DETERMINATION OF ENTHALPY AND HEAT FLOW FOR WET STEAM CIRCUITS

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Abstract. The paper is a theoretically analyse about the possibility to realise a heat flow counter for low pressure wet steam ducts. A constructive scheme, based on the use of an enthalpy-meter with two electrical resistances, is proposed for such counter. The calculus procedure for the heat flow is also presented.

Keywords: wet steam, enthalpy, heat flow rate.

1. INTRODUCTION

As known, in the field of low pressure wet steam, in order to determine the state of the steam, one must know, besides its pressure and temperature, at least one of the state parameters: enthalpy, specific volume, title, or entropy.

The researches done in our department led to the achievement of a device, which allows measuring the enthalpy of the wet steam, called enthalpymeter. The operating mode consists in the superheating of a fraction of the wet steam that flows through the pipe, in two consecutive stages, with two electrical resistances, the steam becoming superheated still after the first stage. The representation of the process in h-s diagram is given in Figure 1.a and the scheme of the enthalpymeter is presented in Figure 2.

From the thermal balance of the two superheating process it is possible to calculate the wet steam enthalpy:

\[ h_1 = h_2 - \frac{R_1}{R_2}(h_3 - h_2) \]  

(1)

The wet steam title can be calculate with the relation:

\[ x = \frac{h_1 - h'}{h'' - h} \]  

(2)

where: \( h' \) is the enthalpy of saturated water, \( h'' \) – enthalpy of saturated steam.

The calculus of the enthalpy and title of the wet steam using the relations (1) and (2) needs the determination of the enthalpies \( h_2 \) and \( h_3 \) as well as of the state parameters \( h' \) and \( h'' \). In order to calculate these parameters, the temperature of the saturated steam and the temperature after every superheating stage were measured and then were used the calculus relations for the water and steam properties. The differences between these relations and the IAWPS 97 [5], for the studied pressure domain, are insignificant.

2. THE PRESSURE LOSSES OF THE DEVICE

In reality, at the steam flow through the device there is on every stage a pressure loss due on one side of the local resistance represented by the electrical resistance, noted \( \Delta p_{12}, \Delta p_{23} \), and on the other side behaves like a thermal nozzle, resulting the pressure losses noted \( \Delta p_{12}, \Delta p_{23} \).

The representation of the process with pressure losses is given in Figure 1.b.

Fig. 1. Representation of the superheating process in enthalpymeter:

a) – without pressure losses; b) – with pressure losses.
By summing the two categories of losses it is obtained the formulas for the pressure losses on each stage:

\[
\Delta p_{12} = \Delta p_{112} + \Delta p_{112} = \zeta_1 \frac{c_1^2}{2v_1} + \frac{m^2}{S} (c_2 - c_1) = \frac{m^2}{S^2} \left( \frac{\zeta_1 v_1}{2} + v_2 - v_1 \right)
\]

(3)

\[
\Delta p_{23} = \Delta p_{123} + \Delta p_{123} = \zeta_2 \frac{c_2^2}{2v_2} + \frac{m}{S} (c_3 - c_2) = \frac{m}{S^2} \left( \frac{\zeta_2 v_2}{2} + v_3 - v_2 \right)
\]

(4)

where: \(\zeta_1, \zeta_2\) are local pressure loss coefficients; \(c_1, c_2, c_3\) - steam velocity at the entrance an at the exit from the two stages; \(v_1, v_2, v_3\) - specific volumes of the steam at the entrance an at the exit from the two stages; \(m\) - steam mass flow rate through the device; \(S\) - flow section through the device.

The study of the influence of the pressure losses of the device on the determination of the wet steam enthalpy and title was made by the determination of the relative errors, between the obtained values using the experimental dates and the calculated values on the hypothesis that the pressure losses are zero.

The relative error for the enthalpy was:

\[\varepsilon_h = -0.045 \div 0.0218\text{ [%].}\]

The relative error for the title was:

\[\varepsilon_x = -0.041 \div 0.061\text{ [%].}\]

The values of the Reynolds numbers for every stage were also calculated and the functions \(\zeta_1 = f(Re_1)\) and \(\zeta_2 = f(Re_2)\) were also established. These functions are:

\[\zeta_1 = -1.1573 \cdot 10^{-10} Re_1^{\frac{4}{2}} + 2.631 \cdot 10^{-4} Re_1 - 0.11232\]

(5)

\[\zeta_2 = 1.5022 \cdot 10^{-9} Re_2^{\frac{9}{2}} - 1.1264 \cdot 10^{-4} Re_2 + 0.32226\]

(6)

3. THE CONSTRUCTIVE SCHEME OF THE HEAT FLOW COUNTER FOR WET STEAM

The measurement of the heat flow rate supplied by the technological steam can be done relatively simple for superheated steam but is difficult for wet or saturated steam, especially for low pressure.

This paper proposes a heat flow counter scheme destined to the low pressure wet steam ducts, the construction of which is based on the use of an enthalpymeter with two electrical resistances. This one, mounted inside of wet steam duct, allows the determination of the heat flow rate. Using the indications of the enthalpymeter it is possible to calculate the mass flow rate. The steam mass flow through the enthalpymeter can be determined using the equation of thermal balance:

\[m = \frac{W_1}{h_2 - h_1}\]

(7)

where \(W_1\) represents the electrical power furnished to the first superheating stage; \(h_1\) and \(h_2\) – the steam enthalpies at the entrance and the exit from this stage.

The scheme of the heat flow counter for the wet steam ducts, which has in its structure an enthalpymeter with two electrical resistances is presented in Figure 3.

The construction of the apparatus must be concept so that the enthalpymeter not behave as a droplets
separator. The avoidance of these phenomena is possible by following two conditions:

– the flow velocity through the apparatus should be equal with the general flow velocity through the duct (the isokinetical condition); this condition can be realised using a transducer $TI$ (with two thermoresistances) and an apparatus for the control of the steam mass flow through the enthalpymeter $ACM$;

– the entrance direction in the apparatus should be parallel with its axe (the orientation condition); assured by the mounting of the enthalpymeter in the centre of the duct, at a suitable distance from the bends or other types of local resistances.

![Fig. 3. Heat flow counter:](image)

$E$ – enthalpymeter; $R_1, R_2$ – electrical resistances; $t_1, t_2, t_3$ – thermocouples amplifier; $TI$ – transducer for isokinetical condition; $SA$ – signal amplifier; $ACM$ – apparatus for control of the steam mass flow.

### 4. THE HEAT FLOW RATE CALCULUS

Using the notations: $c_1$ – the steam velocity at the entrance in the enthalpymeter; $c$ – the steam velocity through the duct; $v_1$ – the specific volume of the steam at the entrance in the enthalpymeter; $v$ – the specific volume of the steam through the duct; $M$ – the steam mass flow that flows through the duct; $m$ – the steam mass flow through the enthalpymeter; $D$ – the interior diameter of the duct; $d$ – the interior diameter of the enthalpymeter, we can calculate the both mass flow rates with following formulas:

$$M = \frac{\pi}{4} D^2 c / v \quad (8)$$

$$m = \frac{\pi}{4} d^2 c_1 / v_1 \quad (9)$$

When the isokinetical condition is releases, the separation of the water droplets from the wet steam can no more be produced and we may consider that the state parameters of the steam that go in the enthalpymeter are equal with state parameters of the steam that flows through the duct, in the proximity of the enthalpymeter: $c_1 = c; \quad v_1 = v; \quad h_1 = h$. The heat flow rate through the duct is:

$$Q = m \cdot h \left( \frac{d}{D} \right)^2 \quad (10)$$

where the mass flow rate and the enthalpy can be determined using the enthalpymeter.

The pressure loss on external circuit of the enthalpymeter, between the annular cross sections 14-35 (Fig. 3), can be calculated, on the hypothesis that the steam does not heat, with the relation:

$$\Delta p_{45} = \zeta_y \frac{c_y^2}{2v_y} \quad (11)$$

where $\zeta_y$ is the local resistance flow coefficient on the circuit 4-5, $c_y$ and $v_y$ – velocity and specific volume of the steam in the annular cross section 14.

The pressure loss inside the enthalpymeter is:

$$\Delta p_{13} = \Delta p_{12} + \Delta p_{23} =$$

$$= \zeta_1 \frac{c_1^2}{2v_1} + \zeta_2 \frac{c_2^2}{2v_2} + \frac{m}{s}(c_3 - c_1) \quad (12)$$

where $\zeta_1, \zeta_2$ are the local resistance flow coefficients for the first and second superheating stage.
As the circuits 1-3 and 4-5 work in parallel, the static pressure loss on these circuits are equal:
\[ \Delta p_{45} = \Delta p_{13} = \Delta p_{12} + \Delta p_{23} \]  \hspace{1cm} (13)
and the steam mass flow inside the enthalpymeter is:
\[ m = \frac{\pi}{4} d^2 \cdot \frac{\zeta_y c_2^2 - \zeta_1^2 c_1^2 - \zeta_2^2 c_2^2}{2v_1} \]  \hspace{1cm} (14)

If the interior cross section of the enthalpymeter is constant for all his length \( c_2/c_1 = v_2/v_1 \) and the mass flow rate through the enthalpymeter is:
\[ m = \frac{\pi}{4} d^2 \cdot \frac{\zeta_y c_2^2}{2v_y} \cdot \frac{c_1^2}{2v_1} \left( \frac{\zeta_1 - \zeta_2 v_2}{v_1} \right) \]  \hspace{1cm} (15)

When the isokinetical condition is satisfied: \( v_y = v_1, c_y = c_1 \) and the previous relation becomes:
\[ m = \frac{\pi}{4} d^2 \cdot \frac{c_1 \left( \zeta_y - \zeta_1 - \zeta_2 v_2/v_1 \right)}{2v_1 (c_3/c_1 - 1)} \]  \hspace{1cm} (16)

Relation (16) actually represents the condition that must be followed by the apparatus for the control of the steam mass flow through the enthalpymeter for the achievement of the isokinetical condition; in this situation the heat flow rate can be calculated with the relation (4).

The calculus of the wet steam heat flow rate through the enthalpymeter with relation (16) requires the experimental determination of the pressure loss coefficients \( \zeta_1, \zeta_2 \) and \( \zeta_y \).

5. CONCLUSIONS

The small value of the errors shows that the pressure losses do not have a significant influence on the determining precision of the enthalpy and title. This allows the simplification of the device, the measuring of the pressure after the two superheating stages being no more useful.

If the enthalpymeter is a part of a wet steam heat counter to know the functions \( \zeta_1 = f(Re_1) \) and \( \zeta_2 = f(Re_2) \) is absolutely necessarily.

REFERENCES