A. Liñán

Escuela Técnica Superior de Ingenieros Aeronáuticos
Universidad Politécnica de Madrid
Plaza Cardenal Cisneros, 3. 28040 Madrid
Spain

EC-Contract JOU2-CT93-0040

Second Periodic Report

THE IGNITION AND ANCHORING OF DIFFUSION FLAMES BY TRIPLE FLAMES

1.7.1994 to 31.12.1994

Research funded in part by
THE COMMISION OF THE EUROPEAN COMMUNITIES
in the framework of the
JOULE II- Programme
sub-programme
Energy Conservation and Utilization

THE IGNITION AND ANCHORING OF DIFFUSION FLAMES BY TRIPLE FLAMES

A. Liñán
F. Higuera
V. Kurdiumov
I. Iglesias

E.T.S.I. Aeronáuticos, Madrid

1. Abstract

The enhancement effects of thermal expansion on the propagation velocity of triple flames in mixing layers have been evaluated by direct numerical simulation of the process.

Numerical calculations have been used for the description of the flow, concentration and temperature field in the diffusion flame attachment region in the near wake of the injector. The numerical analysis provides the criterium for lift-off of the flames.

2. Objetive

Asymptotic techniques, based on the existence of multiple scales, are used to identify the scales involved in the ignition of diffusion flames in mixing layers by triple flames, and to determine the structure of the reacting flow, with reactions modelled by reduced kinetic mechanisms.

3. Introduction

In combustion systems where the mixing of the fuel and air takes place simultaneously with the chemical reaction, the propagation, after ignition, of triple flames along the mixing layers, in the partially mixed fuel jet in air, plays an important role in determining the lift-off distance of the flame, or the structure of the diffusion flame attachment region to the fuel injector, when the flame is not lifted-off.

The work carried out for this Program during the Report period dealt with both problems. That is, we were concerned, on one hand, with the description of the propagation of triple flames along mixing layers and, in addition, with the analysis of the flame attachment region of the diffsion flames. In both cases the analysis has been restricted to the combustion of gaseous fuel jets. However this work will shed light for the analysis of the flame propagation and diffusion flame attachment in the combustion of the turbulent fuel jet sprays in Diesel engines. The combustion occurs in this case in the form of group combustion of the droplets, which vaporize, sorrounded with hot productos of the reaction, to generate fuel vapors. These burn, controlled by diffusion, in envoloping gaseous diffusion flame, when they meet the oxygen coming from the opposite side of the flame.

4. Numerical analysis of laminar triple flame propagation along mixing layers

The work carried out during this period followed the theoretical lines described in the previous Report 1, and the analysis of Reference 2.

It included numerical calculations of the laminar triple flame propagation in mixing layers, accounting for the effects of the thermal expansion associated with the heat release. The calculations were carried out using the computing facilities of the Center of Turbulence Research (CTR), of NASA Ames and Stanford University, with the cooperation of D. Veynante, L. Versbisch, T. Poinsot and G. Ruestsch. The results are presented in the Proceeding of the 1994 Summer Program published by CTR[3]. A paper, written by G.R. Ruestsch, L. Verbish and A. Liñán[4] was accepted for publication in the Juny 1995 issue of Physics of Fluids, to which we refer for the details of results of the calculations.

These were carried out up to large values of the ratio of the adiabatic stoichiommetric flame temperature T_e to the initial temperature T_o in order to validate the square root proportionality of the enhancement factor, U_F/U_{PS}, for the flame front speed U_F over the stoichiommetric planar flame speed U_{PS}, (that is $U_F/U_{PS} = b\sqrt{T_E/T_o}$), in the important practical case when the thickness of the mixing layer is large compared with the thickness of the planar premixed flame.

5. Anchoring of diffusion flames in the near make of the injector

We have also been analysing the cases when. after ignition. the triple flame front propagation occurs upstream. through the cold partially mixed jet. all the way up to the fuel injector rim. Here it stays anchored in the near wake of the injector.

In these cases the heat conduction from the flame to the injector palys a significant role in the anchoring process: particularly if the thickness of the wall of the injector is small enough. as we shall consider to be he case in the following. Even though. with increasing values of the wall. thickness we encounter. in the near wake of the injector. a recirculating zone: then. the recirculating flow of hot gases will facilitate the diffusion flame attachment process.

The analysis carried out during this period follows the outline of Reference[5]. I deas with the description of the quasi-steady laminar. two-dimensional. near wake behing the rim of a fuel injector. We consider a gaseous fuel jet of radius a and uniform velocity U_F. outside a boundary layer of thickess. l_B. small compared with a. We shall consider that we have a coaxial air flow with velocity U_A, of order U_F, and boundary layer thickness also of order l_B.

We shall assume the Reynolds number $R_B = U_F l_B / \nu_o$. based on the kinematic viscosity ν_o of the ambient air. to be $R_B \gg 1$: although not so large as to make turbulent the boundary layer flows on the injector.

When the two boundary layers meet an anular. but locally planar. mixing layer is generated between the two streams: with a deficit of momentum associated with the wake of the injector. This mixing layer will eventually become turbulent. due to the Helmholtz-Kelvin instability. However our analysis deals with what is happening in the near wake of the injector. where the convective instabilities had not yet grown significantly if the upstream boundary layers are laminar.

In the anular mixing layer we can neglect the effects of upstream heat conduction and diffusion downstream of a small region. close to the injector rim. The size of this Navier-Stokes region is $l_N = \sqrt{\nu_o/A}$. evaluated in terms of the wall value. A. of the fuel boundary layer velocity gradient at the end of the injector. and the kinematic viscosity of the gaseous fuel. of the order of that ν_o of the air. This value of l_N and the value, $U_N = \sqrt{\nu_o A}$, of the characteristic velocity in this region are determined by the double requirement that: i) The Reynolds number must be of order unity in this region; i.e. $U_N l_N/\nu_o = 1$. And ii) that the characteristic value, U_N/l_N, of the velocity gradient in this region is of the same order as the characteristic value, $U_F/l_B = A$, of the velocity gradient in the boundary layer, forcing the flow in the Navier-Stokes region. Thus we generate the relations

$$U_N/U_F = l_N/l_B = R_B^{-1/2}$$

The non-dimensional conservation equations are written in terms of the spatial coordinates x and y, measured with l_N as scale, for the velocity components u, v, measured with the scale U_N, the non-dimensional concentration $\hat{Y}_F$ and $\hat{Y}_o$, which are the mass fractions, Y_F and Y_o, of the fuel and oxygen devided by their values Y_{FO} and Y_{oo} in the feed streams. The conservation equations are written for an irreversible Arrhenius reaction of activation energy E with a mass consumption s of oxygen, and a heat release q per unit mass of fuel consumed in the reaction.

Table I

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0$$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{\partial p'}{\partial x} + \frac{\partial}{\partial x}\left(2\mu \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left\{\mu\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\right\}$$

$$\rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} = -\frac{\partial p'}{\partial y} + \frac{\partial}{\partial x}\left\{\mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right\} + \frac{\partial}{\partial y}\left(2\mu \frac{\partial v}{\partial y}\right)$$

$$\rho u \frac{\partial \hat{Y}_F}{\partial x} + \rho v \frac{\partial \hat{Y}_F}{\partial y} - \frac{\partial}{\partial x}\left(\frac{\mu}{P_r}\frac{\partial \hat{Y}_F}{\partial x}\right) - \frac{\partial}{\partial y}\left(\frac{\mu}{P_r}\frac{\partial \hat{Y}_F}{\partial y}\right) =$$

$$= L\left(\hat{Y}_F\right) = L\left(\hat{Y}_0/S\right) = L(-c_p T/qY_{F0}) = -W_F/Y_{F0}$$

$$\rho = T_0/T$$

Then the conservation equations take the form given in Table I. When writing the equation of Table I, the Lewis numbers othe fuel and oxygen are assumed to be equal to 1, and the Prandtl number P_r constant. The bulk viscosity is assumed to be zero, and the ordinary viscosity μ is measured with its ambient air value. For simplicity the mean molecular mass is considered constant and the spatial variations of pressure are neglected in the equation of state, which then simplifies to $\rho = T_0/T$.

The nondimensional burning rate, W_F/Y_{FO}, is, for an Arrhnius reaction, of the form

$$-W_F/Y_{FO} = (B/A)e^{-E/RT}\hat{Y}_F\hat{Y}_o$$

where B is the frequency factor.

The parameter $S = sY_{FO}/Y_{OO}$ is the stoichiommetric mass of air required to burn the unit mass of the fuel stream, is one of the important parameter appearing in the description of the flame attachment process. Other parameters appear in the boundary conditions:

One is $h = d_p/2l_N$, the half thickness of the plate measured with the Navier-Stokes length l_N. Other is $\alpha =$ the ratio of the air and fuel boundary layer wall velocity gradients.

The appropriate boundary conditions are

$$\hat{Y}_o = 0, \quad \hat{Y}_F = T/T_O = 1, \quad u - y + h = v \to 0$$

$$\text{when } \; y > h, \; x \to -\infty \qquad \text{and at } \; y \to \infty$$

$$\hat{Y}_F = 0, \quad \hat{Y}_0 = T/T_O = 1, \quad u + \alpha(y + h) = v \to 0$$

$$\text{when } \; y < -1, \; x \to -\infty \qquad \text{and at } \; y \to -\infty$$

At the interface with the injector:

$$T = T_o, \quad \partial\hat{Y}_F/\partial n = \partial\hat{Y}_0/\partial n = 0 \qquad u = v = 0$$

$$\text{at } \; y = \pm h, \; x < 0 \qquad \text{and at } \; |y| < h, \; x = 0$$

Here $\partial/\partial n$ is the derivative normal to the injector surface. The solution of the system of equations of Table I must approach, downstream, for $x \gg 1$ a self-similar form, involving the single independent variable $\eta = y/\sqrt[3]{x}$, including a thin diffusion flame if the nondimensional frequency factor of the reaction B/A is large enough for the diffusion flame to be attached in the Navier-Stokes region. This asymptotic form of the solution satisfies the boundary layer form of the equations of Table I, with the upstream diffusion effects neglected, but including a pressure gradient term $-\partial p'/\partial x = kx^{-1/3}$ in the stream-wise momentum equation. The parameter k is determined to insure that the boundary conditions at $|y| \to \pm\infty$ do not involve any displacement, as imposed in the boundary conditions written above.

In the Burke-Schumann limiting case, $B/A \to \infty$, the reaction is diffusion controlled. The reactants do not coexist, $\hat{Y}_F \hat{Y}_0 = 0$, and, together with the temperature, are given in terms of the mixture fraction Z by the relations

$$\hat{Y}_0 = 0\ ,\ \ \hat{Y}_F = (Z - Z_s)/(1 - Z_s) = (T_e - T) = /(T_e - T_0)$$

$$\text{for} Z > Z_s = 1/(S+1) \quad \text{and}$$

$$\hat{Y}_F = 0\ ,\ \ \hat{Y}_0 = (Z - Z_s)/(T - T_0)/(T_e - T_0) \qquad \text{for } Z < Z_s.$$

Here T_e is the adiabatic flame temperature

$$T_e = T_0 + qY_{F0}/c_p(S+1) = T_0(1+\gamma)$$

The parameter γ, the nondimensional flame temperature rise above the ambient temperature, is the additional parameter ecountered in the Burke-Schumann limit of infinite reaction rates.

For finite values of the reaction rates two additional parameter to S, γ, and α play an important role. One is the non-dimensional activation energy, or Zeldovich number $\beta = E/RT_e$. The other is the reduced Damköhler number

$$\delta = \beta^4 (B/A) e^{-E/RT_e}$$

Flame lift-off will occur, for the realistic values of β moderately large compared with unity, when δ becomes smaller than a critical value δ_L, of order unity, which will depend on S, γ, and α.

6. Discussion of the numerical results

In the following we give a sample of the numerical results that we have obtained when analysing the flow field in the Navier-Stokes region.

We began by calculating the flow field in the absence of heat release for increasing values of the parameter $h = d_p/2l_N$, the non-dimensional measure of the plate thickness. Some of the results are summarised in Fig.1. where we sketch the form of the streamlines for values of h below the critical value $h_c = 0.46$ and above h_c. When the plate is thin the streamlines adjust to the plate without any recirculation zone. For values of $h > h_c$ a recirculating bubble is formed with transverse size L_T and longitudinal extent L_B growing with h.

In Figure 1. L_B and L_T (measured with the Navier Stokes length l_N) are given as functions of h. An asymptotic analysis for large values of h (which is the local effective Reynolds number of the flow) shows

$$L_T/h - 1 \qquad \text{and} \qquad L_B/h - 0.39\ h^2$$

The calculations of the flow were repeated to account for the effects of heat release. measured by the parameter $\gamma = (T_e - T_0)/T_0$, in the Burke-Schumann limit of infinitely fast reactions. The results. as represented in Fig.2 for $h = 2$. show that the effects of the heat release cause a reduction of the bubble size or even its disappearence for finite h and large enough γ. The variations of the viscosity with T play an important role in the size of the bubble.

As indicated before. the solution of the Navier-Stokes region must approach for $x \gg 1$ a self-similar form. described using the boundary layer approximation. including the effects of a self-induced pressure gradient. required to minimize the deflection of the flow outside the mixing layer. The existence of these similarity solutions for the momentum mixing layer downstream of a splitter plate was discovered for the non-reacting case by Rott and Hakinen[5]. When we take into acount the effects of the heat release. associated with a diffusion flame in the mixing layer, the temperature and velocity fileds are of the type shown in Figure 3. The pressure gradients are. adverse for $\gamma < 1.2$ and favorable for $\gamma > 1.2$. those required to avoid the axial displacement of the velocity profile.

An example of the temperature distribution and the streamlines. when we acount for the effects of heat release in the Burke-Schumann limit. is given. in Fig.4. for the symmetrical case $S = 1$ and $\alpha = 1$.

Examples of the effects of the finite rate chemistry are given in Figs. 5-8 where the stream function, v velocity, temperature and reaction rate level surfaces are shown for decreasing values of the reduced Damköhler number $\delta(=d)$ for $\gamma = 2$, $\beta = 10$ in the symmetrical case $\alpha = 1$, $S = 1$, for an infinitely thin plate ($h = 0$).

Finally in Fig.9 the flame stand-off distance (measured with l_N) and the heat reaching the plate from the flame, represented by a Nusselt number, are shown in terms of δ.

7. Concluding remarks

The effort, during this period, has been devoted to the development of the methods of calculation and numerical schemes required for the description of the dynamics and structure of triple flames in mixing layers, and with the description of the region of anchorage of the diffusion flames to the rim of the injector. The calculations can be extended in the future, to reduced kinetic schemes other than the Arrhenius one-step reaction.

Considerable numerical effort will be required to obtain more information from the analysis.

References

1. A. Liñán: "*Triple flames in mixing layers*". First State of Advance Report (1994). EC-Contract JOU2-CT93-0040.

2. A. Liñán: "*Ignition and flame spread in laminar mixing layers*". Combustion in High Speed Flows. Ed. J. Buckmaster. T.L. Jackson and A. Kumar, pp. 461-476. Kluwer Academic Publ. 1994.

3. D. Veynante. L. Verbisch. T. Poinsot. A. Liñán and G. Ruetsch: "*Triple flame structure and diffusion flame stabilization* ". Center of Trubulence Research. Proc. of the Summer Program 1994, pp.55-73. Stanford Univ. 1994.

4. G. R. Ruersch. L. Verbish and A. Liñán: "*Effects of heat release on triple flames*". Phys. oof Fluids. June, 1995.

5. N. Rott and R.J. Hakkinen: "*Similar solutions for merging shear flows*". J. Aerospace Sci. pp. 1134-1135. 1962.

$\gamma = 0$

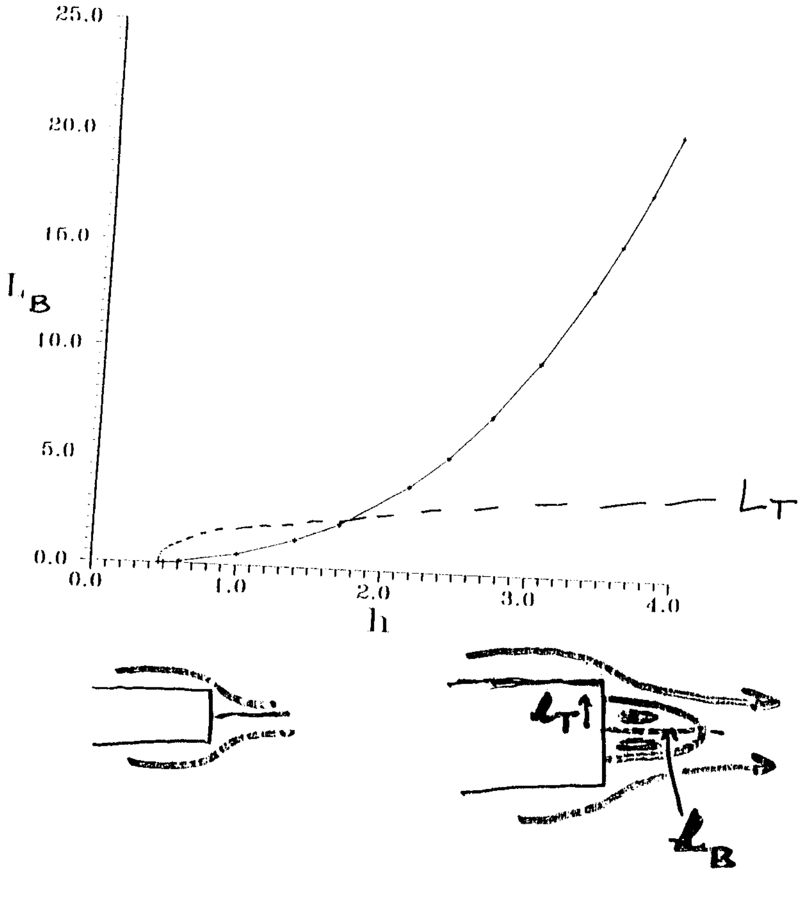


FIG 1

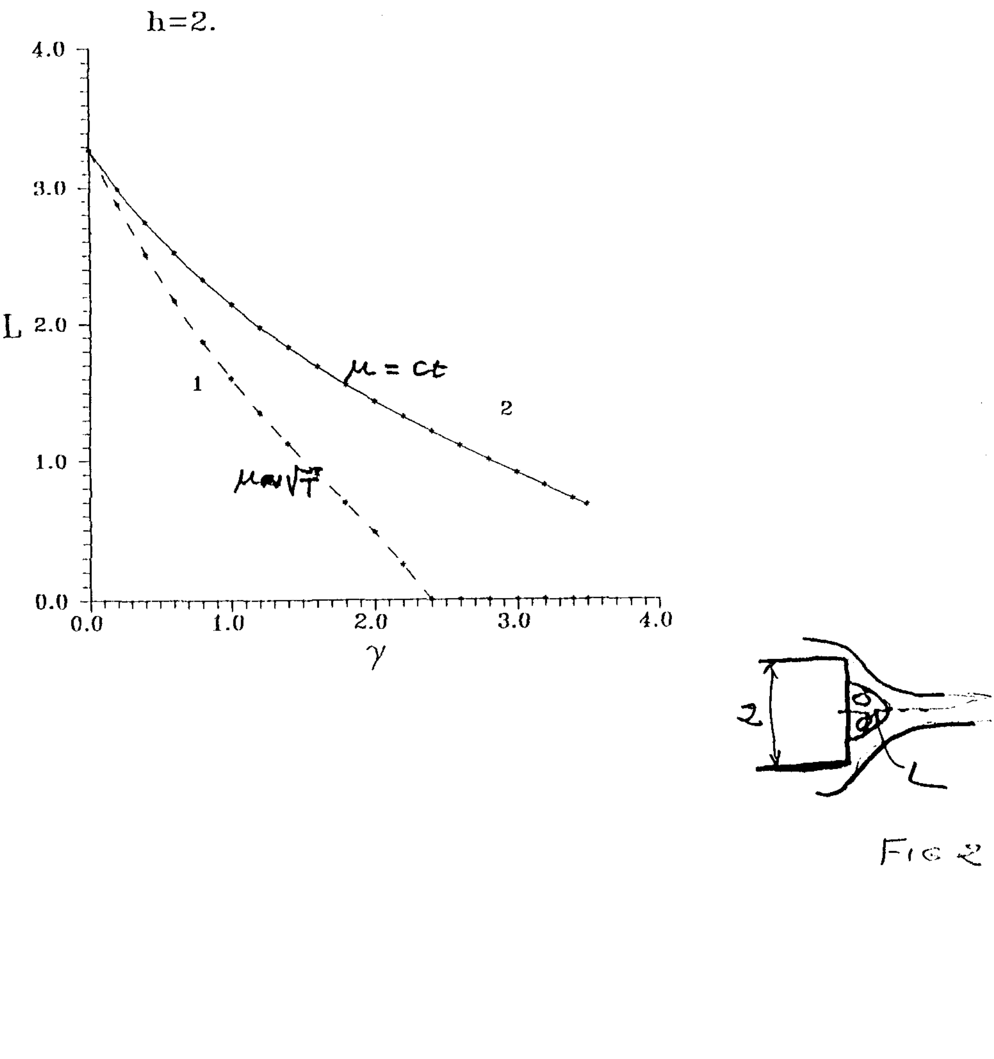
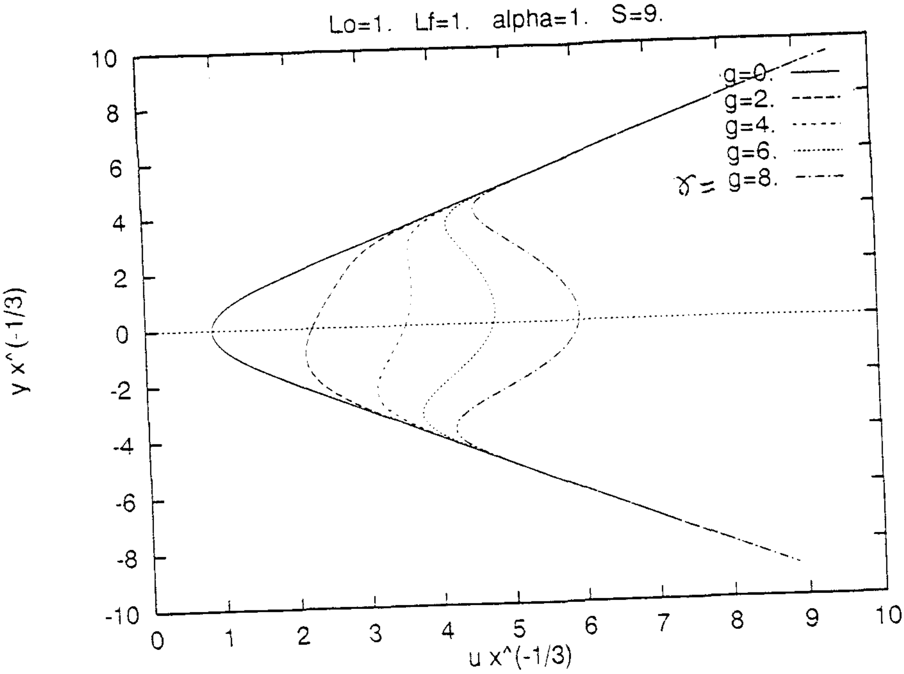


FIG 2


Lo=1. Lf=1. alpha=1. S=9.
g=0.
g=2.
g=4.
g=6.
γ= g=8.
y x^(-1/3)
u x^(-1/3)
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
1
2
3
4
5
6
7
8
9
10

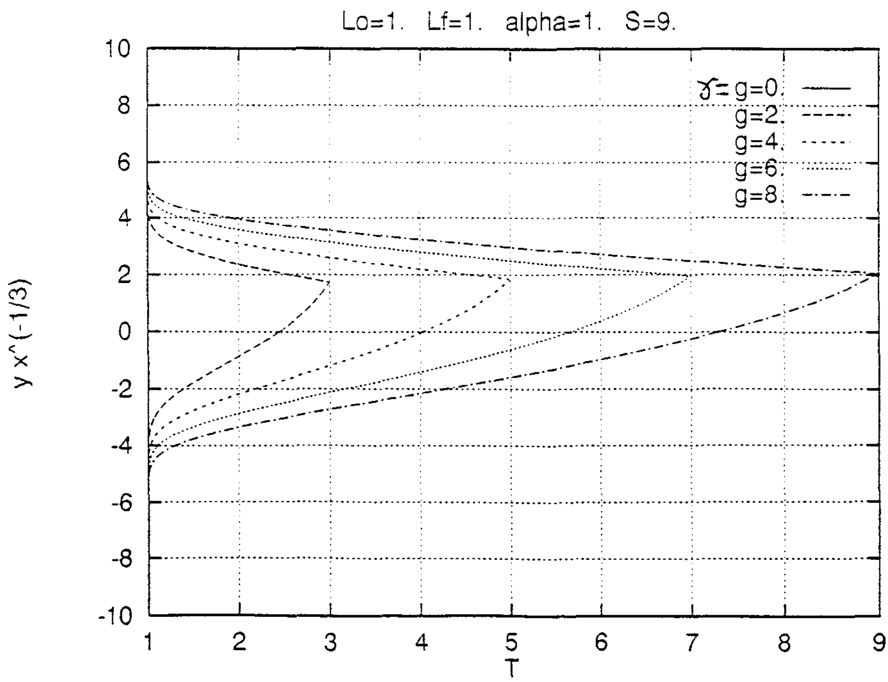

Lo=1. Lf=1. alpha=1. S=9.
γ= g=0.
g=2.
g=4.
g=6.
g=8.
y x^(-1/3)
T
10
8
6
4
2
0
-2
-4
-6
-8
-10
1
2
3
4
5
6
7
8
9

Fig 3

pr=1.

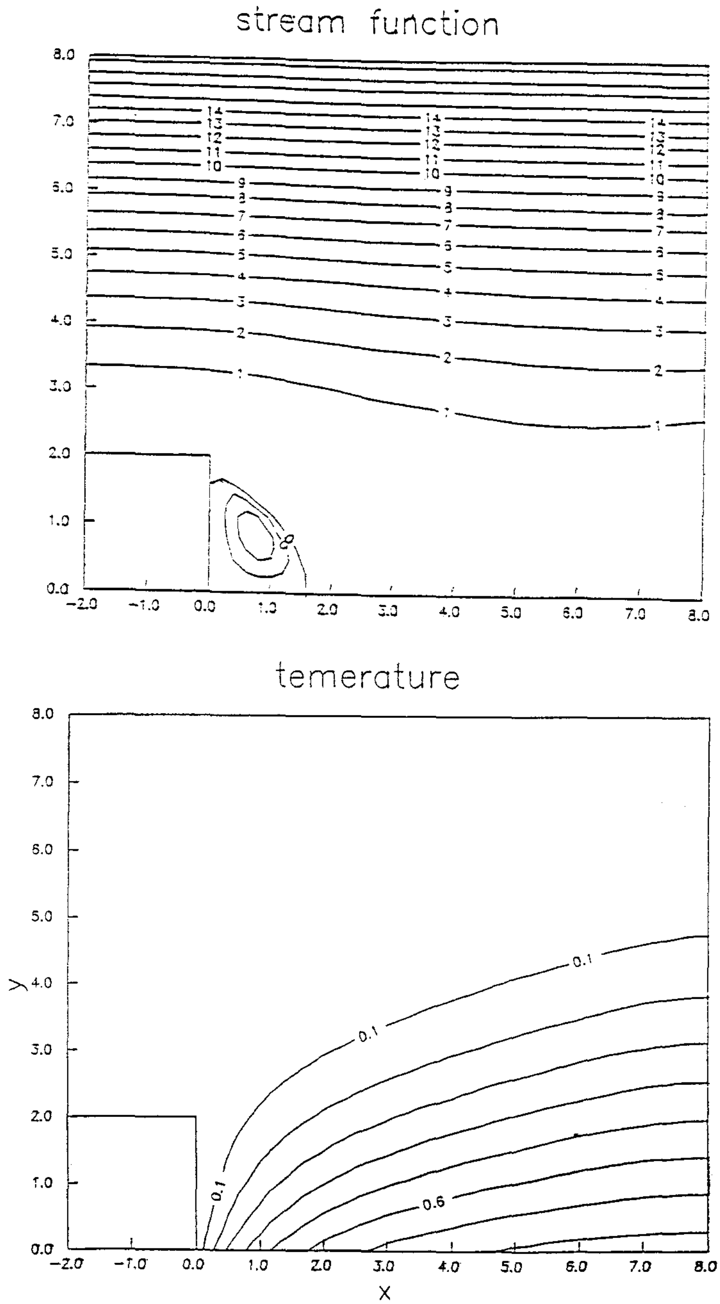
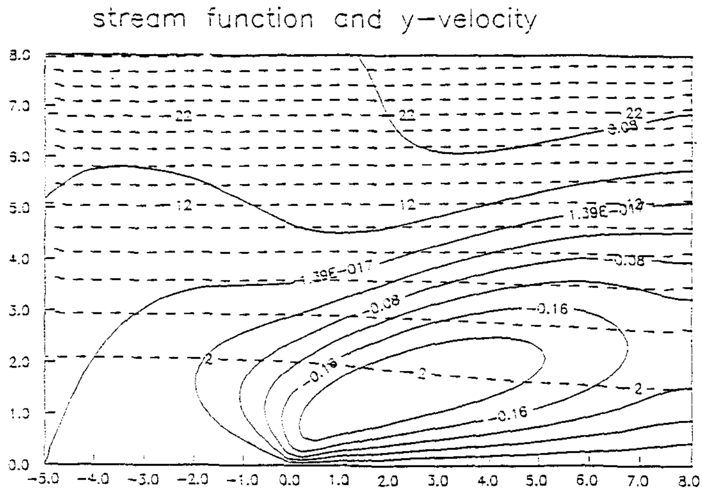


Fig 4

B.−Sch. limit
gama=2
$\delta \to \infty$



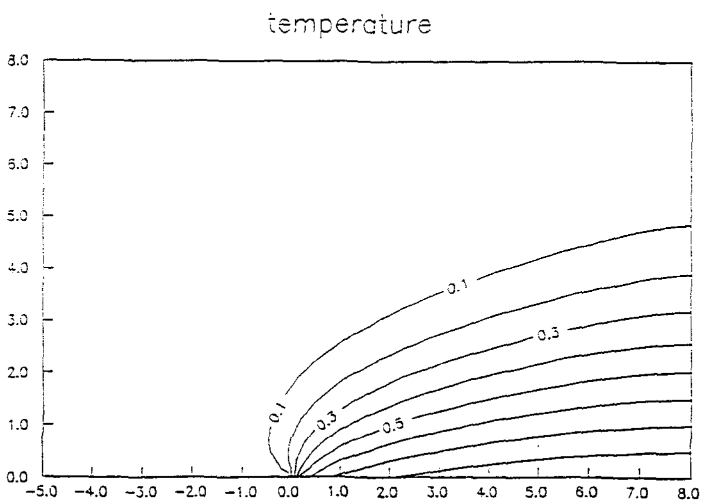


Fig 5

beta=10
gama=2
δ = d=5

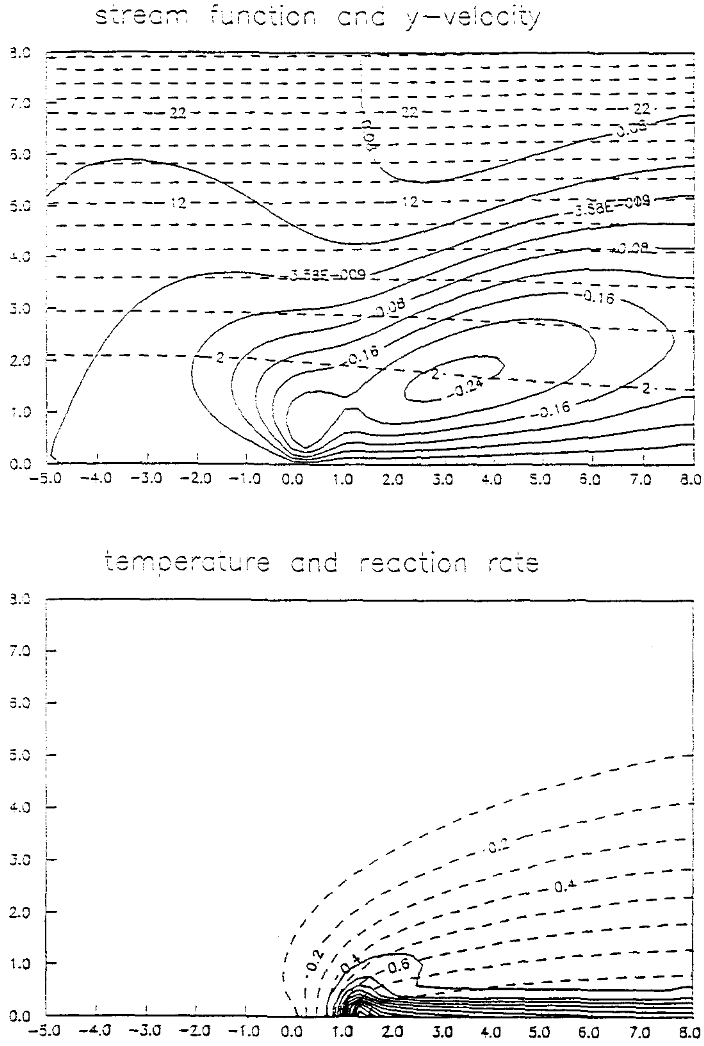


Fig 6

beta=10
gama=2
d=3

stream function and y-velocity

temperature and reaction rate

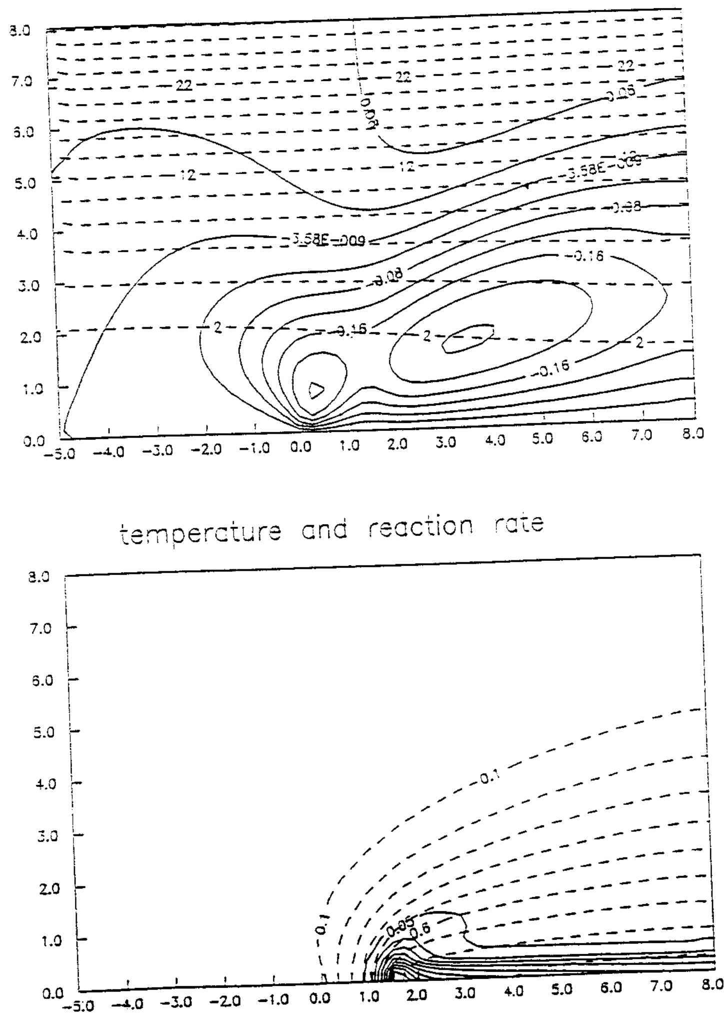


Fig 7

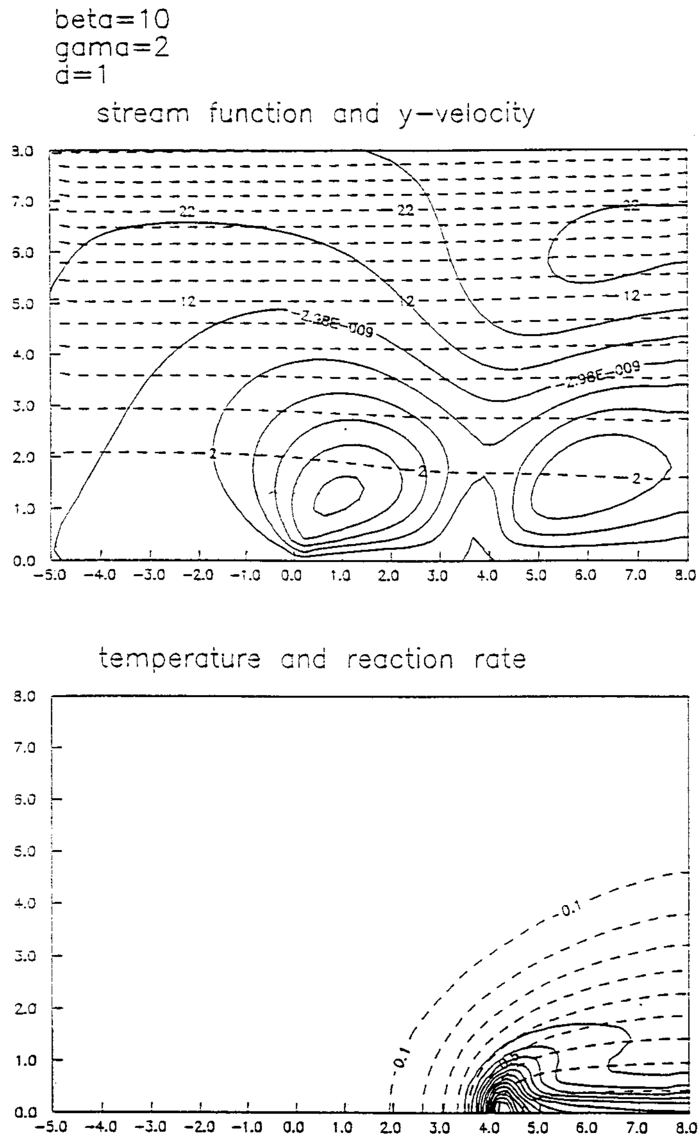
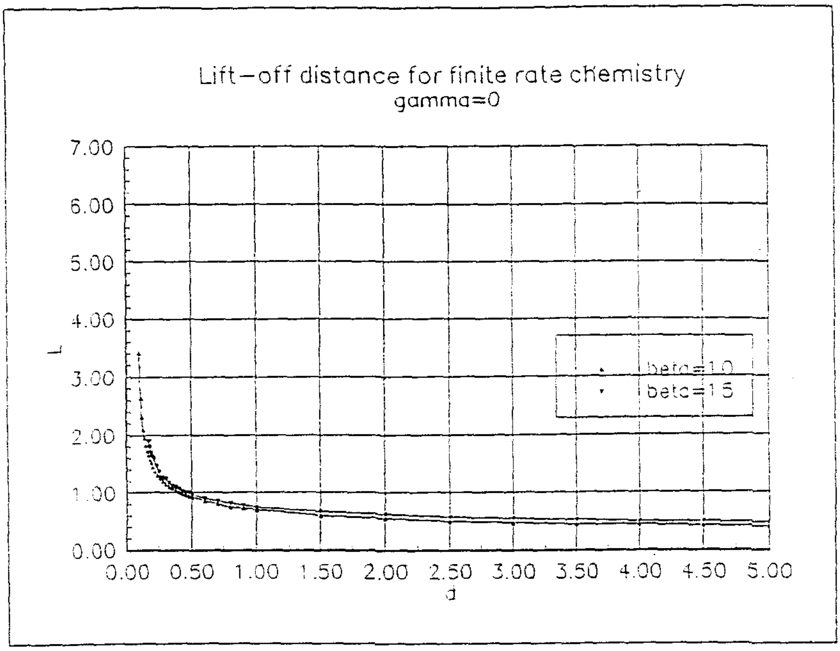

beta=10
gama=2
d=1
stream function and y-velocity
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−5.0 −4.0 −3.0 −2.0 −1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0
22
12
2
2.98E−009
temperature and reaction rate
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−5.0 −4.0 −3.0 −2.0 −1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0
0.1

Fig 8


Lift-off distance for finite rate chemistry
gamma=0
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
L
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
d
beta=10
beta=15

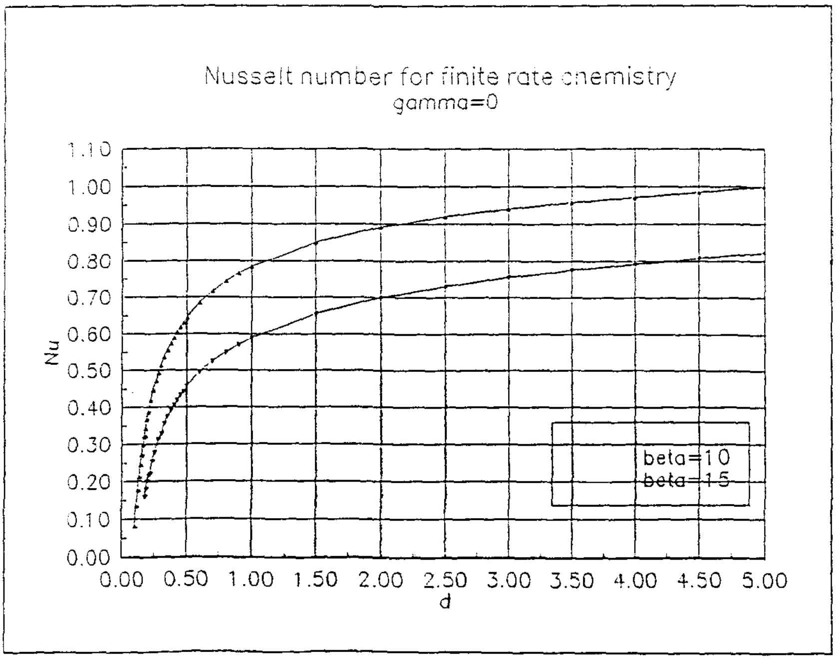

Nusselt number for finite rate chemistry
gamma=0
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Nu
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
d
beta=10
beta=15

Fig 9