

A Simple Model of a Double-Fuel Spray Diffusion Flame

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Abstract

In view of recent experimental findings concerning the advantage of use of two fuel sprays in a dual-fuel direct Injection compression ignition engine, we conduct a fundamental study of a laminar double-spray diffusion flame created in an idealized one-dimensional configuration. The spray, comprised of droplets of two different fuels, is injected at a constant rate in a laminar stream from the bottom of the chamber, whilst an oxidant is supplied from the top of the chamber. The combustion products are transported away by a sufficiently fast flowing stream across the exit, from which the oxidant diffuses inward toward the flame. The fuel sprays are modeled using the sectional approach. It is shown that the range of values for which combustion is sustainable is sensitive to the relative amounts of the two fuels in the sprays. Other key parameters involved in promotion or delay of flame extinction are discussed.

Keywords

Spray combustion, diffusion flame, double fuel spray, extinction

Introduction

Recently, Giramondi [1] investigated, experimentally and numerically, diffusive combustion of ethanol in a dual-fuel direct Injection compression ignition engine. Pure ethanol, as the main fuel, with lesser quantities of diesel, as pilot fuel, were injected via separate injectors. For various operating conditions studied, optimal combinations of the ethanol and diesel were found that enabled diffusive combustion of ethanol throughout the entire engine load range, but with a higher thermal efficiency and lower pollutant emissions than in diesel combustion. (For the interested reader further details and relevant background material can be found in [1]).

In view of these new findings concerning the advantage of utilization of two fuel sprays, we engage in a fundamental study of a laminar double-spray diffusion flame created in an idealized one-dimensional configuration. The spray, comprised of droplets of two different fuels, is injected at a constant rate in a laminar stream from the bottom of the chamber, whilst an oxidant is supplied from the top of the chamber. The combustion products are transported away by a sufficiently fast flowing stream across the exit, from which the oxidant diffuses inward toward the flame. The walls are assumed non-catalytic and are maintained at a constant temperature. A similar one-dimensional configuration was previously used successfully to study (single fuel) gaseous diffusion flames theoretically [2] and experimentally [3]. The current set-up is illustrated in Figure 1. This simple configuration enables the main physico-chemical mechanisms at work to be easily described within a thermal-diffusional framework, thereby stripping the problem of multi-dimensional complexities, yet retaining the fundamental physics of the problem. This permits straightforward numerical solution of the coupled governing equations with finite rate chemical kinetics. In turn, this facilitates investigating the question of how pertinent spray and gas parameters effect flame existence or extinguishment. The degree of combustion is also relevant when considering undesirable

production of pollutants, a practical problem that has serious ecological ramifications that have been addressed by various international protocols.

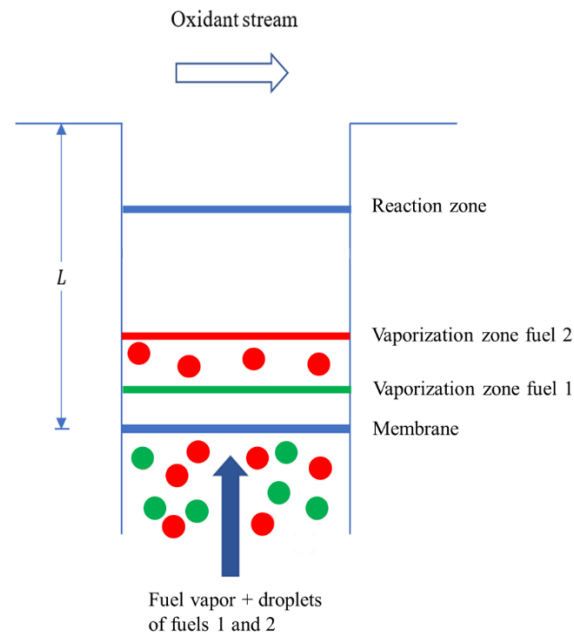


Figure 1. Configuration of the combustion chamber

The Mathematical Model and its Solution

We have already mentioned the configuration and physical conditions in the Introduction and Figure 1. We add that the flow field is taken as uniform throughout the chamber so that variations of the physical quantities only occur along the chamber length. The notation we use is similar to that of [4]. A dilute spray is considered so that the fractional volume occupied by the droplets of the two fuels is relatively small. For simplicity we take the droplets to have virtually completely evaporated before reaching the flame front. Two single-step overall chemical reactions are assumed: $\nu_{F_i} F + \nu_{O_i} O \rightarrow P, i = 1, 2$, where F_i denotes the fuels, O the oxidant, P the products, and $\nu_{F_i}, \nu_{O_i}, i = 1, 2$, are the corresponding stoichiometric coefficients. The reaction rates are assumed to be of Arrhenius type with overall activation energies E_i and pre-exponential factors B_i .

The governing equations are those of conservation of fuel vapor and liquid fuel, for the two fuels, and oxidant and energy. The sprays of droplets are modeled using the sectional approach [5]. For the current exploratory model, a mono-sectional description is considered. Furthermore, it is assumed that the droplets emerge from the bottom of the chamber in dynamic equilibrium with their host carrier gas, which eliminates the need to consider momentum equations for the spray. For sufficiently small droplets and a small Stokes number this assumption is justifiable thereby locating the droplets of both fuels in the far-field [6] relative to the source of the sprays. In a similar way, no separate energy conservation equation is solved for the spray. We essentially assume that the droplets enter the chamber having already almost completed their heat-up stage of life so that the evaporation stage is incipient, starting at $x = x_{v_1}$ and $x = x_{v_2}$ close to the entrance for the two fuels.

The governing equations, presented in non-dimensional form, are:

For the oxidant mass fraction:

$$M \frac{dY_O}{dx} - \mathcal{L}_O^{-1} \frac{d^2 Y_O}{dx^2} = -\rho^2 D a_1 Y_{F_1} Y_O e^{-\frac{\theta_1}{T}} - \rho^2 D a_2 Y_{F_2} Y_O e^{-\frac{\theta_2}{T}} \quad (1)$$

For the fuel vapor mass fractions:

$$M \frac{dY_{F_i}}{dx} - \mathcal{L}_{F_i}^{-1} \frac{d^2 Y_{F_i}}{dx^2} = -\rho^2 D a_i Y_{F_i} Y_O e^{-\frac{\theta_i}{T}} + C_{F_i} \varphi_{F_i}, i = 1, 2 \quad (2)$$

For the temperature:

$$M \frac{dT}{dx} - \frac{d^2 T}{dx^2} = \rho^2 D a_1 Y_{F_1} Y_O e^{-\frac{\theta_1}{T}} + \rho^2 D a_2 Y_{F_2} Y_O e^{-\frac{\theta_2}{T}} - \beta_{F_1} C_{F_1} \varphi_{F_1} - \beta_{F_2} C_{F_2} \varphi_{F_2} - \alpha(T - T_0) \quad (3)$$

The first term on the LHS of each equation represents the convective flux of oxidant, fuel vapor and temperature (Eqs (1), (2) and (3), respectively) whereas the second terms refer to diffusional fluxes. The first term on the RHS of Eq.(1) and the first two terms in Eq. (2) are the chemical reaction rates and the exothermal heat loss due to the chemical reactions (Eq.(3)). In Eq. (2) the second term on the RHS represents the rate at which fuel vapor is produced by virtue of evaporation of liquid fuel. In Eq.(3) the third and fourth terms on the RHS represent the heat loss sustained as a result of evaporation of the two liquid fuels and, subsequently, The fifth term describes volumetric heat loss to the system .

As for the spray's droplets, applying the sectional method [4] for a mono-sectional spray yields the following:

$$M \frac{d\varphi_{F_1}}{dx} = -C_{F_1} \varphi_{F_1} \quad (4)$$

$$M \frac{d\varphi_{F_2}}{dx} = -C_{F_2} \varphi_{F_2} \quad (5)$$

In order to close the problem the boundary conditions must be specified :

At $x = 0$: the fluxes of fuel vapor, oxidant and heat are specified:

$$M Y_O - \mathcal{L}_O^{-1} \frac{dY_O}{dx} = 0$$

$$M Y_{F_i} - \mathcal{L}_{F_i}^{-1} \frac{dY_{F_i}}{dx} = M(1 - \delta_i), \quad i = 1, 2$$

whereas for the liquid content of the droplets, the initial relative fractions of the two fuels are specified:

$$\varphi_{F_i} = \delta_i, \quad i = 1, 2$$

$$\text{At } x = 1: Y_O = Y_{O_1}, Y_{F_i} = 0, T = T_1, i = 1, 2$$

that is, the oxidant and fuel vapor mass fractions for the two fuels are specified, as is the temperature.

A measure of combustion efficiency is afforded by the fraction of the fuels that escape unburned from the chamber. In the absence of combustion the fuel mass flux at the top of the chamber is simply $-M$ so that:

$$\eta = \left(-\frac{1}{M} \sum_{i=1}^2 \mathcal{L}_{F_i}^{-1} \frac{dY_{F_i}}{dx} \right)_{x=1} \quad (7)$$

which represents the fractional mass flux of the fuel that remains unburned, assumes values between zero and unity. Values of η close to zero are indicative of very intense burning in the reaction region with negligible leakage of fuel vapor through the flame. At the other extreme, a value of η equal to unity represents an extinguished state.

The purely gaseous case was previously analyzed numerically by Kirkby and Schmitz [2].It was found that, in addition to the extinguished state, two burning states are possible in a limited range of the mass flux, and none otherwise. The response curve, representing all the possible burning states, forms an isola in the $\eta - M$ plane. The upper branch of the isola corresponds to steady states that are believed to be unstable and therefore cannot be realized in practice. In the current work we concentrate on the lower branch of the isola corresponding to the more intense burning states. In [4] the influence of fuel droplets of a single fuel on these burning states was looked into. In the current work we try to ascertain what the effect of the

double fuel supply is upon the combustion. By increasing/decreasing M above/below its upper/lower limit the flame will be extinguished. The extinction limit that corresponds to the higher value of M results from an incomplete combustion because the mixing time is too short compared with the relatively high rate at which the fuel is supplied. The extinction limit that corresponds to the lower value of M exists because the fuel is supplied at a rate smaller than the diffusion time. As a consequence, the reactants are very dilute so that heat cannot be generated at an appropriate rate to sustain steady burning. As shown in [4], when introducing fuel droplets into the feed stream, some of the heat generated by the chemical reaction is used to evaporate the liquid fuel. The overall effect is thus similar to a volumetric heat loss which, in general, tends to reduce the admissible range of the mass flux for steady burning.

The problem described in Eqs. (1)-(3) is treated numerically coupled to analytical solutions for the droplets in the liquid spray (Eqs (4), (5)). The numerical solution is carried out by using straightforward central difference approximations for the derivatives and rewriting the governing equations as a set of nonlinear algebraic equations, which were solved iteratively. A convergence criterion of 10^{-7} was utilized. The code was validated by reducing it to a purely gas case and comparing with the results of Kirkby and Schmitz [2].

Results and Discussion

Unless otherwise stated, data used for the results to be presented is as follows:

$$\mathcal{L}_O = \mathcal{L}_{F_1} = \mathcal{L}_{F_2} = 1, Da_1 = 10^{10}, Da_2 = 10^{11}, C_{F_1} = 1.32 \times 10^5, C_{F_2} = 2 \times 10^5, Y_{O_1} = 0.21,$$

$$\beta_{F_1} = 0.06, \beta_{F_2} = 0.03, \theta_1 = \theta_2 = 2.6, T(x=0) = 0.05, \delta_1 = \frac{1}{3}, \delta_2 = \frac{2}{3}, \alpha = 0.$$

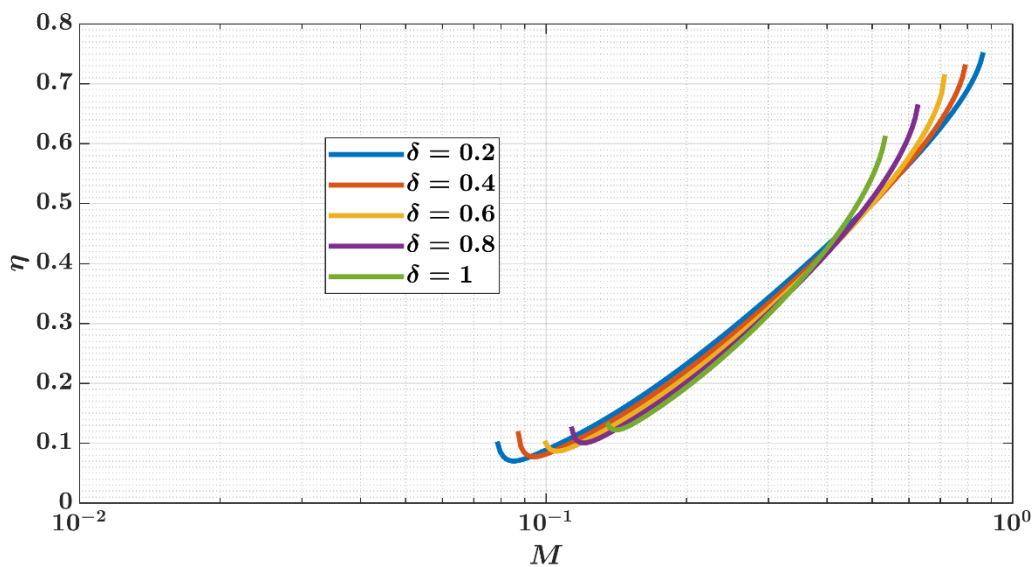


Figure 2. Effect of the total initial double fuel droplet load on steady state spray diffusion flames.

In Figure 2, we illustrate the influence of the total fuel load (i.e. of sum of the two fuels) upon the ability to sustain a steady state diffusion flame. It is evident that, for the data utilized here, as the presence of the liquid fuels increases in the total fuel flux at the chamber entrance, the range of mass fluxes permitting the formation of a flame decreases. One can observe that, when $\delta = 0.2$, the range of values of M lies between about 8×10^{-2} and about 9×10^{-1} . This region shrinks to the range 1.5×10^{-1} to 5×10^{-1} when $\delta = 1$. The effect is related to the increased heat loss due to droplet evaporation as the fraction of liquid fuel at the combustion chamber entrance increases. These results concur with those found previously for a spray of a single fuel [4].

In Figure 3, the way in which the Lewis numbers of the two fuels alter the possibility of combustion is drawn. Note that Le^* represents a reference Lewis number, which is taken as unity for both fuels. It can be observed that there is no significant influence of the Lewis numbers on the range of values of M for the particular conditions considered here. However, the *intensity* of the combustion (measured by the vertical location of the curves relative to one another) is affected. The strongest burning over nearly the entire range of M is obtained when fuel 1 has Lewis number 1.4 and fuel 2 has a unity Lewis number. It is clear that altering the Lewis numbers by using an appropriate diluent enables some control over the combustion process.

In Figure 4, the influence of the Damkohler numbers of the two fuels is shown. The asterisk notation is the same as mentioned before for the Lewis numbers. For both fuels an increase

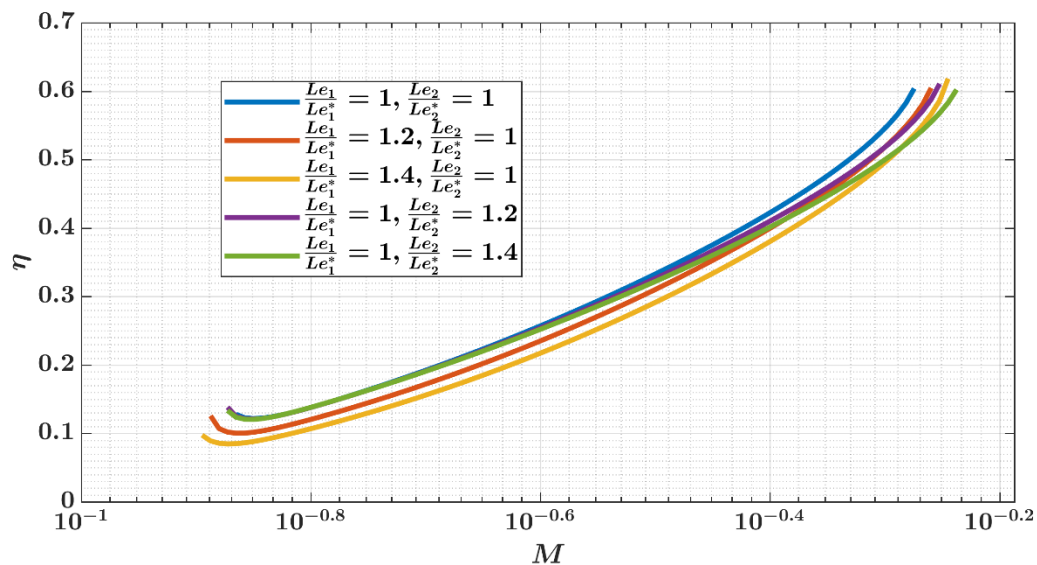


Figure 3. Effect of the two fuels Lewis numbers on steady state spray diffusion flames.

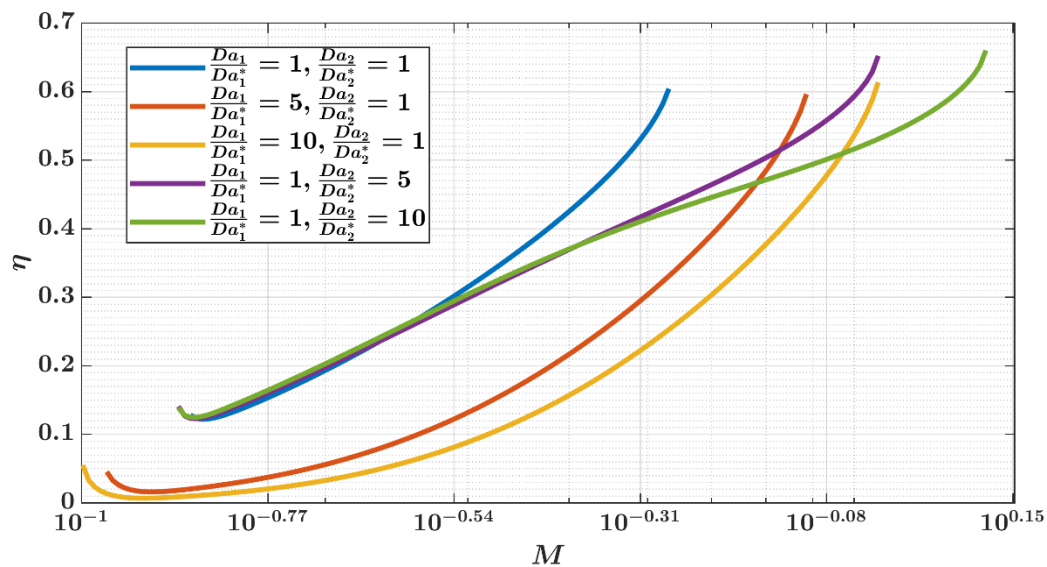


Figure 4. Effect of the two fuels Damkohler numbers on steady state spray diffusion flames.

in the Damkohler, not unexpectedly, extends the range of values of the chamber's entrance mass flux. However, it is evident that the effect on the intensity of combustion is far outweighed by fuel 1. For example, for $M = 10^{-0.54}$, the value of η is about 0.09 for the largest damkohler number for fuel 1, whereas for the fuel 2 largest Damkohler number the intensity is reduced by a factor of almost 3.

Finally, in Figure 5, the impact of volumetric heat loss is shown. The reduction in the permitted range of M as the heat loss factor increases can be clearly seen.

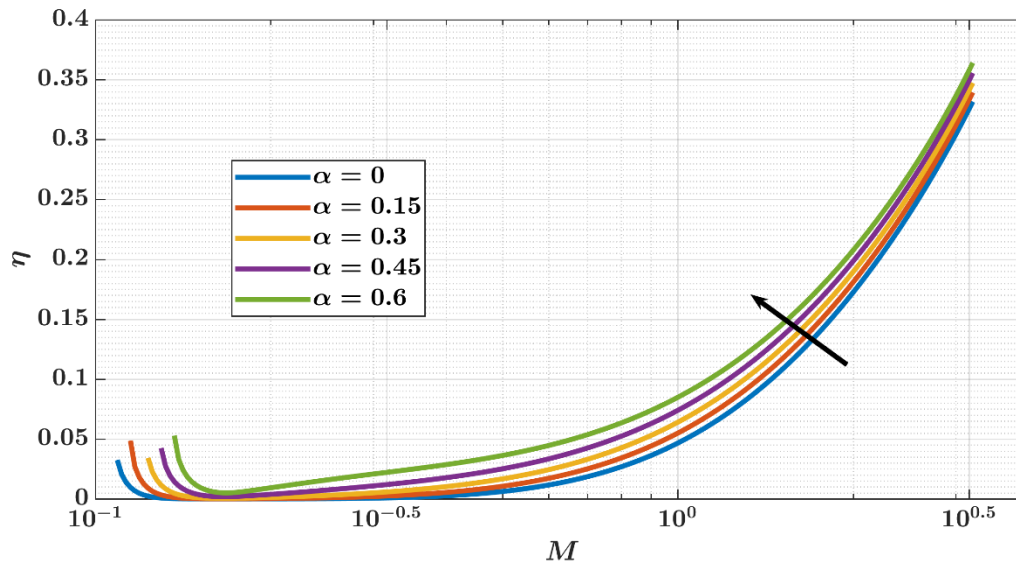


Figure 5. Effect of volumetric heat loss on steady state double spray diffusion flames.

Conclusions

The current study represents a first step in examining the characteristics of diffusion flames supported by a double spray of different liquid fuels. Here, we chose a particular combination of two fuels and concentrated primarily on investigating the influence of combinations of the gas-related properties of the two fuels on conditions for sustaining combustion. Further ongoing research is directed to assessing the effect of altering the properties of the liquid fuels on flame characteristics.

Nomenclature

B	= pre-exponential constant
C_F	= vaporization coefficient
E	= activation energy
β_F	= latent heat of vaporization
η	= fractional mass flux of the fuel that remains unburned
ρ	= density
x	= spatial coordinate
Y, y	= mass fraction
T	= temperature
δ	= Initial ratio of mass fraction of liquid fuel to total fuel
Le, \mathcal{L}	= Lewis number
Da	= Damkohler number
θ	= non-dimensional activation energy
α	= heat loss coefficient
M	= mass flow rate
φ_F	= droplets mass fraction

ν = stoichiometric coefficient

Subscripts

F = fuel

O = oxygen

v = vaporization

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