

WATER MIST BEHAVIOR AS FLAME SUPPRESSANT

M. T. Parra, F. Castro, J. M. Villafruela, C. Méndez, M. A. Rodríguez

Department of Energy and Fluid Mechanics Engineering, University of Valladolid, Spain

Summary The present work focuses on the numerical simulation of the interaction of a water spray barrier and a premixed methane-air flame inside a closed tube. The water mist is modelled as an uniform cloud of monodispersed droplets. The principal mechanisms of interaction of the water spray against the flame are: the break-up, drag, heating and evaporation of the droplets. The final goal is to determine its effectiveness as extinction mechanism.

INTRODUCTION

The fire suppression effects of water mist are attributed to physical effects more than chemical effects. When the water droplets contact hot or burning gas mixture, the water droplet changes from liquid to steam, which means an increase of 1700 times its volume. The expansion of volume reduces the concentration of oxygen in the flame surroundings. The droplet evaporation removes heat from the burning mixture because of the sensible heat of water vapour. Optimum water droplet sizes ranges from 50 to 200 microns of mean diameter. Droplets must be large enough to avoid the drag and small enough to evaporate quickly. Experiments have shown that water spray can be very effective in quenching strong flames.

It is possible to summarize the mechanisms of energy transfer between the flame front and the water spray barrier as: the surface tension energy necessary to break-up the droplets, momentum to accelerate the droplets due to the velocity of the ambient gases, energy to increase the temperature of the droplets due to the ambient temperature and the latent heat energy involved with steam generation, [1].

NUMERICAL MODEL

Drag model

Regarding the momentum interaction between the gas mixture and the water barrier the gaseous flow exerts a drag force on the water droplets. The drag force is a function of the relative velocity between the gas mixture and the droplets:

$F_D = -C_D 0.5 \rho V_{rel}^2 A_P$ where C_D is the drag coefficient, evaluated with different correlations for Reynolds ranging from 0 to $3 \cdot 10^5$ and A_P is the projected area of the droplet, assuming that the water droplets maintain a spherical shape.

Break-up model

It is commonly known that the break-up of a droplet is originated by a deformation of its surface due to the aerodynamic forces imposed by the gas flow. The break-up criterion can be expressed in terms of relative velocity between the droplet and the gas flow, Weber number $We = \rho V_{rel}^2 D / \sigma$, [2]. In the case of water spherical droplets, when the Weber number is bigger than 12 there is bag type break-up, if the ratio of Weber and square root of Reynolds is bigger than 0.5, there is stripping type break-up, [3]. Ranger and Nicholls proposed an empirical expression for the break-up time, [1].

In presence of pressure waves, the break-up criterion comes expressed in terms of the instantaneous acceleration, Eötvös number $Eo = \rho_W (dV/dt) D^2 / \sigma$, [4]. There is bag break-up if the Eötvös number is bigger than 16 and stripping break-up if the Eötvös number is bigger than 100, talking of water droplets.

Vaporization model

It was considered that vaporization can occur according two regimes: mass diffusion transfer and boiling conditions, any of them behaves according the widely used Spalding model, [5].

When the droplet temperature is lower than the saturation temperature, then the vaporization is due to diffusion transport from the droplet to the gas mixture, being the mass transfer from one droplet:

$$\frac{dm_W}{dt} = \pi D \rho_W Sh B_M \quad (1)$$

The thermal energy received by one droplet from the surrounding ambient is:

$$\dot{Q} = \pi D K Nu (T_G - T_W) \quad (2)$$

D_W is the mass diffusion of water vapour in gas mixture, B_M is the Spalding mass transfer number, K is the thermal conductivity of the gas mixture. The Sherwood number, Sh , and the Nusselt number, Nu , are evaluated from the Ranz and Marshall correlation, [6]. The increase of the droplet temperature can be obtained from:

$$m_W c_W \frac{dT_W}{dt} = \dot{Q} - \frac{dm_W}{dt} L \quad (3)$$

When the droplet temperature is around its boiling point, the vaporisation regime is the boiling. In that case, there is not droplet heating and the total energy is employed to vaporize the water, being the new rate of vaporisation evaluated from equation 3.

DISCUSSIONS OF RESULTS

In the calculations described here, an adaptive mesh was used to represent a tube 18 m length with one locked end, the initial temperature in the unburned gas mixture is 300 K and the temperature on the locked end is 1800 K to provide the ignition of the flame. The initial composition is the stoichiometric methane/air mixture. The flame will propagate through

the tube. The water barrier is located at $L = 3$ m from the ignition zone and is characterised by droplets of diameter $D = 50$ μm being the liquid volume fraction $F = 0.05\%$.

The figure 1 represents the temporal evolution of: temperature and diameter of the droplet and the liquid water volume, on the location $x = 4$ m. In order to compare simultaneously the three variables, they have been made nondimensional, they are the rate of the temporary value with reference to the initial value. The water volume, increases due to the drag from upwind sections and decreases with the time because of the vaporization. When the water temperature increases, the diffusion vaporization regime occurs. As soon the water temperature reaches the saturation temperature, then the boiling regime begins with an important decrease of the water volume. The important decrease of the diameter is due to the break-up by effects of the pressure waves while the slow reduction is due to the steam generation. The boiling regime begins when the droplet diameter is small enough and therefore has a high surface/volume ratio.

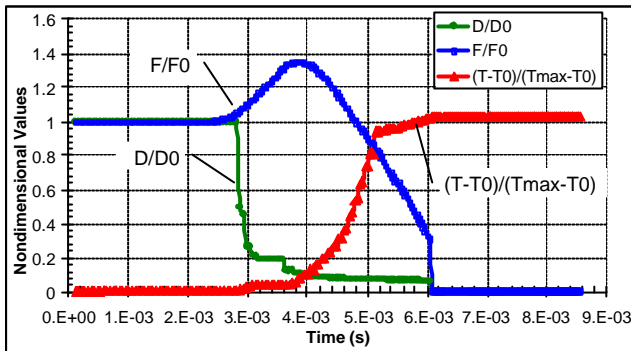


fig. 1. Temporal evolution of the water barrier on $x = 4$ m. Barrier of $D = 50$ μm , $F = 0,05\%$ and $L = 3$ m

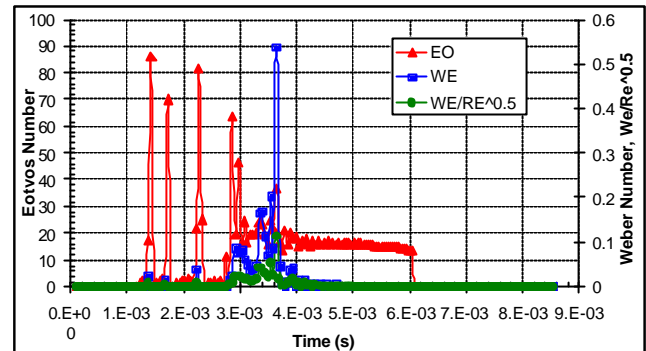


fig. 2. Temporal evolution of break-up parameters on $x = 4$ m. Barrier of $D = 50$ μm , $F = 0,05\%$ and $L = 3$ m

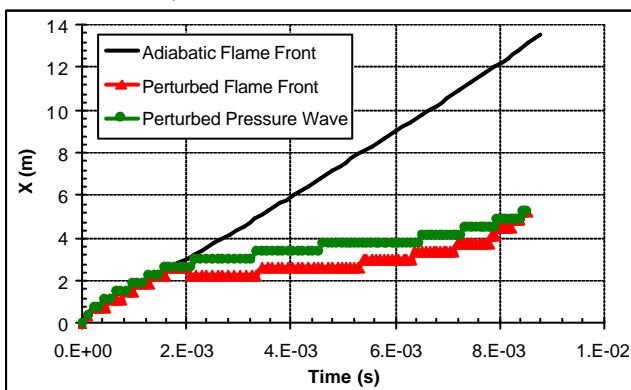


fig. 3. Propagation of the free flame and the flame with the barrier of $D = 50$ μm , $F = 0,05\%$ and $L = 3$ m

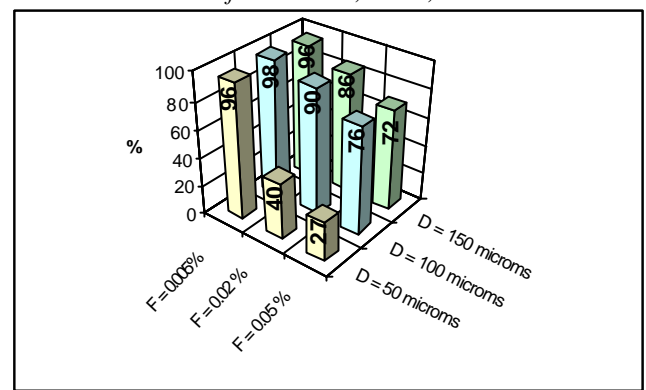


fig. 4. Propagation velocity of the perturbed flame expressed on percentage of the one free flame

Figure 2 shows the Weber and the Eötvös numbers as well as the $We/Re^{0.5}$ on $x = 4$ m. From the pictures, its possible to see that the Weber number takes values lower than 0.54, the $We/Re^{0.5}$ lower than 0.11 while the Eötvös number takes values up to 86. That means that the main break-up agent is the instantaneous acceleration instead of the relative velocity, and there is bag break-up regime.

The figure 3 represents the propagation of the front of a flame without water barrier (adiabatic flame) and a flame interacting with a water barrier. It is clear the important decrease of its velocity of propagation. On figure 4, there is a parametric analysis of the influence of the droplet diameter and liquid fraction of the barrier. The results are the velocity of propagation of different flames expressed as a percentage of the adiabatic velocity of propagation.

CONCLUSIONS

The interaction of a monodispersed water barrier of droplets with a premixed methane/air flame that propagates in a confined domain has been simulated. The main interaction agents taken into account are: the vaporisation: diffusion and boiling regimes, as well as the droplet break-up based on the Weber and Eötvös number. The results show a reasonable behaviour. The parametric analysis reveals the important decrease of the flame propagation velocity for small droplets and large liquid fractions.

Acknowledgements

We thank the Spanish Ministry of Science and Technology for supporting this work, grant REN2002-1598.

References

- [1] Thomas G. O., Edwards M. J. and Edwards D. H., (1990). Studies of detonation quenching by water sprays, *Combust. Sci. Tech.* Vol. 71, pp.233-245.
- [2] Wierzbka A., (1990). Deformation and breakup of liquid drops in a gas stream at nearly critical Weber numbers, *Experiments in Fluids* 9, pp. 59-64.
- [3] Nicholls J. A., (1972). Stream and droplets breakup by shock waves, *Liquid propellant rockets combustion instability*, pp. 126-127, NASA SP-194.
- [4] Catlin C. A., Gregory C. A. J., Johnson D. M. and Walker D. G., (1993). Explosion mitigation in offshore modules by general area deluge, *Trans IchemE*, Vol. 71.
- [5] Reitz R. D., (1987). Modeling atomization processes in high-pressure vaporizing sprays, *Atomisation and Spray Technology* 3, pp. 309-337.
- [6] Sirignano W. A., (1993). Fluid dynamics of sprays - 1992 Freeman scholar lecture, *Journal of Fluid Engineering*, Vol. 115, pp. 345-378.