Laminar Organic Gel Spray Combustion

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What are Gel Propellants ?

- ***Liquid fuels and/or oxidizers whose rheological properties have been altered by the addition of gellants. As a result their behavior resembles that of a solid.***
- ***During storage gels behave as solids.***
- ***During the feeding process gel viscosity decreases under shear stress and atomization occurs. Burning seems to occur as for liquids.***

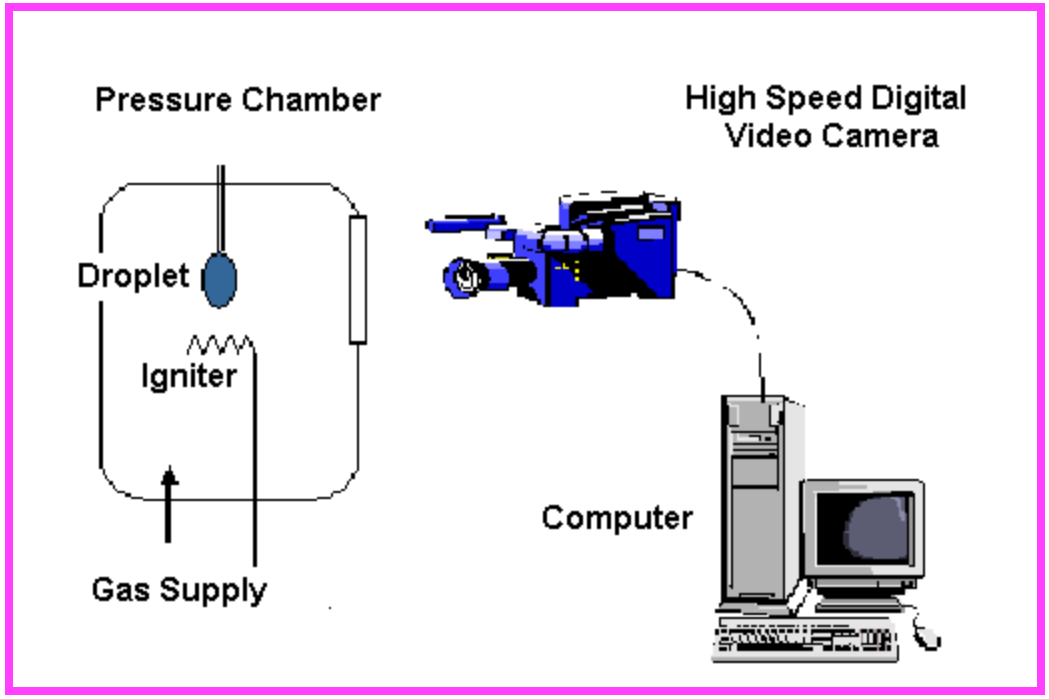
Motivation for the Development of Gel Propellants

- ***High energetic performance of metallized fuels.***
- ***No agglomeration, aggregation or separation of a metal phase from the fuel during storage.***
- ***Full energy management similar to liquid propellants.***
- ***Safety benefits over conventional liquid/solid propellants.***
- ***Long term storage capability.***

Combustion Of An Organic – Gellant Based Gel Fuel Droplet

Some Experimental Results

Experimental Set-Up



Details of Gel-Based Fuel Droplet used in Experiments

- ***Droplet diameter 2.44mm.***
- ***Droplet Composition:***

Fuel	***JP-8***	***68.3%***
Gellant	***Thixatrol***	***31.7%***

- ***Gellant= 50% Liquid MIAK (Methyl Isoamyl Ketone) + 50% Organic Substance***

Experimental Results

- ***This film was made using a high speed video camera during the experiment.***

Movie.wmv

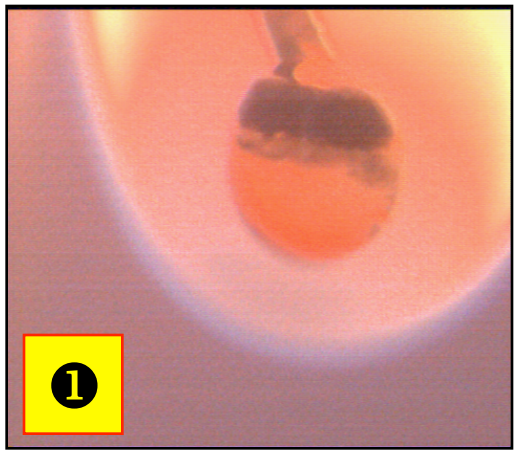
Heat-up of the droplet

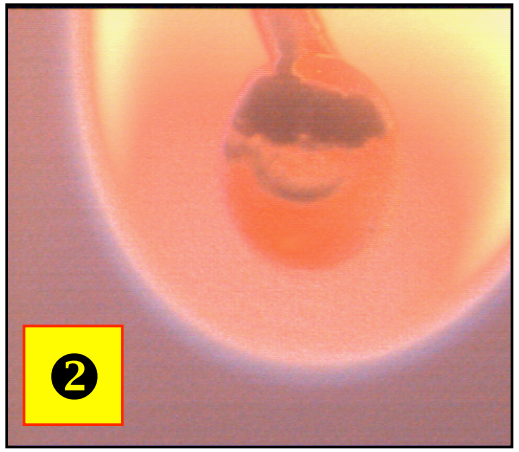
The gel transforms into a mixture of liquids of different viscosities.

Vaporization of the low b.p. liquid.

Formation of a high viscosity gellant layer around the droplet that prevents further vaporization.

Formation of a fuel vapor bubble.



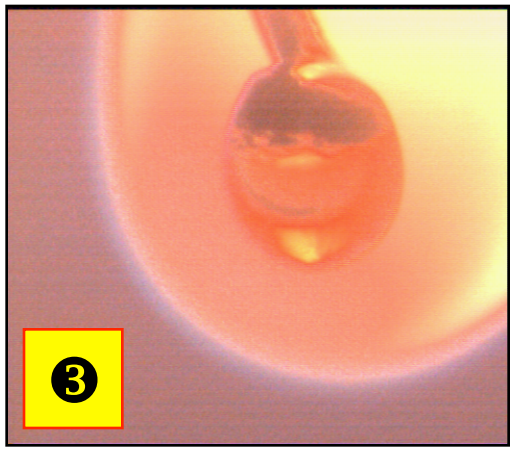


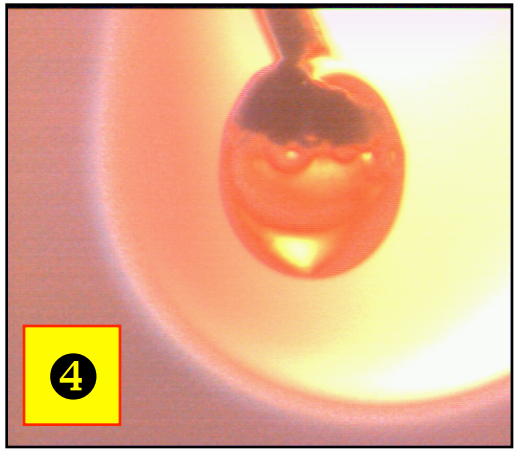
Expansion of the bubble.

Swelling of the droplet and reduction of the viscous gellant layer.

The layer perforates producing a jet of fuel vapor

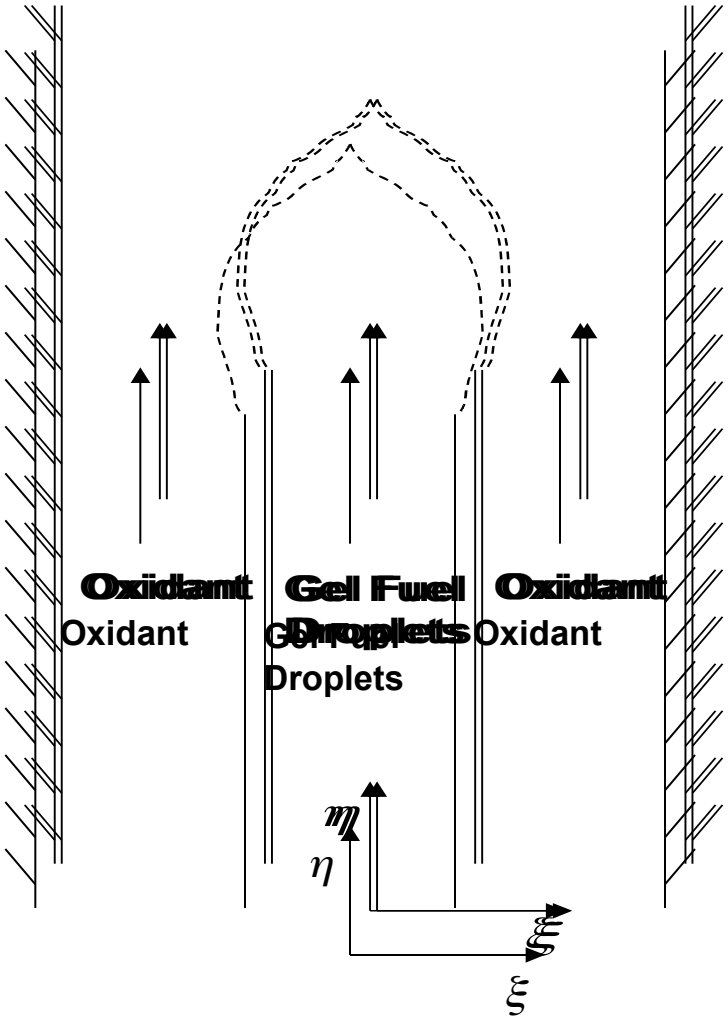
The layer reforms and the cycle repeats itself until the all gellant residue-droplet burns completely





In what way will the Oscillating Evaporation of Gellant-Based Fuel Droplets in a Spray influence the characteristics of the flame it is fueling ?

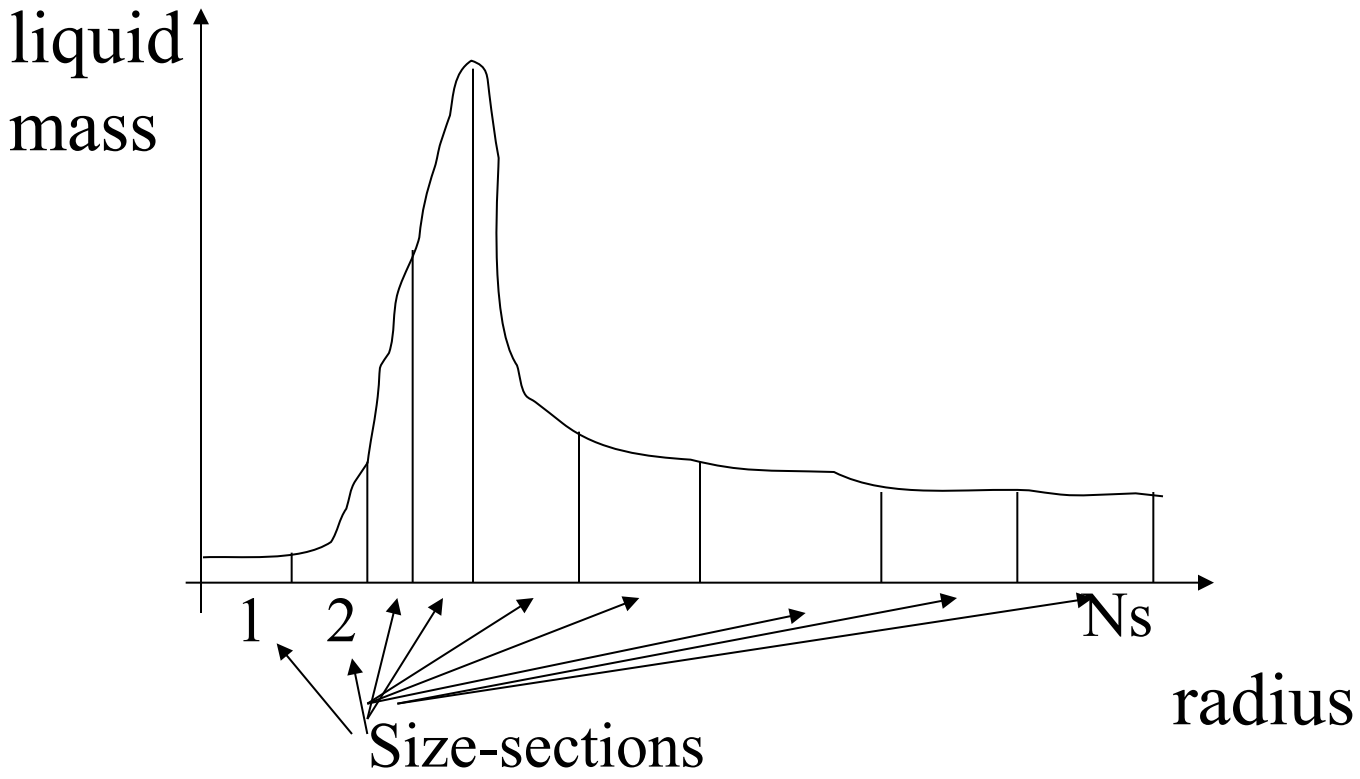
Burke Schumann Gel Spray Diffusion Flame Configuration



How is a spray of evaporating and possibly combusting droplets modelled?

- ***Lagrangian tracking of the behaviour of a large number of individual droplets or somehow statistically representative droplets.***
- ***Solution of the Liouville-type spray equation (Williams) for the droplet density distribution of the spray.***
- ***Size distribution broken up into size sections. Use conservation equations for sectional mass, momentum and energy and include transfer between sections and the host carrier gas.***
- ***Other methods.***

Here use is made of the <u>Sectional Method</u>



Model Assumptions

1. *After diffusive mixing of the two streams, a steady, laminar gel spray diffusion flame is maintained.*
2. *The droplets in the spray are taken to be located towards the end of the near-field region in relation to the spray source.*
3. *Velocities of the inner and the outer ducts are constant and equal.*
4. *Constant density.*

Model Assumptions (Cont.)

5. *Various transport coefficients are at constant temperature.*
6. *Transport properties are determined primarily by the properties of the gaseous species; (gellant/ liquid fuel volume fraction is small).*
7. *Lewis number = 1.*
8. *For simplicity use a mono-sectional spray.*

Model Assumptions (Cont.)

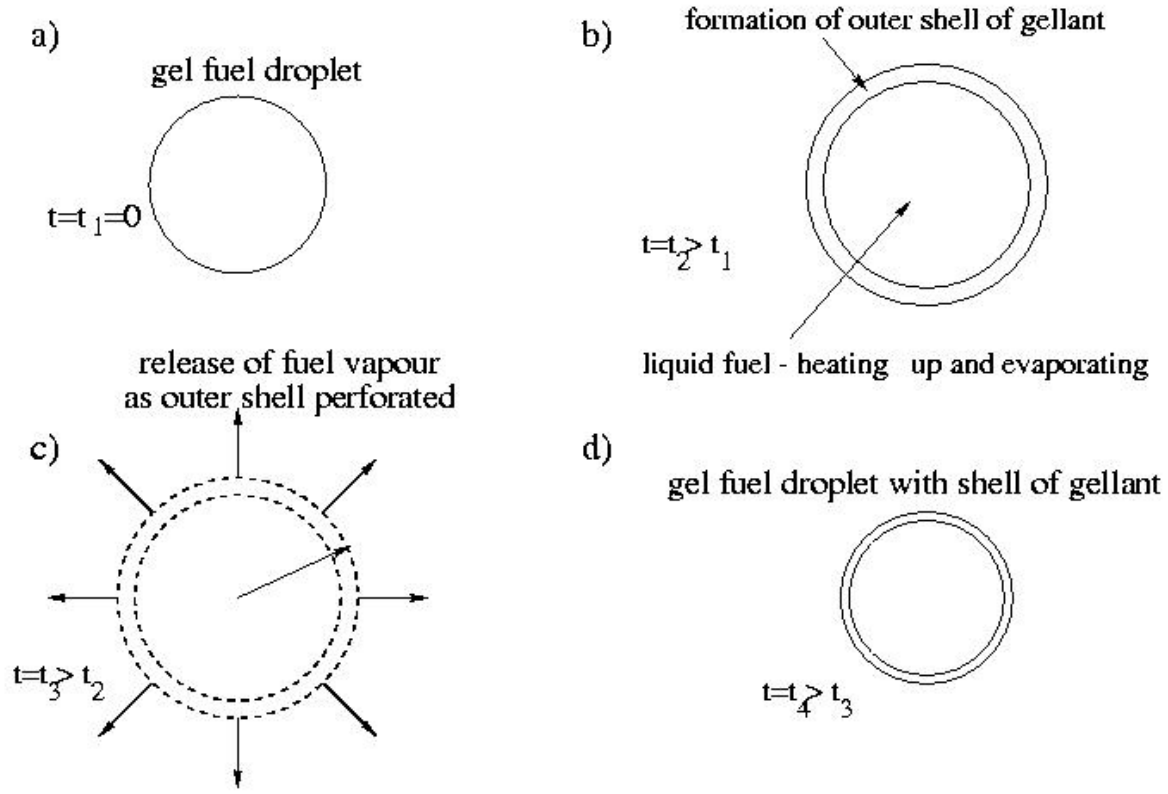
8. *An overall reaction which describes the chemistry is of the form :*

   $$Fuel + \nu\ Oxidant \longrightarrow Products$$

9. *Fast chemistry limit considered - Da* $\rightarrow \infty$

   Da- Chemical Damkohler number.

Schematic description of organic gel fuel droplet burning



Governing Equations

$$\frac{\partial \gamma}{\partial \eta} = \frac{\partial^2 \gamma}{\partial \xi^2} + \Delta_0 \gamma_d H(\eta_{fl.} - \eta) H(c - \xi) + \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi)$$

$$\frac{\partial \gamma_T}{\partial \eta} = \frac{\partial^2 \gamma_T}{\partial \xi^2} + (1 - \Gamma) \Delta_0 \gamma_d H(c - \xi) H(\eta_{fl.} - \eta) + (1 - \Gamma) \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi)$$

$$v_d \frac{\partial \gamma_d}{\partial \eta} = -\Delta_0 \gamma_d H(\eta_{fl.} - \eta) H(c - \xi) - \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi) - \gamma_d \frac{\partial v_d}{\partial \eta}$$

$$v_d \frac{\partial v_d}{\partial \eta} = \Delta_1 (1 - v_d)$$

Governing Equations (cont.)

- ***Translate time-wise oscillation into a space-wise oscillation***

$$\Delta(\eta) = \Delta_0 f(\eta) = \frac{\Delta_0}{2}\left(1 + \cos\omega \int_{\eta_{fl.}}^{\eta} \frac{d\eta}{v_d}\right)$$

- ***Oscillatory evaporation is initiated at the flame surface :***

$$\eta = \eta_{fl.}(\xi)$$

Governing Equations (cont.)

The Schwab-Zeldovitch functions are :

$$\left(\gamma, \gamma_T\right) = \left(\gamma_F - \gamma_O, \gamma_F + T\right)$$

$\gamma > 0$ - ***region with no oxygen, production of fuel vapor due to evaporation of droplets in a pre-flame zone.***

$\gamma < 0$ ***-region containing oxygen, mass fraction of oxygen depleted as droplets burn individually.***

Governing Equations

$$\frac{\partial \gamma}{\partial \eta} = \frac{\partial^2 \gamma}{\partial \xi^2} + \Delta_0 \gamma_d H(\eta_{fl.} - \eta) H(c - \xi) + \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi)$$

$$\frac{\partial \gamma_T}{\partial \eta} = \frac{\partial^2 \gamma_T}{\partial \xi^2} + (1 - \Gamma) \Delta_0 \gamma_d H(c - \xi) H(\eta_{fl.} - \eta) + (1 - \Gamma) \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi)$$

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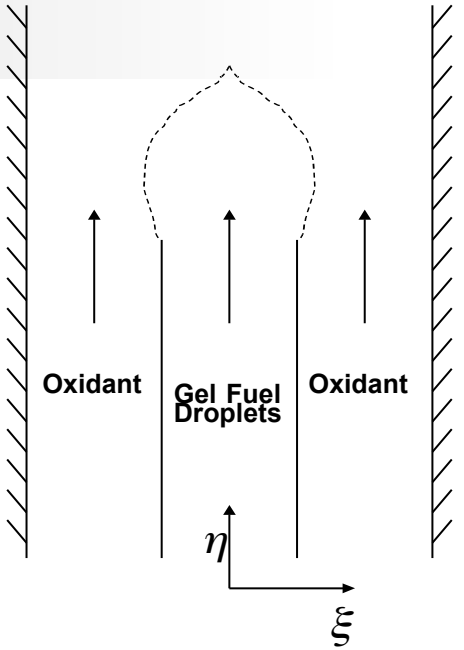
$$v_d \frac{\partial v_d}{\partial \eta} = \Delta_1 (1 - v_d)$$

Boundary conditions

$$\eta = 0, \quad 0 \le \xi \le c: \quad \gamma = 1 - v_{d0}\delta, \quad \gamma_T = T_0, \quad \gamma_d = \delta, v_d = v_{d0}$$

$$\eta = 0, \quad c \le \xi \le 1: \quad \gamma = -V, \quad \gamma_T = T_0, \quad \gamma_d = 0, v_d = 0$$

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



δ- ***Ratio of the mass fraction of liquid fuel to the total fuel at the exit of the inner duct.***

c ***Normalized distance of the inner duct wall from the origin.***

V - ***Normalized oxidant mass fraction at the exit of the outer duct.***

v_{d0} - ***Initial velocity of droplets in the spray***

Solution

- ***Analytical solution for the droplets velocity distribution:***

$$\Delta_1 \eta = v_{d0} - v_d + ln\left(\frac{1 - v_{d0}}{1 - v_d}\right), 0 \le \xi \le c$$

- ***Analytical solution for the liquid fuel distribution:***

$$\gamma_d = \delta\left(\frac{v_{d0}}{v_d}\right) exp\left(-\Delta_0 \eta + \left(\frac{\Delta_0}{\Delta_1}\right)\left(v_{d0} - v_d\right)\right), \ 0 \le \xi \le c, 0 \le \eta \le \eta_{fl.}$$

$$\gamma_d = \delta\left(\frac{v_{d0}}{v_d}\right) exp\left(-\Delta_0 \int_{\eta_{fl.}}^{\eta} \frac{f(\eta)}{v_d} d\eta\right), \ 0 \le \xi \le c, \eta > \eta_{fl.}$$

- ***These expressions are used in the spray source terms in the governing equations for the Schwab-Zeldovitch variables.***

Governing Equations

$$\frac{\partial \gamma}{\partial \eta} = \frac{\partial^2 \gamma}{\partial \xi^2} + \Delta_0 \gamma_d H(\eta_{fl.} - \eta) H(c - \xi) + \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi)$$

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$$v_d \frac{\partial v_d}{\partial \eta} = \Delta_1 (1 - v_d)$$

Solution for infinite drag

$$\gamma_d(\xi,\eta) = \delta \exp(-\Delta_0 \eta) \qquad 0 \le \eta \le \eta_{fl.}\ , \quad 0 \le \xi \le c$$

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

$$\eta_{fl.} \le \eta < \infty\,,\ 0 \le \xi \le c$$

- ***These expressions are used in the spray source terms in the governing equations for the Schwab-Zeldovitch variables.***

Governing Equations

$$\frac{\partial \gamma}{\partial \eta} = \frac{\partial^2 \gamma}{\partial \xi^2} + \Delta_0 \gamma_d H(\eta_{fl.} - \eta) H(c - \xi) + \Delta(\eta) \gamma_d H(\eta - \eta_{fl.}) H(c - \xi)$$

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Results

The location of the flame front is determined by the locus of points for which $\gamma = 0$.

Unless otherwise stated all the results are based on the use of the following data:

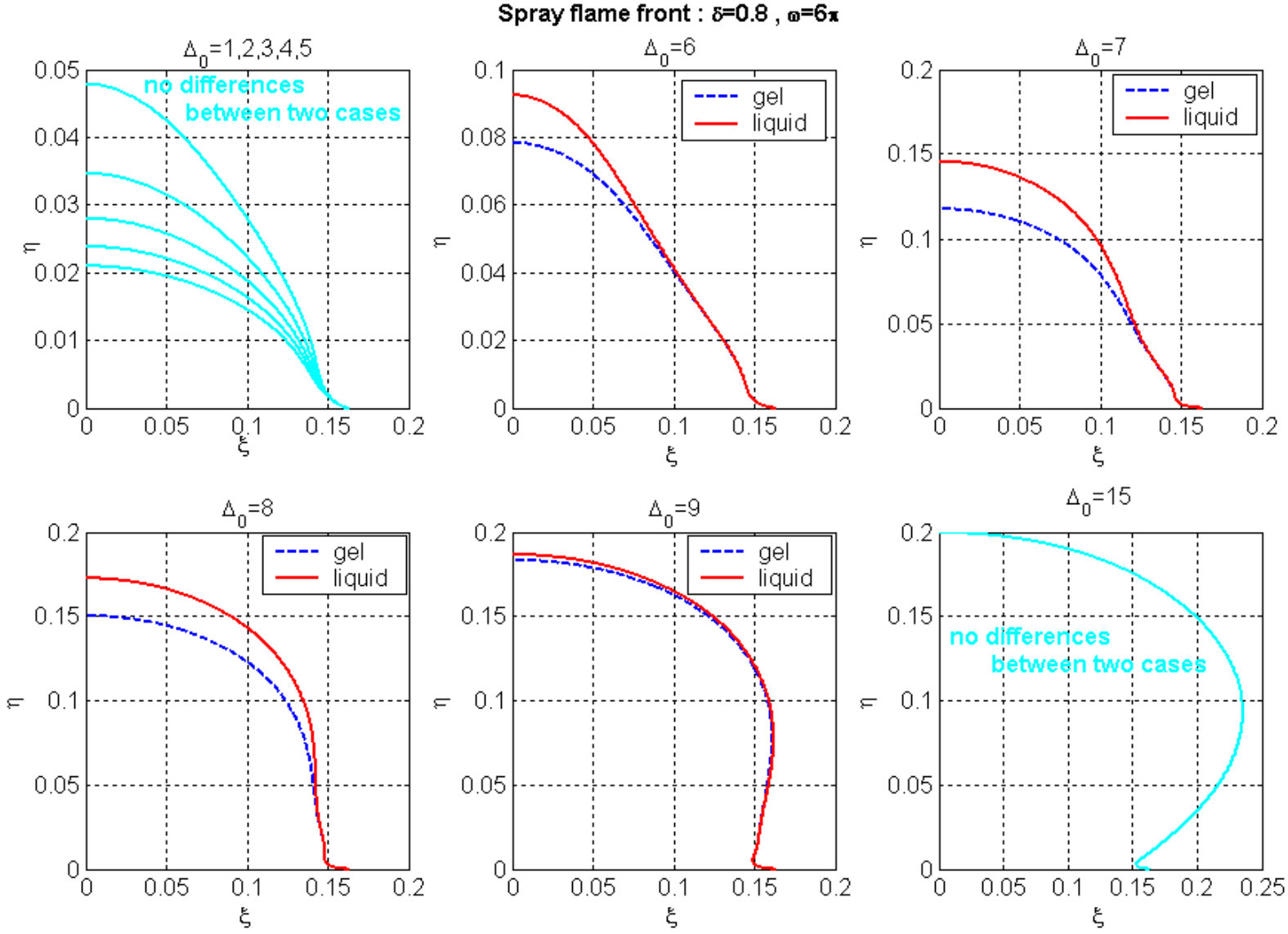
$$V = 0.306, c = 1/6, \omega = 6\pi, T_0 = 0, \quad \Gamma = 0.02$$

Show two sets of results:

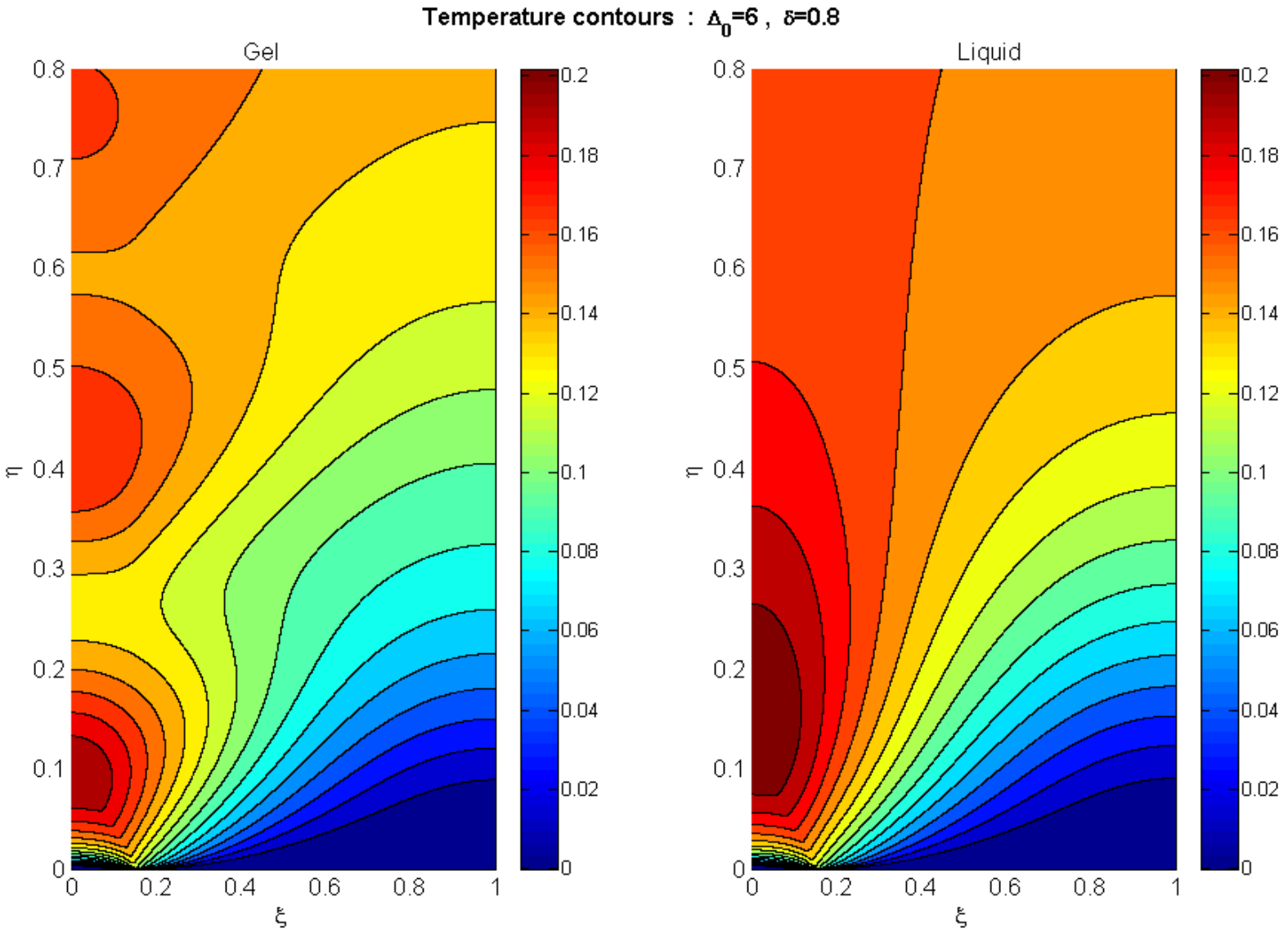
(a) Infinite drag and (b) Finite drag

RESULTS

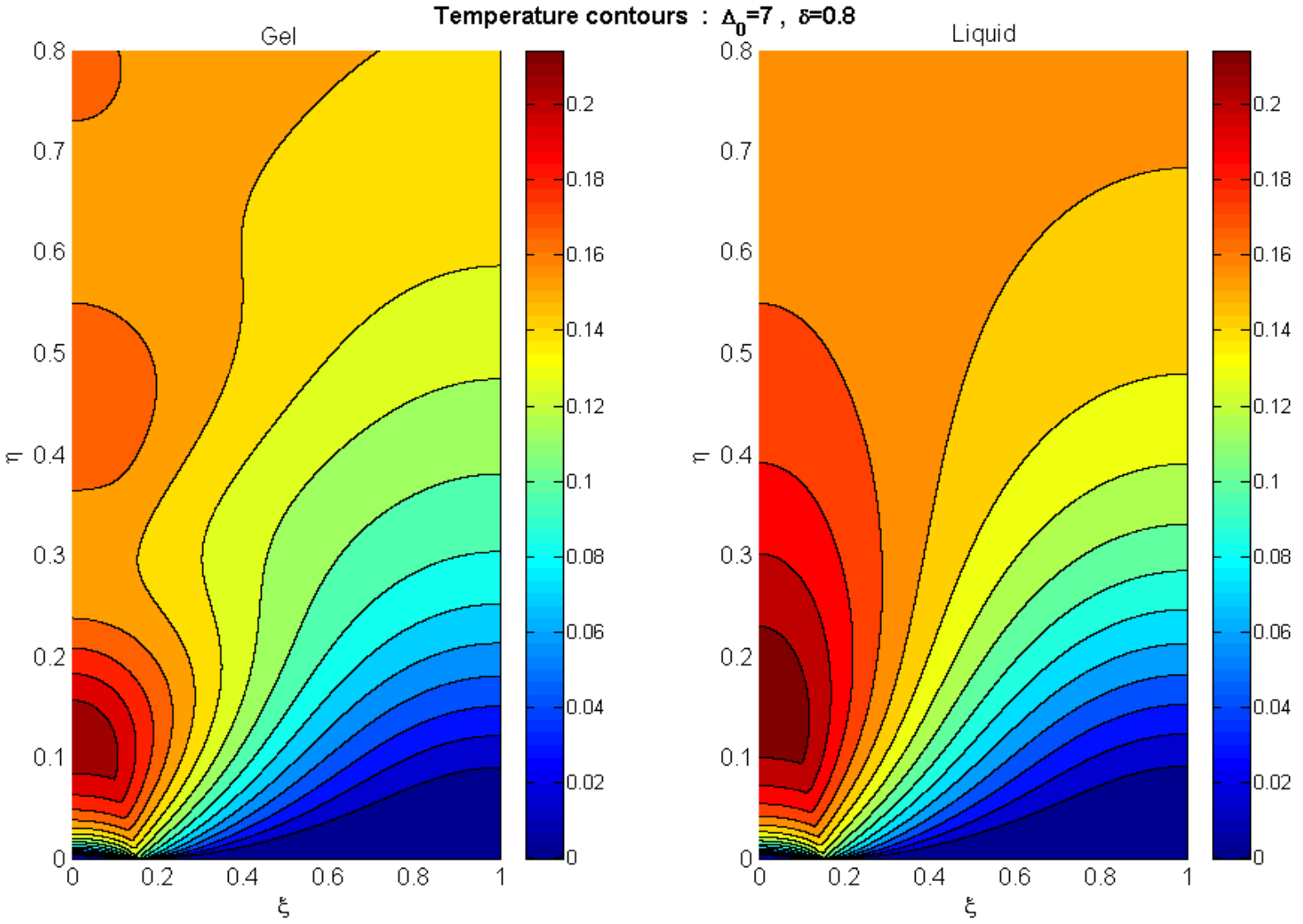
Infinite Drag



Comparison between gel spray and liquid spray flame shapes for different vaporization Damkohler numbers.



Flame temperature contours for gel spray and liquid spray diffusion flames.



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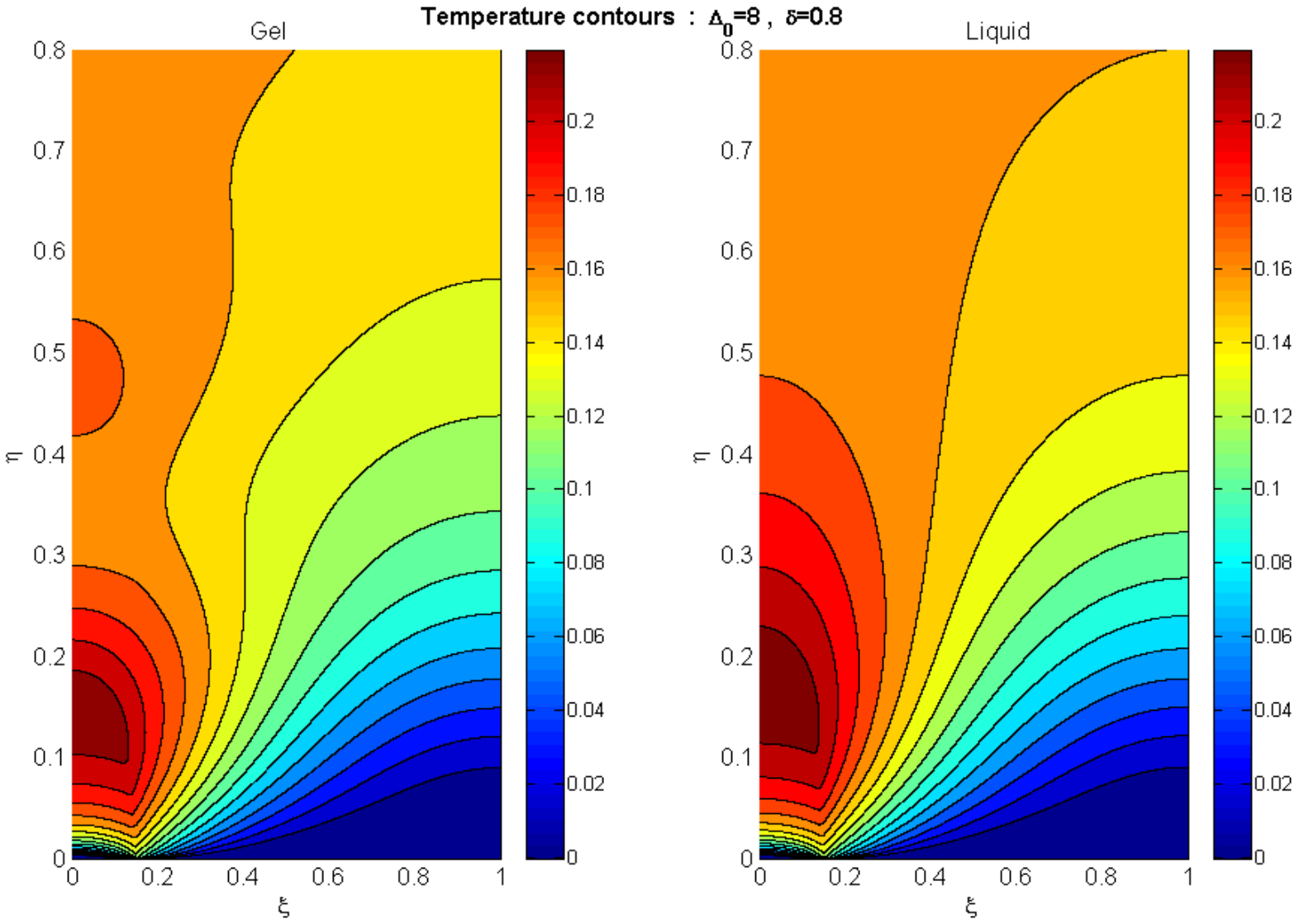

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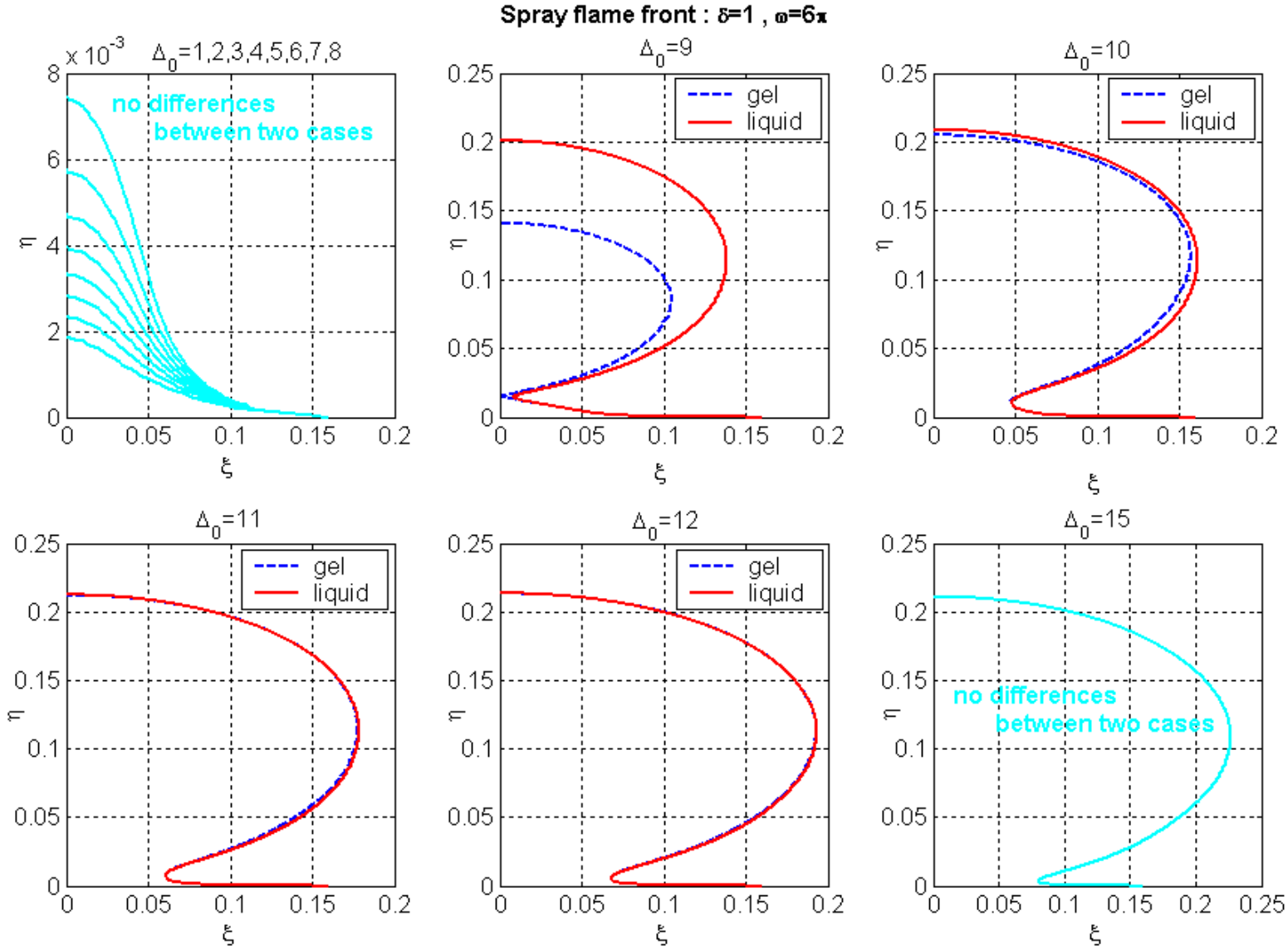

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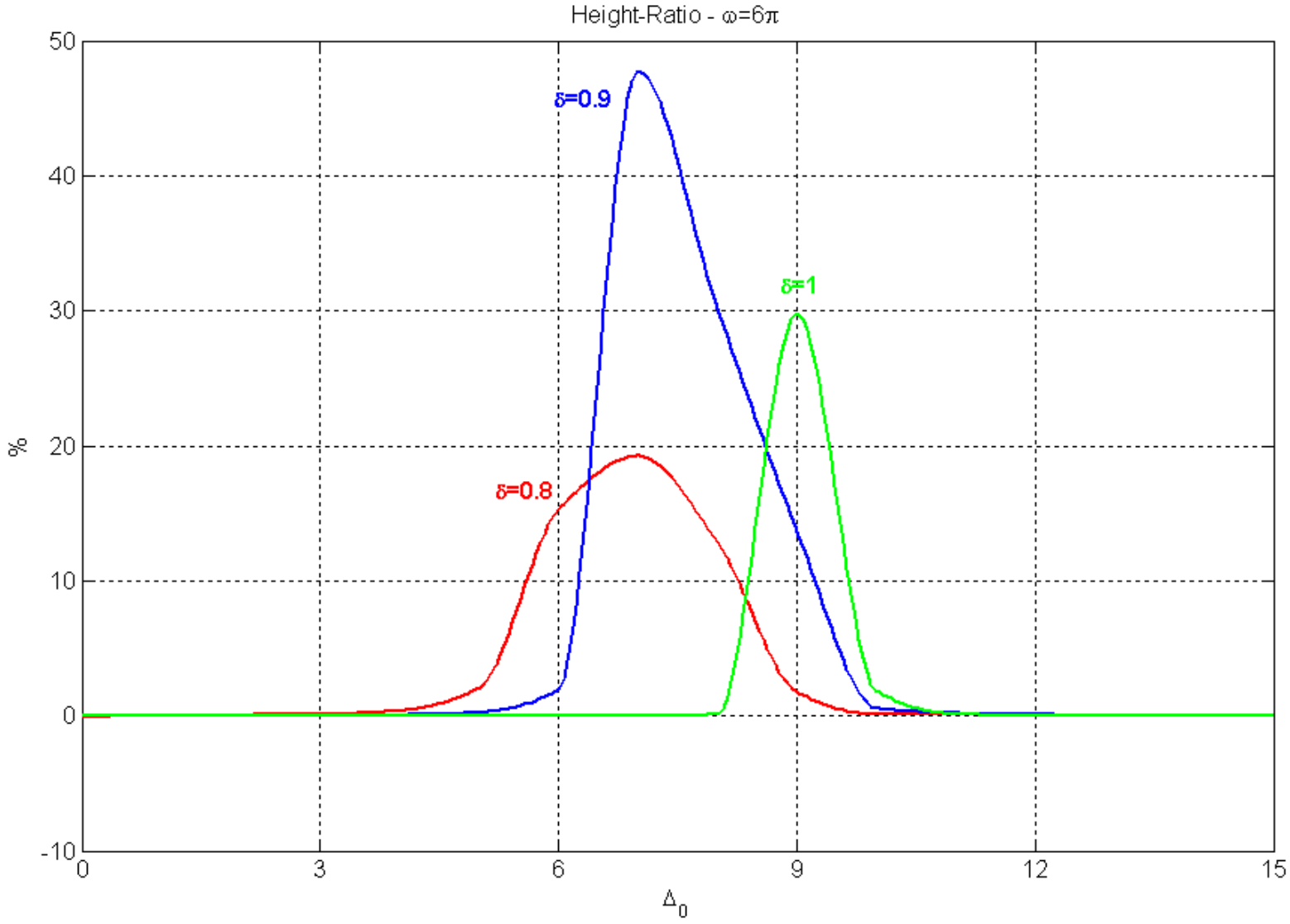
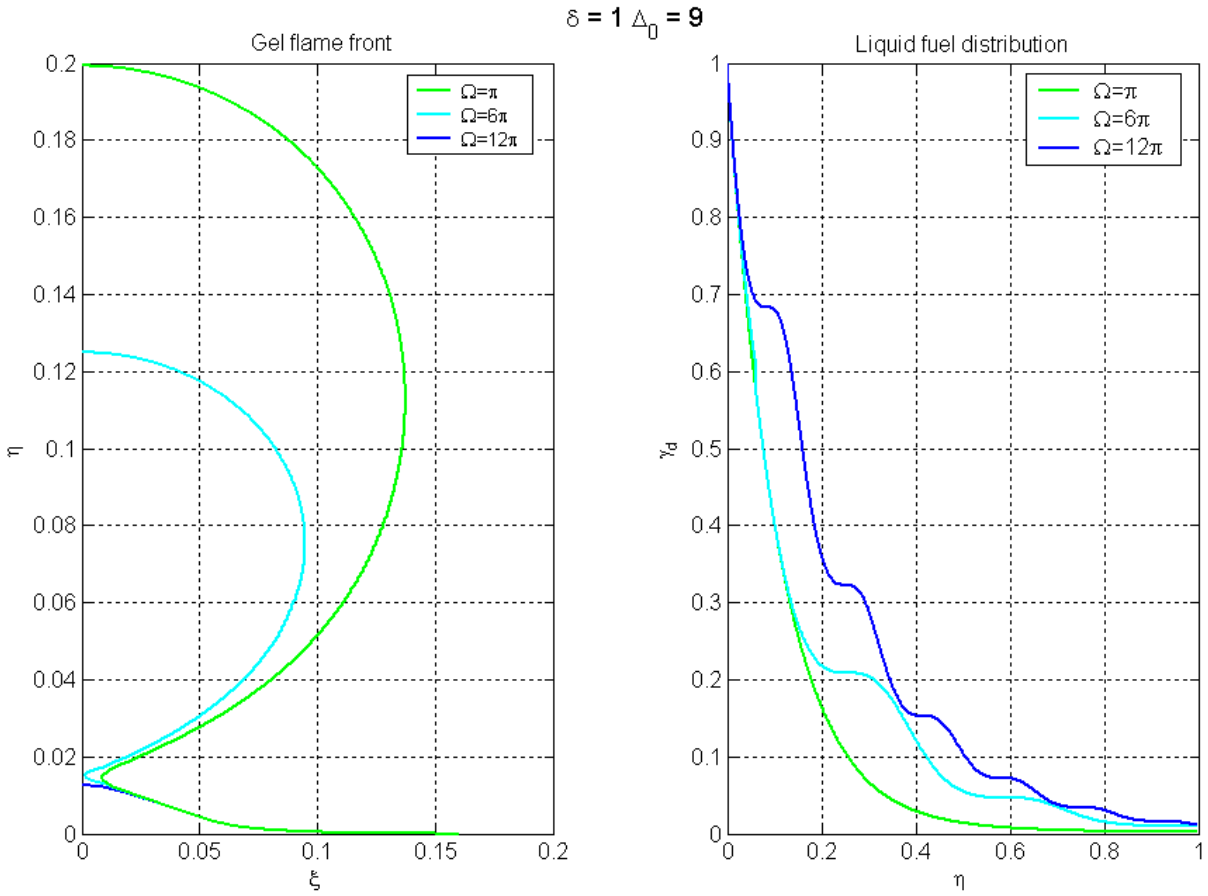


Percentage relative change in the diffusion flame height induced by the use of a gel spray rather than a liquid spray.

Effect of evaporation frequency



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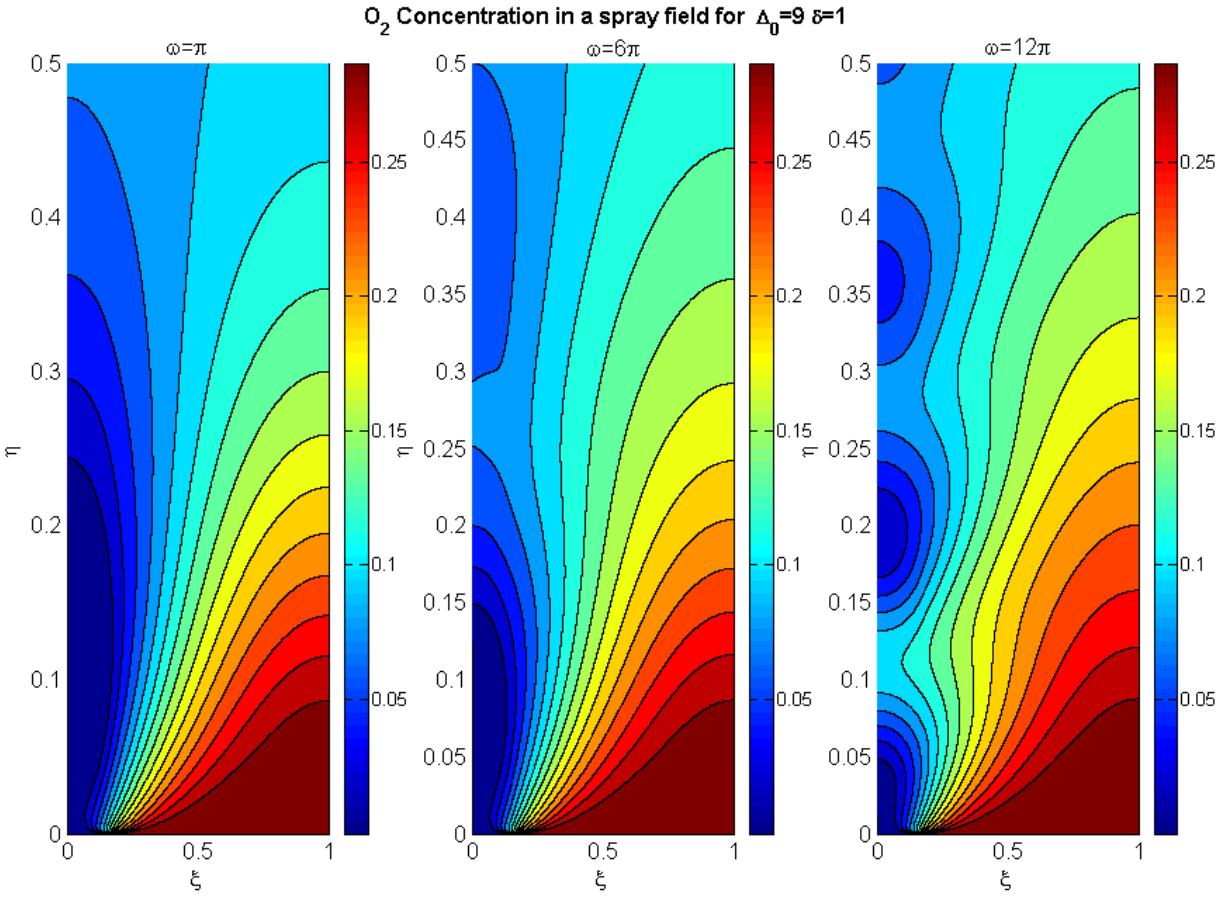

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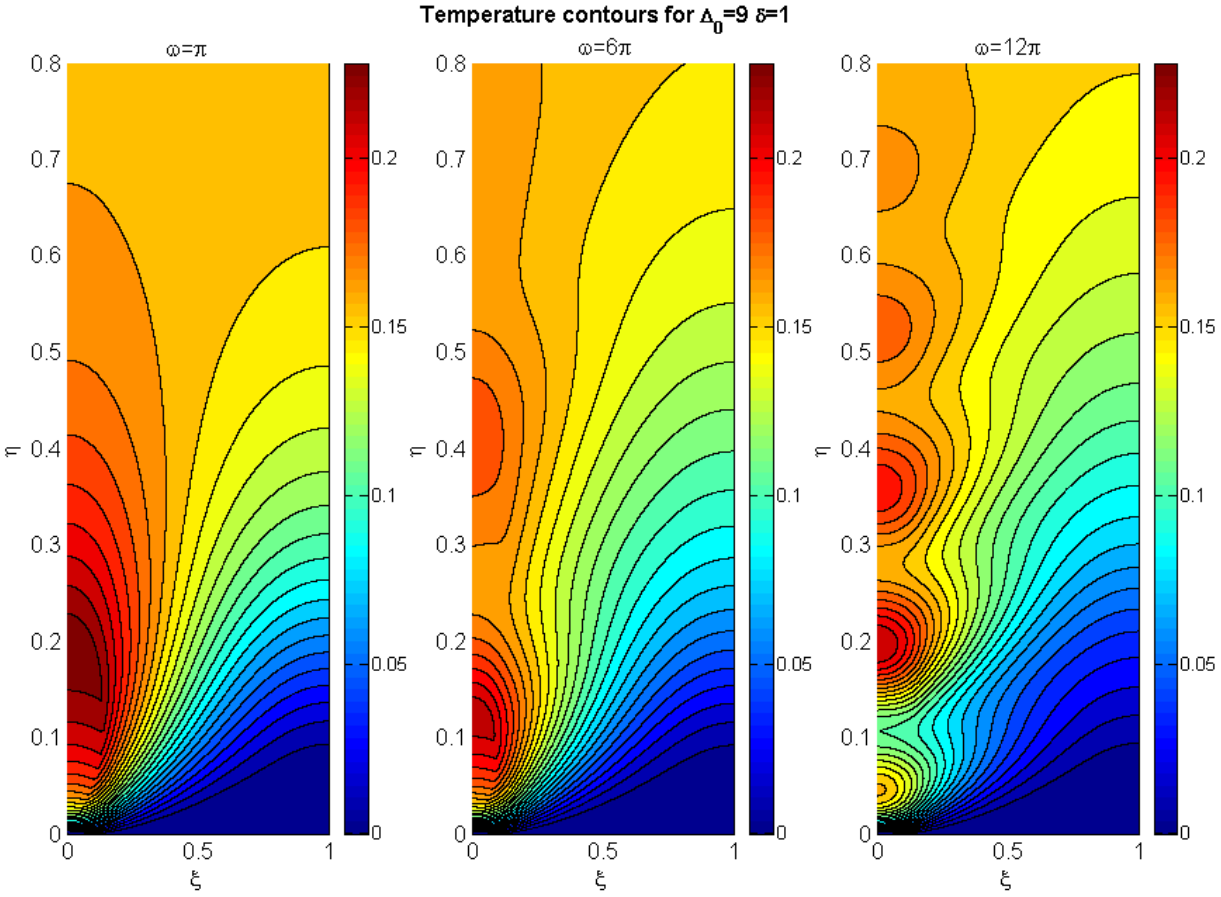


Intermediate Conclusions

Gel fuel spray can lead to:

(a) Reduction in flame height due to the effective reduction in the rate of vaporization.

(b) Trail of hot spots (heterogeneous droplet burning downstream of the main homogeneous diffusion flame front).

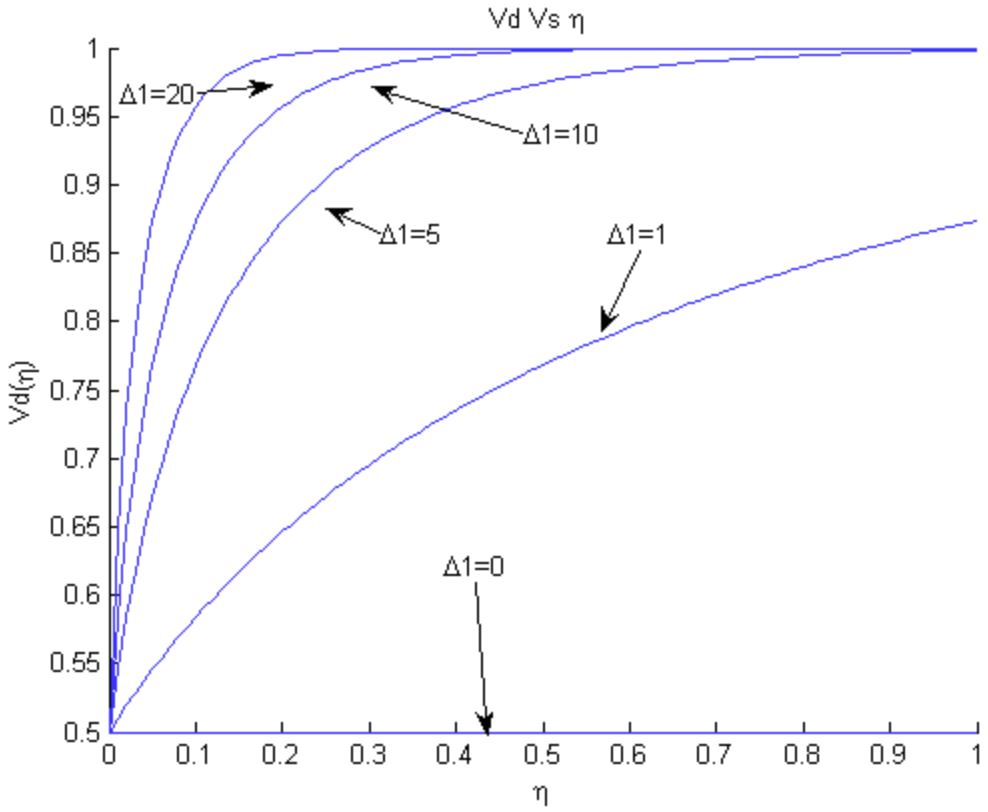
(c) Reduction in the flame temperature.

(d) Shrinking of the hot core region of the flame.

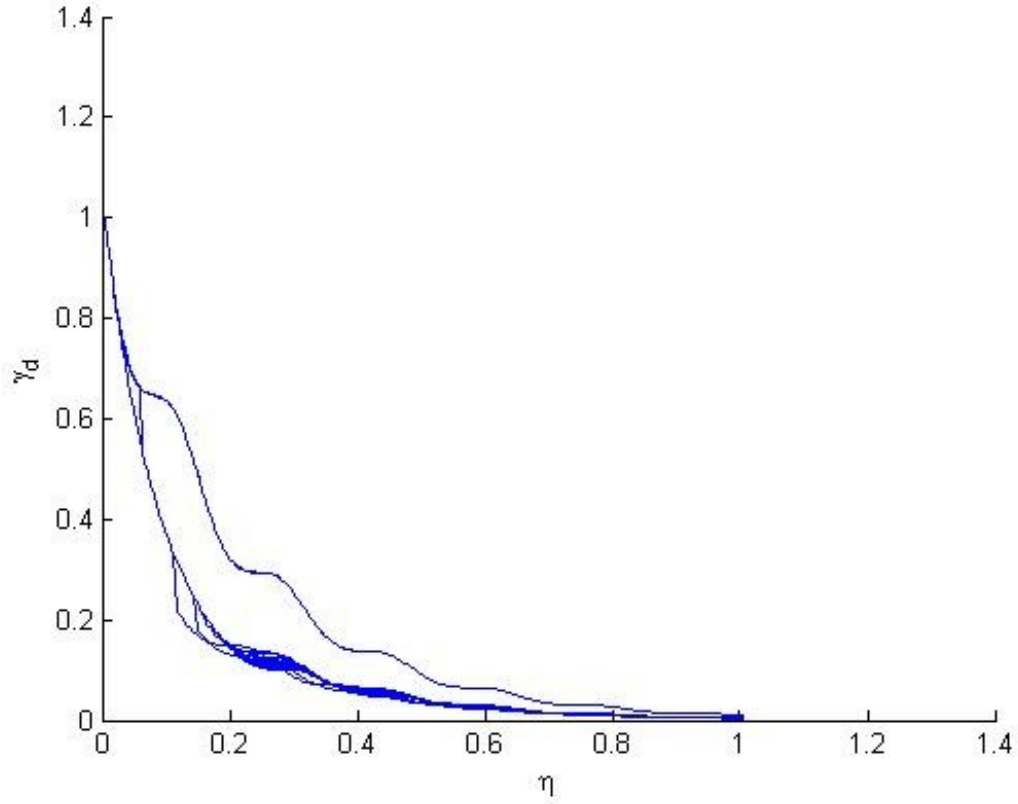
RESULTS

Finite Drag

Spray droplets velocity development for various dimensionless drag parameter values; $v_{d0} = 0.5$

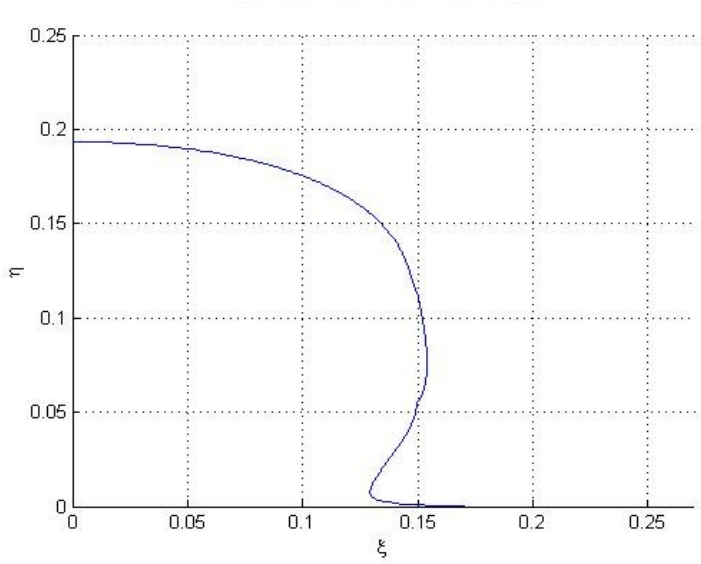


Normalized liquid fuel mass fraction profiles for different transverse locations; Data: $v_{d0} = 0.9, \Delta_1 = 10, \delta = 1, \Delta_0 = 9,$

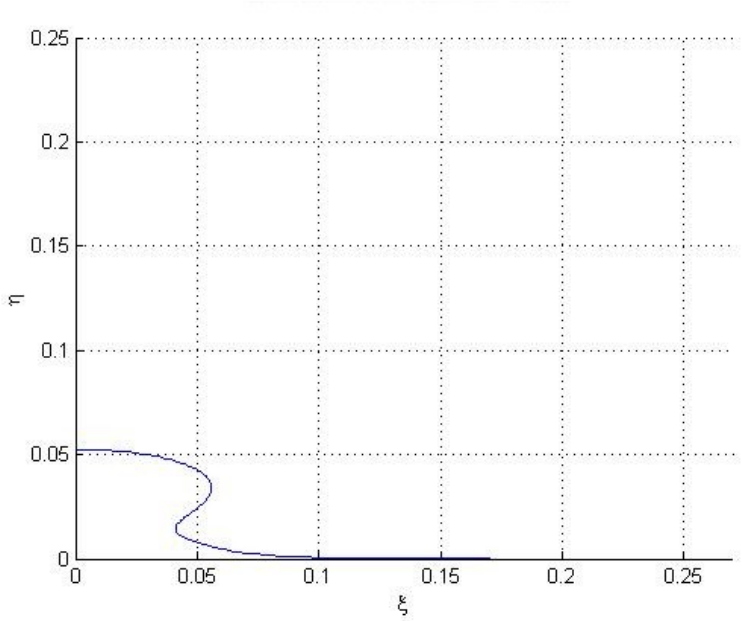


Gel spray flame profiles (a) current model (b) model with infinite droplet drag.

(a)

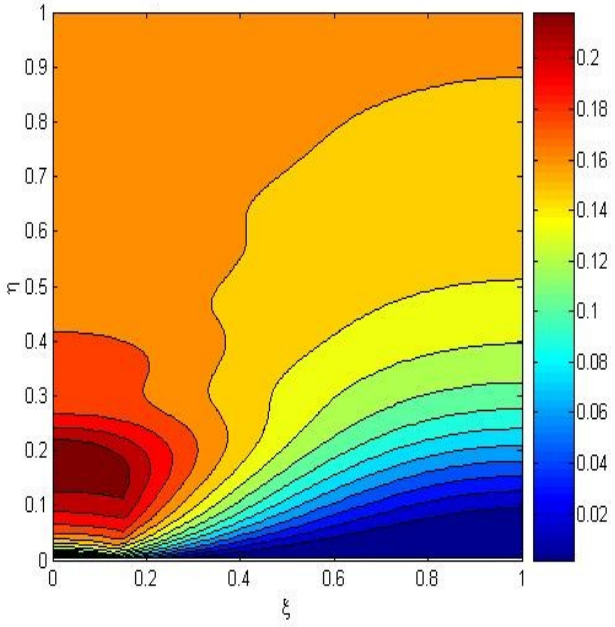


(b)

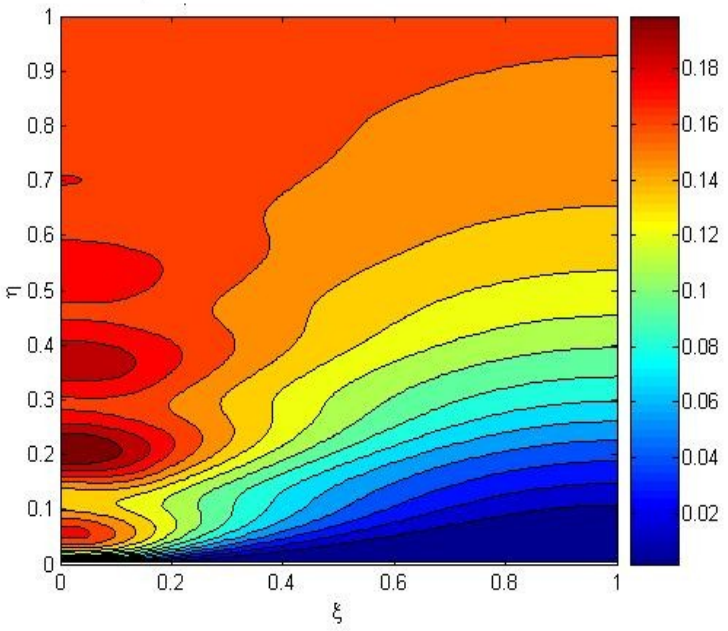


Thermal field of gel spray flames (a) current model (b) model with infinite droplet drag.

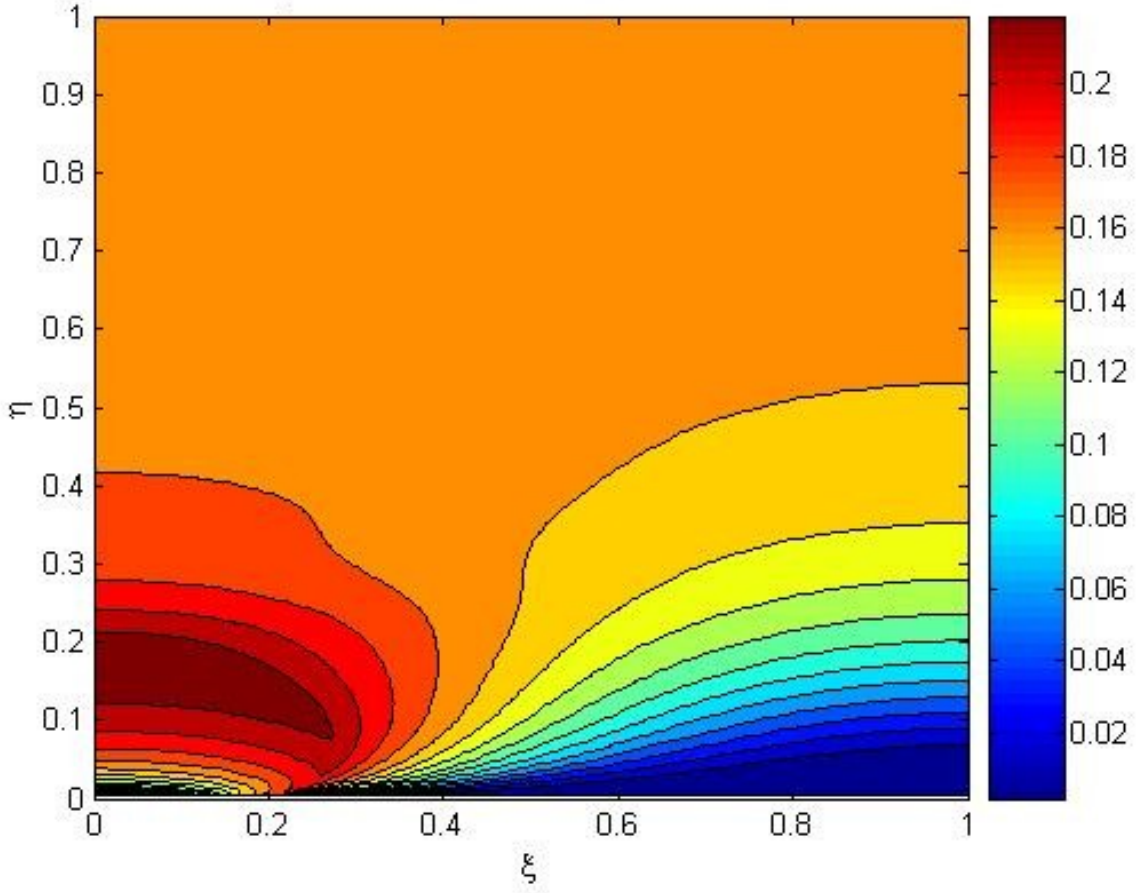
(a)



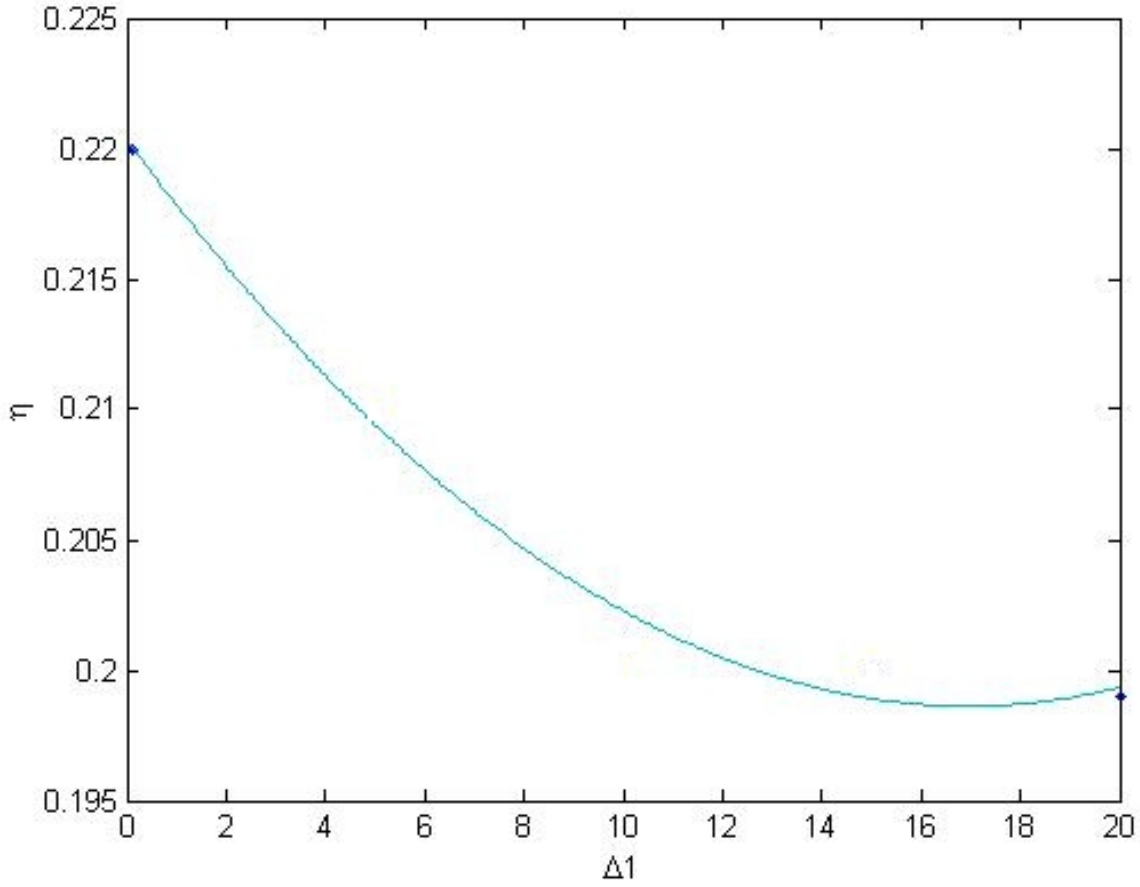
(b)



Thermal field of gel spray flames; Data as before except here $v_{d0} = 0.5$.



Influence of drag parameter, Δ_1 , on organic gel spray diffusion flame height; Data: as per text with $v_{d0} = 0.8, \delta = 1.$



Further Conclusions

- ***For an initial average droplet velocity less than that of the host gas the homogeneous flame heights were greater than those obtained under the assumption of infinite drag.***

- ***The phenomenon of post-diffusion flame hot spots was reduced. The smaller the initial average droplet velocity (and, hence, the mass flux of gel droplets) the greater was the annihilation of the hot spot manifestation.***

Further Conclusions (cont.)

- ***The drag coefficient was also found to have a similar effect on the diffusion flames in that the smaller the coefficient the taller the flame was.***

- ***Both the average droplet velocity and finite drag coefficient effects reflect the augmented upstream production of vapor as a result of the longer upstream residence time of the evaporating droplets.***

Further Conclusions (cont.)

- ***Despite the simplicity of the model the predictions shed light on an effect that is important in more realistic combustion settings in which hot spots in undesirable regions can be the cause of damage to the structural integrity of the chamber. In addition, a reduction in flame temperature is critical when considering flame extinction.***
- ***These gel spray flame features highlight the fact that even though gel fuel sprays may have a distinct advantage over liquid sprays in terms of their safety features it is crucial that the correct operating conditions must be employed in order not to detract from attaining the desired combustion performance.***

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- ***These gel spray flame features highlight the fact that even though gel fuel sprays may have a distinct advantage over liquid sprays in terms of their safety features it is crucial that the correct operating conditions must be employed in order not to detract from attaining the desired combustion performance.***

Acknowledgements

- ***Dr. Benny Natan***
- ***Alina Kunin, Roman Gandelman***
- ***British Council***