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Numerical and Experimental Study of Lean M- and V-Shaped Flames

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Numerical modeling results of M- and V-shaped methane/air flames with an equivalence ratio of 0.7 are presented and compared with experimental results in this paper. The numerical model uses a one-step chemistry model and a vorticity-streamfunction formulation for the flow field. The experimental results used to validate the model consist of flame shapes, stand-off distances, velocity profiles measured with Laser Doppler Velocimetry and critical transition and blowoff gradients. The flame shape and the stand-off distance of the M-shaped flame are reproduced well by the model. The values of the vertical velocity are, however, lower than the experimental values. The lower vertical velocities computed with the model are due to relatively small differences between the computed and the experimental flame shape. The shape of the V-shaped flame is also reproduced reasonably well by the model. The stand-off distance predicted by the model differs 0.8 mm from the experimental value. The vertical velocities predicted by the model are, as for the M-shaped flame, lower than the experimental values. This is also caused by flame shape differences. The small differences between the computed and experimental flame shapes is probably related with the absence of highly diffusive radicals in the one-step model. The model is also used to compute the critical transition (from M- to V-shaped flame) and blowoff (of the V-shaped flame) gradients. The values for the critical gradients predicted by the model differ no more than 10 % from the experimental values obtained with our burner.

INTRODUCTION

The understanding of the stabilization mechanisms of V-shaped flames is generally (Lewis and von Elbe (1961), Edmondson and Heap (1970), Kawamura *et al.* (1979, 1982), Trevino *et al.* (1991) and Sung *et al.* (1992))

believed to be a necessary step towards the unraveling of the blowoff mechanisms of Bunsen-type flames. The stabilization of V-shaped flames is not affected by mixing with and cooling by the surrounding atmosphere since the attachment point is surrounded by the combustible mixture flowing out of the burner. The stabilization of V-shaped flames also resembles the stabilization of flames on multiple-slit burners at high thermal loads which are used widely in domestic heating equipment.

Several phenomena are held responsible for the stabilization of V-shaped flames, such as flow straining (Lewis and von Elbe (1961), Edmondson and Heap (1970)), the curvature of the flame front (Kawamura *et al.* (1979, 1982) and heat loss to the stabilization body or flameholder (Trevino *et al.* (1991)). Sung *et al.* (1992) demonstrated that V-shaped flames can be stabilized with no heat loss to the flameholder and presented an analysis of the stabilization of a V-shaped flame which includes both strain and curvature. This analysis is, however, limited to weak strain rates and low curvature.

No attempt has been made so far to model V-shaped flames numerically. A numerical model can be a powerful means for investigating the mechanisms involved in the flame stabilization process because the importance of the occurring mechanisms (e.g., curvature, flow straining and heat loss to the burner) can be studied in a systematical and detailed manner. A comparable study has been applied recently by de Goey *et al.* (1996) on the tip of a two-dimensional Bunsen flame. This study consists of the calculation of separate contributions to the stretch rate, involving flow straining and flame curvature in the tip of a two-dimensional Bunsen flame.

Numerical modeling results with one-step chemistry of lean M- and V-shaped methane/air flames are presented. The aim of this study is to validate the results obtained with the one-step chemistry model by comparing the results for M- and V-shaped flames with experimental results (Laser Doppler velocity measurements, flame shapes, the velocity gradient at the transition from an M-shaped flame to a V-shaped flame and the blowoff gradient of the V-shaped flame). The work described in this paper is a first step in the investigation of the blowoff mechanism of V-shaped flames and Bunsen flames. This paper can also be seen as a first step towards the modeling of M- and V-shaped flames with more complex chemistry models, e.g., with the skeletal chemistry model used recently in our group by Somers and de Goey (1995) to model a two-dimensional flame on a slit burner. Skeletal chemistry calculations, however, require extremely large memory sizes and are very time consuming. Furthermore, the fluid dynamics modeling is very important and not straightforward for M- and V-shaped

flames. The one-step chemistry modeling is an important and necessary step towards the skeletal chemistry modeling.

The experiments to validate the model are performed on a 4×55 mm rectangular slit burner (see Fig. 1). The slit is divided in two equal parallel slits of 1.75×55 mm separated by a flat plate (the flameholder) with a thickness $2t$ of 0.5 mm. The velocity profiles at the burner exit are fully developed. The shape of the profiles is parabolic in the plane perpendicular to the slits and top-hat like along the slits, so that a 2D numerical study is sufficient (Mallens and de Goeij (1995)). Both the flame shapes and the measured velocity profiles are symmetrical within a few percent.

FIGURE 1 The rectangular slit burner used for the experiments (measures in [mm]). The figure denotes a cross-section perpendicular to the flameholder plate and the rectangular slits.

A short description of the numerical model is given in the following section. Modeling results of an M- and a V-shaped flame with an equivalence ratio $\phi = 0.7$ will be discussed and compared with experimental results in the next section. The experimental results consist of the transition and blowoff gradient and of Laser Doppler velocity measurements near and within the flames, flame shapes, stand-off distances and critical transition and blowoff gradients. The paper ends with some conclusions.

COMBUSTION EQUATIONS AND CHEMICAL MODEL

The combustion equations, boundary conditions, chemical model, physical parameters and numerical method will be discussed briefly in this section. We refer to de Lange and de Goey (1993, 1994) and Mallens *et al.* (1995) for more details.

The 2D stationary flow field is modeled with a *vorticity-streamfunction* formulation (de Lange and de Goey (1994)) including gravity. The vorticity ω and the streamfunction ϕ are treated as in de Lange and de Goey (1993, 1994) and Smooke *et al.* (1989). The conservation equations for the streamfunction ϕ , the vorticity ω , the mass fractions Y_i and energy (in terms of the temperature T) are given by Smooke *et al.* (1989) and de Lange and de Goey. The boundary conditions at the in/outflow boundaries, the symmetry boundaries and the burner wall (shown in Fig. 2) for the flow velocity $V = (u, v)$, the temperature, the mass fractions and the streamfunction and the vorticity (specified in terms of the flow velocity) are treated by Mallens *et al.* (1995). Xu (1993) shows that the boundary conditions for the streamfunction and vorticity at the inlet have a large effect on the accuracy of the solution. The inlet boundary conditions for the streamfunction and the vorticity used in this paper are the same as the boundary conditions proposed by Xu (1993) to obtain agreement with results from primitive variable formulations. They consist of two boundary conditions for the streamfunction. The vorticity is then calculated from the equation for ϕ .

As chemical model, a one-step irreversible reaction *fuel + oxygen* $\rightarrow$ *products* is used with an Arrhenius-type source term for the fuel consumption rate:

$$\dot{p}_{fu}(T, \rho, Y_{fu}, Y_{ox}) = -A\rho^{\alpha+\beta}(Y_{fu})^{\alpha}(Y_{ox})^{\beta}e^{-T_a/T}. \quad (1)$$

Here A, α, β and T_a are reaction rate parameters ($\alpha = 2.8$, $\beta = 1.2$, $A = 2.6 \cdot 10^{15} [\text{kgm}^{-3}]^{-(\alpha+\beta)} \text{s}^{-1}$ and $T_a = 16900 \text{ K}$) and $Y_i (i = fu, ox, pr)$ are the mass fractions of fuel, oxidizer and products, respectively.

FIGURE 2 The computational domain.

The reaction rate parameters in Equation (1) are determined by fitting the numerical dependence of the burning velocity on temperature to experimental results (de Lange and de Goey (1993), van Maaren *et al.* (1994)). The deviation of the burning velocity predicted by Equation (1) from the experimental values is less than 10 % for methane/air flames with a equivalence ratio of $0.8 \leq \phi \leq 1.2$. More details are given by de Lange and de Goey (1993) and Mallens *et al.* (1995). The calculation of the physical transport properties (i.e., the specific heat, the combustion enthalpy, the thermal conductivity and the binary diffusion coefficients) is given by de Lange and de Goey (1993).

The numerical method used to solve the problem are elaborately discussed in de Lange and de Goey (1994). The conservative finite-volume method is applied to discretize the conservation equations. The discretization is performed on adaptive, locally-refined, non-staggered grids and the linearized set of algebraic equations is solved using the ADI method.

The numerical model has already been verified elaborately on flame properties of two-dimensional Bunsen flames on slit burners (de Lange and de Goey (1993), Mallens *et al.* (1995), Mallens and de Goey (1995)). A qualitative study of de Lange and de Goey (1993) showed that the model predicts the flame length and flame shape of premixed methane/air flames on slit burners within 10% accuracy. Recently, the model has been extended to the modeling of flames burning in a surrounding atmosphere of cold air by

Mallens *et al.* (1995). In this paper, the numerical results are compared with Laser Doppler Velocimetry measurements at various heights above the burner and with the shape of an experimental flame. This comparison has shown that the model reproduces the velocity field near and within a Bunsen flame on a 4 mm slit burner well; the largest deviations (equal to $\pm 10\%$) were found at the largest height above the burner. The flame shape of a cylindrical Bunsen flame on a 9.6 mm tube burner is also reproduced with a maximum deviation of $\pm 10\%$. The model has also been used by Mallens and de Goey (1995) to calculate critical flashback gradients for Bunsen flames on slit and tube burners. The gradients produced by the model differ no more than about 5 % from experimental values. An investigation of the energy transport in methane/air flames (Mallens (1995)) has shown that the flame thickness and the general behavior of the terms of the energy equation is in reasonably good agreement with skeletal chemistry simulations performed by Smooke and Giovangigli (1991).

RESULTS FOR M-SHAPED AND V-SHAPED FLAMES FOR $\phi = 0.7$

In this section we will present modeling results for two flames: an M-shaped flame with a *mean* inlet velocity (V) of 0.53 m/s and a V-shaped flame with $V = 0.73$ m/s. We define an M-shaped flame as a flame with a flame front curved towards the outer burner wall which is still cooled by the burner wall; a V-shaped flame is then defined as a flame with a flame front which is not curved towards the burner wall and which is not cooled by the outer burner wall anymore. The computational domain is given in Figure 2. The domain measures (in mm) are: $b = 2.0$, $B = 9.0$, $L_x = 30.0$ and $L_y = 40.0$. The height of the burner wall and the flameholder in y direction is equal to 1.0 mm and half the flameholder thickness (t) in Figure 2 is equal 0.25 mm.

In the remainder of this section numerical results will be presented and compared with experimental results for the M-shaped flame and the V-shaped flame. In the final part of this section critical velocity gradients at the transition from M-to V-shaped flame and at blowoff of the V-shaped flame are discussed.

The M-Shaped Flame

The numerical results for the chosen M-shaped flame, consisting of false color plots of the temperature, the fuel mass fraction and streamlines, are given in Figure 3. The results clearly show the typical shape of the flame.

FIGURE 3 False color plot of the temperature (*left part*) and the fuel mass fraction (*right part*) of the M-shaped flame with an equivalence ratio of 0.7 and a mean inlet velocity of 0.53 m/s. The black lines indicate streamlines. See COLOR PLATE X.

The maximum temperature is equal to 1793 K. This is close to the adiabatic flame temperature ($T_{ad} = 1815$ K) due to the large stand-off distance. The burnt gases above the flame are cooled significantly by the cold surrounding gases and are accelerated by gravitational forces. The numerical solution will be verified in more detail below.

The experimental flame shape (defined as the upstream boundary of the luminous zone) and the shape of the numerical flame (defined as the maximum locus of $\dot{\rho}_{fu}$) is given in Figure 4. The reproduction of the flame shape by the model is quite well above the thin flame holder and burner exit ($x \leq 0.002$ m), apart from small differences in stand-off distance and a slightly larger curvature of the experimental flame. The discrepancy becomes somewhat larger above the outer burner wall. The numerical stand-off distance (defined as the vertical distance between the top of the burner and the maximum locus of $\dot{\rho}_{fu}$) at the flameholder ($x = 0.0$) and the outer burner rim is equal to about 1.4 and 1.9 mm, respectively. The experimental stand-off distance is equal to 1.0 and 1.7 mm. It should be noted that discrepancies in flame position up to approximately 0.4 mm may occur due to differences in flame front definition.

FIGURE 4 The experimental M-shaped flame (defined as the upstream boundary of the luminous flame; markers) and the maximum locus of the fuel source term $\dot{\rho}_{fu}$ (line) in the modeled equivalent of the experimental flame.

The profiles of the vertical velocity component v at four heights y are given in Figure 5. The velocity profiles at the burner outflow ($y = 1.0$ mm) produced by the model and the outflow profiles of the experimental burner (see Fig. 5) differ only a few percent. The velocity profiles in the flame region (see Fig. 5) differ only a few percent. The velocity profiles change rapidly with increasing y and are, therefore, extremely sensitive to small differences in flame position or stand-off distance, i.e. the flow field near and within the flame is, in the cases studied here, almost solely determined by the vertical position of the flame. Furthermore, one has to separate two things: (i) the reproduction of the stand-off distance by the model and (ii) the reproduction of the velocity field by the model. The above implies that a comparison between the experimental and numerical flame is only meaningful if the numerical y values are corrected for the stand-off distance difference. We, therefore, corrected the numerical y values for the difference in the stand-off distance between the numerical and the experimental flame. The y values given in Figure 5 are the experimental values. The profiles at $y = 1.95$ mm in Figure 5, however, still show a different behavior for $x < 1$ mm due to slightly different flame positions. The experimental values of v are up to 25% higher than the numerical values. This is mainly caused by flame shape differences such as a different curvature of the flame front around $x = 0$. Small differences in the radius of curvature (R) of the flame front at $x = 0$ have a large effect on the vertical velocity, especially

FIGURE 5 Measured (left) and computed (right) velocity profiles in the M-shaped flame of the velocity component v at various heights y . The numerical y values have been corrected for the different stand-off distance of the numerical flame.

because the radius of curvature is very small $x = 0$. The decrease of the streamtube area which, together with the temperature increase, causes the velocity increase is very sensitive for small changes in R because of its approximate proportionality to $1/R$. The difference in flame curvature is probably caused by the lacking of highly diffusive radicals in the model. The highly curved flame may lead to high diffusive transport of these intermediates towards the unburnt mixture (out of the central streamtube) which, in turn, modifies the burning velocity and the flame shape. These effects are not incorporated in the one-step model.

It can be concluded from the above that the numerical model describes the global flame properties (flame shape, stand-off distance) of the M-shaped flame ($\phi = 0.7$) reasonably accurate. The absolute values of v predicted by the model are, however, considerably lower (up to 25 %) than the measured values.

The V-Shaped Flame

Figure 6 shows the numerical results for the V-shaped flame ($\phi = 0.7$; $V = 0.73$ m/s). The maximum temperature of the V-shaped flame (1800.0 K) is about equal to that of the M-shaped flame. The results given in Figure 6 will be discussed and verified below by comparing the flame shape, stand off distance and v profiles of the numerical flame with experimental results obtained from the experimental equivalent of the numerical flame.

FIGURE 6 False color plot of the fuel mass fraction (*left part*) and the temperature (*right part*) of the V-shaped flame with an equivalence ratio of 0.7 and a mean inlet velocity of 0.73 m/s. See COLOR PLATE XI.

The shape of the numerical V-shaped flame and its experimental equivalent is given in Figure 7. The difference between the stand-off distance (at $x = 0.0$) of the numerical flame (2.1 mm) and the experimental flame (1.3 mm) has increased to 0.8 mm. This difference in flame attachment point has a direct influence on the flame position at other locations. The difference between the position of the numerical and the experimental flame seems significant despite possible differences caused by different flame front definitions. Another difference between the numerical and the experimental flame is that the experimental flame wing ($x \geq 0.002$ m) is less curved than the numerical flame wing.

Profiles of the vertical velocity v as a function of x are given in Figure 8. As in the case of the M-shaped flame, the y coordinates (except $y = 1.0$) have been corrected for the difference in stand-off distance between the experimental and the numerical flame. The profiles at the burner outflow ($y = 1.0$) are well reproduced by the model. The shape of the profiles at higher y values is also reproduced reasonably well. The absolute values of v , however, differ up to 35 %. The vertical velocities v produced by the model are smaller than the experimental values. This was also the case for the M-shaped flame described in the previous section. In this case the discrepancies are probably also caused by flame shape differences, especially a different flame curvature at $x = 0$. The profile at $y = 1.95$ mm in Figure 8

FIGURE 7 The experimental V-shaped flame (defined as the upstream boundary of the luminous flame; markers) and the maximum locus of the fuel source term $\dot{\rho}_{fu}(\text{line})$ in the modeled equivalent of the experimental flame.

FIGURE 8 Measured (left) and computed (right) velocity profiles in the V-shaped flame of the velocity component v in at various heights y . The numerical y values have been corrected for the different stand-off distance of the numerical flame.

shows that the vertical velocity v for $x < 0.6$ is lower for the numerical flame. This implies that the lateral velocities in the positive x direction are higher for the numerical flame, i.e., the numerical flame wing stabilizes with a smaller angle with the x -axis and is less curved around the central axis. As explained in the previous sub-section, a slightly lower curvature of the flame around $x = 0$ gives rise to lower velocities v above the flame.

The above has shown that the model describes the global flame shape and the global behavior of the velocity field of the V-shaped flame reasonably well. The values of the stand-off distance and the vertical velocity, however, differ significantly. The reasons for this probably lie in the absence of highly diffusive radicals in the one-step model.

The Transition from M-to V-Shaped Flame and Blowoff of the V-Shaped Flame

The velocity gradient at the burner wall at which the modeled M-shaped flame becomes a V-shaped flame and the velocity gradient at which the modeled V-shaped flame blows-off will be compared with experimental results here.

The critical transition (g_t) and blowoff (g_b) velocity gradient at the burner wall is defined as follows:

$$g_{t,b} = \frac{3V_{t,b}}{2(b-t)}, \quad (2)$$

where the indices t and b refer to the transition and blowoff condition, respectively. The numerical gradients are calculated by increasing the inlet velocity of a converged numerical solution step by step with a step size of 5 %. After each velocity adjustment the calculation process is resumed until the solution is converged again. Note that the step size of 5 % introduces an uncertainty in the critical gradients of 5 %. Smaller steps would increase the calculation time too much and model assumptions and experimental irregularities give errors of the same order of magnitude.

The transition from M-to V-shaped flame generally does not happen suddenly at a certain mixture velocity. Instead, the transition starts with the detachment of the M-shaped flame at the outer burner wall (say, at a velocity $V_{t,1}$) and ends with a clearly V-shaped flame (at a velocity $V_{t,2} > V_{t,1}$). The critical transition gradient is calculated with $V_t = (V_{t,1} + V_{t,2})/2$. The uncertainty $(V_{t,2} - V_{t,1})/V_t$ is equal to about 6 % for the experimental and numerical transition gradients.

The velocity gradient at the burner wall of the M-shaped flame discussed above is equal to $g = 1817 \text{ s}^{-1}$. The transition of the numerical M-shaped flame to a V-shaped flame takes place at $g_t = (2115 \pm 75) \text{ s}^{-1}$. The uncertainty indicates the beginning and the end of the transition. The experimental value we obtained is $g_t = (2150 \pm 50) \text{ s}^{-1}$, the one obtained by Kawamura *et al.* (1979) is equal to about 2500 s^{-1} . The burner used by Kawamura *et al.* (1979) has, however, a slightly different geometry than our

burner which could lead to different gradients. The agreement between the measured profile $v(x)$ (Fig. 4) at the burner exit and the profile produced by the model leads to the conclusion that our burner geometry compares better with the numerical model than the one used by Kawamura *et al.* (1979).

The critical blowoff gradient g_b for the numerical V-shaped flame is equal to about $(2850 \pm 100) \text{ s}^{-1}$. The value obtained with our burner is about $(2600 \pm 100) \text{ s}^{-1}$ which is approximately 10 % lower than the numerical value. The gradient g_b obtained by Kawamura *et al.* (1979) ($g_b = 4000 \text{ s}^{-1}$) is considerably higher than the value obtained with our burner. The difference with Kawamura's result is probably also due to the differences in burner geometry.

Concluding we may say that the reproduction of the transition and blowoff gradient by the model is quite well. The numerical V-shaped flame seems slightly more stable than its experimental equivalent. This may be caused by various phenomena, such as differences in burning velocity, or disturbances in the experimental case.

CONCLUSIONS

In this paper one-step chemistry results of lean M- and V-shaped flames are presented and verified. The model describes the global flame properties (such as the flame shape and critical transition and blow-off gradients) reasonably well. This implies that the simplified chemistry and transport model is satisfactory for the present study. The velocity field above the burner is, however, only qualitatively predicted, i.e., the velocity values produced by the model differ considerably from the experimental values. This is caused by (relatively small) flame shape differences which are probably caused by the absence of highly diffusive intermediate species in the one-step chemistry model.

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References

- Lewis, B. and Von Elbe, G. (1961) *Combustion, Flames and Explosions of Gases*. Academic Press, New York, Second Edition, pp. 267–281.
- Edmondson, H. and Heap, M. P. (1970) Blowoff of Inverted Flames. *Combust. Flame*, **14**, 191–194.

- Kawamura, T., Asato, K., Mazaki, T., Hamaguchi, T. and Kayahara, H. (1979) Explanation of the Blowoff of Inverted Flames by the Area-Increase Concept. *Combust. Flame*, **35**, 109–116.
- Kawamura, T., Asato, K. and Mazaki, T. (1982) Reexamination of the Blowoff Mechanism of Premixed Flames-Inverted Flames. *Combust. Flame*, **45**, 225–233.
- Trevino, C., Donnerhack, S. and Peters, N. (1991) LDA Measurements in the Premixed V Flame Stabilized in the Wake of a Flat Plate Boundary Layer. *Combust. Flame*, **85**, 505–510.
- Sung, C. J., Law, C. K. and Umemura, A. (1992) On Adiabatic Stabilization of Inverted Flames. *Twenty-Fourth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh*, pp. 205–212.
- Goey, L. P. H. de., Mallens, R. M. M., Thije Boonkkamp, J. H. M. ten (1996) Application of the Generalized Flame Stretch Concept in Laminar Premixed Flame Modeling. *Sixth International Conference on Numerical Combustion*, March 4–6, 1996.
- Goey, L. P. H. de., Mallens, R. M. M. and Thije Boonkkamp, J. H. M. ten (1996) An Evaluation of Different Contributions to Flame Stretch for Stationary Premixed Flames. *Combust. Flame*, in press.
- Somers, L. M. T. (1995) A Numerical Study of a Premixed Flame on a Slit Burner. *Combust. Sci. and Tech.*, **108**, 121–132.
- Lange, H. C. de. and Goey, L. P. H. de. (1993) Two-dimensional methane/air flame. *Combust. Sci. and Tech.*, **92**, 423–427.
- Lange, H. C. de. and Goey, L. P. H. de. (1994) Numerical flow modelling in a locally refined grid. *Int. J. Num. meth. in Eng.*, **37**, 497–515.
- Mallens, R. M. M., Lange, H. C. de. and Ven, C. H. J. van de. and Goey, L. P. H. de. (1995) Modeling of Confined and Unconfined Laminar Premixed Flames on Slit and Tube Burners. *Combust. Sci. and Tech.*, **107**, 4–6, 387.
- Mallens, R. M. M. and Goey, L. P. H. de. (1995) Energy transport in two-dimensional laminar premixed methane/air flames. *Paper presented at the Eight International Symposium on Transport Phenomena in Combustion*, 16–20 July, San Francisco.
- Mallens, R. M. M. and Goey, L. P. H. de. (1995) Flashback of Laminar Premixed Methane/Air Flames. *Proc. of the Third Asian-Pacific International Symposium on Combustion and Energy Utilization*, ISBN 962-367-195-0, **II**, p. 644–649.
- Smooke, M. D. and Giovangigli, V. (1991) In *Lecture Notes in Physics* (M. D. Smooke, Ed.), 1991, **384**, p.1–29.
- Smooke, M. D., Mitchell, R. E. Keyes, D. E. (1989) Numerical solution of two-dimensional axisymmetric laminar diffusion flames. *Combust. Sci. and Tech.*, **67**, 85–122.
- Xu, Y. and Smooke, M. D. (1993) Application of a Primitive Variable Newton's Method for the Calculation of an Axisymmetric Laminar Diffusion Flame. *J. of Comp. Phys.*, **104**, 99–109.
- Maaren, A. van, Thung, D. S. and Goey, L. P. H. de. (1994) Measurement of flame temperature and adiabatic burning velocity of methane/air mixtures. *Combust. Sci. and Tech.*, **96**, 327–344.