Thermal - fluidics behaviour of water mist and gas fuel flame jets based on experimental results

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Abstract. The main objective of the present paper is to provide a visual investigation of the fire and water mist interference during the extinguish process. This kind of the experimental study for these processes is imposed by the phenomena complexity. The experimental study provides us the information of real behaviour of jets assembly in operation. On this way the physical theoretical model may by better conceived. The main test was focused on the concave shape of ceiling, which gives the better suppression of the flame. From the heat balance, of the studied case, the extinguish efficiency is obtained, the values being around 20%. From these values result that a lot of working agent is lost. That loss is related to the finest of the droplets in the liquid jet. The experimental tests give us the optimal angles between the two jets in aim to realise an efficient extinguish operation.

1. Introduction

The actual systems used for the fire extinguish, must have a short time to suppress the fire and high efficiency of the agent used in this scope. The use of water mist is an opportunity in aim to have an economical method and an ecological way for fire suppression. The most available fluid used is the liquid water. This fluid is not pollutant or toxic, available and has an important heat absorption in comparison with the other agents [1-5]. Liquid dispersed in droplets and the transfer processes occurring in a spray surrounding are complicated and is difficult to model. Droplet dispersion in a jet depends of the atomizer system. The finesse of droplets must be high in aim to have small thermal inertia. Therefore, to accomplish these exigencies must have a droplets diameter less than 20 μm. The dimensions of the pulverized droplets are recommended to be in the range of 10 to 50 μm [2, 5]. Another problem consists in the time interval for evaporation of liquid, which must be a reduced one.

A way to realise this short time is to have an important pressure difference on the nozzle sides, even the magnitude of hundred bars [6]. The authors of this paper projected a heating of water before the entry in the nozzle. On this way a fast evaporation of liquid increases and the useful agent losses diminishes. Our experiences were made with the water heated up to 40°C, its pressure being in the range of (4-6) bar [5, 6]. In fact, the vapour generated by the liquid evaporation pushes the other gases from the affected zone. Consequently, the condition to maintain the flame is not satisfied. By this way the flame volume captured by jet is important and the agent is used efficiently. With these two effects, which take place simultaneously, an efficient cooling of the zone is realisable [5, 7]. Also, by the fast
evaporation of water the gaseous mixture created in the jet has a molar weight of vapour less than the molar weight of surrounding gas. By this way the mixture, rich in vapour, rises and protect the ceiling.

2. Experimental bench arrangement and particularities
The paper is based on the tests made on the experimental layout described below. Considering the above findings, an experimental bench producing the mist jet used for the flame suppression was conceived. The liquid having different temperature at the discharge head of the nozzle is modified in aim to put in evidence its influence on the mist spreading and its evaporation rate. The liquid feed water pressure is in the range of (2-6) bar and the temperature in the range of (20-50)°C. The experimental layout diagram is exposed on the Figure 1 [5, 6]. The tested nozzle shape and diameters are shown on the figures 2 and 3.

The cold water passes the mass flowmeter type Coriolis, is driven to the water coil which is immersed in the oil tank. The oil is heated by an electrical resistance. The electronic thermostat is used to control the heating processes. The core of the liquid dispersion is represented by the nozzle assemblage with a swirl chamber. The swirl device has the function to create the vortex in liquid before that be pushed through the nozzle orifice. By an adequate architecture of the nozzle a short length of the liquid jet is obtained, and the breaking of the liquid is spread in small droplets.

A key element of the nozzle is the shape of the exit section and the angle of this. A qualitative design is presented on the figure 2, and the picture or various exit angles is displayed on the figure 3. These shapes were chosen taking into consideration the Coandă effect consequence which must be
bring into consideration for the jet shape [8]. By reducing the angle $\alpha$ the jet angle envelope increases too. This enhancement of the cone jet volume is necessary in aim to encompasses a high space of flame and to use efficiently the water mist. The nozzle number I has a 2 mm orifice diameter and the angle $\alpha=40^\circ$. For the nozzle number II the diameter is of 1,7 mm and the angle $\alpha=60^\circ$, and for the device number III the diameter is 1,5 mm with the angle of 20°. After the tests we observe that the most efficient nozzle in the spray development, and the finest droplets are realised with the nozzle number III. As example on the jet mist dispersion of warm water followed by the liquid evaporation is shown on the figure 4.

![Figure 2. The nozzle shape and details (nozzle III).](image)

An infrared image of the mist jet is displayed on the figure 5. The exit water temperature from the nozzle is around 34°C. Due of the reduced relative humidity of the adjacent environment the liquid evaporation takes place, and the oxygen concentration in this area decreases. Because of oxygen reduction may arrive at a condition with the flame instability followed by its suppression. From the figure 5 the temperature reduction is relatively obtained in the vertical distance of 70 cm from the nozzle plan, the values being of (19.8-21.5)°C.

For a premixed flame the burner cage is exposed to the mist, and a supplementary vaporisation is obtained. In this case the rate of evaporation is abundant and the local vapor concentration is larger than in the case of the diffusion flame. As a result of this high rate of vapour the suppression of the premixed flame is faster that in the case of diffusion flame. Our experiences were realised using a premixed burner.

Concerning the vertical orientation of the jet to the ceiling, it was chosen in aim to realise a more evaporation of the droplet and to avoid the loss of liquid not yet vaporised. On the other hand, the time passed by the droplet in contact with the hot medium is improved that in the case of the jet orientation to down. That allows also a good fulfilled of the zone with vapour. Using an artificial ceiling the
vapour concentration of the zone of fire increase and the flame is suffocated. The figure 6 b) shows that for the concave ceiling a high concentration of vapour is obtainable.

In aim to improve the experiment field on the flame, issued from burner, may have different angles with the mist jet to find the approached value of these between them, for the most probably extinguish process. The layout from the figure 1 was prepared for the various ceiling forms (plane, curve). The distance between the jet exit nozzle and ceiling was also modified to observe the extinguish behavior. From the first arrangement shown on the figure 6 a) we observe that the fluid line pattern is unfavorable for a mist concentration near the ceiling, a lot of unused extinguish agent being lost. From the figure 6 b) due of the ceiling concavity the fluid is concentrated, especially the vapor phase which remain near the internal surface of ceiling. By this method the increases in two-phase vapor

![Figure 4. Mist jet development using the nozzle II.](image)

![Figure 5. Infrared picture of the free mist jet with the nozzle II.](image)
concentration at the top makes impossible the flame stability, and its suppression is quickly. The third plane shape of the ceiling presented on the figure 6 c) has a certain vapor concentration on the below surface of plate, but not enough to ensure often the flame extinguish. In all the presented cases the Coandă effect is important and must be considered.

Figure 6. Different arrangement of jet-ceiling arrangement.

The figure 7 shown the sketch of the experimental assembly used in the tests with the relevant geometrical data. The nozzle is placed in the middle of the ceiling at 25 cm below the inferior ceiling plane. It is observable that the extinguish take place at about 45 cm in the interior of ceiling. Practically the flame suppression is at the cone limit of the mist jet. The nozzle used in the experiences was of 1.5 mm diameter (number III, figure 3).

Concerning the vertical position, the tests give a good process of extinguish at 45-50 cm high from the nozzle plane, or of (20-25) cm from the inferior plane of ceiling. These phenomena are the conjugated consequences of the high vapor concentration and the reflected droplet by the curvature of ceiling (figure6 b). On the figure 8 there are some images of the concave and plane ceilings.

Figure 7. Schematic drawing of the experimental setup.
3. Results and discussion

Some elements of the jet behaviour issued from the experiments is observed from the figure 5. From other tests at higher temperature, we observe that by increasing the liquid temperature, the droplet dimension diminishes. Complementary, the formed cloudiness shows that due to the high evaporation rate the relative humidity around and, in the jet, increases and the saturation conditions are reached.

The consequence of the evaporation rate growing, the partial vapour pressure in the jet volume rises, and therefore, the oxygen concentration reduces. We found that on the vertical axes the temperature is greater than on the horizontal axes. On the other hand, from our tests, the decreasing in temperature for the temperature around $50^\circ C$ at the nozzle exit, for a certain height, is more than for the jet outgoing at $35^\circ C$. That means that the temperature decrease rate is more important for the higher exit temperature. Therefore, the saturation of the concerned volume in vapor increases faster for higher exit temperature.

Concerning the extinguish efficiency the tests were made using the system with the concave ceiling and the flame issued from a burner supplied with the butane gas. The flowrate was measured with a volume flowmeter as was shown on the figure 1. The flame was introduced at different distance from the liquid nozzle and from the ceiling, implicitly. From the test the more efficient flame extinguish occurs at around (25-35) cm from the nozzle head, and at 40-45 cm deepness in the ceiling (Figure 7). The necessary time for the extinguish was of 4 to 6 s. Other tests were made with the flame at 5 to 10 cm from the ceiling, and the necessary time for the flame extinguish may arrives to 10 s and more, often the extinguish was problematic. On the figure 9 a sample of the flame suppression captured by of the infrared camera is displayed.

![Figure 8. Experimental modes a) concave ceiling; b) plane ceiling.](image)

![Figure 9. Infrared capture during the flame extinguish.](image)
4. Heat balance of for the flame suppression

The experimental layout allows us to realise a heat balance of the system. The model of heat balance was adopted from [9]. The equation of the heat balance, during a time interval $\Delta t$, for the flame suppression is:

$$V_{\text{fN}} H_s = m_l \left( h_v - h_l \right) \approx m_l \left( h_v - h_l \right) \quad \text{[W]} \quad (1)$$

where: $V_{\text{fN}}$ is the volume of gas burned in $\text{m}^3$, calculated as $V_{\text{fN}} = \Delta t \dot{V}_{\text{fN}}$, with the gas flowrate $\dot{V}_{\text{fN}}$ in $\text{Nm}^3/\text{s}$, measured with the gas flowmeter and corrected in function of the gas temperature and pressure according with the manual instruction; $H_s$ is the higher heating value of the fuel, in $\text{kJ/m}^3$; $m_l = \Delta t \dot{m}_l$ represents the liquid water mass, in kg, obtained from the mass flowmeter with $\dot{m}_l$ in kg/s; $h_v$ – specific enthalpy of the generated vapour in the mixture, $\text{kJ/kg}$; $h_l$ – specific enthalpy of liquids at the nozzle exit, in $\text{kJ/kg}$; $l$ is the heat of vaporisation of water, in $\text{kJ/kg}$. At the exit of the nozzle the mass water flowrate $\dot{m}_w$ is measured with the Coriolis equipment.

In the above equation was used the higher heating value of fuel, because in contact with the liquid phase the vapour issued from the combustion process, in contact with the liquid droplets is cooled until the liquid phase. This phenomenon is supposed to take place, considering that the final temperature of gases after the flame extinguish, arrives practically at the environmental temperature before the flame ignition. The water thermodynamic properties were calculated using [9].

For a time interval $\Delta t$, measured from the moment of the incidence between jet mist and flame at the flame extinguish, the heat balance may be written as:

$$\dot{V}_{\text{fN}} H_s \Delta t = \dot{m}_l \left( h_v - h_l \right) \Delta t \approx Q_{\text{abs}} \quad \text{[J]} \quad (2)$$

where $Q_{\text{abs}}$ is the absorbed heat necessarily to be removed during the suppression flame process. The water quantity dispersed, during the time interval $\Delta t$, is $m_l \Delta t = m_l$.

This mass $m_l$ from equation 1 differs of the mass flowrate measured by the Coriolis flowmeter $m_w = \Delta t \dot{m}_w$, since not all this flowrate is used in the flame extinguish, and because a part of this is unused. We may define the mass efficiency of liquid use for the flame extinguish as a ratio between the mentioned mass:

$$\varepsilon_{\text{fe}} = \frac{m_l}{m_w} \quad (3)$$

A similar equation of mass efficiency of liquid for time interval $\Delta t$ is defined as the ratio between the liquid quantities, $m_l$ and $m_w$. Concerning the heat capacity of the liquid water absorption, theoretically possible, to be captured by the mass $m_w$ is:

$$Q_{\text{abs}} = m_w \left( h_v - h_l \right) \approx m_w l_v \quad (4)$$

The real heat absorbed is obtained with the effective mass of water used:

$$Q_{\text{rabs}} = m_l \left( h_v - h_l \right) \approx m_l l_v \quad (5)$$

The ratio between the two heat represents the thermal efficiency of liquid use, expressed as:

$$\eta_{\text{r}} = \frac{\dot{V}_{\text{fN}} \Delta t H_s}{m_w \left( h_v - h_l \right)} = \varepsilon_{\text{fe}} \quad (6)$$

practically the same with the mass efficiency of liquid for the flame extinguish (eq. 2).
Because the liquid is heated from the inlet temperature in system until the exit temperature from the water heater, an added heat flux is necessary for this scope. The heat flux necessary for this aim is:

$$Q_{prl} = m_w \left( h_{ex} - h_{in} \right)$$  \hspace{1cm} (7)

where $h_{ex}$ and $h_{in}$ are the liquid enthalpies at the exit and at the inlet in the water heater (Figure 1).

Considering this additional heat, the effective thermal efficiency of liquid use may be well-defined as:

$$\eta_{eff} = \frac{\dot{V}_{fN} H_s}{m_w \left( h_v - h_f \right) + Q_{prl}} = \frac{\dot{V}_{fN} \Delta t H_s}{m_w \left[ \left( h_v - h_f \right) + \left( h_{ex} - h_{in} \right) \right]}$$  \hspace{1cm} (8)

We may define also the thermal power of flame as:

$$\dot{Q}_{f\beta} = \frac{\dot{V}_{fN} H_s}{60} \times 10^{-3} \text{ [kW]}$$  \hspace{1cm} (9)

with $H_s$ in kJ/Nm$^3$, and $\dot{V}_{fN}$ in Ndm$^3$/min. The heat realised by the flame in the time $\Delta t$, is $Q_{f\beta} = \Delta t \dot{Q}_{f\beta}$.

Using our experimental data, and applying the above model, the main results are displayed on the table 1. The used fuel was butane with the higher heating value $H_s = 128 \text{ 000 kJ/m}^3$. For the heat absorption we consider the heat of vaporisation of water at triple point $l_v = 2501 \text{ kJ/kg}$ [10]. This point is a reference one for the moist air at 760 mm Hg. The superheated heat of vapour up to the environmental temperature is negligible.

**Table 1.** Results.

| Measured parameters | Calculated quantities |
|---------------------|-----------------------|
| $\dot{m}_w$ [kg/min] | $\dot{V}_{f}$ [dm$^3$/min] *at 20°C, $p=750\text{ mm Hg}$ | $\dot{V}_{fN}$ [Ndm$^3$/min] | $\dot{Q}_{f\beta}$ [kW] | $\dot{m}_l$ [kg/min] | $\eta_{eff} = \varepsilon_{fe}$ |
| 2.33 | 8.45 | 7.94 | 16.94 | 0.4064 | 0.174 |
| 2.33 | 8.4 | 7.89 | 16.83 | 0.4037 | 0.173 |
| 2.15 | 9.2 | 8.64 | 18.43 | 0.4421 | 0.205 |
| 2.15 | 11.1 | 9.2 | 19.63 | 0.4709 | 0.219 |

* the flowmeter used was calibrated for 23°C and 760 mmHg, the correction coefficient for butane is 0.93935 according to the apparatus guide.

We note that the thermal efficiency of liquid use is relatively reduced, in the range of 0.174 to 0.219. Consequently, an important liquid quantity is inefficient used, and the damage increases. These observations involve for the future to realise a better nozzle geometry in aim to have the fine droplets and the high rates of the liquid evaporation.

**5. Conclusions**

The paper put in evidence the importance of the temperature and of the nozzle geometry used in fire suppression system, supplied by a warm liquid having the domestic layout pressure in the range of (4-5) bar over the atmospheric pressure. So, a supplementary energy for water pump is not necessary.

The adequate geometry of the nozzle system is required in aim to improve the fineness of the liquid particles in the jet, and for the jet spreading. This characteristic allows to have a good efficiency in fire
extinguish. The Coandă effect is important in the jet spreading in function of the ceiling shape, and for the nozzle geometry.

The observation concerning the ceiling shape are very significant for the fire suppression system, because an additional artificial concave ceiling may create a high vapour concentration and a rapid extinguish. The geometrical dimensions of the system in accordance with the flame structure obtained are relevant (Figure 7).

From the heat balance, and from the extinguish effective thermal efficiency of liquid use, results that an unused liquid is important, with the negative consequences. This may represent an important parameter for the system operation.

References

[1] Andersson P, Arvidson M and Holmstedt G May 1996 Small scale experiments and theoretical aspects of flame extinguishment with water mist, Lund Institute of Technology, Lund University, Report 3080

[2] Chisacof A et al., Clean Jet for the environment structure change, grant CNCSIS ID_1708/2009-2011

[3] Liu Z and Kim A K 2000 A review of water mist fire suppression systems – fundamental studies, Journal of Fire Protection Engineering. 10(3) pp 32-50

[4] Santangelo P E and Tartarini P 2010 Fire Control and Suppression by Water-Mist Systems, The Open Thermodynamics Journal. 4 pp 167-184

[5] Chisacof A, Panaitescu V, Pavel D and Poenar M 2010 The Two Phase Jet Use in Semi-open Space, Proceedings of the ASME 2010 10th Biennial Conference On Engineering Systems Design and Analysis 2010, July 12-14, Istanbul, Turkey, paper ESDA2010-24961

[6] Panaitescu V, Pavel D, Chisacof A and Lazaroiu G 2012 Free Jet of Mist Water use for Fire Heat Absorption, Revista de Chimie. 63(3) p 310-315

[7] Pavel D I and Chisacof A 2016 Experimental Aspects in Two-Phase Jet in Interaction with the Flame, Buletinul Institutului Politehnic din Iaşi, Universitatea Tehnică „Gheorghe Asachi” din Iaşi, Tom. Secţia Construcţii de Maşini.

[8] Coandă H M 1936, brevet nr 792 754 France.

[9] Chisacof A, Pavel and Dimitriu S 2018 Geometrical shape nozzle and liquid temperature influence on the two-phase free jet characteristics. Revista Termotehnica. 2 pp 9-15

[10] IAPWS-IF97 2008 International Association Properties of Water and Steam (editors Wagner W, Kretzschmar), Springer Verlag