_{v1} and $h_{f1}$are found knowing the pressure or the temperature in the steam line, region 1. Rearranging Eq. (2) and substituting in Eq. (3) we have:

$$x_1 = \frac{h_3 - \left(h_{l_1} + \dot{Q}_{2\text{-}3}/\dot{m}\right)}{h_{v_1} - h_{l_1}} \tag{4}$$

To determinate the steam mass flow rate, $\dot{m}$, the working principle of thermal flow meter is incorporate to the calorimeter. Applying the energy balance equation in a control volume between regions 3 and 4 of Fig. 5:

$$\dot{Q}_{3-4} = \dot{m}(h_4 - h_3) \tag{5}$$

Rearranging Eq. (5):

$$\dot{m} = \frac{\dot{Q}_{3-4}}{(h_4 - h_3)} \tag{6}$$

4. SIZING

4.1 Throttling orifice

Firstly is necessary to known the steam pressure at the line and have an initial estimative of the quality that wants to be calculated to size the modified throttling calorimeter. For this case, the pressure and the quality considered were $P_1 = 784.53$ kPa and $x_1 = 0.81$ respectively.

To size it was necessary to solve equations which show how the steam flows through the device. According to Chisholm (1983) the pressure drop following pipe and orifice with diameter of 50.8 mm and 8 mm, respectively, is obtained as follows:

$$\frac{\Delta P}{\Delta P_{l0}} = 1 + \left(\frac{v_{v_1}}{v_{l_1}} - 1\right)\left[B x_1 (1 - x_1) + {x_1}^2\right] \tag{7}$$

The change in pressure if all the mixture that flows through the orifice were liquid is given by:

$$\Delta p_{l0} = -\frac{G^2 v_l}{2} K_0 \tag{8}$$

Where the velocity ratio between phases is $K_0=(v_v/v_1)^{1/4}=3.851$ and the mass velocity is $G = \dot{m}/A = 37.94\ \mathrm{kg/s.m^2}$. Substituting K_0 and G in Eq. 8 we obtain $\Delta p_{l0}=-3.087$ kPa.

The orifice pressure drop coefficient, B, is given by the following equation:

$$B = \frac{\left[\frac{1}{(C_c\sigma)^2} - 1\right]\frac{1}{K_0} - \frac{2}{C_c\sigma K_0} + \frac{2}{{K_0}^{0,28}}}{\frac{1}{(C_c\sigma)^2} - 1 - \frac{2}{C_c\sigma} + 2} \tag{9}$$

Where the contraction coefficient C_c is given as follow:

$$C_c = \frac{1}{0.639(1-\sigma)^{1/2}+1} \qquad (10)$$

The ratio of the cross section area for the throttling is σ=(d/D)²=0.09766. Substituting σ on Eq. 10 we obtain C_c=0.6223. Substituting σ and K_0 on Eq. 9 we obtain B=0.2633. Finally, substituting x_1, Δp_{l0} and B on Eq. 7 we obtain ΔP=-437.7 kPa.

Therefore, if the steam at P_1 and x_1 in a 2 inch tube flows through an orifice of $d = 8$ mm the pressure drops to $P_2 = 310.9$ kPa.

The pressure drop calculated along the 1 and 2 inch tubes are negligible when compared with the pressure drop following the orifice.

4.2 Superheating electrical heater

Equation 2 may be used to find the heat that the superheating electrical heater should send to superheat the wet steam after the orifice. As x_1 and P_1 are known, is possible to find the specific enthalpy at 1 which is $h_1 = 2378$ kJ/kg. If during the throttling process, the enthalpy of steam remains constant, enthalpies at regions 1 and 2 are equal and $h_2 = 2378$ kJ/kg.

Since there is no significant pressure drop along the 2 inches tube, the pressure at region 2 is equal to pressure at region 3, thus $P_3 = 310.9$ kPa. If corresponding saturation temperature for P_3 T_{sat3}=134.7°C, the temperature at the region 3 is $T_3 = 134.7\ °C + 5°C = 134.7\ °C$. As P_3 and T_3 are known, is possible to find the specific enthalpy at 3 which is $h_3 = 2751$ kJ/kg.

Considering that $\dot{m}$ is to be maintained close to 6.705x10^{-3}kg/s and substituting the values of h_2 and h_3 in Eq. 2, we find that the heat required for the superheating electrical heater is $\dot{Q}_{2-3}$=2.500 kW Assuming that all the electrical power supplied to the heater is converted in heat, the electrical heater capacity must be 2500 W.

4.3 Flow meter's electrical heater

Equatin 5 may be used to find the heat that flow meter's electrical heater should send to measure the mass flow rate. Assuming that all the electrical power supplied to the heater is converted in heat, let's consider an electrical heater with capacity of 100 W. Substituting h_3, $\dot{m}$ and $\dot{Q}_{3-4} = 0.100$ kW on Eq. 5, we obtain $h_4 = 2766$ kJ/kg. Therefore, $h_4 - h_3 = 14{,}91$ kJ/kg, which is a difference that can be easily measured. Thus, a heater with capacity of 100 W may be used to find the mass flow rate in the calorimeter.

4.4 Thermal isolation

To size the thermal isolation thickness in order to have a small heat transfer from the steam to surrounds, the thermal resistance concept was used, as expressed by the following equation (Incropera, 2007):

$$Q_r = \frac{T_{\infty,int} - T_{\infty,ext}}{\sum R_t} \qquad (11)$$

Where $\sum R_t$ is the sum of $R_{t,conv\,1}$, $R_{t,cond\,1}$, $R_{t,conv\,2}$ and $R_{t,cond\,2}$, which represents the steam convection resistance, the steel tube conduction resistance, the thermal isolation resistance and the outer air convection resistance, respectively. Figure 6 presents a schematic for the heat transfer by the thermal resistances.

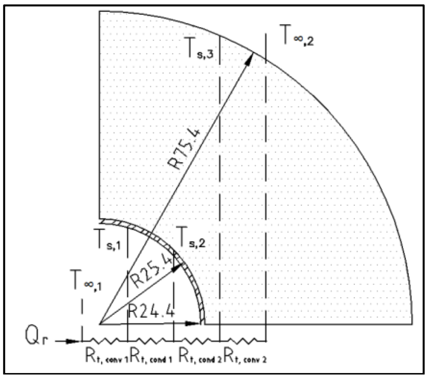


Figure 6. Cross section of calorimeter with the radius and temperatures.

Knowing tube dimensions and, steam thermal properties and velocity its convection resistance is found to be $R_{t,conv1}$=5.545 m².K/W. As thermal properties and, the inner and outer radius of the steel tube are known its conduction resistance is found to be $R_{t,cond1}$=0.009 m².K/W. Considering a thickness of 50 mm for the thermal isolation and knowing its thermal conduction coefficient the conduction resistance is found to be $R_{t,cond2}$=59.32 m².K/W.

According to Oliveira et al (2010) at Belém medium wind velocity is 2.5 $\mathrm{m/s}$ and the annual medium temperature in Belém is 25.9°C. With this information is possible to estimate the outer air convection resistance which is $R_{t,cond2}$=1.996 m².K/W.

Substituting the steam temperature $T_{\infty,int}$, the air temperature $T_{\infty,ext}$ and the sum of the thermal resistances $\sum R_t = 66.87\ \mathrm{m^2.K/W}$, the heat that the steam transfers that to surrounds is $Q_r = 69.45\ \mathrm{W}$. Which is a small value if compared with the amount of heat add by the heaters. Therefore, the thermal isolation thickness of 50 mm is enough for the purpose.

5. INSTRUMENTATION

In order to determine the steam quality the calorimeter needed to be instrumented. Thermocouples and pressures transducer were installed to measures temperature at regions 3 and 4, and pressure at 1 and 3. While the electrical power of the heaters is measured with an analyzer and register of electrical magnitudes named SAGA. Figure 7 presents the calorimeter instruments cited.

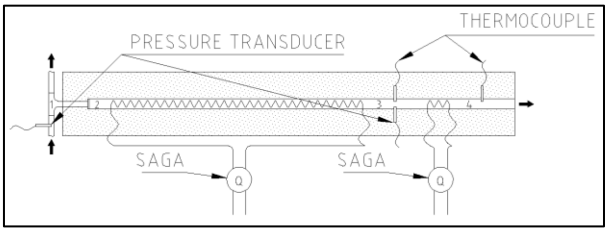


Figure 7. Calorimeter instruments.

The values obtained with instrumentation are lead to an acquisition board before going to a personal computer, where an monitoring and control software is installed. Figure 8 presents a schematic of the calorimeter instrumentation.

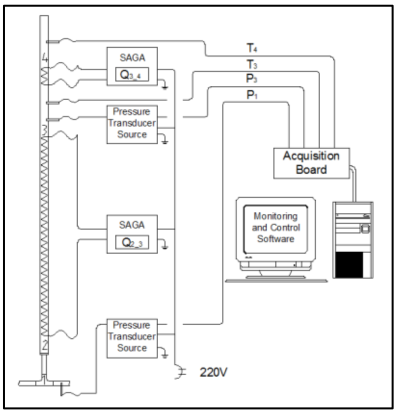
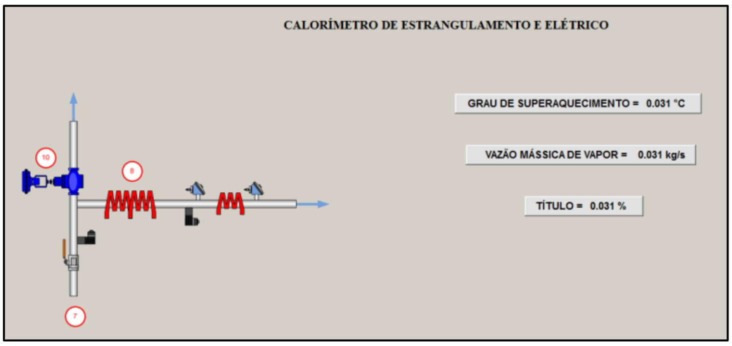


Figure 8. Calorimeter instrumentation.

Using the monitoring and control software a program for acquisition and monitoring of the steam quality was developed. This programs has as inputs T_3, T_4, P_1, P_3, Q_{2-3} and Q_{3-4} and, after solving the equations presented in the working principle section, the main output, the steam quality, is obtained. Figure 9 presents the interface of the acquisition and monitoring program for the calorimeter.


CALORÍMETRO DE ESTRANGULAMENTO E ELÉTRICO

GRAU DE SUPERAQUECIMENTO = 0.031 °C

VAZÃO MÁSSICA DE VAPOR = 0.031 kg/s

TÍTULO = 0.031 %

Figure 9. Interface of the acquisition and monitoring program for the calorimeter.

6. UNCERTAINTY

Since all instruments have some degree of uncertainty on their measurements, these uncertainties will result in an uncertainty at the determination of the steam quality.

Kline and McClintock presented a technique for uncertainty propagation assuming that the data is normally distributed and is not correlated (Moffat, 1988, Figliola and Beasley, 2006). If the calculated value x_1 is a function of 6 measuremets, T_3, T_4, P_1, P_3, Q_{2-3} and Q_{3-4}, each one with its own uncertainty, δ_{T3}, δ_{T4}, δ_{P1}, δ_{P3}, δ_{Q2-3} and δ_{Q3-4}. So the uncertainty in x_1, δ_{x1}, can be divided in its elementary uncertainties originated from each measured variable. For example, the elementary uncertainty in x_1 from the measurement T_3 is given by:

$$\delta_{x_1,T_3} = \frac{\partial x_1}{\partial T_3}\delta_{T_3} \tag{12}$$

The elementary uncertainties can be combined to find δ_{x_1} by the following equation:

$$\delta_{x_1} = \sqrt{{\delta_{x_1,T_3}}^2 + {\delta_{x_1,T_4}}^2 + {\delta_{x_1,P_1}}^2 + {\delta_{x_1,P_3}}^2 + {\delta_{x_1,Q_{2-3}}}^2 + {\delta_{x_1,Q_{3-4}}}^2} \tag{13}$$

The uncertainties of T_3, T_4, P_1, P_3, Q_{2-3} and Q_{3-4} are 1%, 1%, 0.25%, 0.25%, 0.5% and 0.5%, respectively. Solving Eq. 12 for the given variables, we obtain the values of $\delta_{x1,T3}$, $\delta_{x1,T4}$, $\delta_{x1,P1}$, $\delta_{x1,P3}$, $\delta_{x1,Q2-3}$ and $\delta_{x1,Q3-4}$, which are 0.403, 0.401, 0.403, 0.401, $0.079\text{x}10^{-3}$, $0.097\ \text{x}10^{-3}$,$0.898\ \text{x}10^{-3}$and $0.899\ \text{x}10^{-3}$, respectively. Substituting these values on Eq. 13 we obtain steam quality uncertainty, δ_{X1}=0.05685 or 7.00%. The variables T_3, T_4, P_1, P_3, Q_{2-3} and Q_{3-4}, contribute with 50.24%, 49.71%, 0.00%, 0.00%, 0.02% and 0.02%, respectively, in the steam quality uncertainty, δ_{X1}.

7. CONCLUSION

There are many difficulties when using the conventional calorimeters to measure steam quality, as low precision and low range of applicability. The modified throttling calorimeter proposed in this paper tries to overcome these difficult.

The capacity of the modified throttling calorimeter is only limited by the quantity of heat that can be add to the steam. As smaller the steam quality, bigger is the quantity of heat that must be added to it. Thus, theoretically, this device can be used in any range of steam quality.

The uncertainty of the proposed calorimeter is about 7.00%. But this number can be considerably reduced by using a thermocouple with higher precision.

As this calorimeter counts with an instrumentation system the value of the steam quality measured with it can be monitored in real-time and stored in a personal computer.

8. REFERENCES

Chisholm, D., 1983. Two-phase flow in pipelines and heat exchangers. Longman, New York.

Dorfmana, A. and Fridman, E., 2006. Vapor quality measurement by a discharging calorimeter. Elsevier, New York.

Figliola, R. S. and Beasley D. E., 2006. Theory and Design for Mechanical Measurements. WILEY, New Jersey.

Incropera, F. P. et al., 2007. Fundamentals of Heat and Mass Transfer. John Wilei & Sons, Denvers.

Moran, M. J. and Shapiro, H. N., 2009. Princípios de Termodinâmica para Engenharia. LTC, Rio de Janeiro.

Oliveira, M. C. F. et al, 2010. Climatologia e índice de conforto térmico em Bélem - PA.

Rathore, M. M., 2010. Thermal Engineering. 1 ed. McGraw Hill, Nova Delhi.

Moffat, R. J. 1998. Describing the Uncertainties in Experimental Results, Experimental Thermal and Fluid Science. Elsevier, New York.

Singh, O., Bhavikatti S. S., Chandra S., 2006. Introduction To Mechanical Engineering: Thermodynamics, Mechanics and Strength of Materials. 4 ed. New Age International, Nova Delhi.

Tao, Z., Wenda, X., Ying, Bi. and Yan, J., 2008. Development of Standard Device for Steam Flow Measurement Used Condensing Weighing Method. General Administration of Quality Supervision, Inspection and Quarantine of the P.R.C.. Tianjin, China.

9. RESPONSIBILITY NOTICE

The authors Alan Rabelo de Souza Moura, Hussein Felix Gazel and Manoel Fernandes Martins Nogueira are the only responsible for the printed material included in this paper.