

NON-ISOTHERMAL TWO-PHASE FREE JET WITH HIGH POWER OF HEAT ABSORPTION

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Abstract: *The paper presents the theoretical and experimental aspects concerning the use of two-phase jet for the flames extinguish. In the first part of the work are displayed the theoretical basis which determined the experimental bench conception. Consequently, the particularities of the droplet evaporation processes from the liquid jet, sprayed in an air vapour mixture, are shown. The experiment provides that the liquid phase in contact with the flame evaporates instantaneously. By the huge volume expansion, the oxygen concentration in the mixture falls under the ignition limit, and the temperature decreases due to the heat absorption. The proposed system may be use in the fire extinguish equipment.*

Key words: *two-phase jet, droplet life time, water fog, fire extinguish.*

1. Introduction

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 no toxic, no pollutant, has an important absorption capacity of the heat. The modern technology uses the liquid water which is sprayed in the small droplets in aim to form the fog. The important papers on this domain were provided in the papers [8-9], [4-5], [10].

The droplets transfer processes occurring in a spray dispersed in the 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 of the atomizer system. However, the small droplets with the diameter less about 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. 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

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drastically. In fact, the vapour generated by the liquid evaporation pushes the other gaseous compounds from the 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.

An example of the liquid jet use in the fire extinguish is shown in the fig. 1. During the jet scattering in the fine droplets, the fog appears at a short distance from the nozzle exit. We observe that the jet length in which the cloudiness persists is relatively reduced [12]. That means that the evaporation rate is the important one.



Fig. 1. *Fog jet for the fire extinguish*

The transparency zone following the cloudiness region is a vapour-gas mixture, with an important superheated vapour concentration in comparison with the fog zone, in which the liquid phase is abundant. When a liquid is released to atmosphere below the ambient saturation pressure the liquid is called sub-cooled. Conversely, when the liquid contained at conditions above the ambient saturation pressure the liquid becomes “superheated” Due of the fact that the relative humidity of the atmospheric air is reduced the vapour ambient saturation pressure is reduced too, so the vapour becomes superheated. Consequently, a fast evaporation of the liquid occurs, producing two-phase flow.

Simultaneously, the rapid expansion of vapour bubbles breaks the liquid stream producing a fine atomised spray. This phenomenon, known as “flashing”, gives rise to potentially the hazardous heterogeneous two-phase clouds [3].

2. Specific Aspects 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 thermo-physical properties of the gas 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 convection heat exchange. The basic works treating the evaporation process of a drop of liquid in the atmosphere were provided by Mills [7], Taine and Petit [14], and ([15], [1], [11]). In all these papers the thermal equilibrium is considered. The droplet diameter evolution with the time is mentioned. Another important parameter is the life time of the droplet during the evaporation process, which is a function of the initial diameter, and of the ambient properties, the air humidity and temperature. For an efficient mass transfer the number of the droplets of small diameter is required in aim to have an important surface transfer. In the table 1 is shown the droplets number and the surface transfer for one litre of liquid, in function of their diameter [4].

The evaporation model of a droplet implies the simultaneously mass, heat and momentum transfer processes. Also, the thermo-physical 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 in vapour, and also a variable temperature.

Droplets external surface for one litre of liquid Table 1

Droplet diameter [μm]	1000	100	10
Number of droplets	$1,91 \cdot 10^6$	$1,91 \cdot 10^9$	$1,91 \cdot 10^{12}$
Total external surface [m ²]	6	60	600

The Andersson life time relation was used for the diagram displayed on the fig. 2 ([11], [2]). It may be seen that this evolution is a function of the droplet diameter and temperature difference ΔT .

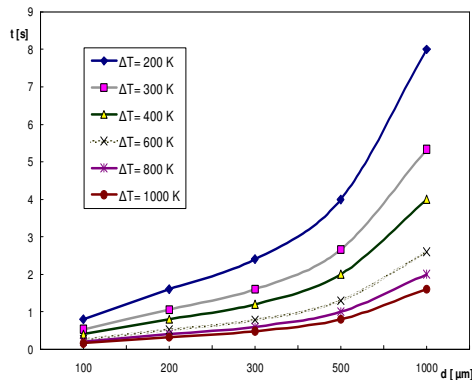


Fig. 2. Droplet lifetime evolution with diameter at different ΔT

Another decisive parameter which acts on the lifetime of a droplet is the surrounding relative humidity. On the figure 3 we observe that an increase in relative humidity, for the same diameter, the lifetime of the droplet increases too. This negative effect diminishes the evaporation rate and consequently, the cooling and the modification of the medium composition is not enough to have an efficient fire extinguish. On the other

hand, the mechanical effect, due to the gravitational force, has as result the lost of the active liquid which drops on the floor. The droplet lifetime, in function of its initial diameter d_0 and the vapour mass concentration difference between the surface and the environment, is provided by the expression [8]:

$$t = \frac{\rho_l d_0^2}{8\rho D_{1,2}(\omega_{1,s} - \omega_{1,e})} \quad (1)$$

where: ρ_l is the liquid density, ρ - the air-vapour mixture density, in $\text{kg}\cdot\text{m}^{-3}$, $D_{1,2}$ - diffusivity coefficient of the vapour in the air, in $\text{m}^2\cdot\text{s}^{-1}$, $\omega_{1,s}$ - the vapour mass concentration at the liquid surface, considered at the saturation temperature; $\omega_{1,e}$ - the vapour concentration in the environment, which is obtained in function of the relative humidity.

The mass concentration of the vapour at the droplet surface $\omega_{1,s}$, is calculated for the mass convection considering $Sh=2$ and $(Pr/Sc)^{-1} \sim 1,13^{-1}$, with the relation [8]:

$$\omega_{1,s} = \omega_{1,e} + \frac{c_{p,air}}{1,13l_v}(T_e - T_s) \quad (2)$$

where: $c_{p,air}$ is the air specific heat, in $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$; l_v is the latent heat of water, in $\text{J}\cdot\text{kg}^{-1}$; T_s represents the surface droplet temperature and T_e is the environment temperature.

The evolution of droplet lifetime, using the expressions (1) and (2), in function of diameter is displayed on the fig. 3 at different relative humidity, for an environmental temperature of 45°C . From this figure we observe that below the droplet diameter below $70\ \mu\text{m}$, the droplet lifetime is reduced and by increasing the relative humidity, the lifetime increases too. From the last two diagrams, we observe that in aim to have a reduction of

the droplet lifetime, for a certain diameter, the temperature difference between the gas and liquid must be high and the relative humidity must be reduced. This continuous variability of the air humidity in the space leads to the different lifetime for the same droplet diameter. For the values of the droplet diameter greater than $70\ \mu\text{m}$, the influence of the relative humidity is significant and the lifetime increases drastically. This fact imposes that the

liquid must be sprayed in fine droplets. Consequently, when the fire flame is in contact with the liquid droplets the evaporation rate is high and the vapour concentration in the surrounding is important. On this way the oxygen concentration from the vapour - air mixture reduces significantly. This is the reason for which the inert gas or the vapour barrier is used to reduce the oxygen penetration in the fire space.

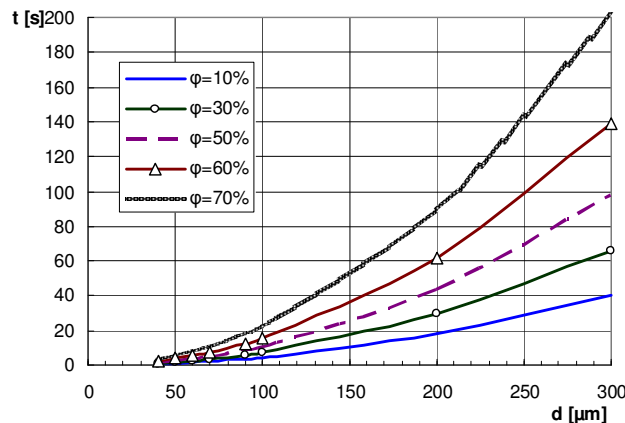


Fig. 3. Droplet lifetime evolution with diameter at different relative humidity at $T=45^\circ\text{C}$

In intend to illustrate these we consider the different temperature of the surrounding for a constant relative humidity (e. g. $\varphi = 50\%$, for surrounding temperature of 50°C (323 K), 70°C (343 K) and 90°C (363 K)). The evolution of the life time in the above conditions, after, is presented on the fig. 4 [10]. As it was expected, the life time of the droplet diminishes with the temperature increasing and consequently, the evaporation rate enhances. Quantitatively, we observe that for the droplet diameter below $70\ \mu\text{m}$, the life time is weakly influenced by the surrounding temperature. For the droplet diameter greater than $250\ \mu\text{m}$ its life time becomes practically double for the surrounding temperature of 323 K in comparison with that of 363 K. By increasing the zone temperature the vaporization rate rises and the molar

concentration of dry air and of oxygen diminish.

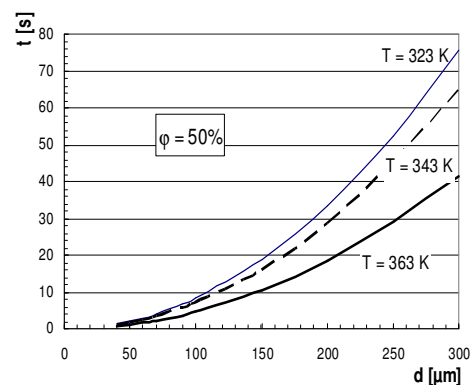


Fig. 4. Lifetime evolution with the surrounding temperature and droplet diameter at constant relative humidity

We may conclude that droplet diameter, which imposes the life time limitation, is a

crucial parameter for the transfer processes. So, from the figures 3 and 4 we observe that the evaporation rate increases for the reduced relative humidity values and for the high temperature of the surrounding gas. In these conditions the life time of the droplet increases with the saturation degree of the gaseous phase in vapour. In aim to reduce the droplet lifetime we propose the preheating of the liquid before the spraying it in the nozzle, for a rapid evaporation. Consequently, the oxygen concentration reduces and the mixture will be far from inflammability limits of a certain fuel.

Using the diagram shown on the fig. 5 we may find the corresponding temperature domain to avoid the flame ignition. For example, the air/methane inflammability limits are in the range of (5.3 – 14) % and for the air/butane these are (1.9 – 8.5) % [13].

From the above theoretical analysis the droplet evaporation rate is determined mainly by its diameter, the relative humidity, the liquid temperature and the surrounding temperature.

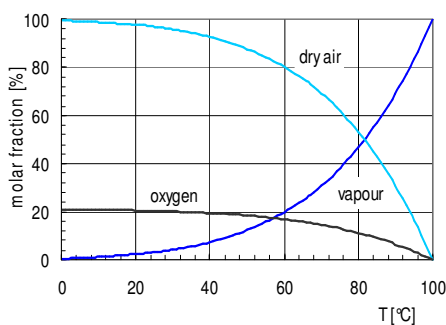


Fig. 5. Molar fraction evolution of water vapour, oxygen and dry air as a function of temperature (1 atm total pressure)

3. Experimental Layout of the Non-isothermal Two Phase Jet

Based on the above considerations, we have proposed an experimental layout

producing the two phase jet, which is sprayed in the air of reduced relative humidity. The liquid temperature at the discharge head of the tube is adapted with the heater at the preset values, in aim to realise different evaporation rate. The tested nozzle diameters are in the range from 0.6 to 2 mm and the liquid feed water pressure is 2.4 bar.

The experimental test bench is shown in the fig. 6. The cold water supplied by the laboratory network passes the flowmeter and is driven to the water coil imerged in the oil tank. The oil from the tank is heated by an electrical resistance. The electronic thermostat is used to control the heating processes. The control of the temperature water supplying the jet is ensured by the electronic thermostat and sensor assemblage.

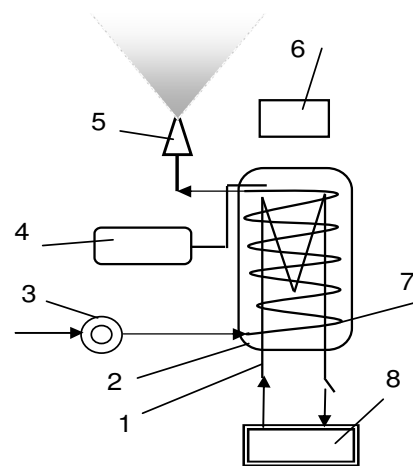


Fig. 6. Experimental layout
1 – electric resistance; 2 – oil tank; 3 – water flowmeter; 4 – electronic thermostat; 5 – water nozzle; 6 – measurement bench; 7 – water heater; 8 – electrical supplier

The figures 7 and 8 show the two phase jet development for the liquid temperature of 20°C and 36°C. It may be observed that by increasing the liquid temperature the droplet dimension diminishes.

On the other hand, the evaporation rate increases forming the fog. The cloudiness, especially at the liquid temperature of 36°C, show us that due to the high evaporation rate the relative humidity around the jet boundary increases and the saturation condition is reached.

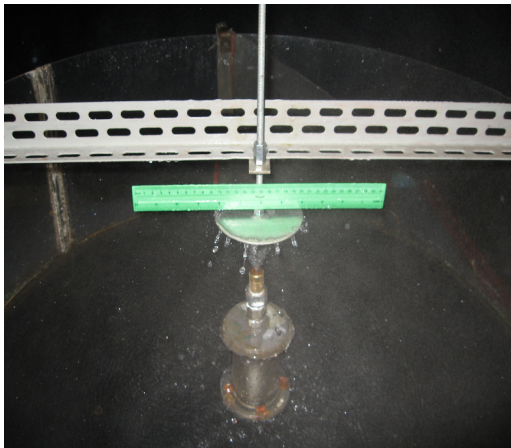


Fig. 7. *The two phase jet at 20°C*



Fig. 8. *The two phase jet at 36°C*

Conversely, by increasing the evaporation rate, the partial vapour pressure in the surrounding rises, and consequently, the oxygen concentration reduces. This fact allow us to conclude that the flame stability reduces up to it's extinguish in contact with the two phase jet frontier. The performance of the water fog jet applied on the butane flame extinguish is presented on the fig. 9.



Fig. 9. *Flame behaviour in the contact with the two-phase jet*

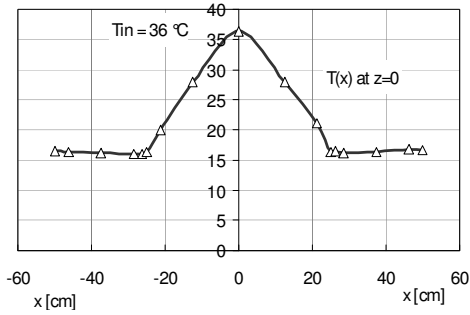
At the jet frontier the temperature diminishes due of the heat absorption during the droplet evaporation. The temperature may drops under the inflammability limit. By cumulating the two effects presented above, oxygen reduction and heat absorption, the flame existing conditions does not exist [13].

4. Experimental Results

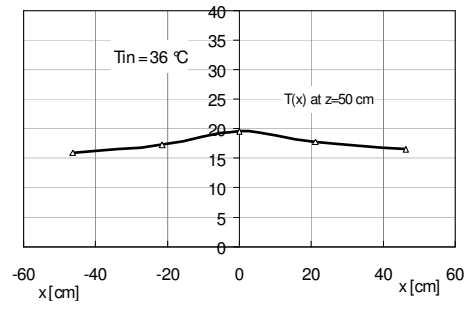
These tests provide us some information for the adequate parameters choice of the jet equipment when the two phase jet is used for the flame extinguish. In this case the test was driven with the free jet.

In the fig. 10 the temperature diagrams evolution are displayed in function of height from the discharge nozzle in the two-phase formed jet. From the fig. 10 a. we note that the temperature in the same plane with the nozzle discharge becomes to vary from the 25 cm around the jet axis. That means that suddenly, at the exit from the nozzle the evaporation of the warm liquid is important.

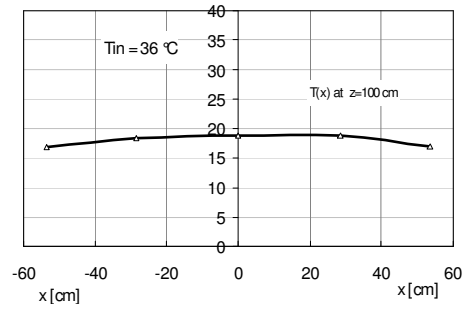
The enlargement of the temperature field at this level may be due of the wet vapour generated at different heights, having the mist density higher as the air. So, the liquid fine droplets fall due to gravitational field.



a.



b.



c.

Fig. 10. *Temperature evolution at different heights in the two phase jet*
 a. $z=0$ cm; b. $z=50$ cm; c. $z=100$ cm

From the next two figures, fig. 10. b. and 10. c., we observe that 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 its cooling. On the other hand, we observe an enlargement of

the variation temperature on the horizontal plane with the height.

Based on the experimental temperature measurements on the fig. 11 is shown the temperature evolution in the two phase jet Oz axis. It is observed that the temperature falls in the first 40 cm from the exit nozzle. Above this height the temperature remains practically constant. This signifies that a thermal equilibrium in the jet occurs. Using the experimental data in the jet axis, a parabolic evolution of the temperature by the regression method [6]:

$$T = T_{in} - 0.008356z + 0.0128 \cdot 10^{-4} z^2 \quad (3)$$

where: T_{in} is the water initial temperature, in °C, and z represents the height from the nozzle in m.

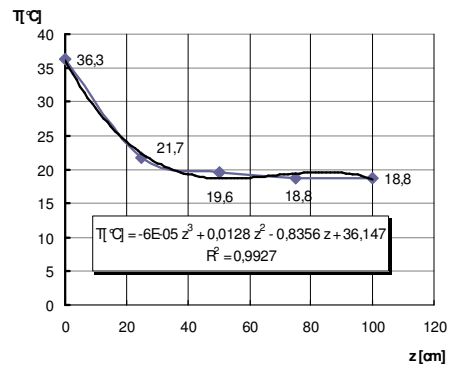


Fig. 11. *Temperature versus jet height*

This phenomenon occurs, probably, due to the surrounding humidity rise, coupled with the flame temperature reduction and the oxygen concentration drop.

5. Conclusions

The present study provides information concerning the liquid temperature influence of the jet dispersion and structure. The lifetime of the droplets in function of the liquid discharge and surrounding parameters displayed.

It has been shown that the liquid spray evaporates in the contact with the surrounding, changing the vapour - gas mixture concentration. This fact generates a decrease of the temperature below the flame stability and an oxygen concentration reduction. Consequently, the flame failure occurs.

The reasons which guided us to the experimental conception of the test stand were described. The qualitative results show that liquid heating plays an important role in overall evaporation process. The correlation between temperature and the jet geometry is developed.

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