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Modelling of a bluff body stabilized CH₄/H₂ flame based on a laminar flamelet model with emphasis on NO prediction

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Abstract: A laminar flamelet model prediction of a bluff body stabilized CH₄/H₂ flame is reported. The predicted results of temperature and major and minor species as well as NO are compared against the Raman/Rayleigh/LIF data available from the University of Sydney. The effect of differential diffusion is also studied. The calculation shows that temperature and concentration of major and minor species are better predicted by the unity Lewis number flamelet. It is also shown that the current steady state flamelet approach has difficulties in predicting experimental NO levels.

Keywords: bluff body, laminar flamelet, non-premixed

NOTATION

a	velocity gradient (strain rate)
$C_{\varepsilon 1}$	constant in the transport dissipation equation
C_{χ}	constant in the scalar dissipation rate equation
D	diameter
k	turbulence kinetic energy
$P()$	probability density function
S_{NO}	NO source term
u_j	velocity vector
x	axial location
Y_{NO}	mass fraction of NO
Z	mixture fraction
ε	turbulent energy dissipation rate
μ_{eff}	effective viscosity
ρ	density
σ_{NO}	Schmidt number
σ_{χ}^2	standard deviation of the log-normal distribution
ϕ	scalar variables
χ	scalar dissipation rate
ω_{NO}	generation rate of NO

Superscripts

-	conventional ensemble average
$\sim$	density-weighted ensemble average
//	density-weighted fluctuation

1 INTRODUCTION

The accurate prediction of combustion in practical systems has attracted the attention of many researchers over the last few decades because of its potential impact on development of improved combustion equipment. Better thermal efficiency and lower pollution emission are two of the benefits that can be obtained from the development of an advanced combustion model. Over the years, several combustion models that account for the interaction of turbulence and chemistry have been developed and applied to a number of flames ranging from simple jet flames to complex combustion chambers. Among the combustion models that are currently available, the most successful models have been the laminar flamelet model [1, 2], conditional moment closure (CMC) [3, 4] and probability density function (PDF) transport model [5, 6]. The present study is concerned with the laminar flamelet model and, in particular, the application of the flamelet model for NO prediction.

The laminar flamelet model considers the turbulent flame as an ensemble of laminar flamelets that are continuously

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stretched by the turbulent field. This model describes the non-equilibrium chemistry by introducing the scalar dissipation rate as a parameter to account for non-equilibrium effects [1, 2]. However, the flamelet approach still relies on the assumption that the time-scales for chemical kinetics are much shorter than the time-scales for convection and diffusion. With this concept, the mean temperature, density and composition in the turbulent field are obtained by appropriately averaging the flamelets, and each of the flamelets is subjected to a different level of fluid dynamic stretching characterized by the scalar dissipation rate. Combustion-generated pollutants such as NO, on the other hand, cannot be obtained from the flamelet library as the reaction rate of NO formation is slow; it is kinetically limited instead of diffusion limited. Therefore, an averaged transport equation for the mean NO mass fraction, $\bar{Y}_{\text{NO}}$, has to be solved. For a given mixture fraction and scalar dissipation rate, the source term for the NO transport equation is evaluated from the corresponding chemistry states in the flamelet library.

So far, the potential of the laminar flamelet model has not been extensively investigated for the prediction of NO formation. The use of the laminar flamelet model for the prediction of NO has begun only in the last few years [7–11]. Sanders *et al.* [7] have reported that the laminar flamelet model can reproduce the scaling behaviour of the NO emission index when the scalar dissipation rate is used as the stretching parameter. However, the absolute level of NO was overpredicted by a factor of 10 in their calculations. They attributed this error to many factors, including differential diffusion and radiation. The work by Schlatter *et al.* [8] and Sanders and Gökalp [9] showed that the scaling behaviour of NO emission was not reproduced when the strain rate was used as the non-equilibrium parameter. Chen and Chang [10] and Vranos *et al.* [11] have investigated the effects of differential diffusion and radiation on NO formation. The inclusion of radiation heat transfer reduced the level of NO by a factor of 2 [10], but the NO level was still overpredicted by a large margin. Vranos *et al.* [11] speculated that the overprediction of the NO level was caused by the differential diffusion effect. However, Chen and Chang [10] disputed that speculation and argued that the overprediction of the NO level could not be explained simply by the preferential diffusion effect. The literature review thus indicates that the formation of NO in turbulent flames is not fully understood yet. As a further example, Barlow and Carter [12] have shown, by using Raman/Rayleigh/LIF measurements, that the peak value of NO occurs at stoichiometric levels and the rich shift previously reported by Vranos *et al.* [11] is due to averaging effects. It is therefore essential that the existing laminar flamelet model is assessed against a large number of non-intrusive, spontaneous measurements to understand different factors influencing the NO formation before the predictive capability can be confidently implemented for design purposes. In the present study, the laminar flamelet model prediction of thermal NO is compared against the experimental data of Dally *et al.*

[13, 14]. The data can be downloaded from the University of Sydney website [15].

2 COMBUSTION MODEL

2.1 Laminar flamelet model

The laminar flamelet model views the turbulent flame as an ensemble of flamelet structures that are corrugated by the action of turbulent fluctuations. The laminar flamelet modelling of turbulent combustion requires an input of the flamelet library. The flamelet library can be generated by solving the flamelet equations that are derived from the transport equations for species mass fraction and energy by means of a coordinate transformation [16]. Alternatively, the flamelet profiles can be calculated by solving the governing equations for a counterflow diffusion flame [16]. The second approach is utilized in the present study mainly because this method allows a suitable means of investigating the differential diffusion effect. A different approach to generating the flamelet library can lead to different approximations in the predicted results. In the present study, the chemical mechanism used to generate flamelet profiles comprises 19 species and 43 reaction steps, including those for the NO mechanism. The reaction mechanism is taken from reference [17] and the flamelet library is generated using RUN-1DL code [18].

The flamelet profiles are described by the mixture fraction and the scalar dissipation rate. The mixture fraction is calculated from the mass fractions of species using Bilger's formula [19]. The scalar dissipation rate as a function of the mixture fraction in a counterflow geometry is given as in reference [1] by

$$\chi(Z) = \frac{a}{\pi} \exp\{-2[\text{erfc}^{-1}(2Z)]^2\} \quad (1)$$

where erfc^{-1} is the inverse of the complementary error function and a is the velocity gradient at the stagnation point. In the present study, the scalar dissipation rate calculated at the stoichiometric mixture fraction is used to identify the flamelet profiles.

For turbulent flames, the mean scalar variables are computed from the laminar flamelet relation of the mixture fraction and the scalar dissipation rate by integration over a joint probability density function as

$$\bar{\phi} = \int_0^\infty \int_0^1 \phi(Z, \chi) P(Z, \chi) dZ d\chi \quad (2)$$

The assumption of statistical independence leads to $P(Z, \chi) = P(Z)P(\chi)$ [1]. The probability density function of the mixture fraction, $P(Z)$, is assumed to be a beta distribution, and that of the scalar dissipation rate $P(\chi)$ to be a log-normal distribution [1]. In computational fluid dynamics (CFD) code, transport equations are solved for the mean mixture fraction, $\bar{Z}$, and mixture fraction variance,

$\tilde{Z}''^2$. The mean and variance of the mixture fraction completely describe the beta function. The mean value of the scalar dissipation rate can be modelled as

$$\tilde{\chi} = C_{\chi} \frac{\tilde{\varepsilon}}{\tilde{k}} \tilde{Z}''^2 \quad (3)$$

where $\tilde{k}$ and $\tilde{\varepsilon}$ are the mean turbulence kinetic energy and energy dissipation rate respectively, and C_{χ} is a constant with a value of 2.0 [1]. The standard deviation for the log-normal distribution of the scalar dissipation rate is set equal to $\sigma_{\chi}^2 = 2.0$ [1].

2.2 Flamelet-based NO modelling

As explained earlier, the concentration of NO in a turbulent flame cannot be obtained from the flamelet library. The slow, kinetically limited production of NO is obtained by solving the transport equation for NO

$$\frac{\partial}{\partial x_j} (\bar{\rho} \tilde{u}_j \tilde{Y}_{\text{NO}}) = \frac{\partial}{\partial x_j} \left(\frac{\mu_{\text{eff}}}{\sigma_{\text{NO}}} \frac{\partial Y_{\text{NO}}}{\partial x_j} \right) + \bar{\omega}_{\text{NO}} \quad (4)$$

where σ_{NO} is the turbulent Schmidt number, which is taken as 0.7. The mean rate, $\bar{\omega}_{\text{NO}}$, is obtained by averaging the instantaneous source term, S_{NO} , according to

$$\bar{\omega}_{\text{NO}} = \bar{\rho} \tilde{S}_{\text{NO}} = \bar{\rho} \int_0^{\infty} \int_0^1 S_{\text{NO}}(Z, \chi) P(Z) P(\chi) dZ d\chi \quad (5)$$

The emission of NO from flames is controlled by three mechanisms [20–23]:

- (a) the thermal NO mechanism,
- (b) the prompt NO mechanism,
- (c) the N₂O intermediate mechanism.

The thermal NO is formed by the well-known Zeldovich mechanism. This route is enhanced by the presence of superequilibrium O and OH and is very sensitive to temperature. In the prompt NO mechanism, hydrocarbon fragments attack the bimolecular nitrogen, producing atomic nitrogen, cyanides and amines, which are subsequently oxidized to NO. The N₂O route is analogous to the thermal route in that the O atom attacks the molecular nitrogen. However, with the presence of a third body, N₂O is formed and this subsequently reacts with O atoms to produce NO. The N₂O route is unimportant at low pressures, [10] and even at high pressures the maximum contribution was reported to be slightly over 11 per cent for a CH₄/air counterflow diffusion flame [21]. The relative contribution from different pathways depends on fuel type, temperature, pressure and residence time [13]. The high NO levels that occur in practical systems can only be reduced by reducing the thermal NO formation.

The NO formed through the thermal mechanism is considered here. The thermal NO is modelled by the

Fig. 1 Flamelet profile of the NO source term for different scalar dissipation rates

Zeldovich mechanism. The reaction rate parameters for the Zeldovich mechanism are well known and are taken from reference [24].

In Fig. 1 the NO source terms ω/ρ are shown as a function of mixture fraction for different stretch conditions. The differential diffusion effect is included in the calculation. The figure shows that the source term is very sensitive to the scalar dissipation rate. At $\chi = 0.064/\text{s}$, the source term is negative in the fuel-rich zone, indicating consumption of NO. At $\chi = 0.427/\text{s}$, the negative zone of the source term almost vanishes, but the peak value remains constant. With increase in the scalar dissipation rate, the temperature decreases while the mass fraction of O first increases, then remains less sensitive to the scalar dissipation rate and finally decreases as the scalar dissipation rate approaches the extinction limit. At $\chi = 0.427/\text{s}$, the decrease in temperature and the increase in mass fraction of O counterbalance each other and the peak source term remains almost constant. At scalar dissipation rates higher than $\chi = 0.427/\text{s}$, the decrease in temperature is more prominent, and that reduces the source term rapidly with increase in the scalar dissipation rate. At $\chi = 77.01/\text{s}$, the formation of NO almost ceases.

3 RESULTS AND DISCUSSION

3.1 Experimental configuration

The bluff body CH₄/H₂ flame investigated here was experimentally studied by Masri *et al.* [13, 14]. The flame was designated as HM1. The experimental data were obtained from the University of Sydney website [15]. The bluff body burner has an outer diameter $D_B = 50$ mm and a concentric fuel jet diameter $D_j = 3.6$ mm. The fuel jet is composed of 50 vol %CH₄ and 50 vol %H₂. The mean velocity of the fuel jet is 118 m/s and the mean air velocity is 40 m/s. A schematic drawing of the bluff body combustor as well as measurement locations is shown in Fig. 2.

Fig. 2 Schematic drawing of the bluff body stabilized flame and measurement locations. The figure is obtained from <http://www.mech.eng.usyd.edu.au/research/energy/resources.html>

3.2 Computational details

The governing differential equations are solved by using a finite volume in-house code based on the SIMPLE algorithm. The k - ϵ turbulence model is used for turbulence closure in the present study. The standard k - ϵ model has known shortcomings for predicting round jets. In particular, the k - ϵ model overpredicts the decay rate and the spreading rate of a round jet. Several modifications to the k - ϵ model are available for correcting this problem [25, 26]. In the present study, a simple modification to the value of $C_{\epsilon 1}$ of the ϵ -transport equation is made. The value of constant $C_{\epsilon 1}$ is modified from 1.44 to 1.60 following the work of Dally *et al.* [27] and Hossain *et al.* [28]. The value of $C_{\epsilon 1} = 1.60$ has also been recommended for modelling bluff body flames [29].

To compute the flowfield around the bluff body, the computational domain was extended to 170 mm in the radial direction and 216 mm in the axial direction. A 99 (axial) $\times$ 89 (radial) grid arrangement was used in all the calculations presented here. A grid sensitivity test using a 217 (axial) $\times$ 197 (radial) grid arrangement did not produce any significant difference in the results [28]. A fully developed velocity profile was specified at the inlet.

3.3 Prediction of flame structure

It is essential that the flowfield be adequately represented in the simulation, because the mixture fraction statistics completely determine the thermochemical state of the flame. It is even more important for the CH_4/H_2 flame, because it has a low stoichiometric mixture fraction ($Z_{\text{st}} = 0.05$). As a result, a small error in the flowfield will lead to a large error in temperature, species concentrations and location of the flame front.

Figures 3 and 4 show radial profiles of mean axial and radial velocities plotted at different locations. The mean axial velocity measurements are well predicted. The mean radial velocity measurements are also well reproduced, except at $x/D = 1.8$. The mean radial velocity measurements show some scatter, and the discrepancy may be attributed to the inaccuracies in the radial component measurements as discussed in reference [27]. There is little difference in the prediction of mean axial and radial velocity by the flamelet with differential diffusion and unity Lewis number.

Figure 5 shows the radial mixture fraction profiles at six axial locations. The mixture fraction profiles are reasonably well predicted in the near field ($x/D < 1.3$) by the flamelet both with and without a differential diffusion effect. Further downstream, the mixture fraction near the axis is under-predicted. This error can be attributed to the known over-estimation of the spreading rate of the round jet by the k - ϵ turbulence model, as explained earlier. Clearly, the decay rate is not well represented even after modifying the constant $C_{\epsilon 1}$.

Radial profiles of the mixture fraction variance are shown in Fig. 6. Mixture fraction variance is overpredicted in the near field ($x/D < 1.3$). The location of the peak in the near field is well reproduced. However, the prediction of the location of the peak is not very good further downstream.

Radial temperature profiles are shown in Fig. 7. The mean temperature distribution is fairly well predicted by the laminar flamelet model. The unity Lewis number flamelet prediction is approximately 100 K less than the differential diffusion prediction and is closer to experiment. However, at $x/D = 0.9$ and $x/D = 1.3$, the differential diffusion flamelet prediction is closer to measurements. This apparent discrepancy is caused by the overprediction of the mixture fraction variance at these locations, which results in lower temperature. It is worth mentioning that the significant overprediction at $x/D = 0.26$ was also observed by Dally *et al.* [27] who stated that the lower measured temperature compared with calculation is due to the averaging effects as a result of the intermittency in

Fig. 3 Mean axial velocity profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 4 Mean radial velocity profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 5 Mean mixture fraction profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 6 Mean mixture fraction variance profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 7 Mean temperature profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 8 Mean H₂O mass fraction profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 9 Mean CO_2 mass fraction profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 10 Mean OH mass fraction profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

Fig. 11 Mean NO mass fraction profile: •, measurements [15]; —, flamelet model with differential diffusion; ---, flamelet model with unity Lewis number

the flame at these locations and the overprediction is not due to the shortcomings in the simulation.

Radial distributions of H₂O and CO₂ mass fraction are shown in Figs 8 and 9 respectively. The flamelet model with unity Lewis number produces a much better agreement than the differential diffusion flamelet.

Radial profiles of OH mass fraction are shown in Fig. 10. The experimental data show that the reaction zone of OH is thin in the near field. The thickness of the reaction zone increases further downstream. The experimental data also show that the peak value of OH is low at $x/D = 0.26$, then gradually increases before decreasing again in the downstream locations. The flamelet model with and without a differential diffusion effect reproduces the general trend of the OH profile, i.e. the width of the reaction zone as well as the rate of decay of OH in the downstream. Again, the flamelet model with unity Lewis number reduces the experimental data quantitatively except at the first station.

3.4 Prediction of NO

The comparison between the predictions and the measurements for the radial mass fraction of NO is shown in Fig. 11. The flamelet model with the differential diffusion effect overpredicts the NO profiles at $x/D = 0.26$. This may be caused by the overprediction of temperature at this location. Further downstream, the difference between the predicted results and the measurements are reduced. The peak NO

level is correctly predicted at $x/D = 0.9$ and $x/D = 1.3$ by the flamelet model with the differential diffusion effect. However, the prediction is poor in the fuel-rich zone. The NO profiles are also overpredicted by a factor of about 1.75 at $x/D = 1.8$ and $x/D = 2.4$. At these locations, the overprediction of temperature as shown in Fig. 7 may induce this error. The flamelet with unity Lewis number underpredicts the NO level severely at every location.

The predicted results presented in the previous section indicate that the unity Lewis number flamelet provides better predictions for temperature and major and minor species. The prediction of NO mass fraction by the flamelet model with unity Lewis number is, however, poor. This inconsistency might have been caused by the chemical mechanism. The NO formed by the Zeldovich route is considered here. Though Chen and Chang [10] have shown that the Zeldovich mechanism is the dominant pathway for the production of NO in a turbulent CH₄/H₂ jet flame, the inclusion of the prompt NO and N₂O mechanism may bring the prediction with the unity Lewis number flamelet closer to the measurements. The NO measurements show that the NO level is low in the rich part (near the axis) of the flame. The NO level then reaches its peak further away from the axis near the flame front. This trend is well reproduced up to $x/D = 0.9$. Further downstream, the calculation shows a relatively high level of NO in the fuel-rich part of the flame. Chen and Chang [10] have shown that the NO is consumed in the rich part of the flame mainly through the reaction step

$\text{HCCO} + \text{NO} = \text{CO} + \text{HCNO}$. The importance of NO reburning through the HCN and CN intermediates in the rich system is described by a number of researchers [22, 23]. Thus, the relatively high level of NO in the fuel-rich part can be attributed to the non-inclusion of the NO reburn mechanism.

4 CONCLUSIONS

A laminar flamelet model prediction of a bluff body CH_4/H_2 turbulent non-premixed flame is reported here. The predicted results of temperature and major and minor species as well as NO are compared against the reported experimental data. In the laminar flamelet model, the mean temperature, density and composition in the turbulent field are obtained by appropriately averaging the flamelets. On the other hand, the concentration of NO is calculated by solving its own transport equation with the source term obtained from the flamelet library. The effect of differential diffusion on the temperature and species concentration is also investigated.

The flowfield is reasonably well reproduced in the calculation. Temperature and concentration of major and minor species are also well reproduced by the flamelet model with unity Lewis number. On the other hand, the concentration of NO is reproduced more reasonably by the flamelet with a diffusion effect. The conclusion must therefore be that the current treatment of turbulence–chemistry interactions is insufficient.

REFERENCES

- 1 Peters, N. Laminar flamelet model in non-premixed turbulent combustion. *Prog. Energy Combust. Sci.*, 1984, **10**, 319–339.
- 2 Peters, N. Laminar flamelet concepts in turbulent combustion. *Proc. Combust. Inst.*, 1986, **21**, 1231–1250.
- 3 Bilger, R.W. Conditional moment closure for turbulent reacting flows. *Physics Fluids A*, 1993, **5**(2), 436–444.
- 4 Bilger, R.W. Future progress in turbulent combustion research. *Prog. Energy Combust. Sci.*, 2000, **26**, 367–380.
- 5 Pope, S.B. PDF methods for turbulent reactive flows. *Prog. Energy Combust. Sci.*, 1985, **11**, 119–192.
- 6 Pope, S.B. Computation of turbulent combustion: progress and challenges. *Proc. Combust. Inst.*, 1990, **23**, 591–612.
- 7 Sanders, J.P.H., Chen, J.-Y. and Gökalp, I.G. Flamelet based modeling of NO formation in turbulent hydrogen jet diffusion flames. *Combust. Flame*, 1997, **111**, 1–15.
- 8 Schlatter, M., Ferreira, J.C., Flury, M. and Gass, J. Analysis of turbulence–chemistry interaction with respect to NO formation in turbulent, nonpremixed hydrogen–air flames. *Proc. Combust. Inst.*, 1996, **26**, 2215–2222.
- 9 Sanders, J.P.H. and Gökalp, I.G. Flamelet based predictions and scaling laws of NO formation in turbulent hydrogen diffusion flames. In 18th International Symposium on Transport Phenomenon in Combustion, San Francisco, California, 1995, pp. 286–297.
- 10 Chen, J.-Y. and Chang, W.C. Flamelet modelling of CO and NO_x emission from a turbulent, methane hydrogen jet non-premixed flame. *Proc. Combust. Inst.*, 1996, **26**, 2207–2214.
- 11 Vranos, A., Knight, B.A., Proscia, W.M., Chiappetta, L. and Smooke, M.D. Nitric oxide formation and differential diffusion in a methane hydrogen diffusion flame. *Proc. Combust. Inst.*, 1992, **24**, 377–384.
- 12 Barlow, R.S. and Carter, C.D. Raman/Rayleigh/LIF measurements of nitric oxide formation in turbulent hydrogen jet flames. *Combust. Flame*, 1994, **97**, 261–280.
- 13 Dally, B.B., Masri, A.R., Barlow, R.W., Fiechtner, G.J. and Fletcher, D.F. Measurements of NO in turbulent non-premixed flames stabilized on a bluff body. *Proc. Combust. Inst.*, 1996, **26**, 2191–2197.
- 14 Dally, B.B., Masri, A.R., Barlow, R.W. and Fiechtner, G.J. Instantaneous and mean compositional structure of bluff-body stabilized nonpremixed flames. *Combust. Flame*, 1998, **114**, 119–148.
- 15 Masri, A.R. Database available from Mechanical and Mechatronics Engineering, The University of Sydney, NSW 2006, Australia, <http://www.mech.eng.usyd.edu.au/research/energy/resources.html>
- 16 Peters, N. *Turbulent Combustion*, 2000 (Cambridge University Press).
- 17 Peters, N. Flame calculations with reduced mechanisms—an outline. *Reduced Kinetic Mechanisms for Applications in Combustion Systems* (Eds N. Peters and B. Rogg), 1993, Ch. 1, pp. 3–14 (Springer-Verlag, Berlin).
- 18 Rogg, B. RUN-1DL: The laminar flame and flamelet code, 1995.
- 19 Bilger, R.W. Structure of turbulent non-premixed flames. *Proc. Combust. Inst.*, 1988, **22**, 475–488.
- 20 Turns, S.R. Understanding NO_x formation in nonpremixed flames: experiments and modelling. *Prog. Energy Combust. Sci.*, 1995, **21**, 361–385.
- 21 Bonturi, S., Pourkashanian, M., Williams, A. Oskam, G. and Wilson, C. NO_x formation in counterflow opposed-jet diffusion CH_4/air flames. *Combust. Sci. Technol.*, 1996, **121**, 217–233.
- 22 Dupont, V., Pourkashanian, M., Richardson, A.P. and Williams, A. The importance of prompt-NO formation and of NO reconversion in strained binary rich partially premixed flames. In 18th International Symposium on Transport Phenomenon in Combustion, San Francisco, California, 1995, 263–274.
- 23 Miller, J.A. and Bowman, C.T. Mechanism and modeling of nitrogen chemistry in combustion. *Prog. Energy Combust. Sci.*, 1989, **15**, 287–338.
- 24 Warnatz, J., Mass, U. and Dibble, R.W. *Combustion: Physical and Chemical Fundamentals, Modelling and Simulation, Experiment, Pollutant Formation*, 1996 (Springer-Verlag, Berlin).
- 25 McGuirk, J.J. and Rodi, W. The calculation of three-dimensional free jets. 1st Symposium on Turbulent Shear Flows (Eds F. Durst *et al.*), 1979, pp. 71–83.
- 26 Pope, S.B. An explanation of the turbulent round-jet/plane-jet anomaly. *Am. Inst. Aeronaut. Astronaut. J.*, 1978, **16**, 279–281.
- 27 Dally, B.B., Fletcher, D.F. and Masri, A.R. Flow and mixing fields of turbulent bluff body jets and flames. *Combust. Theory Model.*, 1998, **2**, 193–219.
- 28 Hossain, M., Jones, J.C. and Malalasekera, W. Modelling of a bluff-body nonpremixed flame using a coupled radiation/flamelet combustion model. *Flow Turbulence and Combust.*, 2001, **67**, 217–234.
- 29 Website of the International Workshop on Measurements and Computation of Turbulent Nonpremixed Flames, <http://www.ca.sandia.gov/tdf/Workshop.html>