

A ONE-DIMENSIONAL MODEL OF JET FIRES AND OF ITS INTERACTION WITH OBSTACLES

Jorge Servert

Departamento de Ingeniería Energética y Fluidomecánica
ETSIIIM
Madrid
Spain

Antonio Crespo

Departamento de Ingeniería Energética y Fluidomecánica
ETSIIIM
Madrid
Spain

Julio Hernández

ETSII, UNED
Madrid
Spain

ABSTRACT

This paper describes a one-dimensional model of turbulent jet diffusion flames, which has been developed for releases of gaseous fuels considering the presence of non-uniform incident wind, the interaction with an engulfed obstacle, and thermal radiation. It is based on a one-dimensional formulation of the fluid dynamics equations complemented with models for chemical reaction, thermal radiation and an adaptation of the k- ϵ -g closure method. To formulate the one-dimensional model, the problem is considered to be parabolic along the center line of the flame and self-similar profiles in planes normal to this line are assumed. To evaluate the validity and usefulness of the model, its results have been compared with those of a three-dimensional model, developed by the authors, and with available wind-tunnel and full-scale experimental results, and a good agreement is found.

INTRODUCTION

Turbulent jet fires are present in many industrial processes, either as a hazard or as a result of a controlled relief of gas in some operational or emergency situations. It is of interest to know the characteristics of the flame and the heat transferred, either convective or radiative, to surroundings objects or engulfed obstacles. To assess the effect of these fires, mathematical models based on the Navier-Stokes equations, complemented with some appropriate models describing the combustion and a closure procedure to model the turbulent transport terms, are useful. Numerical models are generally based on finite-difference approximations of the fluid dynamics equations

(Fairweather et al., 1992; Hernández and Crespo, 1992), which are fairly difficult and time consuming to solve.

The flow equations can be simplified if a jet center line and self-similar profiles in planes normal to it can be defined. Then, the partial differential equations may be converted to ordinary differential equations, with the distance along the center line as independent variable. The problem is then simpler and the computer time is substantially reduced, from hours to fractions of minutes. This type of one-dimensional or integral model has been used extensively by Escudier (1972), Fay (1973), Tamanini (1981), Peters and Göttgens (1991), Cook (1991), and Caulfield et al. (1993), among others. In this work, we present a rigorous way to deduce the one-dimensional equations, that, in our knowledge, has not previously been formulated. A more detailed description of the derivation of this model, UPMFIRE, can be found in Servert (1993). Fay (1973) proposed a model somehow similar to ours, but it has a more complex interpretation and the definition of the average quantities depends on the existence of an ambient wind. UPMFIRE applies to situations in which there is both ambient wind with shear and no wind.

Whereas other models (Escudier, 1972; Cook, 1991; Caulfield et al., 1993; Tamanini, 1981) either assume top-hat profiles or sine-type profiles that end at a finite distance from the center line, UPMFIRE can also be applied using self-similar profiles that extend to infinity in the transverse direction.

The three-dimensional equations describing the flow field are formulated assuming that the flow is parabolic along the center line. The k- ϵ -g model is used to close the turbulent equations, and relations for the mixture fraction

and its variance are formulated.

The combustion model is based on an infinitely-fast reaction mechanism and a prescribed shape for the probability-density function of the mixture fraction. The mass fractions of fuel, carbon dioxide and water vapor are obtained as functions of the mixture fraction and its variance, and the temperature is determined as a function of these same variables and of the enthalpy. A separate method, similar to the one proposed by Caulfield et al. (1993), is used to calculate the soot mass fraction.

Integrating the three-dimensional equations in cross sections and applying an spatial average to the different flow quantities, the one-dimensional equations are obtained. If the turbulent diffusivities of all the variables are equal, a single relationship between the average and maximum values of the quantities is obtained that simplifies the numerical calculation, in particular the calculation of the source terms.

Further manipulation of both the one-dimensional and the three-dimensional equations leads to a generalization of Tamanini's (1981) expression for the production term of the turbulent kinetic energy and of the variance of the mixture fraction, so that it takes into account the cross-wind effect, and its validity is extended to arbitrary spatial distributions.

The one-dimensional model has been modified to include the effect of an engulfed obstacle, small in comparison with the characteristic length of the flame, by means of a finite jump in the flow conditions.

Finally, a comparison is made with wind-tunnel experimental results (Duijm, 1993; Verheij and Duijm, 1991) and with full-scale measurements (Ott, 1991). The model has also been validated with a three-dimensional model (Hernández and Crespo, 1992). In general, the results seem to be in good agreement, and UPMFIRE can be considered as a useful tool in risk assessment.

3-D GOVERNING EQUATIONS

The one-dimensional model will be derived from the Favre-averaged, three-dimensional conservation equations of mass, momentum, energy, mixture fraction, turbulent kinetic energy, dissipation rate of the turbulent kinetic energy and variance of the mixture fraction (Hernández and Crespo, 1992), which may be written in the general form

$$\nabla \cdot (\bar{\rho} \bar{v} \bar{\phi} - \vec{\Gamma}_{\phi}) = S_{\phi} \quad (1)$$

where ϕ can be equal to: 1, any component of the velocity, \bar{v} , total enthalpy, h , mixture fraction, ξ , turbulent kinetic energy, k , dissipation rate of the turbulent kinetic energy,

ϵ , or variance of the mixture fraction, g . In this equation, ρ is the density and S_{ϕ} is the source term. The Favre average is denoted by a tilde and the temporal average by a dash. The diffusion vector (except for the velocity components, for which some additional terms appear) is expressed as

$$\vec{\Gamma}_{\phi} = \frac{\mu_t}{\sigma_{\phi}} \nabla \bar{\phi} \quad (2)$$

where μ_t is the turbulent dynamic viscosity, and σ_{ϕ} is the turbulent Prandtl number for the variable ϕ . The turbulent viscosity is obtained from

$$\mu_t = C_{\mu} \bar{\rho} \frac{k^2}{\epsilon} \quad (3)$$

where $C_{\mu} = 0.09$.

The source terms include buoyancy effects in the vertical momentum equation, thermal radiation in the energy equation (in which gravity has been neglected and the Mach number is assumed to be low), and production and dissipation terms in equations for k , ϵ and g .

The model is completed with a perfect gas law and the state equation for enthalpy.

COMBUSTION MODEL

To define the combustion model, the classical hypothesis of one-step, irreversible reaction, represented by [Fuel + r_s Oxidizer \rightarrow (1+ r_s) Products], fast chemistry and equal diffusivities for all the species are made. This leads to the classical conserved-scalar approach and to the well known relation

$$Y_f(\xi) = \frac{\xi - \xi_s}{1 - \xi_s}; \quad \xi > \xi_s \quad (4)$$

$$Y_f(\xi) = 0; \quad \xi \leq \xi_s$$

where Y_f is the fuel mass fraction and ξ_s is the stoichiometric mixture fraction.

From the instantaneous value, the Favre average is obtained through

$$\bar{Y}_f = \frac{1}{1 - \xi_s} \int_{\xi_s}^1 (\xi - \xi_s) P(\xi) d\xi \quad (5)$$

Two predefined shapes for the probability-density function, $P(\xi)$, are used: a two-delta function and a beta function, whose parameters are expressed in terms of the mean and the variance of the mixture fraction. An alternative approach is to correct the expression (4) applied to the average mixture fraction to account for the unmixedness due to the turbulence:

$$\tilde{Y}_F = Y_F(\bar{\xi}) + \frac{Y_{F1}}{1 - \xi_s} \sqrt{g} J \left(\frac{\xi_s - \bar{\xi}}{\sqrt{g}} \right) \quad (6)$$

where J can either be estimated from (5) or from the following correlation (Mudford and Bilger, 1984):

$$J = 0.45 \exp \left(- \frac{|\xi_s - \bar{\xi}|}{\sqrt{g}} \right) \quad (7)$$

The mass fractions of oxygen and products are

$$\tilde{Y}_O = (r_s \tilde{Y}_F + \tilde{Y}_{O_s}) - \xi (r_s + \tilde{Y}_{O_s}) \quad (8)$$

$$\tilde{Y}_P = (r_s + 1) (\xi - \tilde{Y}_F) \quad (9)$$

where r_s is the stoichiometric ratio and the subscript a represents ambient conditions.

The products are mainly H_2O and CO_2 , whose mass fractions are obtained from the stoichiometry. Other products are assumed to have small mass fractions, and are not relevant except for soot, which is considered because it plays an important role in radiative processes. The soot mass fraction calculation procedure is discussed latter.

Enthalpy and temperature are related by

$$d\tilde{h} = c_p d\tilde{T} + Q d\tilde{Y}_F \quad (10)$$

If the specific heat at constant pressure, c_p , and the heat of reaction, Q , are constant,

$$\tilde{h} = c_p \tilde{T} + Q \tilde{Y}_F \quad (11)$$

This relation is used to obtain temperature from enthalpy and fuel mass fraction.

AMBIENT FLOW

The ambient flow, where the jet diffuses, corresponds to the surface layer of the atmospheric boundary layer. For the case of neutral conditions, if the magnitudes change only with the vertical distance to the ground, the only velocity component is

$$v_s = v_{zs} = 2.5 u^* \log \frac{z}{z_0} \quad (12)$$

where u^* is the friction velocity and z_0 the surface roughness. In the model, a similar equation which retains stability effects in the atmosphere by means of the Monin-Obukhov length as a parameter can also be used (Servert, 1993).

The distributions of the turbulent kinetic energy and its dissipation rate are given by

$$k_s = \frac{u^{*2}}{C_{\mu}^{0.5}}, \quad \varepsilon_s = 2.5 \frac{u^{*3}}{z} \quad (13)$$

The variations of density, pressure and enthalpy can be easily obtained. In a first approximation, density and enthalpy are assumed to be constant. Finally, the ambient is considered to be free of fuel, so that $\xi_s = 0$ and $g_s = 0$.

It can be observed that the ambient flow satisfies the general equation (1):

$$\nabla \cdot (\rho_s \vec{v}_s \phi_s - \Gamma_{\phi_s}) = S_{\phi_s} \quad (14)$$

DEFINITION OF THE SPATIAL AVERAGES

The central hypothesis of 1-D models is the existence of self-similar axisymmetric profiles for the dependent variables of equation (1), such as

$$\bar{\phi} - \phi_s = (\phi_0 - \phi_s) \psi_{\phi} \left(\frac{r}{R} \right) \quad (15)$$

$$\text{where } \psi_{\phi} \text{ satisfies } \int_0^{\infty} \psi_{\phi} 2\pi r dr = \pi R^2, \quad \psi_{\phi}(0) = 1$$

R and ϕ_0 are the spatial distribution parameters, which are functions of the coordinate along the flame, and r is the radial coordinate. In the initial sections, while the jet is developing, no self-similarity exists. At the jet exit, the

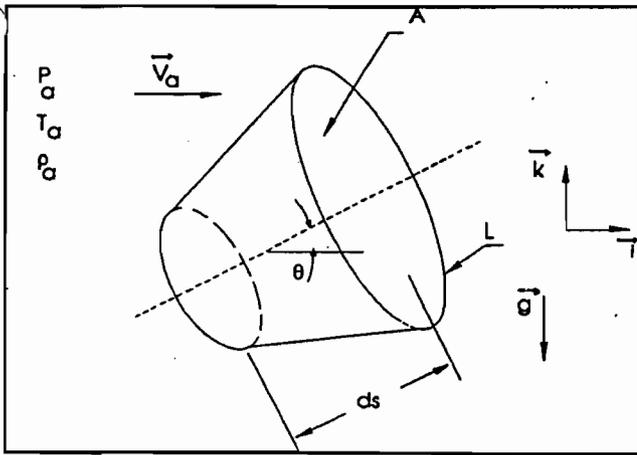


Figure 1. Control volume.

profile is usually a top-hat which relaxes downstream to a more Gaussian-like profile. The hypothesis of self-similarity and axial symmetry are not strictly true due to the cross-wind and buoyancy effects.

A typical difficulty of the one-dimensional models is the divergence of the integrals defining the average values when the flame perturbation extends to infinity. To avoid this difficulty, we propose the following spatial-average method:

$$\dot{m}(\langle \bar{\phi} \rangle - \phi_a) = \lim_{A \rightarrow \infty} \int_A \bar{\rho} \bar{u} (\bar{\phi} - \phi_a) dA \quad (16)$$

where \bar{u} is the velocity normal to the surface A. This surface is perpendicular to the center line, and the average value of the velocity component contained in A, $\langle \bar{u} \rangle$, is equal to zero.

The mass flow rate, \dot{m} , across A is defined by

$$\dot{m} - \dot{m}_a = \lim_{A \rightarrow \infty} \int_A (\bar{\rho} \bar{u} - \rho_a v_a \cos \theta) dA \quad (17)$$

where

$$\dot{m}_a = \dot{m} \frac{\rho_a v_a \cos \theta}{\langle \bar{\rho} \rangle \langle \bar{u} \rangle} \quad (18)$$

and θ is the angle that the normal to the surface A forms with the horizontal plane.

The average density is defined using an equation of state:

$$\langle \bar{\rho} \rangle = \frac{p_a}{R_g \langle \bar{T} \rangle} \quad (19)$$

where p_a is the ambient pressure, R_g is the gas constant, and equation (16) is used to evaluate $\langle \bar{T} \rangle$, even though temperature is not a dependent variable of equation (1).

The radius of the flame is

$$b = \sqrt{\frac{\dot{m}}{\langle \bar{\rho} \rangle \langle \bar{u} \rangle \pi}} \quad (20)$$

ONE-DIMENSIONAL CONSERVATION EQUATIONS

To obtain the one-dimensional conservation equations, the following procedure is used. First, the general equations for the perturbed and unperturbed flows are subtracted

$$\nabla \cdot (\bar{\rho} \bar{v} \bar{\phi} - \rho_a \bar{v}_a \phi - \bar{\Gamma}_\phi + \Gamma_{\phi a}) = S_\phi - S_{\phi a} \quad (21)$$

and integrated over the control volume shown in Fig. 1, which is limited by two cross-sections, infinitely close to each other, and a lateral surface far enough from the center-line, where ϕ tends to ϕ_a . Then, the result is simplified using the parabolic hypothesis and assuming that the difference between the perturbed and unperturbed diffusion fluxes decrease with radial distance faster than $A^{-1/2}$; as a consequence, the diffusion vector vanishes over all the surfaces enclosing the control volume. Finally, the definitions (16) to (20) are applied.

For the particular case of $\phi = 1$, the mass conservation equation is obtained,

$$\frac{d\dot{m}}{ds} = \dot{m}'_0 \quad (22)$$

where

$$\dot{m}'_0 = \frac{d\dot{m}_a}{ds} - \lim_{A \rightarrow \infty} \int_L (\bar{\rho} \bar{w} - \rho_a v_a \cos \theta) dl \quad (23)$$

\dot{m}'_0 is the entrained mass per unit length and time. The argument of the last integral tends to zero as $A^{-1/2}$ does; hence, this term tends to a finite value.

For ϕ different from 1,

$$\frac{d}{ds}(\dot{m}\langle\bar{\phi}\rangle) = \phi_s \dot{m}'_0 + \dot{m}_s \frac{d\phi_s}{ds} + \Delta\Sigma_\phi \quad (24)$$

where the source term is

$$\Delta\Sigma_\phi = \lim_{A \rightarrow \infty} \int_A (S_\phi - S_{\phi_s}) dA \quad (25)$$

The first term in the r.h.s. of (24) represents the entrainment of ϕ_s . The second and third terms represent the source contribution. In equations (16), (17), (23) and (24), the ambient values have been subtracted to make the integrals converge; therefore, other terms appear in these equations: $\dot{m}\phi_s$, \dot{m}_s , $d\dot{m}_s/ds$ and $\dot{m}_s d\phi_s/ds$, respectively.

The flame trajectory and angle θ are given by

$$\tan(\theta) = \frac{dz}{dx} = \frac{\langle\bar{v}_z\rangle}{\langle\bar{v}_x\rangle}, \quad ds = (dx^2 + dz^2)^{1/2} \quad (26)$$

MASS ENTRAINMENT ASSUMPTIONS

To estimate the mass entrainment, two models are used. In the first one,

$$\dot{m}'_0 = 2\pi b \bar{\rho}_s \sqrt{\frac{\langle\bar{\rho}\rangle}{\rho_s}} (\alpha |\langle\bar{u}\rangle - v_s \cos\theta| + \beta |v_s \sin\theta|) \quad (27)$$

where the factor $(\langle\bar{\rho}\rangle/\rho_s)^{1/2}$ is due to Ricou and Spalding (1961), and $\alpha = 0.057$ and $\beta = 0.5$ in the present model. The second one, due to Tamanini (1981), in which

$$\dot{m}'_0 = C_m \mu_t \quad (28)$$

is based on the analytical solution for a jet obtained by Schlichting (1968). In UPMFIRE, C_m is given the value 20, whereas $C_m = 17$ in Caulfield et al. (1993), who include additional terms representing the entrainment due to the wind component normal to the flame.

The turbulent viscosity is evaluated using the classical k- ϵ method directly applied to the average values

$$\langle\mu_t\rangle = C_\mu \langle\bar{\rho}\rangle \frac{\langle k \rangle^2}{\langle \epsilon \rangle} \quad (29)$$

RELATIONSHIP BETWEEN THE AVERAGE VALUES AND DISTRIBUTION PARAMETERS

A useful expression, relating spatial averaged values to the spatial distribution parameters ϕ_0 and R , can be obtained by applying (16) to the dependent variables of equation (1) and to the temperature (even though the temperature does not satisfy the self-similar profiles defined by equation (15)).

If the function ψ_ϕ is equal for all the magnitudes, the following relation holds for each ϕ

$$\gamma = \frac{\langle\bar{\phi}\rangle - \phi_s}{\phi_0 - \phi_s} = \frac{R^2}{b^2} \quad (30)$$

where

$$\gamma = \frac{\int_0^\infty (\bar{\rho}\bar{u} - \rho_s v_s \cos\theta) \Psi dA}{\int_0^\infty (\bar{\rho}\bar{u} - \rho_s v_s \cos\theta) dA} \quad (31)$$

In this equation, density is evaluated from temperature using the state equation. Temperature is obtained from equation (11) in terms of enthalpy and fuel mass fraction, which is related to the mixture fraction and its variance through equations (5) or (6). Servert (1993) has evaluated γ for a Gaussian shape of ψ , $\psi = \exp(-r^2/R^2)$, and has shown that it mainly depends on the value of the mixture fraction, and that it tends to 0.5 far downstream.

Equation (30) is always valid for the velocity components and for all the dependent variables whose distribution ψ_ϕ is equal to that of the velocity components.

GENERAL FORMULATION OF THE SOURCE TERM

If the distribution profile ψ_ϕ were a top-hat, the source term would be

$$\Delta\Sigma_\phi = (S_\phi - S_{\phi_s}) \pi b^2 \quad (32)$$

However, the top-hat assumption is not always a good approximation, particularly upstream of the flame due to the behavior of the density and the temperature. To overcome this difficulty, it is more convenient to write

$$\Delta\Sigma_s = \alpha_s (\hat{S}_s - S_{s*}) \pi b^2 \quad (33)$$

$$\hat{S}_s = S_s \langle \phi_s \rangle$$

where the average source term is defined by substituting the local values of the variables by their averaged values. The correction coefficient α_s is expressed as a function of the averaged values through equation (30). For a top-hat, α_s would be equal to one. This coefficient usually depends mainly on the spatial-averaged mixture fraction.

In the vertical momentum equation, the buoyancy term is

$$\Delta\Sigma_{vz} = \lim_{A \rightarrow \omega_A} \int (\rho_s - \bar{\rho}) g_r dA = \alpha_{vz} (\rho_s - \langle \bar{\rho} \rangle) g_r \pi b^2 \quad (34)$$

where g_r represents the gravity acceleration. The coefficient α_{vz} is close to one downstream of the flame tip, and larger than one upstream.

Assuming that the gas is optically thin and that the absorption coefficient is constant in the plane normal to the center line, equation (33) can be written as follows:

$$\Delta\Sigma_s = -\alpha_s \epsilon_r \sigma_b (\langle \tilde{T} \rangle^4 - T_s^4) 2\pi b \quad (35)$$

where σ_b is the Boltzmann constant and $\epsilon_r = 2ba$, with a being the absorption coefficient. This equation has been generalized to the case of a non-thin gas, and the flame is considered locally as a cylindrical surface of radius b and emissivity ϵ_r . The Modak (1975) method is used to evaluate ϵ_r .

For the turbulent kinetic energy, there are several source terms. The mechanical production, $\Delta\Sigma_{pk}$, could be estimated using a direct calculation (Caulfield et al., 1993),

$$\Delta\Sigma_{pk} = \lim_{A \rightarrow \omega_A} \int \mu_t \left(\frac{\partial \bar{u}}{\partial r} \right)^2 2\pi r dr \quad (36)$$

where the parabolic approximation is used. However, this method fails for a top-hat profile. We have extended an alternative procedure, originally suggested by Tamanini (1981) for non-wind and top-hat profiles, to the case of having a cross-wind and any distribution profile. Servert (1993) shows that

$$\Delta\Sigma_{pk} = m'_0 \frac{(\langle \bar{v} \rangle - \bar{v}_s)^2}{2} \alpha_{k1} \quad (37)$$

plus some additional terms due to ambient flow variation.

The production of $\langle k \rangle$ by buoyancy is neglected by some authors, or retained using a top-hat approximation. We have kept this term and, due to its small contribution, the correction coefficient has been considered equal to one.

For the dissipation rate of $\langle k \rangle$, $\Delta\Sigma_{Dk}$, it can be shown that the correction coefficient can be taken equal to one,

$$\Delta\Sigma_{Dk} = -(\langle \bar{\rho} \rangle \langle \epsilon \rangle - \rho_s \epsilon_s) \pi b^2 \quad (38)$$

We consider that the source terms in equation for $\langle \epsilon \rangle$ are equal to those in equation for $\langle k \rangle$ corrected by the factor $\langle \epsilon \rangle / \langle k \rangle$. The classical constants of the k- ϵ model are used: $C_{\epsilon 1} = 1.44$, $C_{\epsilon 2} = 1.82$, and $C_{\epsilon 3} = 0.95$.

The production of g , $\Delta\Sigma_{pg}$, and $\Delta\Sigma_{pk}$ are of a similar nature. It can be shown that

$$\Delta\Sigma_{pg} = \alpha_{pg} m'_0 \langle \xi_s \rangle^2 \quad (39)$$

The dissipation term in the three-dimensional equation for g is used in the one-dimensional equation by direct substitution of the averaged quantities, and the correction coefficient is considered equal to one, so that

$$\Delta\Sigma_{Dg} = -C_g \langle \bar{\rho} \rangle \langle \epsilon \rangle \frac{\langle g \rangle}{\langle k \rangle} \pi b^2 \quad (40)$$

where $C_g = 0.8$ is a constant of the k- ϵ -g model.

Caulfield et al. (1993) have adapted a model of soot production proposed by Fairweather et al. (1991) to the one-dimensional case. We use a similar one where soot formation proceeds from the pyrolysis of acetylene through nucleation and surface growth. Acetylene mass fraction is evaluated from calculations of CH₄/air laminar flames using a strain rate of 60 s⁻¹. There are two coupled equations: one for the soot mass fraction, where the source terms correspond to nucleation, surface growth and oxidation processes, and another one for the particle number density, where there are source terms for nucleation and coagulation.

JUMP IN FLOW CONDITIONS ACROSS AN OBSTACLE

The analysis of the interaction of turbulent diffusion flames with an obstacle has different applications; i.e., the estimation of the heat transferred to a pipe-line or a tank in accidental situations.

One-dimensional models are useful to evaluate the interaction with an obstacle whose characteristic length is much smaller than the flame size. We assume that the obstacle is completely engulfed by the flame. The interaction is represented by the drag force, D_i , and the heat exchanged, Q_i . Due to the small size of the obstacle, we assume that the problem can still be considered as parabolic, although this assumption fails locally.

To estimate the drag force, we use

$$D_i = \frac{1}{2} \langle \bar{\rho} \rangle \langle \bar{u} \rangle^2 A_T C_D \quad (41)$$

here A_T is the projected area of the obstacle over the plane normal to the center line and C_D is a drag coefficient. The heat exchanged between the flame and the obstacle has two contributions: radiation, which is discussed latter, and convection, calculated using

$$Q_{ic} = \kappa_g \langle \bar{T} \rangle - T_{ob} \rangle L_{ob} Nu \quad (42)$$

where κ_g is the gas conductivity, T_{ob} the obstacle temperature, L_{ob} the characteristic length of the obstacle and Nu the Nusselt number.

The jump in flow conditions across the object is represented by source terms in the conservation equations:

$$\Delta(\dot{m}) = 0 \quad (43)$$

$$\Delta(\dot{m} \langle \bar{v}_z \rangle) = -D_i \cos \theta \quad (44)$$

$$\Delta(\dot{m} \langle \bar{v}_x \rangle) = -D_i \sin \theta \quad (45)$$

$$\Delta(\dot{m} \langle k \rangle) = -D_i \langle \bar{u} \rangle \quad (46)$$

$$\Delta(\dot{m} \langle \epsilon \rangle) = -D_i \langle \bar{u} \rangle \frac{\langle \epsilon \rangle}{\langle k \rangle} C_{\epsilon 1} \quad (47)$$

$$\Delta(\dot{m} \langle \bar{h} \rangle) = -Q_i \quad (48)$$

$$\Delta(\dot{m} \langle g \rangle) = 0 \quad (49)$$

$$\Delta(\dot{m} \langle \bar{\xi} \rangle) = 0 \quad (50)$$

It has been assumed that the energy dissipated by drag is fully converted into turbulent kinetic energy. The classical coefficient of the k - ϵ - g model for the production of ϵ , $C_{\epsilon 1}$, is kept in (47) because the mechanism involved is the same. Although the mixing enhancement due to the presence of the obstacle decreases the value of g , this effect is partially taken into account by the increase of ϵ , and thus no source term is included in equation (49).

RADIATION TO OBJECTS ENGLUFED BY THE FLAME

To evaluate the heat exchanged by the flame to an engulfed object surface, we adapt to this case the zoning method (Hottel and Sarofim, 1967), considering an average absorption coefficient for each section, so that

$$Q_{ir} = \int_{A_s} \int_{A_{ob}} a \frac{\sigma_b \bar{T}^4}{\pi} \frac{\cos \theta_{ob}}{s^2} \exp\left(-\int_0^{s^*} a ds\right) dA_s dA_{ob} \quad (51)$$

where s^* is the distance from the flame volume element to the surface element of the obstacle and θ_{ob} is the angle between the normal to the surface and the line which joins the volume and surface elements. We estimate the absorption coefficient assuming $a = \log(1-\epsilon)/(2b)$. This integral is evaluated for each cross section; a detailed description can be found in Servert (1993).

EXPERIMENTAL VALIDATION

The one-dimensional model UPMFIRE has been validated by comparison with both wind-tunnel experiments carried out by Duijm (1993) and Verheij and Duijm (1991) and full-scale measurements carried out by Ott (1991). A comparison with a three-dimensional model (Hernández and Crespo, 1992) has also been made.

In Fig. 2, a comparison between the temperature contours in the vertical plane containing the burner axis obtained with the one-dimensional model, the three-dimensional model and wind-tunnel experimental results is shown. This case corresponds to a release of methane through a 5 mm nozzle at 250 mm over the ground, with

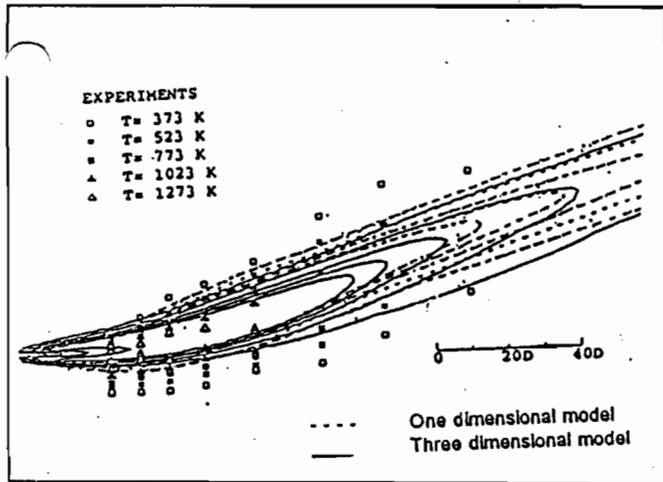


Figure 2. Temperature contours.

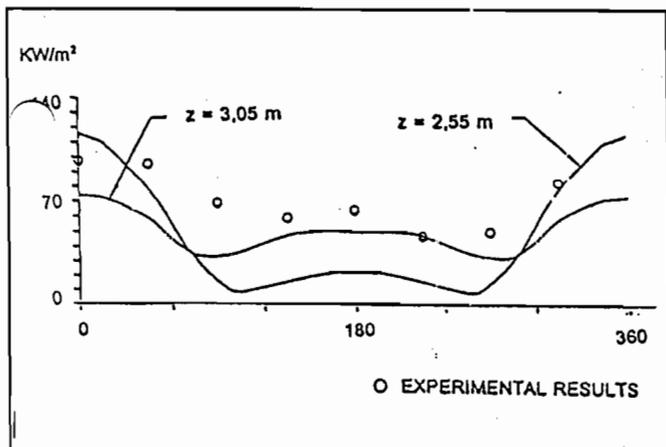


Figure 3. Radiation to a vertical cylinder.

a fuel exit velocity of 26.2 m/s and a wind speed of 1.52 m/s at 500 mm over the ground, with a ground roughness of 3.9×10^{-5} m. The agreement is good, although the temperature contours are in general longer and thinner in the one-dimensional model than in the three-dimensional one.

In Fig. 3, experimental data are compared with the results obtained from the model for the thermal radiation flux emitted by the flame on an engulfed vertical cylinder. The case corresponds to a release of methane through a 50 mm nozzle at 2.5 m over the ground, with a fuel exit velocity of 82.94 m/s, and a wind speed of 3.74 m/s at 7 m over the ground and of 6.59 m/s at 18 m. The radiation flux has been measured at the horizontal slice of the cylinder where the flux is maximum, and it has been computed for slices at 3.05 m and 2.55 m over the ground, located around the place where the measurements were made. A good agreement between experiments and model results is found.

ACKNOWLEDGEMENTS

This work has been supported by the CEC under contract CT90-0098 within the programme STEP.

REFERENCES

- Caulfield, M., et al., 1993, "An Integral Model of Turbulent Jets in a Cross-Flow; Part 1-Gas Dispersion, Part 2-Fires," *Trans. IChemE* 71:235-251.
- Cook, D.K., 1991, *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 653-660.
- Duijm, N.J., 1993, JIVE Progress Report no. 3; TNO-IMET Report no. 93.
- Escudier, M.P., 1972, "Aerodynamics of a Burning Turbulent Gas Jet in a Crossflow," *Combust. Sci. Technol.* 4:293-301.
- Fairweather, W.P., et al., 1991, "Predictions of Radiative Transfer from a Turbulent Reacting Jet in a Cross-Wind," *Combust. Flame* 84:361-375.
- Fay, J.A., 1973, "Buoyant Plumes and Wakes," *Ann. Rev. Fluid. Mech.* 5:151-160.
- Hernández, J., and Crespo, A., 1992, "A Numerical Modelization of Horizontal Turbulent Jet Diffusion Flames," *The PHOENICS Journal of Computational Fluid Dynamics*, Pre-print papers, Conference 1992, Vol. 2, pp. 205-221.
- Hottel, H.C., and Sarofim, A.F., 1967, *Radiative Transfer*, McGraw-Hill, N.Y.
- Modak, A.T., 1979, "Radiation from Products of Combustion," *Fire Research* 1:339-361.
- Mudford, N.R., and Bilger, R.W., 1984, "Examination of Closure Models for Mean Chemical Reaction Rate Using Experimental Results for an Isothermal Turbulent Reacting Flow," *Twentieth Symposium (International) on Combustion*, pp. 387-394.
- Ott, S., 1991, "An Experimental Study of Large Natural Gas Flames," Final Report CEC Contract on Torch Fires, RISO contribution.
- Peters, N., and Göttgens, J., 1991, "Scaling of Buoyant Turbulent Jet Diffusion Flames," *Combust. Flame* 85:206-214.
- Ricou, F.P., and Spalding, D.B., 1961, "Measurement of Entrainment by Axiallysymmetrical Turbulent Jets," *J. Fluid Mech.* 11:21-32.
- Schlichting, H., 1968, *Boundary Layer Theory*, McGraw-Hill, N.Y.
- Servert, J., 1993, "Modelado de llamas de difusión turbulenta y de su interacción con el medio ambiente y objetos circundantes," Ph.D. Thesis, E.T.S.I. Industriales, UPM, Madrid.
- Tamanini, F., 1981, "An Integral Model of Turbulent Fire Plumes," *Eighteenth Symposium (International) on Combustion*, pp. 1081-1090.
- Verheij, F.J., and Duijm, N.J., 1991, "Windtunnel Modelling of Torch Fires," TNO Report 91-422, Apeldoorn, The Netherlands.