

Influence of a Water-in-Fuel Spray on an Edge Flame

O. Shalev*¹, J.B. Greenberg²

^{1,2}Aerospace Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

*Corresponding author: ohad.slv@gmail.com

Abstract

Water-in-fuel emulsion droplets are comprised of an inner water droplet immiscible with and surrounded by an outer liquid fuel layer. The use of water-in-fuel liquid droplets was suggested as a means to enabling cleaner and more complete combustion. This is mainly due to a reduction in the burned gas temperature induced by the water content and to secondary droplet atomization, as parent droplets micro-explode producing faster-evaporating smaller offspring droplets leading to better mixing.

In the current work, a new two-dimensional thermal-diffusional model is formulated to describe the edge flame formed by two laminar co-flowing streams, one of an oxidant and the other of fuel vapor and water-in-fuel emulsion droplets, separated initially by a splitter plate. We perform a numerical investigation of how the initial presence of the water-in-fuel droplets and their micro-explosions effect the thermal structure of the compound flame in the mixing layer downstream of the splitter plate.

Keywords

Water-in-fuel droplets, emulsion, edge flame, pollution.

Introduction

Water-in-fuel emulsion droplets are a potential candidate for ameliorating some of the ecological damage sustained by the use of conventional fuels employed for combustion purposes. A major advantage of such droplets is their propensity to micro-explode, thereby producing a finer spray of offspring droplets leading to more rapid evaporation enabling better mixing, resulting in a more uniform mixture of fuel vapor with the oxidizer. These droplets are made-up of an inner water droplet immiscible with and surrounded by an outer liquid fuel layer. The use of water-in-fuel liquid droplets has been suggested as a means to enabling cleaner and more complete combustion. This is mainly due to a reduction in the burned gas temperature induced by the water content and to secondary droplet atomization as parent droplets micro-explode producing faster-evaporating smaller offspring droplets leading to better mixing.

Previous research on the behavior of such droplets, either as single droplets or within a spray, was carried out experimentally, theoretically and numerically. A comprehensive review of this research appears in a recent publication [1] to which the interested reader is referred.

In realistic combustion engineering settings the flames that are created are turbulent and of complex geometry. Often edge flames can be found within them. A comprehensive review by Buckmaster [2] addresses the special nature and characteristics of many edge flames.

In the current work, we consider, for the first time, two laminar co-flowing streams, one of an oxidant and the other of fuel vapor and water-in-fuel emulsion droplets, separated initially by a splitter plate. A mixing layer is formed, downstream of the end of the plate, in which diffusive mixing of fuel vapor and oxidant occurs. A steady-state edge flame is thereby created comprised of a partially premixed flame attached to which is a trailing diffusion flame. A two-dimensional thermal-diffusional model is adopted. In the spray, the inner water droplets and outer fuel layers are assumed spherical in shape and concentric. We solve the governing equations numerically and carry out a parametric investigation of how the initial presence of

the water-in-fuel droplets effects the dual premixed-diffusion structure of the edge flame in the mixing layer. In particular, we examine what influence droplet micro-explosions have on the different parts of the flame by comparing with cases for which the droplets do not micro-explode.

Governing Equations and their Solution

We consider two parallel streams of equal (constant) laminar velocity, U_0 , one of water-in-fuel liquid droplets and vapor fuel and the other of oxygen. Both streams are assumed to contain a dominant diluent. Upstream the two streams are separated by a semi-infinite flat plate (see Figure 1).

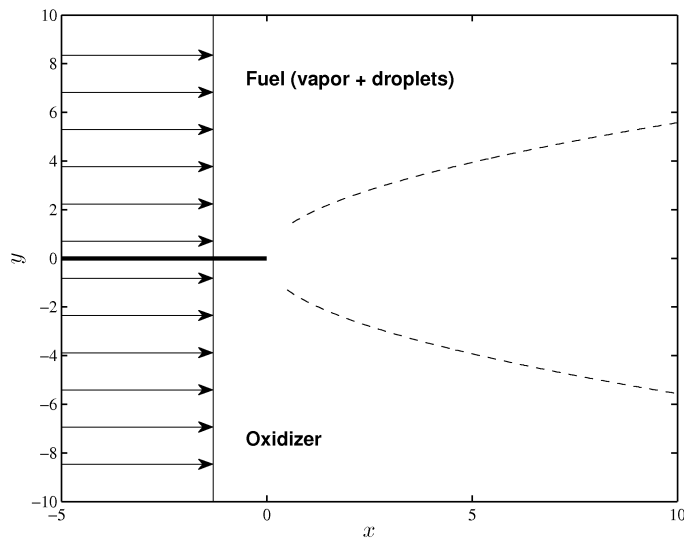


Figure 1. Configuration for study of an edge flame with fuel spray: the broken line delineates the mixing layer.

The temperature of the plate is assumed constant and equal to the upstream temperature of the two streams, T_0 . Downstream of the plate, under appropriate operating conditions, chemical reaction occurs. It will be taken to be represented by a single global reaction step of the form: Fuel + ν Oxidizer \rightarrow (1+ ν) Products + thermal energy, where ν is the stoichiometric coefficient. The rate of fuel vapor consumption is given by:

$$\Omega_F = B\rho^2 Y_F Y_O \exp(-E/RT) \quad (1)$$

where B is the pre-exponential term, ρ is the mixture density, Y_F, Y_O are the mass fractions of fuel vapor and oxygen respectively, E is the activation energy, R is the gas constant and T is the temperature. The spray of water-in-fuel liquid droplets is assumed to be in dynamical equilibrium with its host environment so that no slip is permitted. For droplets having diameters of less than about $80\mu m$ this is a reasonable assumption as any velocity differences rapidly dissipate under these circumstances.

For simplicity, a diffusive-thermal model is adopted here so that the density is constant as are the molecular diffusivities of the fuel vapor, \mathcal{D}_F , and oxygen, \mathcal{D}_O , the thermal conductivity of the mixture, λ , and the specific heat, c_p . This model enables the heat and mass transfer conservation equations to be divorced from the flow equations whereby, for the gas phase, only balance equations for the fuel vapor, oxygen and the energy need be considered. Let the

total mass fraction of fuel (i.e. vapor +liquid) at the supply conditions be Y_{F_0total} and that of the oxygen Y_{O_0} . Then normalizing the fuel vapor and oxygen mass fractions with respect to these quantities, respectively, now defines the normalized mass fractions. Similarly, the non-dimensional temperature rise is introduced:

$$\theta = (T - T_0) / (T_a - T_0) \quad (2)$$

with

$$T_a = T_0 + QY_{F_0total} / c_p (1 + \phi) \quad (3)$$

in which T_a is the adiabatic flame temperature, Q is the heat per unit gram of fuel generated by the chemical reaction, and ϕ is the initial mixture strength which is the ratio of the mass of fuel supplied above the splitter plate to the mass of oxidant supplied below the plate, normalized by their stoichiometric ratio.

The spray is described using the sectional approach [3] and, for simplicity, a mono-sectional model is utilized here. The mono-sectional vaporization coefficients of the fuel and water are denoted by C_F, C_W and is defined in terms of the sizes of the droplets comprising the spray and their evaporation parameter (see [3]). The mass fraction of liquid droplets in the mono-sectional spray are also normalized using Y_{F_0total} .

Thus, making use of $\lambda / \rho c_p U_0$ as a unit of length and $\lambda / \rho c_p U_0^2$ as a unit of time the governing equations for the problem at hand assume the following non-dimensional form:

$$\underbrace{\frac{\partial Y_F}{\partial t} + \frac{\partial Y_F}{\partial x}}_{transport} = \underbrace{\frac{1}{Le_F} \left(\frac{\partial^2 Y_F}{\partial x^2} + \frac{\partial^2 Y_F}{\partial y^2} \right)}_{diffusion} - \underbrace{\omega}_{reaction} + \underbrace{\Delta_F Y_{d,F} H(y) H(\theta - \theta_V) H(\theta_E - \theta)}_{evaporation before ME} + \underbrace{f \cdot \Delta_F Y_{d,F} H(y) H(\theta - \theta_E)}_{evaporation after ME} \quad (4)$$

$$\frac{\partial Y_O}{\partial t} + \frac{\partial Y_O}{\partial x} = \frac{1}{Le_O} \left(\frac{\partial^2 Y_O}{\partial x^2} + \frac{\partial^2 Y_O}{\partial y^2} \right) - \phi \omega \quad (5)$$

$$\frac{\partial Y_{d,F}}{\partial t} + \frac{\partial Y_{d,F}}{\partial x} = \begin{cases} -\Delta_F Y_{d,F} H(y) H(\theta - \theta_V), & x < x_E \\ -f \cdot \Delta_F Y_{d,F} H(y), & x > x_E \end{cases} \quad (6)$$

$$\frac{\partial Y_{d,W}}{\partial t} + \frac{\partial Y_{d,W}}{\partial x} = -\Delta_W Y_{d,W} H(y) H(\theta - \theta_E) \quad (7)$$

$$\begin{aligned} \frac{\partial \theta}{\partial t} + \frac{\partial \theta}{\partial x} &= \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) + (1 + \phi) \omega - \eta_F \Delta_F Y_{d,F} H(y) H(\theta - \theta_V) H(\theta_E - \theta) \\ &\quad - f \cdot \Delta_F Y_{d,F} H(y) H(\theta - \theta_E) - \eta_W \Delta_W Y_{d,W} H(y) H(\theta - \theta_V) \\ \frac{\partial Y_F}{\partial t} + \frac{\partial Y_F}{\partial x} &= \frac{1}{Le_F} \left(\frac{\partial^2 Y_F}{\partial x^2} + \frac{\partial^2 Y_F}{\partial y^2} \right) - \omega + \Delta_Y H(y) H(\theta - \theta_V) \end{aligned} \quad (8)$$

where the reaction rate is:

$$\omega = DZe^3 Y_F Y_O \exp \left(\frac{Ze(\theta - 1)}{(1 + \gamma\theta) / (1 + \gamma)} \right) \quad (9)$$

Equations (4) and (5) are the conservation equations for the normalized fuel vapor and oxygen mass fractions, Y_F, Y_O , respectively. The second terms on the right hand sides of these equations are the dimensionless reaction rates, whereas the third term in Equation (4) is the rate at which fuel vapor is supplied due to droplet evaporation starting from a pre-dictated evaporation temperature θ_V . H is the Heaviside function and is used here to apply the spray

related terms in the region $y > 0$ only since, as mentioned previously, the droplets are taken to be in dynamic equilibrium with their surroundings so that there is no mechanism to enable their trajectory to deviate in the y -direction. In addition, there is no evaporation if the local non-dimensional temperature, θ , is below that of the liquid fuel's boiling point, θ_v . The final term on the RHS of Eq. (4) represents the evaporation rate of the off-spring fuel droplets produced by the micro-explosion of parent droplets which occurs when the temperature is θ_E . At this location the water vapor in the center of the original droplets is released instantaneously. The aforementioned evaporation rate is the original rate increased by the micro-explosion factor f denoted by:

$$f = [0.27(1 - \alpha^{1/3})]^{-2} \quad (10)$$

where α is the ratio of the initial water content to the initial total liquid content in each water-in-fuel droplet (see [4] for the development of this factor).

It is assumed that thermal adjustment of the droplets to the host gas temperature is instantaneous. Equation (8) is the energy conservation equation. The second term on the right hand side is the chemical energy, whereas the remaining terms are the heat absorbed by the droplets for evaporation, and η_F, η_W are the ratios of the latent heats of evaporation of the fuel and water, respectively, to the heat of reaction. Equations (6) and (7) describe the conservation of the normalized mass fraction of liquid fuel and water in the droplets, respectively. Le_F, Le_O are the Lewis numbers of the fuel vapor and oxygen, respectively. D is the chemical Damkohler number, Ze is the Zeldovitch number, γ is the heat release parameter given, respectively, by:

$$D = \left(\frac{\lambda}{\rho c_p U_0^2} \right) Ze^{-3} \rho B Y_{O_0} \exp(-E / RT_a) \quad (11a)$$

$$Ze = E(T_a - T_0) / RT_a^2 \quad (11b)$$

$$\gamma = (T_a - T_0) / T_0 \quad (11c)$$

Finally, $\Delta_i (= C_i \lambda / \rho c_p U_0^2 \quad i = F, W)$ is the vaporization Damkohler number representing the ratio of a characteristic flow time to a characteristic time for evaporation of either fuel or water. The boundary conditions for the steady state problem, which we examine here by setting $\partial / \partial t = 0$, are specified as follows:

At the upstream (left) boundary: $\theta = 0$, and

for $y > 0$: $Y_O = 0$, $Y_F - Le_F^{-1} \partial Y_F / \partial x = 1 - \delta$, $Y_{d,F} = \delta(1 - \alpha)$, $Y_{d,W} = \delta\alpha$,

for $y < 0$: $Y_O = 1$, $Y_F = Y_{d,F} = Y_{d,W} = 0$.

On the upper and lower boundaries: $\partial Y_F / \partial y = \partial Y_O / \partial y = \partial \theta / \partial y = 0$

and on the splitter plate: $\partial Y_F / \partial y = \partial Y_O / \partial y = \theta = 0$.

At the domain exit, extrapolation is applied from values within the solution domain.

The numerical solution of the governing equations is obtained using standard finite differences to cast the equations as a set of nonlinear algebraic equations on about 120,000 mesh points, which are then solved iteratively using the Gauss-Seidel method till an iterative convergence criterion of 10^{-9} is achieved.

Results and Discussion

Unless specified otherwise the data used for the computations were:

$\Delta_F = 0.1$, $\Delta_W = 173$, $\eta_F = 0.06$, $\eta_W = 0.48$, $\theta_v = 0.08$, $\theta_E = 0.12$, $D = 12$, $Le_F = 1$, $Le_O = 1$, $\phi = 5$, $Ze = 10$,

We divide our discussion of the results into the way the upstream partially premixed flame is influenced by the presence of the water in the droplets followed by its effect on the trailing diffusion flame.

In Figure 2 we examine the influence of the initial water load in the spray's water-in-fuel droplets on the temperature at the point of maximum reaction in the partially premixed zone of the compound flame. This influence is drawn for different total liquid loads, i.e. water+fuel (shown through different colors) and for different (normalized) latent heats of vaporization of the water (represented by different line thicknesses). The latter can be achieved by doping the water in the droplets. For a given liquid load and latent heat of vaporization the aforementioned temperature drops as the initial load of the water in the droplets increases. This is the result of (a) an increase in the focused endothermic effect of the sudden evaporation of the water as the droplets micro-explode, and (b) a reduction in the total fuel vapor available from the droplets as the liquid fuel is replaced by water. The same qualitative behavior is obtained as both the initial total liquid load and the latent heat increase, reflecting reasons (a) and (b) above. However, the temperature decrease of about 2% at the most which translates into just less than 20K.

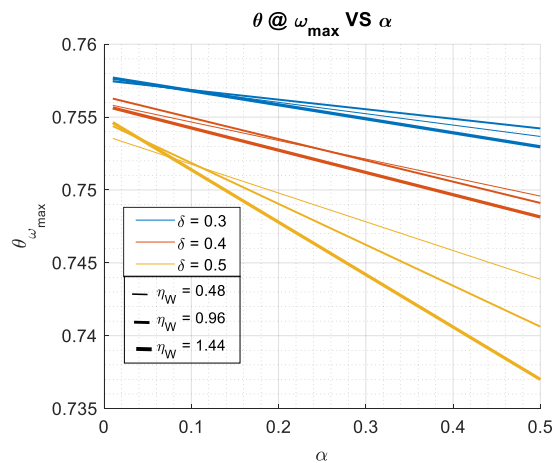


Figure 2. Normalized temperature at point of maximum reaction rate in the partially premixed flame region of water-in-fuel edge flames as a function of the water loading, for different initial liquid loads (water+fuel) and latent heats of vaporization of the water.

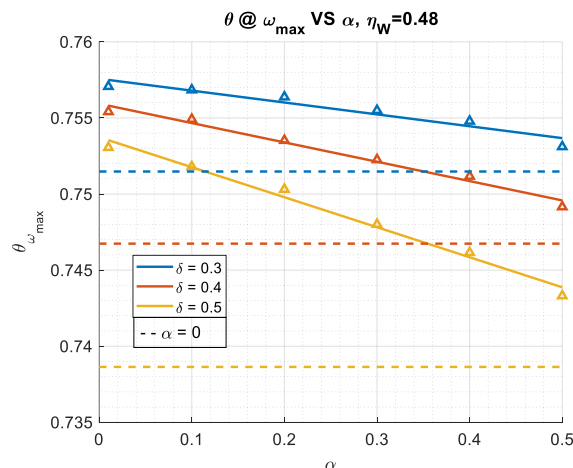


Figure 3. Normalized temperature at point of maximum reaction rate in the partially premixed flame region of water-in-fuel edge flames as a function of the water loading, for different initial liquid loads and comparison with results when the droplets are comprised of liquid fuel only.

In Fig. 3 the influence of the initial water load in the droplets (when the latent heat is 0.48) on the same temperature of Fig. 2 is shown once again but compared to the temperature attained when the spray is composed on purely liquid fuel with no water (drawn as dashed lines). For the latter case no micro-explosions occur. Now, as a result of micro-explosions, the fuel droplets are shattered into much smaller, more rapidly evaporating fuel droplets thereby enabling more rapid availability of vapor to fuel the premixed flame than available by the pure liquid droplets. This can cause a higher temperature at the point of maximum reaction relative to that of the pure fuel spray flame for which the droplets are larger. However, the micro-explosion also invokes a relatively large heat loss as the water vapor is released suddenly. This should lead to a reduction in the temperature. Fig. 3 teaches that the micro-explosion “heating” effect prevails over the water evaporation cooling effect for a range of values of α . But, for larger values of α and less vapor supplied by the shattered compound droplets the cooling effect dominates.

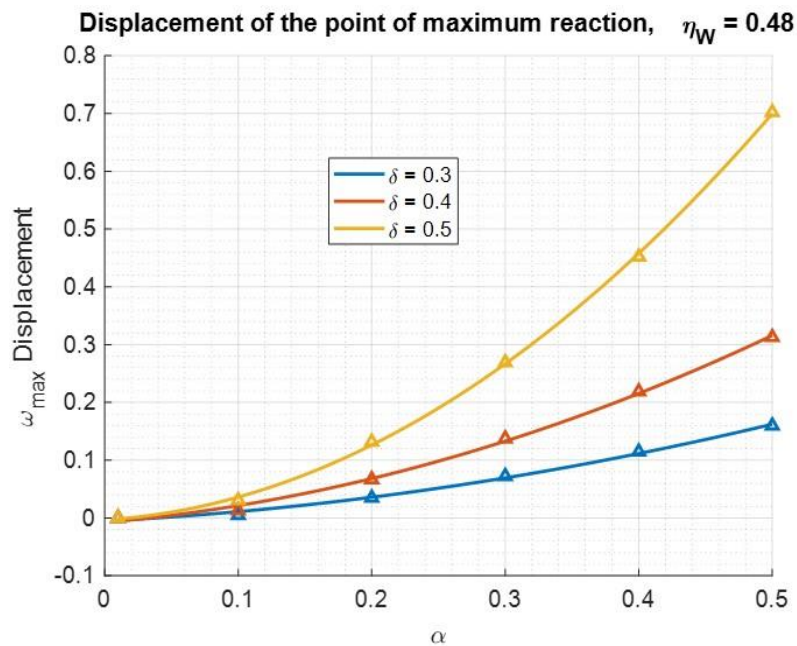


Figure 4. Displacement of the point of maximum reaction rate location in the partially premixed flame region of water-in-fuel edge flames as a function of the water loading, for different initial liquid loads, measured relative to the location when $\alpha \rightarrow 0$

The shift in the location of the point of maximum reaction rate as the water load in the droplets is increased is illustrated in Fig. 4, for various initial liquid loads. Clearly, for all cases shown, the partially premixed flame moves downstream as the water load increases. Once again, this is due to the two factors of greater heat loss through evaporation of the water and the availability of less fuel vapor. As a result, conditions for flame formation are only achieved further downstream. It is interesting to note that the downstream location is approximately proportional to α^2 .

We now turn to the diffusion section of the edge flame. Fig. 5 is the equivalent of Fig. 3 for the diffusion flame maximum temperature (within the solution domain). The double effect of increased heat loss from the sudden water vapor release, accompanied by the higher temperature due to faster evaporation of the off-spring fuel droplets, relative to that of the slower evaporating larger pure liquid fuel droplets, observed in Fig. 3, is evident for the diffusion flame region. However, the effect is some six times greater than in Fig. 3. Here, the greatest decrease in temperature is about 6.25%, which is equivalent to over 60K. It should be noted that these effects, brought about by the presence of the water in the spray’s droplets,

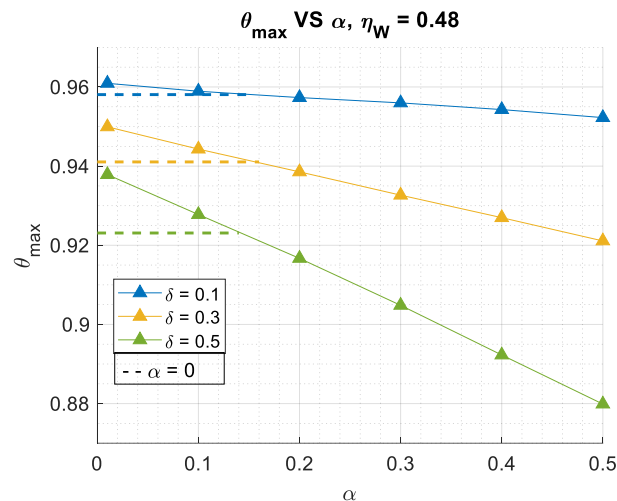


Figure 5. Normalized temperature in the diffusion flame region of water-in-fuel edge flames as a function of the water loading, for different initial liquid loads and comparison with results when the droplets are comprised of liquid fuel only.

can be responsible for destabilizing of the flame, leading to flame oscillations or even blow-off. In addition, the temperature perturbations can be critical when addressing the question of pollutant production by the flames.

Conclusions

The effects of water-in-fuel spray characteristics, including micro-explosions, on a laminar steady state edge flame were studied for the first time. It was found that the trailing diffusive flame temperature was significantly more affected by the water presence than that of the partially premixed root flame. Counteracting effects were found to play a role: micro-explosions lead to an increase in the temperature relative to that of a purely liquid fuel spray flame, due to the faster evaporation of the shattered fuel droplets, whereas the focused water evaporation tends to cool the flame. The higher the water load in the droplets the further downfield was the compound flame shifted. The variation in both the temperature of the partially premixed and diffusion parts of the flame, induced by the water in the droplets, may have ramifications on flame extinguishment/existence, blow-off and undesirable pollutant production and are part of an ongoing research effort.

References

- [1] Greenberg, J.B., Shpitz, Sahar, 2021, Combustion Theory and Modelling, 25, pp. 1086-1109.
- [2] Buckmaster, J., 2002, Progress in Energy and Combustion Science, 28 (5), pp. 435-475.
- [3] Greenberg, J.B., Silverman, I., Tambour, Y., 1993, Combustion and Flame, 93, pp. 90-96.
- [4] Yokev, N., Greenberg, J.B., 2019, Combustion Theory and Modelling, 23(2), pp. 310-336.