Free Jet Mist Water Use for Fire Heat Absorption

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The paper presents mainly the experimental aspects concerning the two-phase jet use for flames extinguish. The first part of the work displays the basic features concerning the life time evolution of liquid droplets with the atmosphere humidity and temperature. Due to the liquid evaporation, a decrease of the atmosphere temperature and a change in mixture composition occur. Taking into consideration these particularities of the droplet evaporation processes, an experimental bench was developed. The influence of the liquid temperature on the fineness spray atomisation in the surrounding was exposed. The aspects regarding the experimental tests, as the jet development followed by the evaporation rate, were mentioned. The free jet of warm liquid water represents an adequate way to change the surrounding composition. The experiment provides that the liquid phase in contact with the flame evaporates instantaneously, and due of the heat absorption the surrounding temperature decreases. Combining this effect with the huge volume of vapour expansion the oxygen concentration in the mixture might falls under the ignition limit. The experimental diagrams concerning the temperature and liquid droplet distribution in the two-phase jet are shown. From the experimental tests made on the mist jet the typical diagrams, concerning the thermal cone and heat absorption capacity, were obtained. Therefore, by using the preheated liquid the improvements of the fire extinguish efficiency is realised. Consequently, the proposed solution is a good one. Also, the projected system is a clean one and its use as fire extinguished equipment is suitable.

Keywords: droplet evaporation, droplet life time, two-phase jet dispersion, fire suppression

The modern systems used for the fire extinguish systems, must have a short time of reaction and an appropriate efficiency. It is well known that often the liquid quantity is limited and the extinguishing processes must be realised so that the minimum damages occur. In these conditions in the fire space the temperature should arrive below the ignition point and consequently, the flame does not exist. The most available fluid used for the proposed scope is the liquid water. This fluid is not toxic, or pollutant, and has an important absorption capacity of the heat. The modern technology uses the liquid water which is sprayed in the small droplets in order to form the mist [1-5].

Droplets transfer processes occurring in a spray surrounding are complex and it is difficult to model. Following the primary atomisation of the liquid jet and the subsequent break-up of larger droplets, a large range of droplet size and velocities is realised. Droplet trajectories depend on the atomizer system. However, the small droplets with the diameter less than 20 μm have the little thermal inertia. The dimensions of the pulverized droplets are recommended to be in the range of 10 to 50 μm [3, 5]. In contact with the hot surrounding the transfer processes of heat and mass occur at high rates. A supplementary turbulence due to the huge rate of the specific volume, done by the liquid evaporation, is realised. In this situation the oxygen rate which might penetrate in the cooling space reduces drastically. In fact, the vapour generated by the liquid evaporation pushes the other gaseous compounds from the concerned space and a high concentration of the sprayed substances appears. Adding these two effects, which take place simultaneously, an efficient cooling of the zone is realisable [4, 6].

During the jet scattering due of the droplets fineness, the mist appears at a short distance from the nozzle exit. From the experiences we observe that the jet length in which the cloudiness persist is relatively reduced. That means that the evaporation rate is the important one. When a liquid contained at conditions above the ambient saturation pressure is released to atmosphere the liquid becomes superheated. A partial evaporation of the liquid phase jet occurs, producing two-phase flow. Simultaneously, the rapid expansion of vapour bubbles breaks the liquid stream and helps to produce a finely atomised spray. This phenomenon, known as flashing, gives rise to potentially hazardous heterogeneous two-phase fog. Due to the fact that the molar weight of vapour is less than the molar weight of the air, the vapour rises creating a higher concentration of this at the high levels, so near the ceiling of a room.

Particularities of the droplets evaporation in two phase jet

The evaporation process involves the mass and heat specific phenomena with the major changes of the gaseous phase composition, and of the flowing structure around the liquid droplet. These aspects are strongly affected by the continuous variability of thermophysical properties of the gaseous phase near the droplet and in the jet bulk. On the other hand, the evaporation process
produces a non-uniform blowing at the liquid–gas surface which diminishes the heat exchange rate by the monophasic convection.

The basic works treating the evaporation process of a drop of liquid in the atmosphere are [7-11]. In all these papers the thermal equilibrium is considered and the droplet diameter evolution with the time is mentioned. Consequently, the central parameter is the life time of the droplet during the evaporation process. Therefore the life time of the droplet is a function of the initial diameter, of the air humidity and temperature. For an efficient mass transfer the number of the droplets of small diameter is required in order to have an important surface transfer. The number of droplets and their external surface transfer for one litre of liquid, function of their diameter. As a result, for one milimeter droplet diameter the number is $1.91 \times 10^6$ which corresponds of an external surface of 6 m² and for droplet diameter of 100 µm, the number of droplets becomes $1.91 \times 10^9$ and the external surface matches 60 m².

The evaporation model of a droplet implies the simultaneously mass, heat and momentum transfer processes [7-10]. Also, the thermophysical properties of the sprayed liquid and of the surrounding gas have a crucial influence in both phases. Due of the liquid evaporation the gaseous surrounding of the droplet has a variable concentration of vapour and a variable temperature too. The droplet life time is a function of its initial diameter $d_0$ and the vapour mass concentration difference, between the surface and the surrounding. A significant parameter which acts on the droplet lifetime is the surrounding relative humidity. From the figure 1 we can notice that at an increase in relative humidity, for the same droplet diameter, the lifetime increases too [6].

![Fig. 1. Droplet lifetime evolution with diameter at different relative humidity at ambient temperature $T=45^\circ C$](image1)

This negative effect of the relative humidity reduces the evaporation rate and consequently, the external cooling of the surrounding is not sufficient to change quickly the medium composition. On the other hand, due to the gravitational force, the necessary time to evaporate the droplet is not enough and the active liquid dropping on the floor is unusable. This continuous variability of the air humidity in the space leads to the different life time for the same droplet diameter. The life time evaporation function is displayed on the figure 2, for different surrounding temperatures and at the relative humidity $\varphi = 50\%$ [12]. From this figure we observe that up to the droplet diameter of 70 µm, the influence of the surrounding temperature on the droplet life time is relatively reduced. For the values of the droplet diameter higher than 70 µm, the surrounding temperature influence on the droplet life time becomes significant. Consequently, by increasing the liquid temperature the droplet life time diminishes. To illustrate these, the different temperatures of the surrounding were chosen at the constant relative humidity (e. g. for surrounding temperature of 50°C (323 K), 70°C (343 K) and 90°C (363 K)).

![Fig. 2 Lifetime evolution with the surrounding temperatures and droplet diameter for the constant relative humidity of $\varphi = 50\%$](image2)

This fact shows us that the liquid must be sprayed in fine droplets. Consequently, for the fire extinguish the evaporation rate must be high, so, the vapour concentration in the surrounding is important and the oxygen concentration from the vapour - air mixture reduces significantly. This is the reason for which the inert gas and the vapour barrier are used to reduce the oxygen penetration in the fire space. Combining the remarks resulted from the diagrams displayed on the figures 1 and 2, we observe that in order to have a reduction of the droplet life time for a certain diameter, the temperature difference between the gas and liquid must be high and the surrounding relative humidity must be reduced. Quantitatively, we observe that for the droplet diameter up to 150 µm, the life time is weakly influenced by the surrounding temperature. On the other hand, for the droplet diameter higher than 250 µm and for the surrounding temperature of 323 K the life time becomes practically double in comparison with that of 363 K. Therefore, by increasing the zone temperature the vaporization rate rises, and the molar concentration of the dry air or of the oxygen diminishes. Consequently, the oxygen concentration reduces and the air-vapour mixture will be far from inflammability limits corresponding of a certain fuel. For example, the dry air/methane inflammability limits are in the range of (5.3 – 14%) and for the air/butane these are (1.9 – 8.5 %) [13].

Consequently, the more important transfer processes, involved in droplet evaporation, are the coupled mass and heat transfer. On the other hand, the total evaporation of a liquid droplet is related to its dimension. Therefore, for the small diameters the intensive combined transfer processes occur. In order to reduce the droplet life time and to have a rapid evaporation, we propose the preheating of the liquid before to be sprayed by the nozzle.

Consequently, based on the above theoretical aspects, the droplet evaporation rate is determined mainly by the relative humidity, the liquid temperature and the surrounding temperature combined with the key parameter for the transfer processes represented by the droplet diameter.

**Experimental set-up of the two phase free jet**

Taking into consideration the above theoretical aspects, we have proposed an experimental set-up producing the two phase jet, which is sprayed in the air of reduced relative humidity. The liquid temperature at the discharge head is modified in order to put in evidence its influence on the
droplet dimension on the combined mass and heat transfer during its evaporation. The tested nozzle diameters are 0.6, 1, 1.5 and 2 mm. The liquid feed water pressure is in the range of 2-4 bars and its feed temperature is around 12-15°C. The main devices of the experimental test bench are shown in the figure 5 [14].

Experimental Results Analysis

The analysis of tests results provides us the evolution of the jet parameters in different points of its geometry. In function of this distribution it may be found the heat capacity absorption of the jet by the liquid evaporation. These observations lead to the adequate constructive parameters of the nozzle jet equipment, which it is used for the flame extinguish. In the figure 6 is displayed the temperature evolution in function of height from the discharge nozzle.

The tests were made for a liquid temperature of 30 °C, for a nozzle of 0.6 mm diameter, a surrounding temperature of 18°C and a relative humidity of around 55%. The temperature measurement was made with a temperature digital apparatus with the data acquisition system recording the values with the step of 0.2 m and 2 seconds [15, 16]. We started the data record from two meters distance from the jet axis, for different heights from the nozzle exit.

Figure 6 shows in the two phase jet development for the liquid temperature of 20°C and of 40°C. By increasing the liquid temperature the droplet initial diameter becomes smaller and the evaporation rate increases. The cloudiness near the discharge head, for the liquid temperature of 40°C, shows that due to the high evaporation rate the saturation conditions are reached around the jet boundary (fig. 6). As we have seen, at elevated liquid temperature, due the rise of the evaporation rate, the partial vapour pressure in the surrounding rises, and consequently, the oxygen concentration reduces.

This assumption is verified, indirectly, by the fact that the liquid clusters obtained by the droplets impact with the disk, diminish in volume and number with the liquid temperature augmentation. These conclusions were applied for a butane flame extinguish. The picture from the figure 7 shows the fact that the flame disappeared at the conical limit of the two phase jet. That means that the flame existing conditions inside the conical volume of the air-wet vapour jet are not present. This phenomenon occurs probably, due to the surrounding humidity rise, coupled with the flame temperature reduction by heat absorption during the liquid evaporation, so the oxygen concentration falls. These tests provided the important information for the adequate parameters choice of the jet equipment when water mist is used for the flame extinguish. The effect of the thermal radiation is insignificant in this case.
It is noticed that the temperature in the same plane with the nozzle discharge has an important variation from the 25 cm around the jet axis \((z=0)\). That means that suddenly, at the exit from the nozzle the evaporation of the warm liquid is important. The enlargement of the temperature field at this level may be due to the wet vapour generated at different heights, and to the reduced temperature of the wet mixture at higher levels. Consequently if the mixture density increases the gravitational effect increases too. From the same figure it is deduced that for heights above 25 cm the temperature variation becomes smaller with the temperature difference being under 5 K. This is a consequence of the heat absorption from the surrounding gas phase resulting in the jet cooling. At \(z = 1\) m height from the nozzle, the temperature along the central axis has a tendency to increase. That occurs because of the fact that the jet evaporation is finished and at this level, the heat absorption reduces. On the other hand, the mixture gas-vapour at the interior levels is governed by higher temperature and thus a lower density, as it is illustrated in figure 8. Also, the fact that the temperature at \(x=2\) m is different at diverse levels is a consequence of the lateral diffusion. The measurements were performed in a closed space under steady conditions. The temperature stratification on the horizontal level is an effect of vapour concentration variation, and as a result the corresponding mixture density depends on the level of measurement. The thermal cone was obtained under the aforementioned conditions. The thermal envelope was drawn taking into account only the horizontal variation of the temperature at the indicated levels. On the figure 7 is shown the thermal cone using the measured values and the infrared image. The shape of the cone is linear and the temperature variation appears at about 40 cm distance from the jet axis, at the nozzle level. In the figure 8 is shown the temperature evolution in the jet axis. It is observed that the temperature falls in the first 70 cm from the exit nozzle. Above this height the temperature have a small variation. That signifies that a thermal equilibrium in the jet occurs. Using the experimental data in the jet axis, a parabolic evolution of the temperature is obtained by the regression method [16].

Heat absorption potential was evaluated using the experimental data at different inlet liquid temperature for several nozzle diameters. In this case we present the droplet dispersion from a nozzle of 0.6 mm diameter for two temperatures 30 and 60°C. The droplet concentration was measured with a reservoir with a volume of 8 L. A hydraulic seal was used to take a sample of wet gas [16]. With the humidity correction at the probe temperature, we may estimate the volume droplet concentration \(c_{\text{drop}}\) in kg/m^3. The values of \(c_{\text{drop}}\) are presented on the figure 9 in the jet axis for the mentioned temperatures. At the level \(z=0\) the probe was taken in the vicinity of the nozzle. We note that the droplet concentration reaches a maximum value at a height around 0.45-0.5 m.

In connection with the previous diagram figure 10 presents the heat capacity absorption \(q_{\text{cap}}\) in kJ/m^3 in the jet axis. It is obvious that the maximum of the droplet concentration and the heat absorption occurs in the jet axis at the same level. The evolution of the heat capacity absorption in a section of the jet, at the level of 75 cm, is shown on the Figure 11. We observe that due of the nozzle geometry an important quantity of liquid is dispersed on the jet envelope. Consequently, the absorption of the heat is concentrated in this zone. This fact may be observed also from the picture shown on the figure 9.

In this case due to the jet interaction with the flame the vapour concentration inside the jet cone and in the vicinity of its boundary increases. Therefore the oxygen concentration falls under the inflammability values and the flame extinguishes.

Fig. 7. Thermal cone of the two-phase jet (nozzle 0.6 mm) a) experimental data; b) infrared image

Fig. 8. Axial temperature evolution versus the jet height

Fig. 9. Droplet concentration in the jet axis (nozzle of 0.6 mm)
Case study with experimental results

The analysis of tests results provides us the evolution of the jet parameters in different points of its geometry. Therefore the heat capacity absorption of the jet during the liquid evaporation is evaluated. In the figure 8 the temperature diagrams evolution are displayed in function of height $z$ in the two-phase formed jet from the nozzle. The tests were performed for a liquid temperature of 30°C, for a nozzle of 0.6 mm diameter, for a surrounding temperature of 18°C and a relative humidity around 55%. The temperature measurement was made with a temperature digital with the data acquisition system recording the values with the step of 0.2 m and 2 s [14]. We started the data record from two meters distance from the jet axis, for different heights from the nozzle.

We note that the temperature in the same plane with the nozzle discharge becomes to have an important variation from the 25 cm around the jet axis ($z=0$). That means that suddenly, at the exit from the nozzle the evaporation of the warm liquid is important. The enlargement of the temperature field at this level may be due of the wet vapour generated at different heights. So, the liquid density being higher than the air, the droplets fall due to gravitational field. From the same figure we observe for the heights above 25 cm the temperature variation becomes smaller, the difference being under 5 K. This effect occurs due of the heat absorption from the surrounding, which has as the effect the jet cooling. Also, an enlargement of the variation temperature on the horizontal plane with the height is observed. From the figure 8 it is observed that the temperature falls in the first 50 cm from the exit nozzle.

Heat absorption potential of the liquid jet, was evaluated using the experimental data at various inlet liquid temperatures for several nozzle diameters. In the analysed case we present the droplet dispersion from a nozzle of 0.6 mm diameter for two temperatures 30 and 60°C. The droplet concentration was measured with a reservoir of eight litres having a hydraulic seal. At the end of the probe absorption, in which we have only the moist vapour-air mixture, and after the cooling at the surrounding temperature we obtain a certain quantity of liquid. With the humidity correction at the probe temperature, we may estimate the volumetric droplet concentration $c_{\text{drop}}$ in kg/m$^3$. This way we obtained the droplet concentration at different points in the two-phase jet. The values of $c_{\text{drop}}$ are presented the figure 9 in the jet axis for the mentioned temperatures. At the level $z=0$ the probe was taken in the vicinity of the nozzle. We note that the droplet concentration reaches a maximum value at a height around 0.45-0.5 m.

The heat absorption potential, $q_{\text{abs}}$ in kJ/m$^3$, in the two-phase jet axis, corresponding at the volumetric droplet concentration is displayed in the figure 10. According to the droplet concentration, the maximum heat absorption matches the same level in the jet.

The heat absorption potential, obtained by experiment, at the level of 75 cm from the nozzle is presented in the figure 11. We observe that due to the high droplet concentration near the cone envelope, the heat absorption is determined in this zone. That fact explains why the flame vanishes on the jet boundary (fig. 5).

Due of the nozzle geometry an important quantity of liquid is dispersed on the jet envelope. Consequently, the absorption of the heat is concentrated in this zone. In this case, the vapour concentration inside the jet cone increases. Due of the fact that the generated vapour is pushed by the flame in the jet, the oxygen concentration falls under the inflammability values of a certain fuel, and the flame extinguishes.

Conclusions

The present study provides practical information concerning the liquid temperature influence of the jet dispersion and structure. The life time evolution of the droplets depending on the liquid temperature, diameters and surrounding parameters are shown. By the liquid spray evaporation, in the contact with the surrounding, the changing of the vapour - gas mixture concentration occurred.

The case study analysis gives us the useful information concerning the allure of the jet cone, its amplitude in function of the liquid temperature and the surrounding properties. The liquid droplet concentration and the volume heat capacity absorption were also evaluated. These distributions in the jet cone may furnish the place with the high values of heat absorption and consequently, the zone with an efficient extinguish of fire. This fact generates a decrease of the temperature below the flame stability and an oxygen concentration reduction. Consequently, the flame failure may occur.

The experimental results illustrate that the liquid heating plays an important role in overall evaporation process: the droplet size and lifetime, jet boundary layer. The reasons which guided us to the experimental conception of the test stand were described. The impact of the water mist concerning the extinguish performance applied on the butane flame was shown.

There are not necessary high values of the liquid pressure to supply the jet equipment.

The fluid used for the proposed system is the clean one, in small quantities at an acceptable temperature for action.
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References
5. PAVEL, D., CHISACOF, A., Thermodynamic aspects concerning the droplets use for the closed and semi-closed space cooling (in Romanian). Proceedings of the XIVth Conference of the Romanian Society of Applied Thermodynamics, Bucharest-Romania, 2004;

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