

# PULSATING COMBUSTION OF AN ORGANIC GEL-FUEL DROPLET AND ITS INFLUENCE ON THE THERMAL FIELD OF A SPRAY DIFFUSION FLAME

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## Abstract

*An experimental study of the unusual pulsating evaporation/combustion of organic gellant-based-fuel droplets is presented. Data from the experiments is employed in a phenomenological mathematical model of a gel-based fuel spray diffusion flame. Computed results demonstrate the appearance of downstream hotspots in the thermal field and parameters responsible for their existence are identified.*

## 1. Introduction

Two important parameters must be carefully weighed when considering the use of a propellant in various aerospace applications – energetic performance and safety features. Gel propellants have been found to be particularly advantageous inasmuch as they provide a promising response to both of these important requirements. In this particular liquid-solid state these unique propellants have the potential to combine the advantages of liquid and solid propellants.

Gel fuels are liquid fuels whose rheological properties have been altered by the addition of gellants, so that they behave as non-Newtonian fluids. The existence of yield stress and the increased viscosity can prevent agglomeration, aggregation and separation of a metal solid phase from the fuel during storage. Consequently, these propellants are valuable because of their capability to provide both full energy management and safety benefits over conventional liquid and solid propellants. Their performance characteristics and operational

capabilities, which are similar to liquid propellants, as well as their high density, increased combustion energy and long term storage capacity, make them attractive for many applications, especially for volume-limited propulsion system applications.

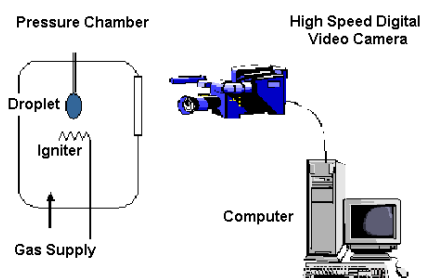
A comprehensive review on the state of the art until the year 2000 was given by Natan and Rahimi [1]. Evidence of the growing interest and research activity in the field of gel fuels since 2000 can be found in the literature. However, most of the reported research is dedicated to the non-combustion gel issues mentioned above [2-11].

In the current work attention is focused on *organic gellant-based-fuel droplets* which were observed to exhibit a rather different evaporation/combustion behavior than that of conventional liquid droplets and inorganic gellant-based fuel droplets.

The structure of the paper is as follows. We begin by briefly describing experimental apparatus that was used for examining the evolutionary behavior of a burning organic gel fuel droplet. A discussion of the main observations follows. Based on the latter we present a phenomenological model of a laminar diffusion flame supported by an entire spray of organic gel fuel droplets. Solution of the governing equations is outlined after which numerical predictions of the model are discussed. Finally, some preliminary conclusions are drawn.

## 2. Experimental Apparatus and Results

The experimental set-up is shown schematically in Fig. 1. It is comprised of two parallel systems: a pressure chamber and a video recording system.



‘Fig. 1: Experimental Apparatus.’

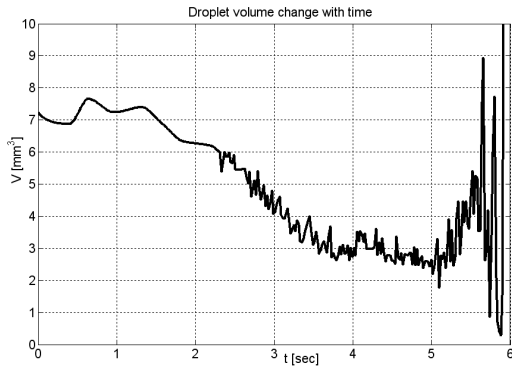
After a gel droplet is suspended in the chamber, an appropriate gas mixture is introduced. The chamber permits work at pressures up to 150 atm. The droplet is ignited using an electrically heated platinum wire. The digital color video camera was a Redlake motionScope e/Cam 2000SC which is capable of filming up to 2000 frames per sec. The image processing was done using appropriate software and a PENTIUM III computer. The software enabled calculation of a droplet’s burning rate in real time as well as particle motion within a droplet. The latter property was important for detecting changes in a droplet’s viscosity.

Experiments were carried out using gel fuel droplets (of about 2 mm in diameter) consisting of X percent of gellant and (100-X) percent of liquid fuel (mostly kerosene based JP-8 fuel), with X=29.7% and 22.5%. The gellant (Thixatrol 289) was made up of two components – 50% liquid MIAK (Methyl Isoamyl Ketone), that acted as a solvent and 50% an unknown organic substance which was the actual gel. MIAK has a boiling temperature of 144 °C. The boiling point temperature of the gel and its heat of vaporization are significantly higher than those of JP-8. JP-8 is a kerosene-based multi-component fuel (18% aromatics, 35% naphthenes, 45% paraffins and 2% olefins) with a boiling point temperature range of about 160-270 °C, determined by its constituent components. It was found that the burning

characteristics of the gel fuel droplet were strikingly different from those of inorganic gellant-based fuel droplets [12]. It was observed that the internal *structure* of the organic gel fuel droplet alters as heating occurs and an elastic layer of gellant forms around the liquid fuel. This is due to the difference between the boiling point temperature and the heat of vaporization of the liquid fuel and the organic gellant. As a result the homogeneity of the mixture cannot be maintained and the concentration of the liquid fuel at the outer part of the droplet decreases continuously. At some point, a film of very high viscosity gellant is formed around the droplet, enclosing the gel, and the result is that liquid fuel cannot pass through the gellant layer and evaporate towards the flame. Consequently, heating-up of the droplet results in the formation of fuel vapor bubbles inside the droplet. Expansion of the bubbles results in significant swelling of the droplet while the pressure inside the bubbles remains approximately constant. The thickness of the viscous gellant layer decreases as the droplet expands until the film is ruptured, and a jet of fuel vapor is released. The envelope collapses back onto the droplet and a new gellant layer is formed. This process repeats itself several times until the almost all-gellant residue-droplet burns out completely.

The actual sequence of mutually interacting physical mechanisms that lead to this pulsating-type of evaporation behavior is far from understood and remains to be elucidated. However, the experimental observations point to the fact that the organic gellant-based fuel droplets evaporate and burn in an oscillating fashion upon reaching a critical temperature. This behavior is strikingly different not only from that of inorganic gellant-based fuel droplets but also from that of purely liquid droplets (that are widely used in a range of combustion engineering applications) for which  $d^2$ -law behavior is relevant.

In Fig. 2 typical evolutionary behavior of a combusting droplet’s volume is illustrated for a droplet having an initial diameter of 2.4 mm and 29.7% gellant and clearly reflects the aforementioned pulsating type of behavior.



‘Fig. 2: Burning Organic Gel Fuel Volume Evolution.’

The evolution of another droplet having an initial diameter of 2.1 mm and 22.5% gellant is

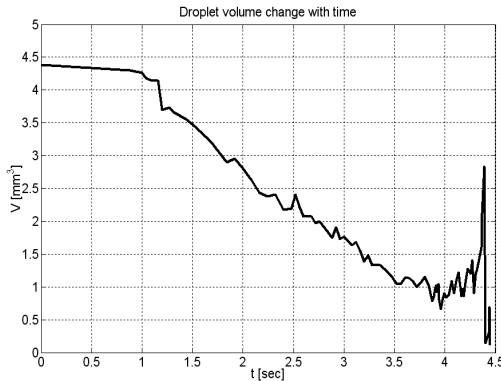


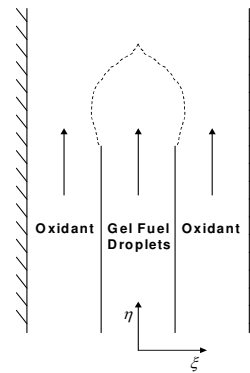
Fig. 3: Burning Organic Gel Fuel Volume Evolution.’

shown in Fig. 3. Although a comparison of Figs. 2 and 3 reveals clear differences, the overall pulsating features of the changes in volume persists in both cases. In general, these and other experiments demonstrated that the frequency of the pulsations is a function of droplet size and the gellant/liquid fuel ratio. The frequencies of oscillation were found to vary through the range of  $3\pi$  to  $20\pi$ . These observations and results conform to and verify earlier experimental results reported in the literature [13]. In view of these results we address the fundamental question: given the phenomenological pulsating evaporation of an organic gellant-based fuel droplet how will a *spray* of such droplets influence the characteristics of the flame they are being used to fuel?

### 3. Theoretical Model of Gel Fuel Spray Diffusion Flame

In order to attempt to answer the question posed at the end of the previous section a frequently adopted approach in laminar combustion theory is employed. We consider a geometrically simple system that lends itself to a fairly straightforward mathematical-numerical analysis, thereby enabling dominant physical and chemical mechanisms at play to be isolated and categorized in a clear-cut manner, in terms of their relative importance. We implement such an approach here and present a simple phenomenological model of a gellant-based fuel spray diffusion flame.

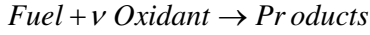
We consider a Burke-Schumann gel spray flame configuration (see Figure 4) in which fuel vapor and organic gellant-based fuel droplets flow in an inner duct and air flows in an outer duct.



‘Fig. 4: Configuration for Gel Spray Diffusion Flame Formation.’

Under appropriate operating conditions, after diffusive mixing of the two streams, a steady, laminar gel spray diffusion flame is maintained. A constant density model is taken and the velocities of the inner and outer ducts are taken to be constant and equal, as per Burke-Schumann's original gas flame analysis. The effect of relaxing this latter assumption was examined by Khosid and Greenberg [14] and shown to be of quantitative rather than qualitative significance. The droplets in the spray are taken to be located in the far-field region in relation to the spray source so that on the average they are in dynamic equilibrium with their host carrier environment. It is

assumed that the various transport coefficients such as thermal conductivity, diffusion coefficients, specific heat at constant temperature, latent heat of vaporization of the droplets etc. can be satisfactorily specified by representative constant values. Furthermore, the transport properties will be supposed to be determined primarily by the properties of the gaseous species. This follows from the implicit assumption that the gellant/liquid fuel volume fraction is sufficiently small. In addition, the Lewis numbers of the reactants (and products) are supposed to be unity. An overall reaction of the form



is taken to describe the chemistry and we consider the fast chemistry limit, i.e.  $Da \rightarrow \infty$ , where  $Da$  is the chemical Damkohler number. The droplets are viewed from a far-field vantage point, i.e. their average velocity is equal to that of their host environment. The actual description of the spray is based on the sectional approach [15,16]. In this method the "point-wise" size distribution of droplets in the spray is subdivided into a finite number of size sections ( $N_s$  say) each of which contains droplets of diameters that fall within a certain size bracket. The mass balance of droplets in section  $j$  accounts for (a) the influx of droplets from section  $j+1$  which have diminished in size and have thus become eligible for membership in section  $j$ , and (b) mass loss due to evaporation of droplets in section  $j$ . An arbitrary multi-size spray can be considered. Sectional mass conservation equations can then be rigorously derived for the droplets in each size section. For the sake of simplicity at the current stage, we take the spray to be mono-sectional. Under this assumption the governing equations written in terms of non-dimensional quantities [17] become

$$\begin{aligned} \frac{\partial \gamma}{\partial \eta} &= \frac{\partial^2 \gamma}{\partial \xi^2} + \frac{1}{(Pe)^2} \frac{\partial^2 \gamma}{\partial \eta^2} \\ &+ \Delta_0 \cdot \gamma_d \cdot H(\eta_{flame} - \eta) \cdot H(c - \xi) \\ &+ \Delta(\eta) \cdot \gamma_d \cdot H(\eta - \eta_{flame}) \cdot H(c - \xi) \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{\partial \gamma_T}{\partial \eta} &= \frac{\partial^2 \gamma_T}{\partial \xi^2} + \frac{1}{(Pe)^2} \frac{\partial^2 \gamma_T}{\partial \eta^2} \\ &+ (1 - \Gamma) \Delta_0 \gamma_d(\eta) H(\eta_{flame} - \eta) H(c - \xi) \\ &+ (1 - \Gamma) \Delta(\eta) \gamma_d(\eta) H(\eta - \eta_{flame}) H(c - \xi) \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial \gamma_d}{\partial \eta} &= -\Delta_0 \gamma_d H(\eta_{fl.} - \eta) H(c - \xi) \\ &- \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi) \end{aligned} \quad (3)$$

where

$$\Delta(\eta) = \Delta_0 f(\eta) = \frac{\Delta_0}{2} (1 + \cos \omega(\eta - \eta_{fl.})) \quad (4)$$

and

$$\Delta_0 = 1.5 (E / R^2 D) \{ 3d_u - 2d_l \} / \{ d_u^3 - d_l^3 \} \quad (5)$$

The current model extends previous work [17] by considering both axial and transverse diffusion.

The  $\eta$ -dependent vaporization Damkohler number  $\Delta(\eta)$  reflects the fact that the evaporation of the organic gellant-based fuel spray differs in the post homogeneous diffusion flame regions ( $\eta > \eta_{fl.}$ ), as will be discussed in more detail later.

The Schwab-Zeldovitch functions  $\gamma$  and  $\gamma_T$  are defined by

$$(\gamma, \gamma_T) = (\gamma_F - \gamma_O, \gamma_F + T) \quad (6)$$

As usual, the stoichiometric coefficient is also incorporated in the denominator when normalizing the oxygen mass fraction. The evaporation of the organic gellant-based fuel spray is characterized differently in the pre- and post homogeneous diffusion flame regions ( $\eta < \eta_{fl.}$  and  $\eta > \eta_{fl.}$ , respectively), see equations (1) to (3). The experimental evidence culled from single gel drop burning indicates that oscillatory type of vaporization sets in at some specific ambient temperature at which there is (in some sense) sufficient heat transfer to the droplet. The experimental results are rather sparse and it is unclear whether the onset of the oscillations occurs with or before the combustion of the single droplet. Here we make the non-essential assumption that oscillatory evaporation is initiated at the flame surface,  $\eta = \eta_{fl.}(\xi)$ . Upstream of this surface, in the region containing no oxygen, evaporation is characterized by a constant vaporization

Damkohler number,  $\Delta_0$ , whereas downstream of the flame surface, in the oxygen-containing region, the vaporization Damkohler number is assigned a cosine dependence on distance from the flame surface, as described in equation (4). It is not hard to show that, under the assumption that the droplets are in dynamic equilibrium with the host carrier gas, the time pulsations of the evaporating droplet of the experiments can be translated into oscillatory space-dependent behavior of the vaporization Damkohler number. Upstream of the flame surface the constant value of  $\Delta_0$  is based on the  $d^2$ -law dependence of an evaporating gel droplet observed by Bar-Or and Natan [18]. Note that a large value of  $\Delta_0$  represents a highly volatile fuel and/or small droplets in the spray whereas, conversely, small values correspond to a non-volatile fuel and/or large droplets [19].  $\Delta_0$  is actually a complicated function of initial droplet diameters, the temperature differential between the droplets and the surrounding gas and the diffusivity and other properties of the fuel and its surroundings. This renders *analytical* solution of the problem at hand unfeasible. So, while bearing in mind the restrictive nature of such a step,  $\Delta_0$  is taken as constant for some mathematical tractability. Further justification for the use of the  $d^2$ -law for a description of the vaporization coefficients is expounded in detail [20].

Eq.(3) is valid for the region  $0 \leq \xi \leq c, \eta \geq 0$ , where  $c$  is the normalized distance of the inner duct wall from the origin; elsewhere  $\gamma_d$  is identically zero. This expresses the fact that droplets are to be found only in the region above the inner duct since, *in this model*, there is no mechanism by means of which they may be diverted transversely.

It is important to note that the governing equations implicitly account for the different possible scenarios that are physically viable viz. complete evaporation of the droplets before reaching the homogeneous diffusion flame front *or* pre-homogeneous flame front evaporation followed by post-homogeneous-diffusion-flame burning of individual (or clusters of) gel

droplets that survive the main flame front. That both these possibilities are encapsulated is readily discernible from the governing equations. First, Eq. (3) applies at all downstream stations i.e. for all  $\eta > 0$ , so that there is no restriction on the rate of vaporization, the latter being expressed via the specified value of the vaporization Damkohler number. Second, Eq. (1) for the Schwab-Zeldovitch function  $\gamma$  also reveals the comprehensive nature of the model. In the region where no oxygen is present  $\gamma$  is positive by definition and the source term on the right-hand side relates to the production of fuel vapor due to the evaporation of droplets in the spray in the pre-flame zone. However, when  $\gamma$  is negative the equation describes the behavior of the normalized mass fraction of oxygen, and the spray source term is still applicable, but now downstream of the homogeneous flame front (within the lateral bounds set by the Heaviside function). Here it serves as a *sink* that removes oxygen at a rate dictated by the (oscillating) rate of vaporization of the droplets. This corresponds to the post-flame individual droplet-burning situation. Which scenario is under consideration will be strongly dependent on the value of the vaporization Damkohler number,  $\Delta_0$ .

Finally, it is important to note that the use of a mono-sectional description of the spray implies that the spray's actual droplet size structure is dealt with in an overall integral fashion and predictions of the model must be interpreted accordingly. Nevertheless, this approach ensures that the main gross spray characteristics and their influence on the combustion process can be usefully deduced.

The boundary conditions are

$$\eta = 0, 0 \leq \xi \leq c: \gamma - \frac{1}{(Pe)^2} \frac{\partial \gamma}{\partial \eta} = 1 - \delta, \gamma_d = \delta,$$

$$\gamma_T - \frac{1}{(Pe)^2} \frac{\partial \gamma_T}{\partial \eta} = 1 - \delta$$

$$\eta = 0, c \leq \xi \leq 1: \gamma - \frac{1}{(Pe)^2} \frac{\partial \gamma}{\partial \eta} = -V, \gamma_d = 0,$$

$$\gamma_T - \frac{1}{(Pe)^2} \frac{\partial \gamma_T}{\partial \eta} = 0$$

$$\eta > 0, \xi = 0, 1: \frac{\partial \gamma}{\partial \xi} = \frac{\partial \gamma_T}{\partial \xi} = 0$$

$$0 \leq \xi \leq 1, \eta \rightarrow \infty: \frac{\partial \gamma}{\partial \eta}, \frac{\partial \gamma_T}{\partial \eta} \rightarrow 0$$

In these conditions  $\delta$  represents the ratio of the mass fraction of liquid fuel to that of the total fuel (i.e. fuel liquid + vapor) at the exit of the central duct. We shall take the total fuel mass fraction to be constant so that different values of  $\delta$  correspond to different combinations of the initial liquid and vapor mass fractions.

The first six initial conditions imply specified fluxes at the entrance to the duct in which combustion occurs. The third set of conditions specifies the symmetry at  $\xi = 0$  and the fact that the outer duct's walls are impervious to heat and mass transfer. The last conditions relate to equilibrium far downstream.

#### 4. Solution

In order to develop a solution to the governing equations we note that the solution domain is essentially divided into two regions, upstream and downstream of the flame front. However, at this stage, the location of the flame front, given by those values of  $(\xi, \eta)$  for which  $\gamma = 0$ , is unknown. In the current study we consider over-ventilated flames only so that the flame tip is located at  $\xi = 0, \eta = \eta_{fl}$ . The flame temperature can be derived from both  $\gamma$  and  $\gamma_T$  by noting (see Eq.(6)) that in the oxygen-free zone  $T = \gamma_T - \gamma$  whilst in the fuel vapor-free zone  $T = \gamma_T$ .

Integrating Eq.(3) with respect to  $\eta$  and applying the initial condition readily yields

$$0 \leq \xi \leq c, 0 \leq \eta \leq \eta_{fl}: \gamma_d(\xi, \eta) = \delta \exp(-\Delta_0 \eta) \quad (7a)$$

and

$$0 \leq \xi \leq c, \eta_{fl} \leq \eta < \infty: \quad (7b)$$

$$\gamma_d(\xi, \eta) = \gamma_d(\xi, \eta_{fl}) \exp\left(-\frac{\Delta_0}{2}\left((\eta - \eta_{fl}) + \frac{1}{\omega} \sin \omega(\eta - \eta_{fl})\right)\right)$$

This analytical solution for the liquid fuel distribution is substituted in the appropriate source terms in equations (1) and (2). These equations for  $\gamma$  and  $\gamma_T$  are elliptic and are solved numerically using a standard finite difference method combined with an iterative procedure. As mentioned previously the location of the flame front is determined by the

locus of points for which  $\gamma = 0$ . Satisfactory step sizes in the  $\xi$  and  $\eta$  directions were obtained by comparing computed results using a series of increasingly refined finite difference meshes to cover the region of the solution.

#### 5. Results

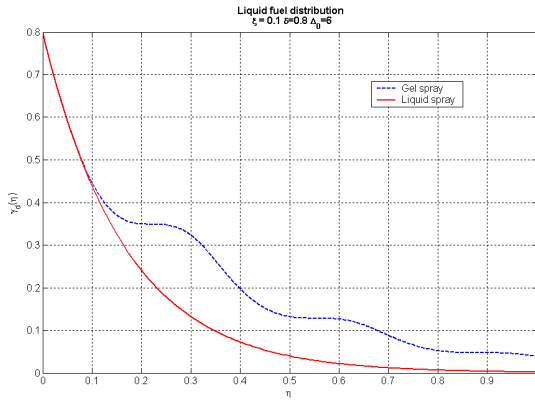
In the ensuing discussion our main focus will be on the effect of the organic gel droplet-related parameters on the flame shape and the temperature field. In the current model these are the initial droplet load,  $\delta$ , the vaporization Damkohler number,  $\Delta_0$ , and the frequency of droplet evaporation,  $\omega$ . The vaporization Damkohler number depends inter alia on the evaporation parameter,  $E$ . Even if the liquid fuel in the gel fuel spray is multi-component utilization of the ideas of Hallet [21] allow us to specify a single value for this parameter. Also, the range of sizes of droplets in the spray need not be specified as it is appears within the definition of the vaporization Damkohler number (see Eq. (5)). However, it is envisaged that in a typical spray of practical use the droplet diameters will range from about 20-100  $\mu m$ . The frequency of droplet evaporation will depend on the make up of the gel fuel droplets but typical values that have been observed will be considered.

To bring to the fore the specific features of the gel spray flames we compare their shapes to those of spray flames that would be obtained under identical operating conditions but with a purely liquid rather than a gel spray. For the results to be presented the following data was used:  $V = 0.306, c = 1/6, \omega = 6\pi$ , and  $Pe = 10$ , unless otherwise stated in the appropriate context.

In Fig. 5 typical normalized liquid fuel mass fraction profiles for both pure liquid and gel fuel sprays are presented.

The post homogeneous flame wavy behavior indicates the way in which the oscillatory gel fuel droplet combustion is accompanied by periods of evaporation and delay, as seen experimentally. This is in strict contrast to the

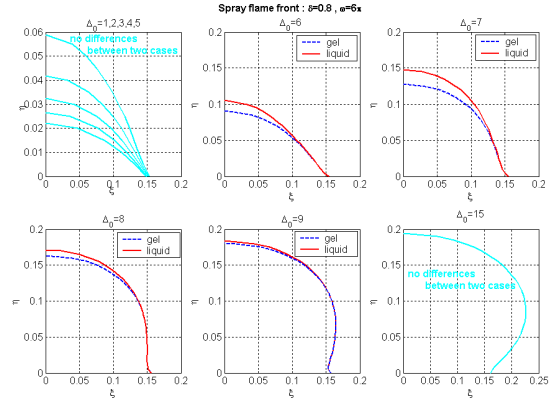
## PULSATING COMBUSTION OF AN ORGANIC GEL-FUEL DROPLET AND ITS INFLUENCE ON THE THERMAL FIELD OF A SPRAY DIFFUSION FLAME



‘Fig 5: Normalized Liquid Fuel Mass Fraction Profiles; Data:  $\xi = 0.1, \delta = 0.8, \Delta_0 = 6$  .’

smooth exponential decay that a purely liquid spray exhibits.

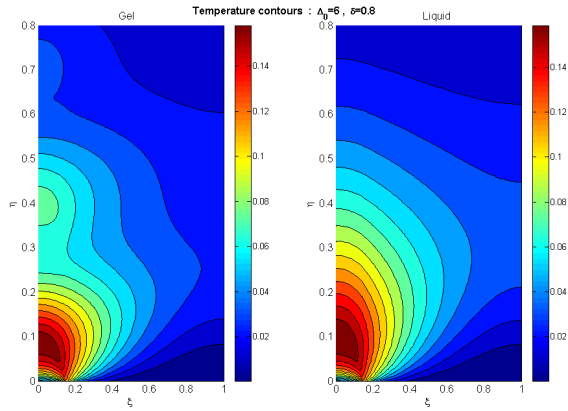
Typical flame shapes showing the effect of the vaporization Damkohler number,  $\Delta_0$ , are drawn in Fig. 6. It is clear that there is a range of values of this parameter (roughly between 6 and 9) for which differences in the flame shapes obtained using a gel fuel spray as opposed to a purely liquid spray are found. In this range the gel spray flames are lower than their purely liquid spray flame equivalents. This is due to the fact that, as indicated by Fig. 5, heterogeneous burning of *liquid* droplets beyond the homogeneous diffusion flame front removes oxygen more rapidly from the system than does the oscillating combustion of the gel spray’s droplets. According to Chung and Law [22] a reduction in the upstream supply mass fraction of oxygen in co-flow gaseous diffusion flames (keeping all other parameters constant) leads to taller over-ventilated flames. Translated into the current context the upstream removal of more oxygen by the burning liquid fuel droplets than by the burning gel droplets is responsible for the discrepancy in the flame heights. Outside the aforementioned critical range of vaporization Damkohler numbers the flame shapes are identical. For  $\Delta_0 < 6$  the evaporation is slow so that the flame shapes are primarily determined by the initially available vapor rather than by vapor produced by the evaporating droplets. Most of the vapor initially in the droplets is



‘Fig. 6: Comparison Between Gel Spray and Liquid Spray Flame Shapes for Different Vaporization Damkohler Numbers; Data:  $\delta = 0.8$  , other data as in text’

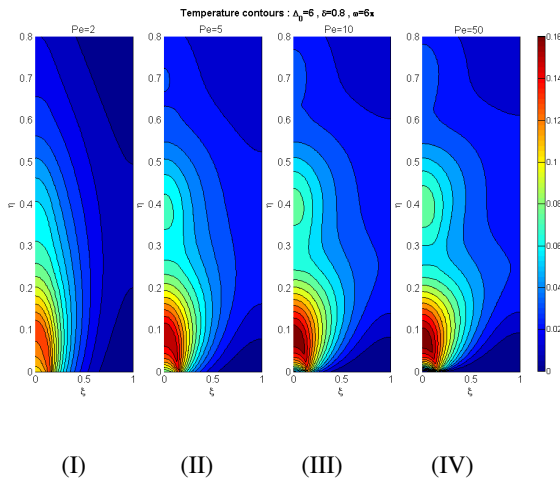
burned downstream of the homogeneous flame front, in a heterogeneous mode. For  $\Delta_0 > 9$  the evaporation of the droplets is rapid enough that most of the vapor is available upstream of the homogeneous flame front to fuel it. However, a more striking picture of the influence of the gel fuel spray on the combustion field is afforded by Fig. 7 in which the thermal fields of a gel fuel spray flame and a purely liquid spray flame are plotted. Comparing the two sets of contours it can readily be observed that not only does the gel spray reduce the height of the flame but it also produces a smaller core region of hot temperature than does the liquid spray flame. However, downstream of this flame front the gel spray is seen to burn heterogeneously and, because of the pulsating nature of the droplet combustion in this region, an avenue of downstream hot spots can be observed.

The presence of unwanted hotspots in a combustion chamber can be detrimental, not only to the combustion performance but also to the chamber’s structural integrity if they are located close to the walls.



‘Fig. 7: Flame Temperature Contours for Gel Spray and Liquid Spray Diffusion Flames; Data:  $\Delta_0 = 6$ , other data as in text.’

However, this effect is not always so pronounced. For example, it is

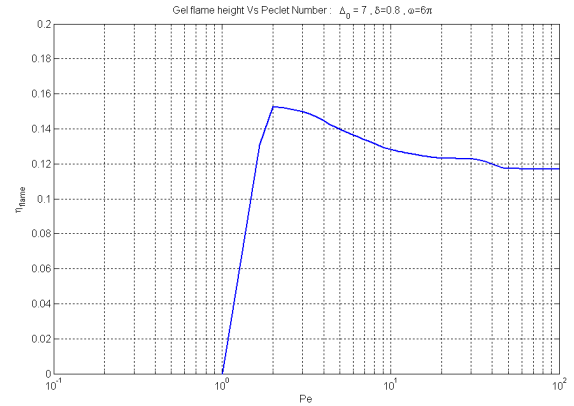


‘Fig. 8: Effect of Peclet Number on Gel Flame Temperature Contours. Data:  $\Delta_0 = 6; \delta = 0.8$ . (I)  $Pe = 2$ , (II)  $Pe = 5$ , (III)  $Pe = 10$ , (IV)  $Pe = 50$ .’

found that the Peclet number of the system influences not only the homogeneous diffusion flame height but also the nature and number of downstream hotspots. This is illustrated in Fig. 8 where temperature contours are drawn for four different Peclet numbers. It can be observed that as the Peclet number increases the downstream

pulsating gel spray combustion assumes a greater role with the accompanying influence on the temperature field. This is understandable inasmuch as the lower the Peclet number the greater the delay of the droplets in the region upstream of the homogeneous diffusion flame front. This delay enables the droplets to evaporate primarily in this upstream region leaving a negligible number of droplets to traverse the flame front to burn individually in a pulsating manner downstream.

The effect of the Peclet number on the homogeneous diffusion flame height is shown in Fig. 9.



‘Fig. 9: Effect of Peclet Number on Gel Spray Diffusion Flame Height. Data:  $\Delta_0 = 7; \delta = 0.8$ .’

In a study of liquid spray diffusion flames Greenberg [17] found a similar trend. For low Peclet numbers the flame height increases with Peclet number until it reaches a maximum. Subsequent increases in  $Pe$  produce a decrease in the flame height which eventually reaches an asymptotic value.

## 6. Conclusions

An experimental study of the unusual pulsating evaporation/combustion of organic gellant-based-fuel droplets has been presented. Data from the experiments was employed in a phenomenological mathematical model of a quasi-monodisperse gel-based fuel spray diffusion flame. Computed results demonstrate the appearance of downstream hotspots in the thermal field. Some parameters responsible for their existence are the vaporization Damkohler



number, the frequency of pulsating droplet combustion and the Peclet number of the host gas field. These parameters also determine the number of hotspots produced. However, the existence of these hotspots points to a potential negative feature of the use organic gel-fuel sprays (under certain operating conditions) which must also be included when weighing up the pros and cons of employing such sprays in real propulsion engineering applications.

Finally, it is noted that the adoption of a phenomenological description of organic gel fuel droplet oscillatory evaporation is to be viewed as a preliminary stage in attempting to gain a complete understanding of the experimentally observed phenomenon and its practical ramifications. The formidable task of formulating and solving a model that actually *predicts* the pulsating evaporation and combustion of a single organic fuel-gel droplet is currently ongoing and will be reported on in the future.

## 7. Acknowledgements

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## 8. Nomenclature

$c$  inner duct's half-width (normalized with respect to outer duct walls' half-width)

$c_p$  heat capacity

$d$  droplet diameter

$D$  diffusion coefficient

$Da$  chemical Damkohler number

$E$  evaporation frequency

$H$  Heaviside function

$Pe$  Peclet number ( $vR/D$ )

$Q$  heat of reaction

$R$  outer duct's half-width

$T$  difference between local value of temperature and its value at  $\eta = 0$  (normalized by  $c_p / Qm_{totalfuel}$ )

$T_0$  ( $=0$ ) temperature difference at  $\eta = 0$

$v$  velocity

**Greek letters**

$\gamma, \gamma_T$  Schwab-Zeldovitch functions, Eq.(6)

$\gamma_i$  mass fractions normalized with respect to total initial fuel mass fraction

$\Gamma$  normalized latent heat of vaporization

$\delta$  ratio of mass fraction of liquid fuel to that of total fuel at central duct exit

$\Delta$  vaporization Damkohler number

$\nu$  stoichiometric coefficient

$\omega$  vaporization frequency

$\xi, \eta$  transverse and axial coordinates

### Subscripts

$d$  relating to liquid fuel

$F$  relating to gaseous fuel

$Fl$  relating to value at flame front

$l$  relating to lowest droplet diameter in a section

$O$  relating to oxidant

$u$  relating to greatest droplet diameter in a section

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