CLEAN WATER MIST TECHNOLOGY USED TO SUPPRESS ETHANOL POOL FIRES – EXPERIMENTAL STUDY

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Nowadays, extinguishing ethanol pool fires become more and more a priority, due of the biofuel use and of the oil reserves depletion. The aim of this work is focused on the suppression efficiency of an ethanol pool fire with using the water mist discharged by a nozzle. A series of experiments were conducted under different conditions in a closed space. The water temperature generating water mist ranging from 15 °C to 30 and 40 °C gave pertinent results. The authors obtained information on the influence of the temperature of suppression agent (water generating water mist), on the suppression efficiency.

Keywords: ethanol fire suppression, clean mist fire suppression, warm water mist jet, ecological fuel, fire safety engineering

1. Introduction

Starting with the development of constructions in the 20th century, the importance of fire safety and fire suppression became very essential [1, 2]. Meanwhile, as the oil reserves deplete, economic entities are looking for other types of fuel than gasoline. As lots of people know, one of the solutions already applied with success, is the use of ethanol instead of gasoline, or in mixture.

Ethanol deposits and warehouses are becoming a wide spread reality today but mainly tomorrow, in conclusion fire safety engineering principles should take into account the protection of this type of building / enclosures.

In industrial plants where large amounts of ethanol and other alcohols are used, special fire extinguishing foams are used in case of fire occurrence [3]. As these fire extinguishing methods are rather expensive, one should take into account other fire suppression methods or systems, than the industrial chosen ones. Today's fire safety industry uses for such spaces, water sprinklers or water mist deluge systems. Removing these systems and bringing new ones would be an expensive solution. In conclusion, retrofitting would be the best solution.

Basically, the water mist deluge system remains the same, the only thing that changes, is the temperature of the water [4]. This is the area that is covered by the present paper. In the following, the authors are studying the phenomenological particularities of this idea and its applicability.

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Also ethanol, in comparison to gasoline, is a rather clean fuel. Starting with the eighties (including Montreal Protocol in 1987) researchers searched for clean methods to extinguish fires, as an alternative to halons (environment polluting fire extinguishing agents). In a lot of the researches starting 1980 to nowadays, emphasis was placed on reducing droplet size, increasing thus the heat transfer surface that leads to a quicker fire cooling and suppression [5, 6]. Also, some attention was paid to the use of various additives [7]. Very little attention was affected by researchers at the temperature of the extinguishing agent, water that generates mist, on fire suppression. Sprays have been employed in the field of fire control and suppression for many years and water has been the most employed fluid. Water mist plays its role in a strong direct action in fire suppression. Also a reduced quantity of fluid is required for fire suppression, the residual damage diminishes. Water mist brings a low quantity of stored water needs, with respect to traditional sprinkler. Due of this fact the application in naval and even in aerospace area may be exploited [8, 9, 10].

Experiments have shown that boil-over or spillage is not present when water mist is discharged into the burning oil at high temperature (greater than 300 °C) [8]. Santangelo and Tartarini [11], have also carried out an experimental and theoretical research on portable water-mist systems with respect to a variety of fire scenarios. Among these latter, flammable liquids, cooking oil and wood cribs stand as the most interesting applications. Different portable extinguishers have been developed to the purpose and generally good effectiveness has been achieved in suppression and extinguishment, provided that suitable water flux density and spray momentum are imposed [9]. A recent interest in water-mist systems has been shown for fire protection in tunnels. This application represents a real challenge in terms of harms and damages [10].

However, for the presented situation, extinction is successfully achieved in an enclosure of 9 m^3 for water-flow rates as small as 10 liters per minute [4].

2. The influence of the water mist temperature on the effectiveness of ethanol fire suppression

In normal sprinkler cases, the dimension of water droplet is rather large, up to 1 mm in diameter or more. In conclusion, when a sprinkler head discharges water on an ethanol pool fire, very little of the water participate directly to fire extinguishment. In a classic case, the water droplet will travel through the flames and will mix with the liquid ethanol volume.

Indubitably, the droplet will decrease in volume inside the flame, by releasing water vapors, but a lot of water quantity will be lost, diluting the ethanol pool [11, 12].

As other studies state [13], the rate of dilution is small, so the flames will grow larger, eventually igniting other materials in the vicinity, before an effective dilution. This is the reason why water mist is more suitable for fire suppression. With a droplet smaller than 200 microns, more than 90% of the water volume turns into water vapors when meeting with the flame envelope [16, 10, 11]. As water volume expands aproximatively 1600 times when going into vapor state, so oxygen diminution occurs. This oxygen reduction is the main fire extinguisher.

To retrofit the existing fire extinguishing water mist deluge systems means to find ways to effectively use what is already in place, and improve it in order to be more effective.

As minimizing the water droplet dimension would not be the best option [10]. It is hard to get the droplets smaller than they already are. The attention should be focused to the water droplets qualities. By studying the international steam tables, the authors have found out that around the value of 35°C, the surface tension has a change of the decreasing slope.

The surface tension and the dynamic viscosity of liquid water decrease with the temperature [14, 15, 16]. For the jet fluid atomization the surface tension plays an essential role. Based on water data obtained from international tables [15], the evolution of surface tension with the temperature is presented in the figure 1. Regarding this variation, we can see a visible change in the slope angle (a break of the line), around the temperature of 35°C - 40°C (see figure 1).

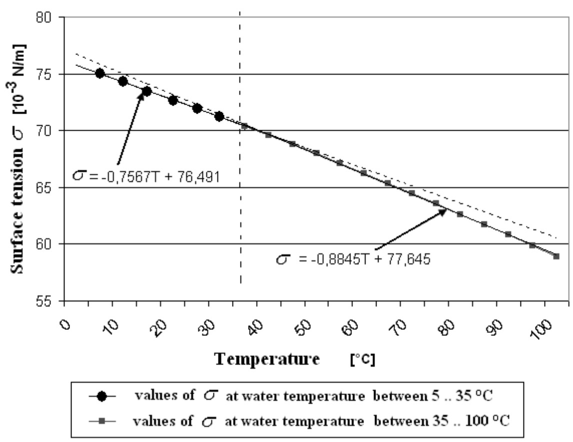

Fig. 1. Graphic that shows the water droplet surface tension values with the temperature

Based on the above finding, the authors chosen a range of temperatures including the 35°C - 40°C interval. Water with these temperatures (15, 30 and 40 °C), was used in different fire suppression tests, and the results were compared in order to obtain a set of rules to be taken into account by designers of fixed water mist fire suppression systems. In experimental tests below, one starts from the premise that warm water evaporates quickly, cooling the fire in a shorter time than cold water. As fire suppression takes place faster, less water will be used reducing the collateral damage. If warm water temperature is used, suppression occurs earlier, the temperature values of the fire are smaller and less damage results, in comparison to conventional water mist [18, 19, 20].

Weber similarity criterion is the ratio of inertial forces of the environment and the surface tension of the liquid, and is defined by the following equation [21]:

$$We_g = \frac{\rho_g u_p^2 d_p}{\sigma} \tag{1}$$

where: ρ_g is the density of the gaseous environment [kg/m^3]; u_p – the speed of the droplet [m/s], d_p - the diameter of the droplet [m]; σ – surface tension of the droplet, in N/m. Similarly, the Weber number is defined reported to the liquid state, where one takes into account the inertia forces of the liquid:

$$We_l = \frac{\rho_l u_p^2 d_p}{\sigma} \tag{2}$$

The Sauter average diameter determines the vaporization speed and the intensity of the process that creates the mixture gases – liquid by secondary break/up and is given by the relation [21]:

$$d_{ms} = 6{,}2\frac{\sigma}{\rho_g u_p^2}\left(\frac{\rho_l}{\rho_g}\right)^{0,25}\sqrt{\frac{\mu_l}{\rho_l d_p u_p}We_l} = 6{,}2\frac{1}{\rho_g u_p^2}\left(\frac{\rho_l}{\rho_g}\right)^{0,25}\sqrt{\sigma\mu_l u_p} \tag{3}$$

Where ρ_l is the density of the liquid phase, in kg m^{-3} and μ_l is the dynamic viscosity of the liquid, in N s m^{-2}. By this relation, one can see that the Sauter average diameter depends of the surface tension and of the dynamic viscosity of the liquid, being proportional with the square root of their product.

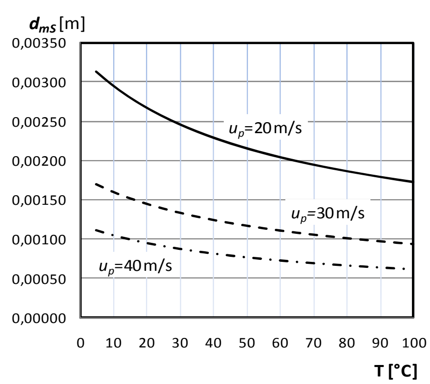

Fig. 2. The evolution of the Sauter medium diameter function of the liquid temperature for different droplet speed values

Figure 2 presents the evolution of the Sauter average diameter with the temperature of the liquid for different droplet speeds. It is observable that at a certain speed of the droplet, the diameter drops with the temperature, especially between 5 - 40 temperature intervals. Also, as the speed of the droplet u_p increases, its diameter reduces. By combining the two factors, one can obtain reduced values of the droplet diameters, and a rapid vaporization could be obtained.

3. Experimental setup and data

A number of 15 suppression tests were performed. The conditions of all tests were similar, only the temperature of water generating the mist was different. Figure 3 presents the design of the test room. Pressure of fire extinguishing agent is 120 bar, the volume of the fire enclosure is 8,95 m^3, dimensions are as in figure three. Direction of the water mist jet is horizontally placed and not vertically, because of the need of interaction time between water mists drops and flame (in terms of temperature measurements). Figure 4 displays the ethanol pan and the flames at the liquid surface. The fire was set on an ethanol pan of 30 x 40 cm, containing one liter of combustible. The thermocouples situated on the centerline of the ethanol pan fire, at three different elevations (see explanations at figure 3) gave detailed temperature graphics, by using computer data acquisition [4]. As there were five different tests for every water temperature, an average of parameters values was calculated for each temperature, in aim to have reliable data.

Fig. 5 presents the temperature evolution in time, at different levels, for each initial temperature of water. Roughly, we observe that the maximum temperature of the flame, at the height of 20 cm, is obtained for the cold water of 15 °C. For the same level, the smaller flame temperature is obtained for the warm water of 40 °C. On the same figure, we observe that the group of curves at 180 cm height is located in the temperature interval of 65 – 95 °C. The curve corresponding to initial water temperature of 40 °C is situated above the other two. That means that the partial pressure vapors are important and consequently, the oxygen concentration decreases. In accordance with the steam tables, the partial pressure of water vapor is 0,25 bar that means that dry air pressure is 0,75 bar, and the oxygen concentration is 15,7 %. The same oxygen concentration decreases at 3,23 % for 95 °C at 180 cm height. It is well known that the ignition oxygen concentration is 14 % for the ethanol vapor [20, 21], so practically we are situated below this concentration, which means that the conditions for the flame existence vanish. On the same figure we regard that at the same initial water temperature the maximum value of temperature at a certain level, is obtained at a certain time. As, for the initial water temperature of 40 °C, at 180 cm height, the temperature range from 95 to 100 °C, has a time interval around 10 seconds, starting from second 7.

In the range of mentioned temperatures, the mean pressure of vapor is situated around 0,9 bar, the correspondent oxygen concentration is 2,1 %, thus any burning stops. This is a very important effect of the warm water use as a suppression agent.

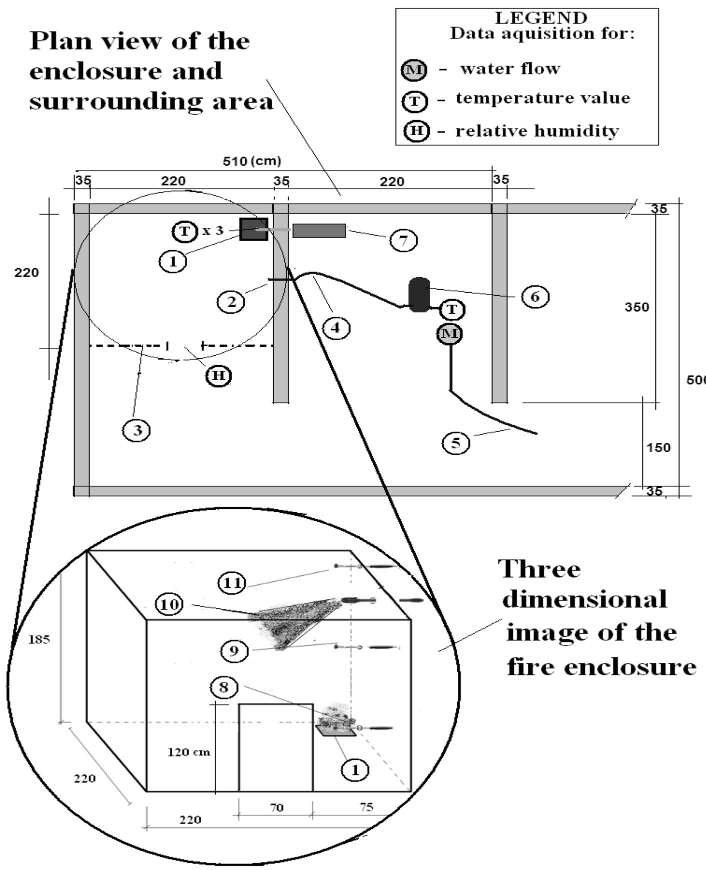

Fig. 3. Plan view of the testing area with three-dimensional view of the fire suppression testing area

1– Ethanol fire pan; 2 – Water mist nozzle, 3 – Gypsum cardboard enclosure; 4 – Water tube at 120 bar; 5 – Water tube at 2 bar, 6 – Water pump from 2 to 120 bar; 7 – Monitoring and data acquisition area; 8 – Centerline thermocouple at 20 cm from ethanol surface pan; 9– Centerline thermocouple at 100 cm from ethanol surface; 10 – Water mist jet; 11 – Centerline thermocouple at 180 cm from ethanol surface

For the other two tested water initial temperatures, which are smaller than 40 °C, we observe in Fig. 5 that the temperature values at the same level of 180 cm, are below 70 °C and the flame stability may continue involving negative damages.

We note that the results apply to conditions under which experiments were carried out for the considered time interval.

Fig. 4. Images taken during tests. From left to right: Ethanol pan fire before the water mist discharge, and during the water mist discharge

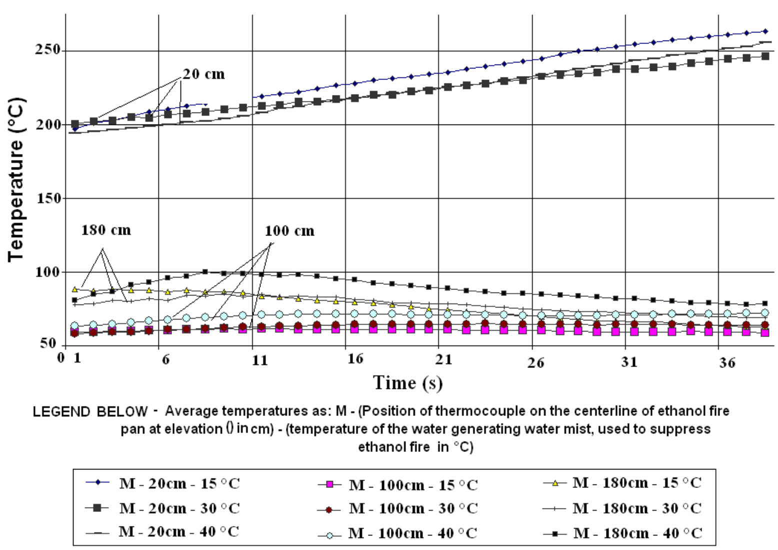

Fig. 5. Average temperatures obtained from the 15 fire suppression experiments

4. Results and discussions

The figures 6 and 7 presents the comparison between the curves, separately grouped three by three, depending on the position of the thermocouples: 20 cm (Fig. 6), 100 cm (Fig. 7). Also, all these figures contain the regression temperature function for each level. Figure 6 displays the linear regression equations for the three experimental obtained curves, having a linear form:

$$T = a + b \cdot t \tag{3}$$

where T is the temperature in °C and t is time in seconds. The values of regression coefficients are displayed on figure 6. It is also observed in figure 6 that the curve values for temperatures of 30°C and 15°C hit at the first second, values close to 200 °C and one of them (M - 20 cm - 15 °C) reaches to about 265 °C and the other one (M - 20 cm - 30 °C) to about 248 °C. To obtain accurate values at the point of maximum difference on the graphic, 39 seconds (*t* axis), one needs to replace t in the two equations of the respective linear regression, with the value 39. For M - 20 cm - 15 °C is obtained $T = 267{,}65$ °C and for M - 20 cm - 30 °C is obtained $T = 248{,}01$ °C. The result is a maximum difference between the two curves of 20 K. As the tests were not performed in the same initial temperature, the clamed values are arbitrary, given the conditions. In the experimental tests have been employed mainly the modern, precise and sensible thermocuples and hygrometers, using the data acquisition system and the computer.

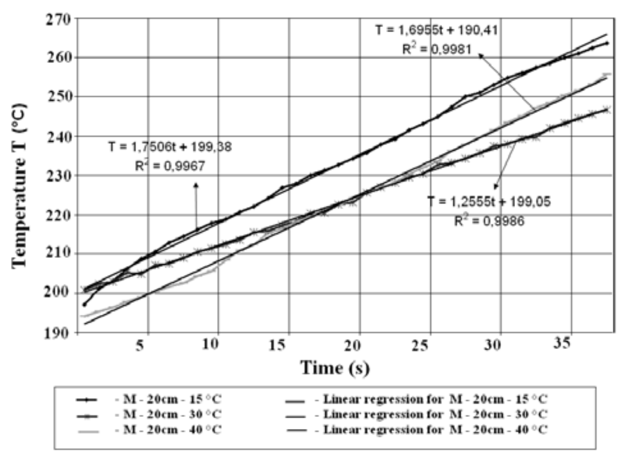

Fig. 6. Experimental medium temperature values for the thermocouple placed at 20 cm elevation

For the thermocouple in elevation 100 cm, (figure 7), the polynomial regressions have the following form (in order for temperatures of 15, 30 and 40 °C):

$$T = a + bt + ct^2 + dt^3 \tag{4}$$

As the starting point for the two polynomial regressions are closer one to each other, in the following, one will compare the values M – 100 cm – 15 °C and M – 100 cm – 30 °C, at second number 31. For M – 100 cm – 15 °C one obtains *T*=64,49°C and for M – 100 cm – 30 °C, *T*=59,89 °C. The result is a maximum difference between the two curves, of 5 K.

After a similar analysis, for the height of 180 cm thermocouple, it results that by using warm water, the combustion conditions are no longer fulfilled.

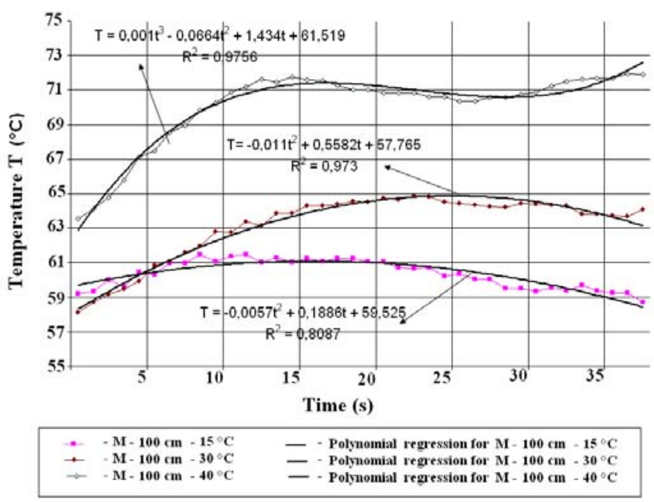

Fig. 7. Experimental medium temperature values for the thermocouple placed at 100 cm elevation

From the above analysis, based on the experimental data plotted on figures 4-6, in function of time, height and under the considered conditions, result the following:

- the temperature at 100 cm elevation above the fire pan remains approximately constant at a value of 61 °C for water mist generated with water at 15 °C;
- the temperature values, at 100 cm elevation, for water mist at 30 °C, maintains close to the value of 65 °C;
- the temperature values, at 100 cm elevation, for water mist at 40 °C remained constant around 70 °C throughout the graphic;
- the temperature at 180 cm elevation above the fire pan for all three cases has a sinuous value, with many intersecting, but on average we can say that the

results obtained in terms of suppression efficiency, are increasingly in the following order: water mist at 40, 30, 15 °C.

Also, in the case of 20 cm elevation above the fire pan, the order is reversed, meaning that water mist at 15 °C has smaller suppression efficiency than the other two values.

From our observations it results that the maximum suppression effect is given by water mist at 40 °C, but in the second half of the interval, maximum suppression effect it given by water mist generated by water at 30 °C temperature.

5. Conclusions

As depletion of oil reserves is more present today than ever, the ethanol deposits and warehouses will be present more and more, even in housing areas. Ethanol pool fires suppression systems should use this trend, and the optimal solution is retrofitting the existent systems. The most important finding of the authors is connected to the temperature of the water droplet coming out of the sprinkler head. Generally, a water temperature of 30 °C was found to be effective in extinguishing fires more rapidly than the ones of 15 °C or 40°C, by experimental testing.

From the above analysis were found the associations between water temperatures, used to create mist and the effectiveness of fire suppression as:

- overall, for optimal suppression in all three points placed on the height, above the fire pan (20 cm, 100 cm and 180 cm) is preferable to choose the water temperature of 30 °C;
- if a temperature drop is needed at the elevation of 100 cm, it is advisable to use cold water (15 ° C);
- for best results in the flames area, at 20 cm elevation, one can use both 40 and 30 °C water mist. The water at 30 °C temperature in the final point of the graph in figure 4, implies a decrease of 19,6 °C compared to the situation of cold water of 15 °C;
- if a decrease in temperature at 180 cm level is required, it is recommended to use cold water at 15 ° C, which is more effective in suppression, than the water at 40 °C.

The experimental results give the fundamental information to develop the proposed system and allow an application for the future ethanol storage system.

The preaheat of the liquid agent allows a fine droplet distribution in the jet. This fact enhanced mass and heat transfer processes during the evaporation, and consequently, a short time of action on the fire seat. Also, the protection of the ceiling is ensured due of the high temperature of gas vapour mixture, in this case the vapour dislocates the oxygen.

The findings of this study can be dirrectly applied to already installed water mist deluge fire suppression systems, in different types of enclosures, by adding water heating devices. Also, for an effective suppression, attention must be payed to the positioning of the water jet. As seen in practical tests, a dirrect jet would not be effective, as flames will change shape rapidly, potentially leading to the ignition of other materials in the vicinity. Water mist should flood the fire enclosure, as a mist cloud, and not as a mist jet.

The described water mist fire suppression system, using a clean agent, is a recommended alternative to other pollutant fire protection system (e. g. halon).

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