

MODELIZATION OF THE INTERACTION OF A JET FIRE WITH AN OBSTACLE

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1. INTRODUCTION

Two models have been developed to study jet fires and their interaction with obstacles. One of them is one-dimensional (1D), and is described by Crespo et al. (1994). The other one is three-dimensional (3D), is based on PHOENICS, has an elliptic character, and is described by Hernández et al. (1995). The physical assumptions underlying both the 3D and 1D models are essentially the same, except for radiative losses, which are supposed to be a fixed fraction of the heat of combustion in the 3D model. Therefore, the energy equation has not to be solved in the 3D model. The 1D code is able to simulate the interaction with obstacles of a size moderately smaller than the flame width at the place where interaction occurs. A zoning method is used to calculate the radiative heat flux to the object. The results of the two models are compared among themselves and with experimental results of Ott (1993).

2. THREE-DIMENSIONAL MODEL

The conservation equations may be written in the general form

$$\frac{\partial \bar{\rho} \bar{\phi}}{\partial t} + \frac{\partial}{\partial x_i} (\bar{\rho} \bar{v}_i \bar{\phi} - \Gamma_{\phi_i}) = S_{\phi}, \quad (1)$$

where $\bar{\phi}$ can be equal to: 1, any component of the velocity, \bar{v}_i , the total enthalpy, \bar{h} , the mixture fraction, $\bar{\xi}$, the turbulent kinetic energy, k , the dissipation rate of the turbulent kinetic energy, $\bar{\epsilon}$, or the variance of the mixture fraction, g . In this equation, $\bar{\rho}$ 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 averaged magnitudes are assumed to be steady, so that the first term in the left hand side of equation (1) is zero. To calculate the diffusion term, Γ_{ϕ_i} , the classical k - ϵ model is applied. The source terms include buoyancy effects in the vertical momentum equation, and production and dissipation terms in the equations for k , ϵ and g . In the energy equation, the work of the gravity force has been neglected and the Mach number has been assumed to be low enough, so that the kinetic energy is negligible compared to the thermal energy; then, the only source term that is left is the one corresponding to thermal radiation. The model is completed with a perfect gas law and a state equation for enthalpy.

To define the combustion model, the classical hypothesis of one-step, irreversible reaction, represented by [Fuel + r_o Oxidizer \rightarrow (1+ r_p) Products] (where r_o is the stoichiometric ratio), fast chemistry, and equal diffusivities for all the species are made. This leads to the classical conserved-scalar approach and to a well-known relation between the instantaneous values of the fuel mass fraction and the mixture fraction, $Y(\xi)$. The average value of the fuel mass fraction is obtained from the integral, $Y_F = \int Y(\xi) P(\xi) d\xi$, where $P(\xi)$ is a Favre-averaged probability density function of ξ of a predefined shape, whose parameters are expressed in terms of the average value of the mixture fraction and of its variance, g . For the predefined shape of $P(\xi)$ a two-delta function has been used; also an alternative approach based on a correlation for the unmixedness integral (Mudford and Bilger, 1984) can be employed. A detailed explanation may be found in Hernández et al. (1995).

The temperature is obtained from the equation of state as a function of the enthalpy and the mass fraction of fuel. Alternatively, Hernández et al. (1995) use an expression giving the instantaneous value of the temperature as a function of the mixture fraction, $T(\xi)$, proposed by Sivathanu and Faeth (1990) for natural gas that takes into account radiative losses; then, the Favre average of the temperature can be easily obtained, $T = \int Y(\xi) P(\xi) d\xi$.

To calculate the emissivity, it is necessary to know the concentrations of CO_2 , H_2O and soot. The mass fractions of CO_2 and H_2O are obtained from the stoichiometry as functions of ξ and Y_F . The procedure for the calculation of soot mass fraction is similar to the one proposed by Fairweather et al. (1991). Soot formation proceeds from a pyrolysis intermediate, acetylene, that is considered to form solid carbon through nucleation and surface growth.

The physical domain considered is a rectangular parallelepiped, with the supply pipe of fuel located at a certain height above the ground surface, horizontal and parallel to the air stream. At the upstream boundary, the incoming air flow is taken as that corresponding to the neutral atmospheric surface layer with uniform, flat terrain, and its properties are assumed to be functions of height, surface roughness, and turbulent friction velocity, according to the law of the wall; these functions satisfy the flow equations (1). The fuel jet is assumed to have a uniform exit velocity. The properties at the ground are fixed and made equal to those corresponding to the wall-law profiles of the unperturbed wind. At the downstream boundary, far enough from the pipe exit, the pressure is fixed to the external ambient pressure and normal derivatives of all dependent variables are set equal to zero. At the rest of the boundaries of the parallelepiped, far enough from the flame, the pressure is fixed to the external ambient pressure and the flow convected into the domain through them is assumed to have the properties of the unperturbed wind.

There is a vertical rectangular plate immersed in the flame, as in the tests of Ott (1993) described in section 4. The boundary conditions at the surface of this object for velocity, k and ε are also those corresponding to the law of the wall, assuming that the wall is smooth. For the pressure there is no boundary condition at the object; and for the other variables it is assumed that there is zero flux. The temperature at the wall is not imposed, and has the adiabatic value resulting from the calculations. For this condition to be satisfied, the radiative heat flux from the hot gases to the object either has to be evacuated or, if it is accumulated in the solid, its heat capacity should be large enough so that the corresponding temperature increase is negligible.

3. ONE-DIMENSIONAL MODEL

In the problem described previously, if a jet center line and self-similar profiles in planes normal to it can be defined, the partial differential equations presented in equation (1) may be converted to ordinary differential equations, with the distance along the center line, s , as the independent variable. The computer time to solve the problem is then substantially reduced, from hours to fractions of minutes. This type of one-dimensional (integral) model has extensively been used by many authors. The model UPMFIRE, presented by Crespo et al. (1994) and Servert (1993), gives a new definition of the averages in a cross-section that is valid also for self-similar profiles extending to infinity. This allows the 1D equations to be derived rigorously from the 3D parabolic equations, and the source terms to be calculated using a systematic method. The one-dimensional version of equations (1) is

$$\frac{d}{ds}(\bar{m}_i \langle \bar{\phi} \rangle) = \phi_a \bar{m}'_0 + \Delta \Sigma_\phi + \bar{m}_a \frac{d\phi_a}{ds}, \quad (2)$$

where the brackets denote the average in a cross section, \bar{m} is the mass flux in a cross-section of the flame, ϕ , as in equation (1), stands for one in the continuity equation and for each dependent variable in its respective conservation equation, \bar{m}'_0 is the mass entrained per unit length of flame and time, $\Delta \Sigma_\phi$ is the source term, and \bar{m}_a is the mass flux of ambient flow through a cross section of the same equivalent area. The term on the left-hand side is the convective term, the first term on the right-hand side represents entrainment from ambient flow, the second one is the source term, and the last one, not present in similar 1D models, is associated to the variation of ambient flow properties with height. It should be noticed that very far downstream, where there is no perturbation of the flame, the source term disappears, $\bar{m} = \bar{m}_a$, and equation (2) is identically satisfied.

The model also includes the interaction with objects of small size compared to the flame diameter. The interaction results in the drag force and the heat added to the obstacle by the surrounding fluid. The jump in flow conditions across the obstacle is represented by source terms in the conservation equations, associated to these two

parameters. The heat added to the obstacle is made up of both convective and radiative contributions, although in this particular application there is only a radiative part. To evaluate it, a zoning method is adapted to this case considering an average absorption coefficient for each flame section.

4. HEAT TRANSFER TO THE OBSTACLE

In figures 1 and 2, a comparison between the calculated (both with 1D UPMFIRE and the 3D elliptic codes) and measured values (Ott, 1993) of the radiative heat flux at the surface of a vertical flat plate located in the symmetry plane of a horizontal flame, at a downstream distance of 2 m in figures 1a and 1b, and 3 m in figures 2a and 2b is presented. The fuel is natural gas, and the exit velocities are 283 m/s in figures 1a and 1b, and 311 m/s in figures 2a and 2b. The wind velocities are 4.5 m/s in figures 1a and 1b, and 3.1 m/s in figures 2a and 2b. The jet exit is 2.5 m above the ground, and its diameter is 25 mm in all cases. The plate is 1.7 m long, 10 cm wide, and 2 cm thick; it has been assumed that it is held in some way 1.5 m above the ground. Figures 1a and 2a correspond to the side of the plate looking upstream, and figures 1b and 2b correspond to the side of the plate looking downstream. In figure 1a, corresponding to the front side, both 1D and 3D codes agree well with experiments, reproducing the dip at the center, although both models give slightly smaller values than the experimental ones. In figure 1b, corresponding to the back side, both codes give smaller values of heat transfer than the measured ones; the 3D code gives a slightly better agreement with experiments than the 1D code, and predicts a peak in heat transfer at a higher position than the one corresponding to measurements. In figures 2a and 2b, corresponding to a location of the obstacle further downstream, both the 1D and 3D elliptic codes underpredict the measured results, although the 3D code gives a substantially better agreement both quantitatively and qualitatively. This behavior has also been observed by Crespo et al. (1994) when comparing UPMFIRE with other field experiments: there is good agreement between the numerical model and experiments when the obstacle is close enough to the jet exit, and the numerical model underpredicts the heat transfer as the obstacle is moved downstream. Figures 3a and 3b give the temperature contours in vertical planes parallel to the plate respectively upstream and downstream of it; it can be observed that in the front of the plate, there is a maximum in temperature at the symmetry line, whereas in the back, the maximum is not in the symmetry line, and there are two maximums at both sides of the symmetry line.

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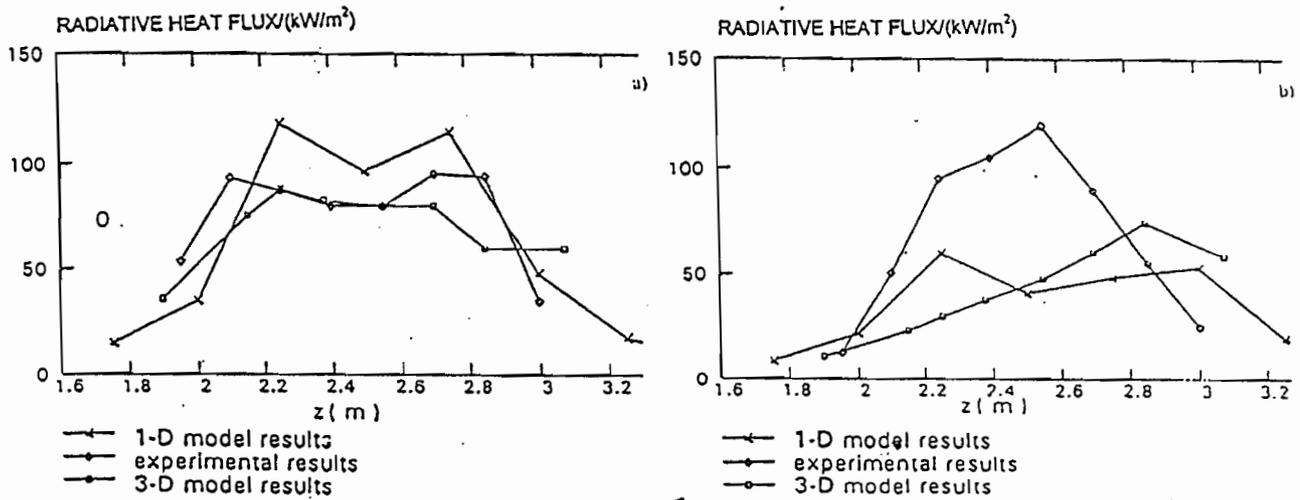


Figure 1. Radiative heat flux to a vertical plate in the symmetry plane. Comparison of results of 1D and elliptic models with experiments (Ott, 1993). Exit velocity: 283 m/s. Downstream distance from fuel exit is 2 m. a) side of the plate looking upstream. b) side of the plate looking downstream.

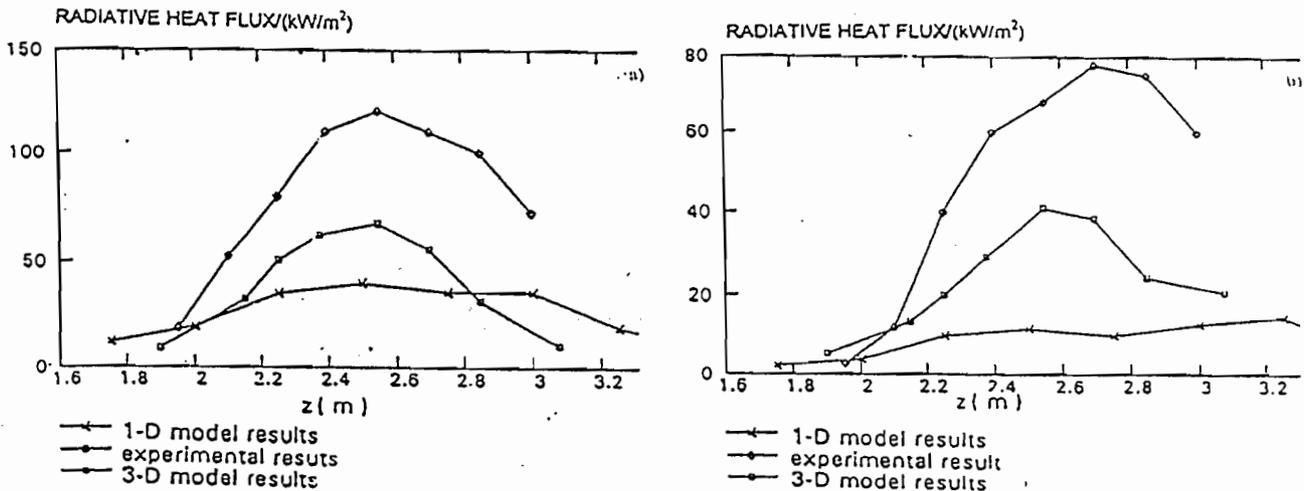


Figure 2. Radiative heat flux to a vertical plate in the symmetry plane, experiments by Ott (1993). Comparison of results of 1D and elliptic models with experiments. Exit velocity: 311 m/s. Downstream distance from exit is 3 m. a) side of the plate looking upstream. b) side of the plate looking downstream.

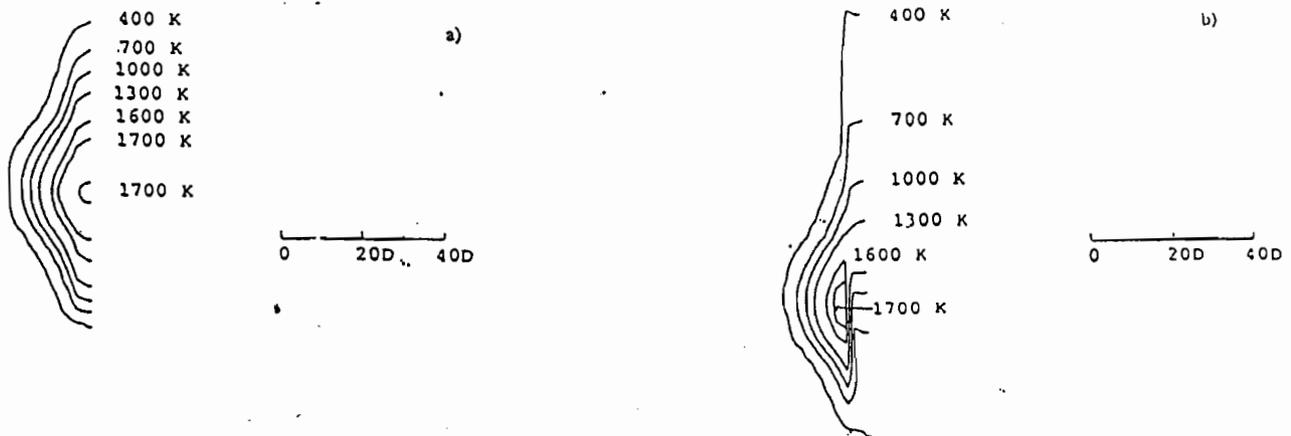


Figure 3. Temperature contours, in vertical planes corresponding to both the upstream (a) and downstream (b) sides of the plate, from calculations with the 3D elliptic code. Conditions as in figure 1.