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

Assoc. Prof. ***Constantin POPA*** [1]***,*** *Prof.* ***Alexandru CHISACOF*** [2]***,***
Prof. ***Valeriu PANAITESCU*** [2]

FIRE ENGINEERING FACULTY, [2] „POLITEHNICA“ UNIVERSITY OF BUCHAREST

Abstract. The present work tries to clarify by the experimental results, some phenomenological aspects concerning the use of water mist jet of different temperature for the liquid fuel suppression. The role of some significant parameters of the mist jet have been observed in a fire extinguish evolution. In order to study the effectiveness of the suppression of an ethanol pool fire with one water mist nozzle, a series of experiments were conducted under different conditions in a closed space. The fire source is a square shaped pan of 30 by 40 cm of ethanol. The water temperature generating water mist ranged from 15 °C to 30 and 40 °C. The temperatures graphics in three points situated above the flame at different heights, throughout all the 15 fire suppression tests, allowed the authors to present findings concerning different effects and limitation of suppression, for each temperature (15, 30 and 40 °C). An important conclusion issued from this paper is very promising in terms of potential of mist jet in fire control and suppression. However, it should be noted that the results are limited to the experimental conditions because it is still difficult to get the functional relationships of pool fire extinction mechanisms with water mist. The water mist fire suppression system represents a preferred alternative to other related fire protection systems. Due of its behaviour, the mist water systems, as clean ones, are now used in many areas, including the electrical zones of the industrial plants and civil buildings.

Keywords: ethanol pool fire suppression, clean mist suppression, warm water mist jet, ecologic suppression agent, fire safety.

1. INTRODUCTION

It is well known that today the use of ethanol increases, as it is an ecological fuel. Consequently, 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 [1]. As these fire extinguishing methods are rather expensive, one should take into account other fire suppression methods or systems. Today's fire safety industry uses for such spaces, water sprinklers or water mist deluge systems. In conclusion, retrofitting would be the best solution.

Basically, the water mist deluge system remains the same, the only thing that changes in our proposal, is the temperature of the water [2]. In the following, the authors are studying the phenomenological particularities of this idea and its applicability.

Also ethanol, in comparison to gasoline, is a rather clean fuel. The present environmental restrictions impose us to find the suitable ecological systems using a clean agent. By reducing droplet size, the heat transfer surface increases and that leads to a quicker fire cooling and suppression [3, 4]. Also, some attention was paid to the use of various additives, [5]. 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. 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 [6, 7, 8].

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) [6]. 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 [7, 9]. A recent interest in water-mist systems has been shown for fire protection in tunnels [8].

2. THE WATER TEMPERATURE ON THE 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 vapours, but a lot of water quantity will be lost, diluting the ethanol pool [9, 10].

As other studies state [11], 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 vapours when meeting with the flame envelope [12, 13, 14]. As water volume expands approximately 1600 times when going into vapour 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.

The influence of the temperature on the thermo-physical properties is decisive especially for surface tension and dynamic viscosity of a liquid [15, 16, 17].

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 [18, 2]:

$$\begin{aligned} d_{ms} &= 6{,}2\frac{\sigma}{\rho_g u_p^2}\left(\frac{\rho_l}{\rho_g}\right)^{0{,}25}\sqrt{\frac{\mu_l}{\rho_l d_p u_p}We_l} = \\ &= 6{,}2\frac{1}{\rho_g u_p^2}\left(\frac{\rho_l}{\rho_g}\right)^{0{,}25}\sqrt{\sigma\mu_l u_p} \end{aligned} \qquad (1)$$

where: ρ_l is the density of the liquid phase, ρ_g – gas phase density, in kg m^{-3}; μ_l – the dynamic viscosity of the liquid, in N s m^{-2}; d_p – droplet diameter, in m; σ –surface tension, in N m^{-1}; u_p – droplet velocity, in m s^{-1}. 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.

Figure 1 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 K temperature intervals.

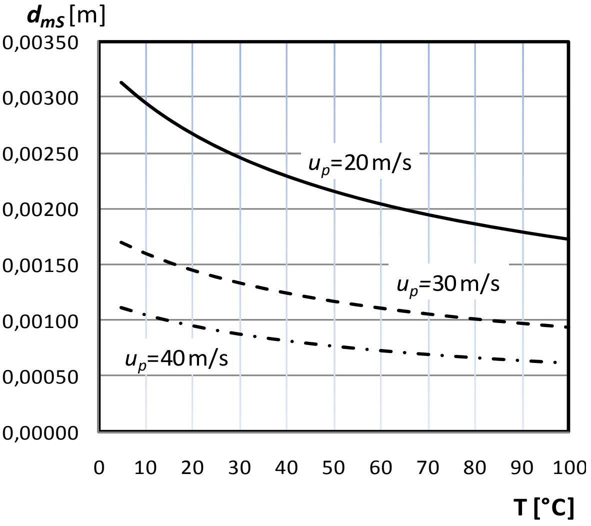

Fig. 1. The evolution of the Sauter medium diameter function of the liquid temperature for different droplet speed values.

Also, as the speed of the droplet 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 LAYOUT AND DATA

The conditions of all tests were similar, only the temperature of water generating the mist was different. Figure 2 presents the layout 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 3. 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 3 displays the ethanol pan and the flames at the liquid surface. The fire was set on an ethanol pan of 30 × 40 cm, containing 1 liter of combustible. The thermocouples situated on the centerline of the ethanol pan fire, at three different elevations (see explanations at figures 2 and 3) gave detailed temperature graphics, by using computer data acquisition [4].

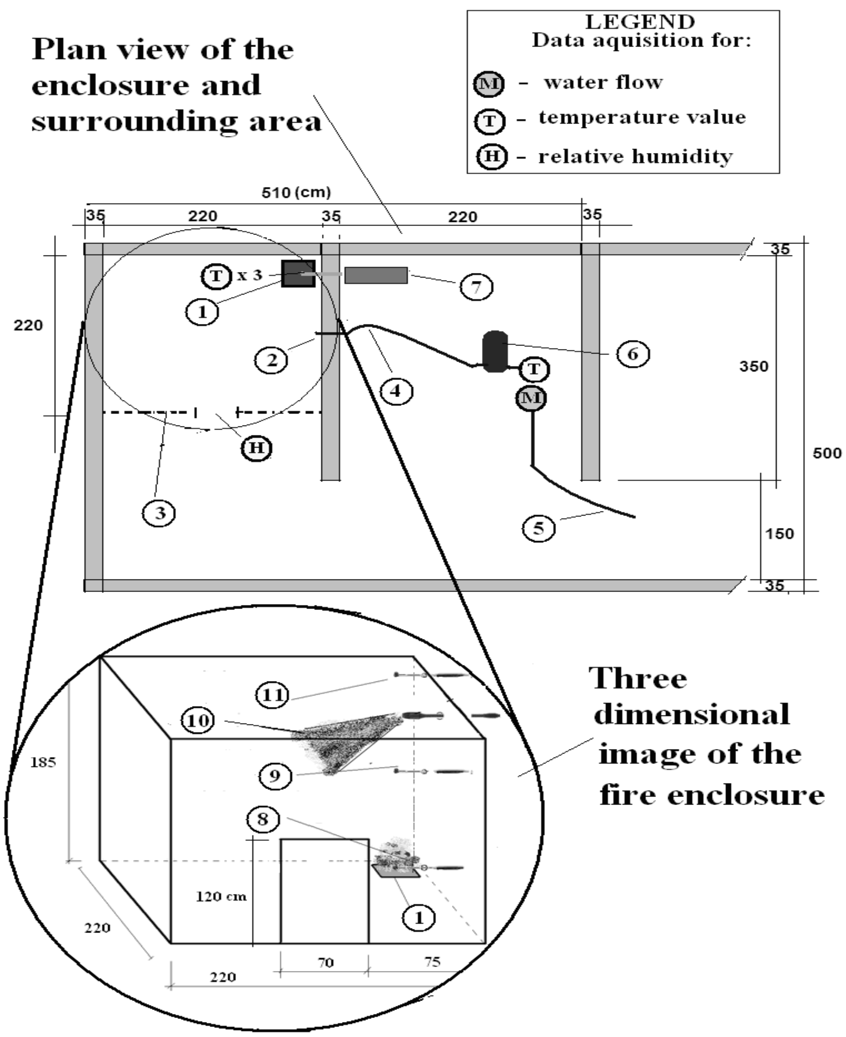

Fig. 2. Plan view of the testing area with three dimensional view of the fire suppression testing area: *1* – ethanol fire pan; *2* – water mist nozzle, *3* – gypsum cardboard enclosure; *4* – water tube at 120 bar; *5* – water tube at 2 bar, *6* – water pump from 2 to 120 bar; *7* – monitoring and data 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.

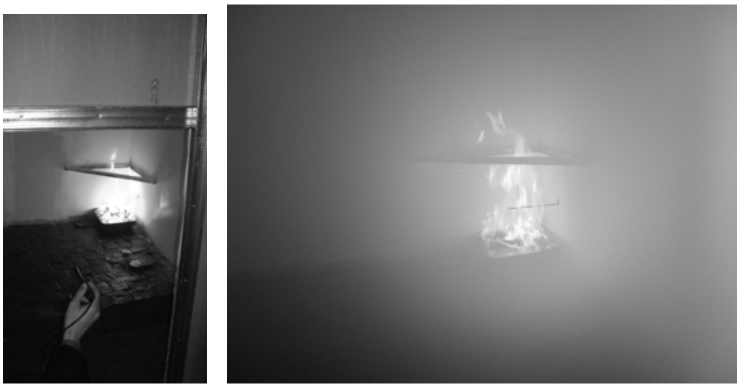

Fig. 3. Images taken during tests. From left to right: Ethanol pan fire before the water mist discharge, and during the water mist discharge.

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.

Figure 4 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 height of 20 cm, the smaller flame temperature corresponds to the warm water of 40 °C. The group of curves at 180 cm height are located in the temperature interval of 65 – 95 °C. As can be seen, the curve corresponding to initial water temperature of 40 °C, is situated above the other two. That means that the partial pressure vapors is 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 vapour [20, 21], so practically we are situated below this concentration, which means that the conditions for the flame existence vanishes. 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. For the mentioned temperatures, the mean pressure of vapor is around 0,9 bar and the correspondent oxygen concentration is 2,1 %, thus any burning stops. This is a crucial effect of the warm water use as a suppression agent.

For the other two tested water initial temperatures, which are smaller than 40 °C, we observe in figure 4 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.

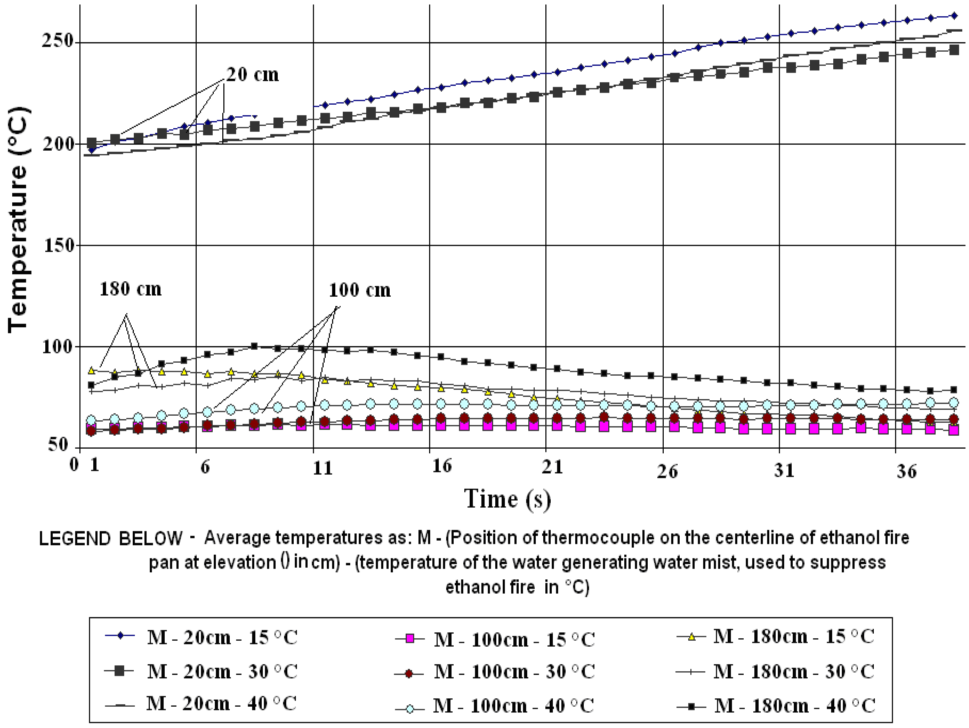

Fig. 4. Average temperatures obtained from the 15 fire suppression experiments.

4. RESULTS AND DISCUSSIONS

The figures 5 and 6 presents the comparison between the curves, separately grouped three by three, depending on the position of the thermocouples: 20 cm (Fig. 5), 100 cm (Fig. 6). 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:

$$T = a + b \cdot t \tag{2}$$

where T is the temperature in °C and t is time in seconds.

The values of regression coefficients are displayed on figure 5. It is also observed in figure 5 that the curve values for water discharged 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. In the experimental tests have been employed mainly the modern, precise and sensible thermocuples and hygrometers, using the data acquisition system and the computer.

For the thermocouple in elevation 100 cm (Figure 6), the polynomial regressions have the following form (in order for temperatures of 15, 30 and 40 °C):

$$T = a + bt + ct^2 + \mathrm{d}t^3 \tag{3}$$

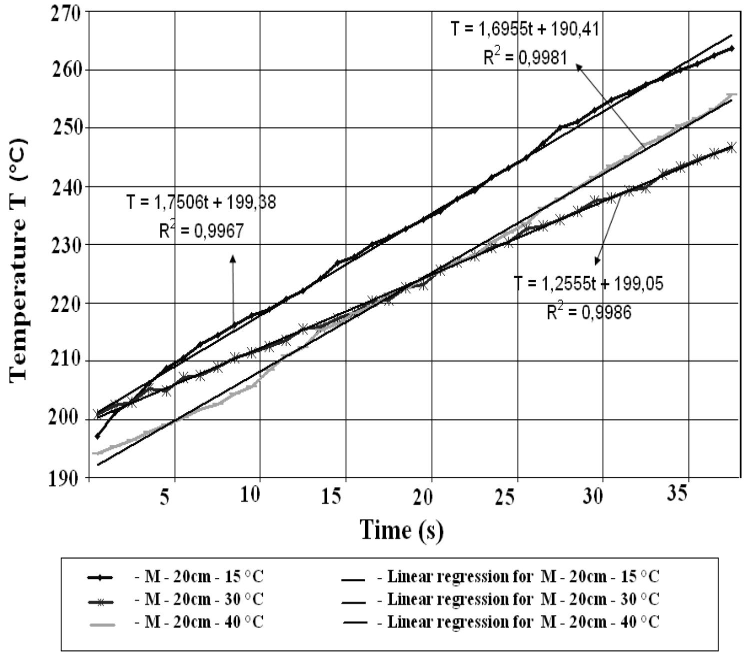

Fig. 5. Experimental medium temperature values for the thermocouple placed at 20 cm elevation.

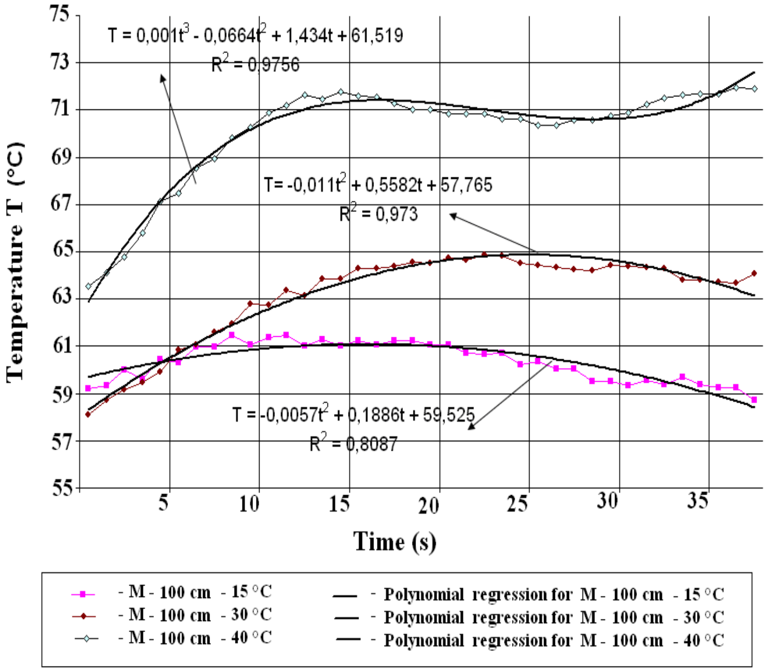

Fig. 6. Experimental medium temperature values for the thermocouple placed at 100 cm elevation.

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 was obtained $T = 64{,}49$°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 180 cm for thermocouple height, it results that by using warm water, the combustion conditions are no longer fulfilled.

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 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;
- the temperature at 180 cm elevation above the fire pan for all three cases has a sinuous value, but 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 temperature values.

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

5. CONCLUSIONS

Ethanol pool fires suppression systems should be retrofitted. The most important finding of our study the authors is related to the temperature of the water droplet coming out of the sprinkler head. From our observation, 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 relations between water temperatures, used to create mist and the effectiveness of fire suppression.

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 result of this study can be directly applied to the existent water mist deluge fire suppression systems, in different types of enclosures, by only adding a water heating device. Also, for an effective suppression, attention must be focused to the positioning of the water jet. As seen in practical tests, a direct 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, involving a clean agent, is a recommended alternative to other pollutant fire protection system (e. g. halon).

ACKNOWLEDGMENTS

The authors gratefully acknowledge to the National Council of Scientific Research (CNCS-CNCSIS) for the financial support Grant ID-1708/2009.

REFERENCES

[1] Anghel I. 2008, *The current state of research, nationally and internationally, on modeling, simulation and numerical analysis of fire development in structures and industrial systems* – Doctoral report no. 1, U.P.G. Ploiești, Romania.

[2] Popa C 2011, *Contributions concerning fire modeling, simulation and suppression in vertical structures*, doctoral thesis – Politehnica University of Bucharest, Romania.

[3] Liu Z, Kim A K. 2001, *A Review of water mist fire suppression technology: Part II - Application studies", Journal of Fire Protection Engineering*, v. 11, no. 1, 16-42

[4] *** Labmate Spotlight 2009, *Droplet size analysis in the development of enhanced water mist fire suppression systems.*

[5] Beihua C., Guangxuan L. 2009, *Experimental studies on water mist suppression of liquid fires with and without additives* - Journal of Fire Sciences vol. 27 no. 2 101-123.

[6] Sheinson R. S., Williams F. W. 2004, *Feasibility evaluation study of very fine water mist as a total flooding fire suppression agent for flammable liquid fires*, report, Navy Technology Center for Safety and Survivability Combustion Dynamics Section.

[7] *** *The Current and Future Applications of water Mist Fire Suppression Systems*, SFPE Atlanta Symposium, report (2009).

[8] ***NFPA 750 *Standard on water mist fire protection systems*, 2010 Edition, USA.

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

[10] ****CEA Specifications for Sprinkler Systems Requirements and test methods for ESFR Sprinklers*, 1999/ 60 pag.

[11] McGarry Amy J., Milke J.A. 1997, *Full scale room fire experiments*, raport, Departement of fire protection engineering, NIST-GCR-97-9716.

[12] Paulsen B., Hertzberg T. 2004, *The physics behind water mist systems*, IWMA Conference 6-8 October 2004, Roma, Italy.

[13] Chisacof A. et al, *Clean fluid jet in evaporation for the environment structure change* – CNCSIS research ID_1708 Romania (2009-2011).

[14] Sirigano W. A., *Fluid dynamics and transport of droplets and sprays*, University of California – Irvine - Cambridge, 2010.

[15] Wagner W., Kretzchmar H.J. 2008, *International Steam tables*, IAPWS – IF97 – Springer, 2nd ed.

[16] Chisacof A. et al. 2009, *Non-isothermal two-phase free jet with high power of heat absorption*, Termotehnica, 57-62.

[17] Popa C., Chisacof A., Panaitescu V. 2012, *Experimental Clean ethanol pool fire suppression by using warm water mist.* Revue Roumaine des Sciences techniques, Série Électrotechnique et Énergétique. 57, nr.3.

[18] Ashgriz N (Ed.) 2011, *Handbook of Atomization and Sprays - Theory and Applications*, Springer New York pg. 150-175.