Contribution to the Modelling of Vertical Burning Walls

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ABSTRACT

Until now, very few works have been devoted to the prediction of the flame structure resulting from the combustion of a vertical burning wall adjacent to a rectangular pool fire at the floor level. We describe the application of a three-dimensional model to the prediction of the aerodynamic field and the thermal structure using a finite volume method for solving the fluid dynamic equations. The model employs a two-equations k-ε turbulence model. The gas-phase, non-premixed combustion process is modeled via the conservated scalar/prescribed density function approach. We also incorporated our parabolized numerical technique into a turbulent diffusion flame model to predict the pyrolysis rate and buoyancy-induced flow between vertical parallel burning walls. The strong coupling of the pyrolysis rate and wall fire-induced flow, in parallel configuration, is for the first time modeled, by including the effects of the streamwise pressure gradient. Transport equations for momentum, mass, gas-phase mixture fraction and enthalpy are solved using a finite volume method. A two-dimensional adaptation of the Discrete Ordinates Method is used for estimating the flame radiation energy to the burning wall. Soot model is also included in order to permit application to radiative heat transfer within a flame.

INTRODUCTION

From its beginning the modelling of fire presents a formidable challenge. However, whether by physical or mathematical means, it has played an important role in the development of fire science and its application. Thomas [1] traced the origin of the concept of fire modelling and emphasized upon the limitations to the use of computational fluid dynamics in fire related researches and underlined the need to develop the understanding of basic phenomena and the means by which to describe them in a way usable by engineers. Cox in his review [2] explored the current state of art in the development of modelling, and highligthed successes, domains of particular difficulties and work in progress to meet the challenges posed by the improvement of fire safety.

Among the different phenomena basically involve in the development of a fire in a room, the wall fire problem and its interaction with the neighbourghood appears of importance. In their paper related to wall fires and the development of flashover in a room , Mitler and Steckler [3] underlined that it has long been observed that the fastest growth of a fire is up a vertical surface. Joulain [4] noticed that a detailed and fine evaluation of fire risk in a particular building requires rather sophisticated models. Models necessarily based upon a good knowledge of the various thermodynamical, aerodynamical and chemical phenomena involved during the combustion of solid materials in an environment of complex geometry. One situation of great concern, as also mentioned by Thomas [1], is the modeling of the propagation of fire along a vertical wall. However Fernandez-Pello demonstrated in [5] that the distinction between wall (or vertical) and pool (or horizontal) fire is somewhat arbitrary since, except for the physical difference between a solid and a liquid, the phenomena underlying both burning processes are basically the same.

Most of the literature related to the study of wall fires concerns one burning vertical wall. For many years, the challenge of fire safety in wall fire situations has attracted attention from researchers [6 to 18]. Both experimental and numerical works have been focused on the development of fire with a buoyancy-induced flow along a single vertical wall. More works [19 to 29] concern the development of a wall fire in an enclosure and its interaction with the environment (ceiling, corner wall, stratified atmosphere,.....) phenomena of great importance from the point of view of fire safety. However these situations require, prior to be realistically modeled, a rather precise description of the basic physical processes involve in the interaction between a wall fire and its surroundings. To the best knowledge of the authors, the first analysis addressing the parallel wall fires is the work of Tamanini and Moussa [30]. Nevertheless in the past two decades our laboratory in Poitiers has been working on experimental and numerical studies related to such fire situations [4, 31 to 38]. The experimental studies has been carried out, at laboratory or medium scale, using sintered water-cooled porous wall burner considering different fire configurations from a lonely wall or pool fire to the interaction between vertical walls or between a pool and a wall.

Below we intend to summarize some of our results concerning the modeling of the interaction between a vertical wall and a pool and then between two parallel vertical walls using an efficient parabolized procedure developed earlier [36].

VERTICAL BURNING WALL - POOL FIRE INTERACTION

Until now, very few works have been devoted to the prediction of the flame structure resulting from the combustion of a vertical burning wall adjacent to a rectangular pool fire at the floor level (Fig.1). We describe the application of a three-dimensional model to the prediction of the aerodynamic field and the thermal structure using a finite volume method for solving the fluid dynamic equations. The model employs a two-equations k-ε turbulence model. The gas-phase, non-premixed combustion process is modeled via the conservated scalar/prescribed density function approach.

The flame shape and flow field structure developing along the vertical burning wall are really sensitive to the presence of the pool fire. By comparison with the results for a single burning wall the following trends can be extracted:

1. In the presence of the pool fire, the linear dependence of the flame thickness (d_f) to the height (H) no longer exists. At the base of the vertical burning wall, where the two flames merge d_f is important and then remains nearly constant ($d_f = 0.07$ m).

2. The buoyancy-induced acceleration of the flow increases drastically with the height to reach 2.8 m/s at 1m above the floor for a single wall but much more with the pool and up to 3.2 m/s at the same height.

3. It can easily be concluded, in the presence of a pool fire, the air entrainment at the base of the vertical wall is stronger than that of a single vertical wall. Then, far downstream away from the low base, the air entrainment decreases progressively with a linear dependence of the height first and later increases above a height of 0.4 m due to the increase of the hot gas boundary layer.

4 The flame shape and flow field structure of the pool fire are significantly dependent upon the vertical burning wall. The visible flame shape corresponds to the zone where the temperature is higher than 650K.

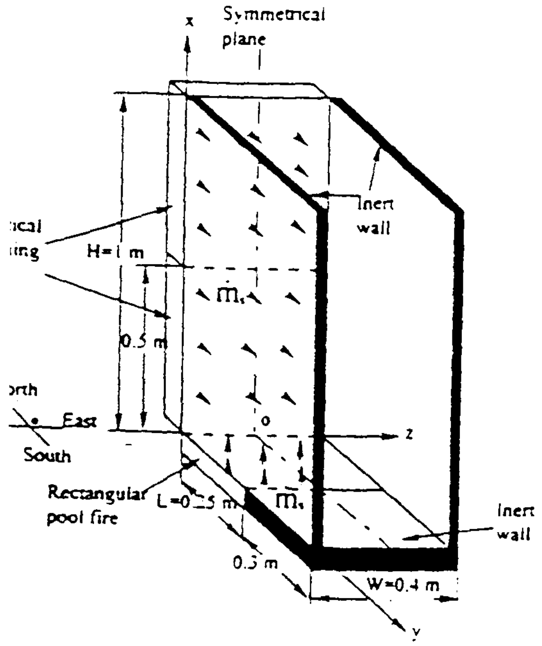


Figure 1:Schematic diagram of the wall/pool configuration

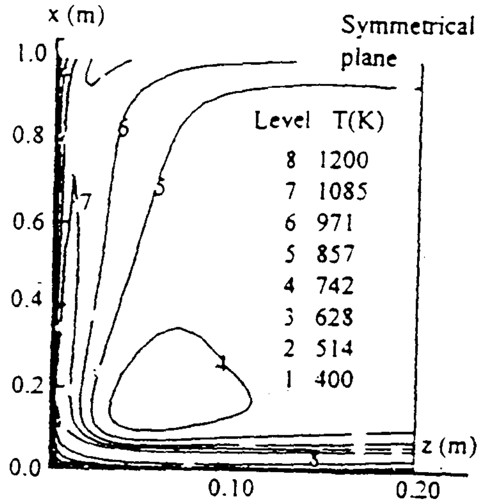
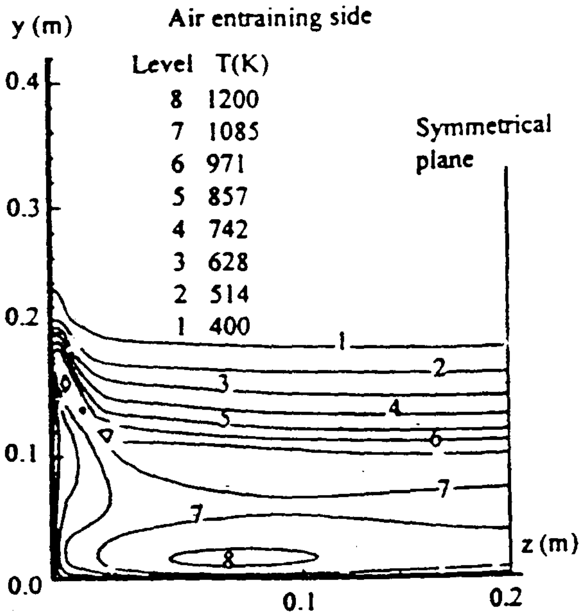


Figure 2:Temperature contours on the x,z plane close to the vertical burning wall

The three dimensional nature of the temperature and flow fields on the x,z plane near the vertical burning wall has been clearly shown. The temperature profiles are stratified with the hottest gas located in the boundary layer near the walls, and almost uniform over most of the cross-section (Fig.2). Correspondingly, the three-dimensionnal flow is confined only to the corner region between horizontal and vertical wall. The air flow deflects locally inward toward the inert wall due to a strong acceleration of the flow in the low corner region. Outside this region, the flow is essentially two-dimensional, as evidence by a uniform parallel flow between the vertical inert walls. The temperature contours on the plane y,z, just above the horizontal burner surface is given in (Fig.3). In the entrance region the temperature stratification seems negligible and the flow practically two-dimensional in the sense the deflection is not generated. However near the vertical burning wall the temperature of the ambient gas increases progressively by mixing with the hottest gas located near the burning wall where the flow is also strongly deflected toward the low corner region.

When the predicted temperature profiles at various locations along the vertical burning wall are compared with experiments, it can be seen that the general shape of the temperature profiles is correct, but that the calculated flame spread is significantly underestimated. The temperature peaks very close to the burning wall but far away from the experimental location. Moreover the temperature outside the burning zone is 20% smaller than the measurements, discrepancy related to model assumptions. Concerning the velocity field the agreement between experiment and model



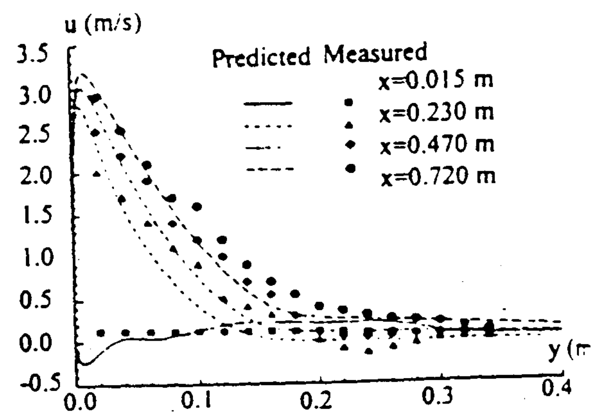


Figure 3: Temperature contours on the y,z plane just above the pool fire (x=0.015m)

Figure 4: Predicted (lines) and experimental (symbols) axial velocity profiles

is rather satisfactory and especially for the axial velocity field (Fig.4), thanks to the correct description of the dominant buoyancy term in the momentum equation. Since the temperature and velocity fields are strongly coupled for the buoyancy-induced flow, similarly to the temperature profiles, the discrepancy in the velocity profiles is seen to be underestimated by around 20% to. Concerning turbulence, it has been shown that in presence of a strong buoyant instability, conventional, even modified, k-ε model can not realistically predict the turbulent scalar and Reynolds flux.

VERTICAL PARALLEL BURNING WALLS

We incorporated our parabolized numerical technique into a turbulent diffusion flame model to predict the pyrolysis rate and buoyancy-induced flow between vertical parallel burning walls. The strong coupling of the pyrolysis rate and wall fire-induced flow, in parallel configuration, is for the first time modeled, by including the effects of the streamwise pressure gradient. Transport equations for momentum, mass, gas-phase mixture fraction and enthalpy are solved using a finite volume method. A two-dimensional adaptation of the Discrete Ordinates Method is used for estimating the flame radiation energy to the burning wall. Soot model is also included in order to permit application to radiative heat transfer within a flame

The test fixture is similar to these of Fig.1 but with two parallel sintered water-cooled porous wall burners at L, as schematized on (Fig.5).

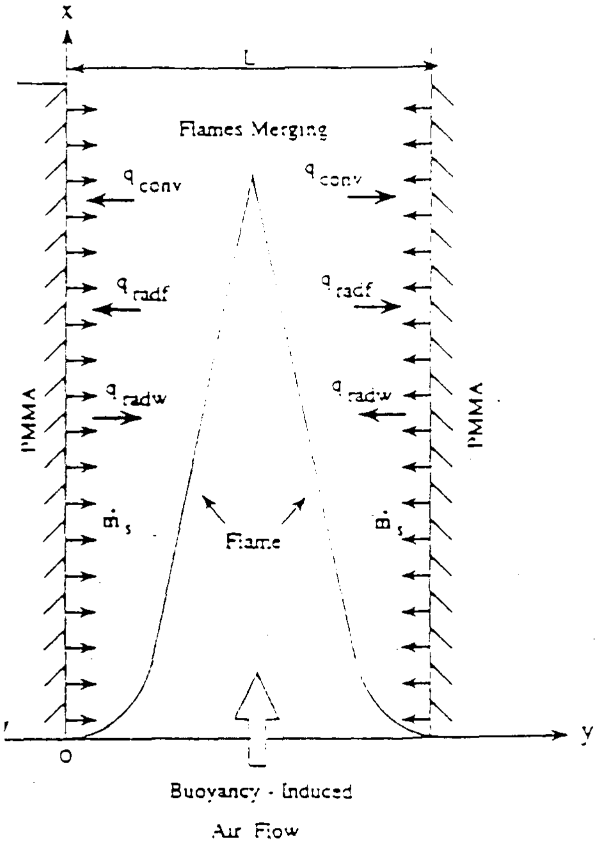


Figure 5: Schematic of the two burning PMMA walls situation

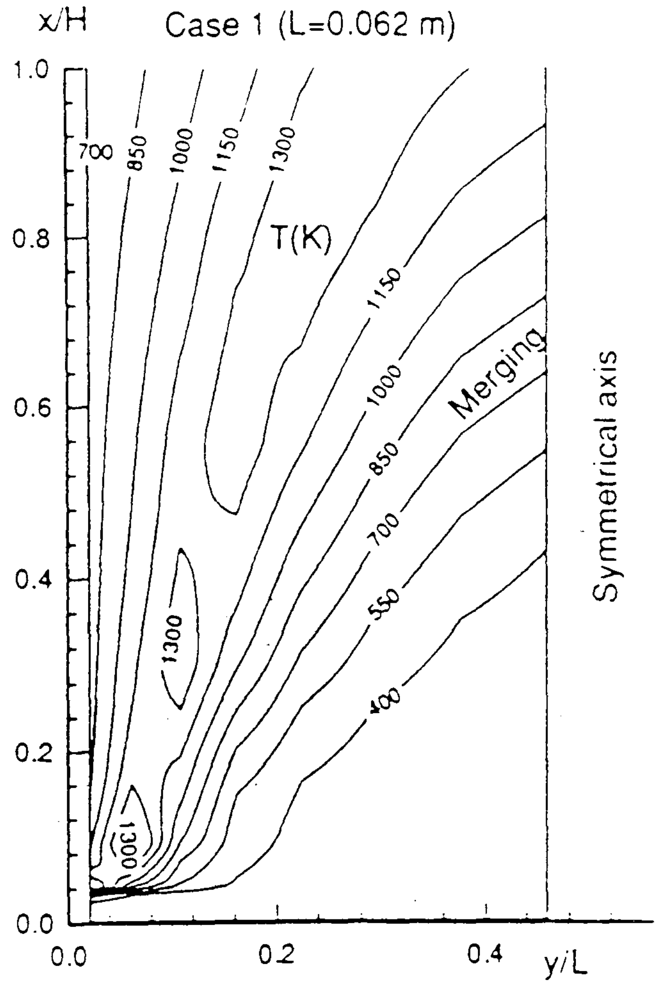


Figure 6: Flame structure between burning walls

As an illustration, the isotherm lines are plotted in Fig.6 for test 1. The predicted visible flame shape corresponds to the zone where the temperature is higher than 700 K. It can be seen that the increase of the flame thickness is rather fast with a non-linear dependence of the height along the walls. Then the merging of the two diffusion occurs only at the height of 0.6m.

From the mean temperature profiles, it can be said that the general shape of the profiles is correctly predicted (Fig.7). However the model tends to overestimate the extent of the highest temperature domains. Again the location of the temperature peak is far beyond its experimental location. The predicted temperature is also 5 to 20% higher respectively for the smaller and larger wall spacing, discrepancies mainly due to the one-step reaction assumption. About mean velocity, (Fig.8), the agreement, in term of magnitude, is much better. This suggests that the inlet velocity value of the buoyancy induced flow is correctly determined by the requirement that the driving pressure goes to zero at the exit. Nevertheless the predicted velocity are underestimated by 15% in the core region for the narrower wall spacing (test 1 with L= 0.062 m) and by 6% for the larger spacing (test 2 with L= 0.1 m). About velocity fluctuations, the agreement is satisfactorily in the core flow region.

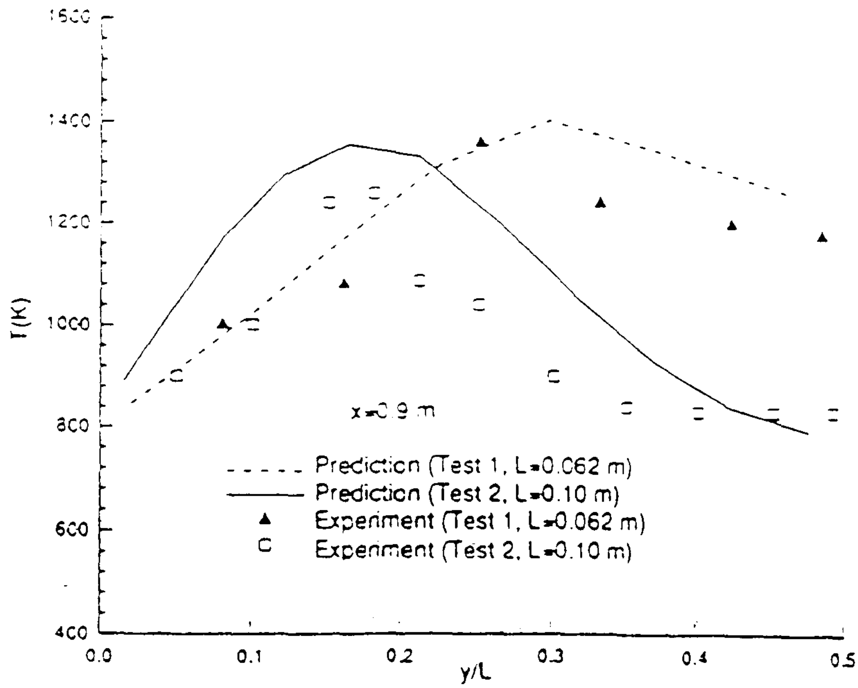


Figure 7: Comparison between experimental and numerical temperatures profiles (parallel burning walls)

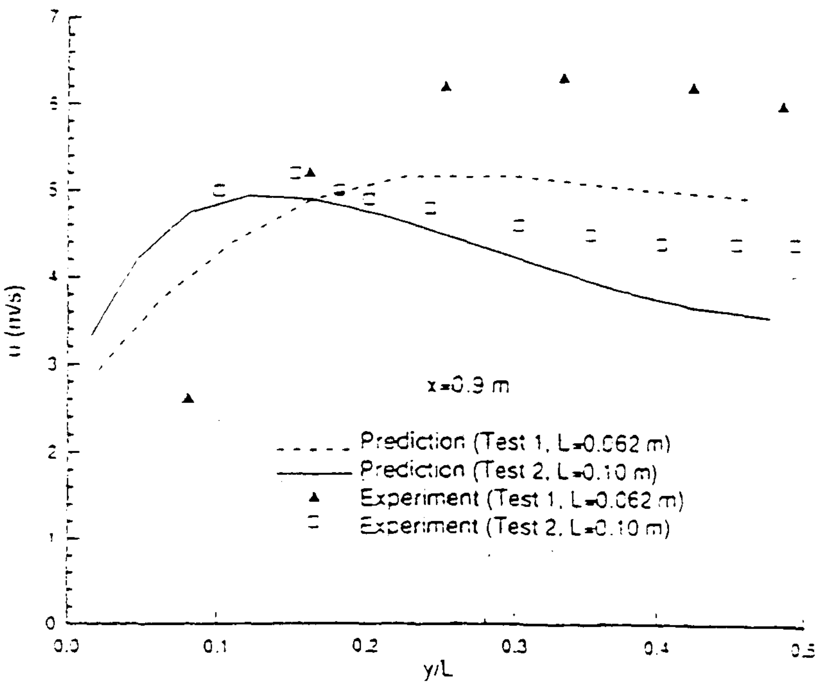


Figure 8: Comparison between experimental and numerical axial velocity profiles (parallel burning walls)

According to temperature plots, three different cases have been observed as a function of wall spacing separated flame, partially merging flames and totaly mixed flames. For narrow L the increase of the flame thickness is rather fast with a nonlinear dependence to the height of the burning wall. As a consequence the merging of the two flames occurs at a height below 0.6 m, but around 0.8 m for L=0.1 m. When the wall spacing is larger (L>0.2 m) the flame structure is characterized by the separation of the two diffusion flames all along the channel height. At the entrance and up to x/H>0.2, the flame thickness has a strongly nonlinear dependence to H, but above the following linear relation can be established:

$$d_f \approx 0.006 + 0.04\,x \qquad (m)$$

Wall spacing has also some influence on the velocity field and more precisely on the velocity enhancement in the channel. Under free convection conditions, ambient air flows upward due to buoyancy forces produced by density stratification. From Fig.9 for the axial mean velocity, near the exit (x/H = 0.9), it can be seen that for narrow wall spacing the maximum velocity occurs in the core flow region where the two flames merge. By increasing L the location of the maximum velocity is shifted towards the burning walls, causing a strong velocity gradient in the cross-section. However the maximum axial velocity appears independent of L but only function of x:

$$U_{max} \approx 5\,(x)^{1/2} \qquad (m/s)$$

Nevertheless the inlet velocity, U_0, as indicated in Fig.9, is a function of L for a given wall height, H, and its value is determined by the streamwise driving pressure that must go to zero at the end of the channel. We have also to notice that the driving pressure decreases monotonously with L. The buoyancy effects are very strong and consequently the inlet flow is strongly accelerated upward up to about five times the inlet velocity. But in the upper zone the flow accelerates more progressively. It appears that the agreement is only good for L above 0.1m.

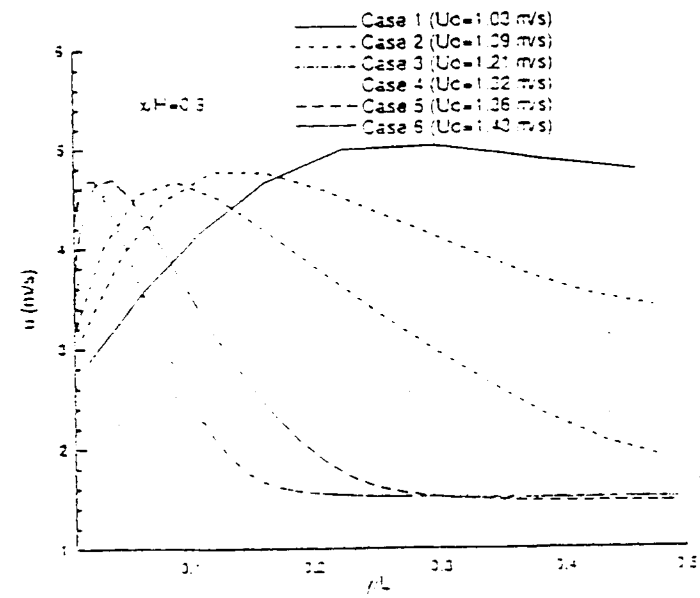


Figure 9: Axial mean velocity profiles for H = 0.9 m

To determine the mass burning rate it is necessary to get or guess the different fluxes to the burning or pyrolyzing surface. Concerning convection, it is easily shown that its contribution increases with wall spacing. Along the channel, the flux first drastically decreases from its highest value near the leading edge and then very slightly downstream far away from the inlet zone. Concerning radiation, the increase of L leads to a slight increase, about 10%, at the beginning, corresponding to the case where the interactions between the two diffusion flames is again important. Moreover the radiation fluxes decrease significantly once the separation of the two flames occurs. In the axial direction, in general, the radiation flux increases along the burning walls due to the increase of the flame thickness. Because of the link between soot level and radiation flux, we also considered the effect of wall spacing on soot formation. One can notice that the highest levels of soot are almost insensitive to L with a peak soot volume fraction around $3.6\ 10^{-6}$. Therefore the decrease of the radiation flux is mainly due to the reduction of the interaction between the flames as L increases. Apart near the leading edge where the contribution by radiation is less than 45% o f the total heat flux, and thus convection becomes the dominant mode of heat transfer with 55%, the numerical results confirm that in the burning of two vertical parallel walls, facing each other, convection plays a secondary role on the burning rate. The inlet singularity is due to a very steep temperature gradient near the leading edge, thus increasing the convection flux. As shown in Fig.10, the fraction of total flux by radiation decreases with the increasing of L (cases 1 to 6: L = 0.062, 0.1, 0.15, 0.25, 0.35, and 0.5 m). At the top of the burning channel, contribution by radiation account for 90% of the total heat feedback to the burning surface for the narrowest channel and only 70% for the largest. It may be intuitively expected that the turbulence level as a whole, which is proportionnal to the buoyancy-induced mass flow rate, enhances the convective heat transfer.

According to the analysis of the contribution of convection and radiation fluxes to the local burning rate, Fig.11-13, it has been found a rapid decrease in the entrance region from the highest value at the leading edge where both contributions are maximum. It is also shown that the local mass burning rate remains pratically identical for the moderate increase in walls spacing. This seems due to the fact that when the two diffusion flames are not largely separated, decrease of the radiation flux can be just compensated by the increase of the convective contribution, thus maintaining an identical burning rate. However further increases of L leads to a monotonous decrease of the burning rate corresponding also to the decrease of the radiative flux and to the constant value of the convective one.

From Fig.14 we also intend to summarize the effects of wall spacing on the average convective flux, radiative flux, burning rate and buoyancy induced air mass flow rate.

1. The average convective flux increases with L following the trends of the buoyancy induced air mass flow rate.
2. The radiative flux increases first and later decreases monotonously.
3. The average mass burning rate remains nearly inchanged for L between 0.062m and 0.1m and equal to $10\ 10^{-3}$ kg/m²/s, and decreases later monotonously, as the radiative flux.

The variation between the mass burning rate for the largest value of L, corresponding to non merging flame, and the transitionnal situation, corresponding to partially merging flame, is of about 60% (respectively 10 and $6.2\ 10^{-3}$ kg/m²/s). Globally the predicted average burning rate is close to the data obtained for one PMMA burning vertical wall by Kim and all [39] some years ago in Poitiers ($7\ 10^{-3}$ kg/m²/s).

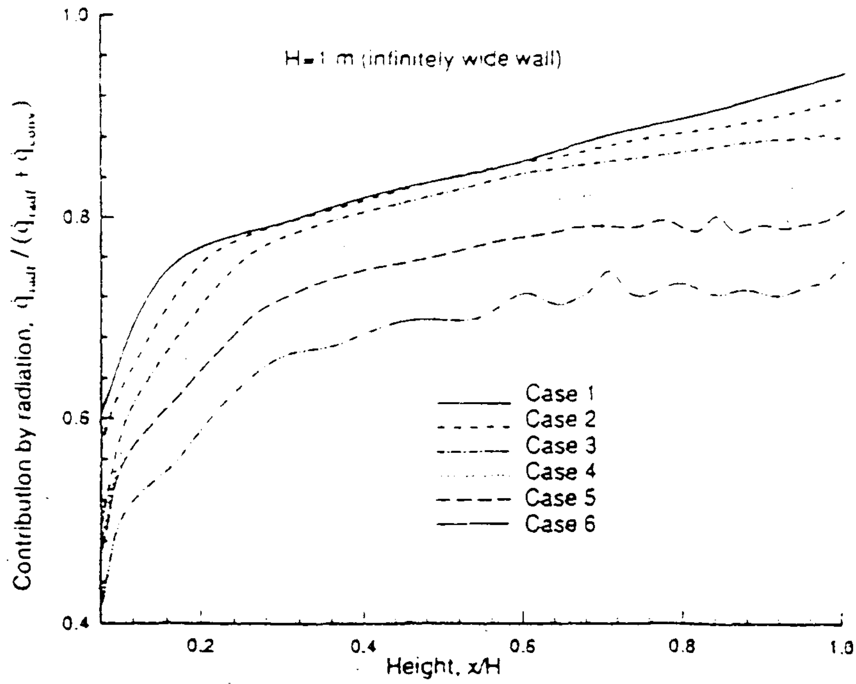


Figure: 10 Radiative to total heat flux ratio as a function of height and wall spacing.

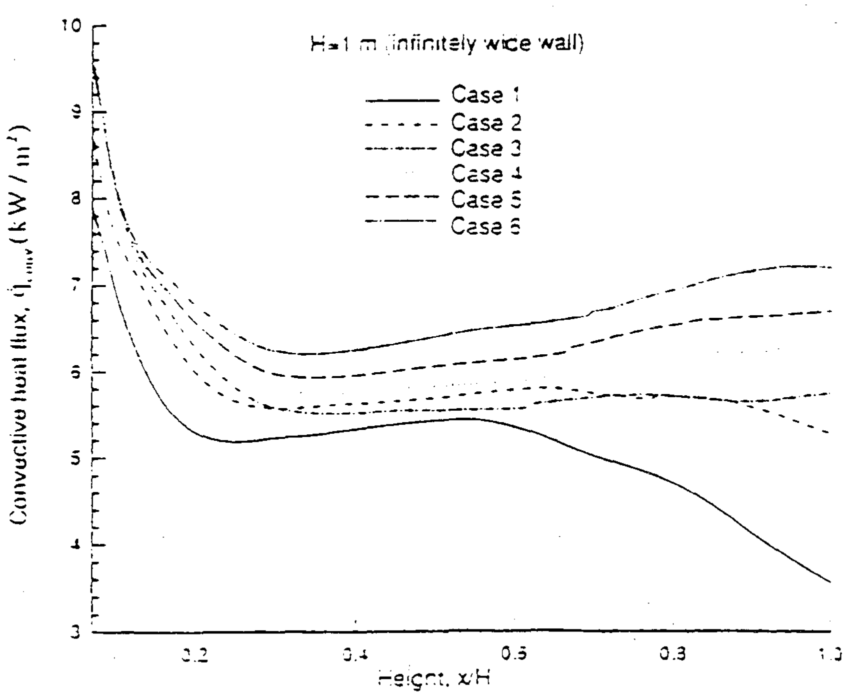


Figure 11: Convective heat flux as a function of height and spacing

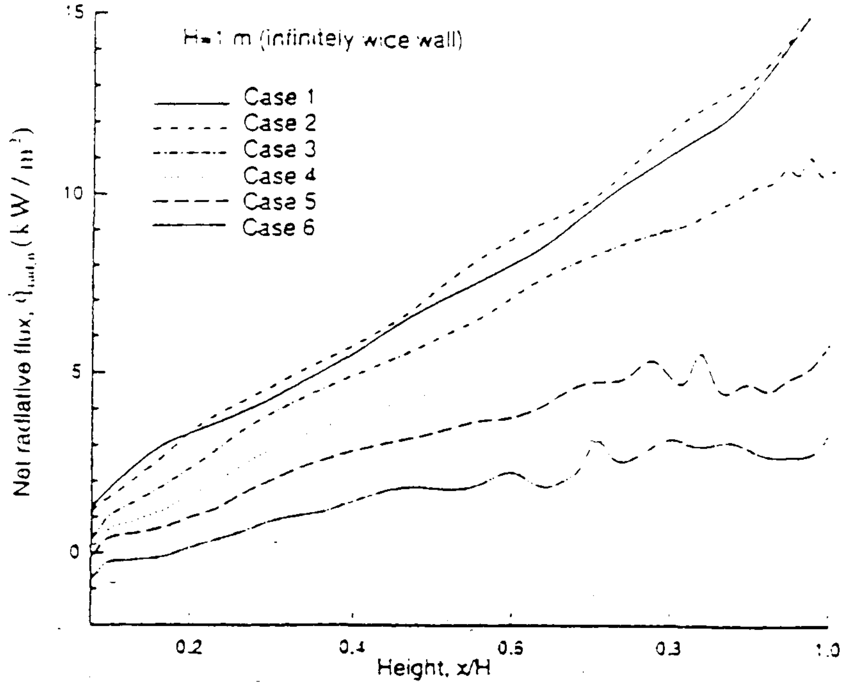


Figure 12: Net radiative heat flux as a function of height and wall spacing.

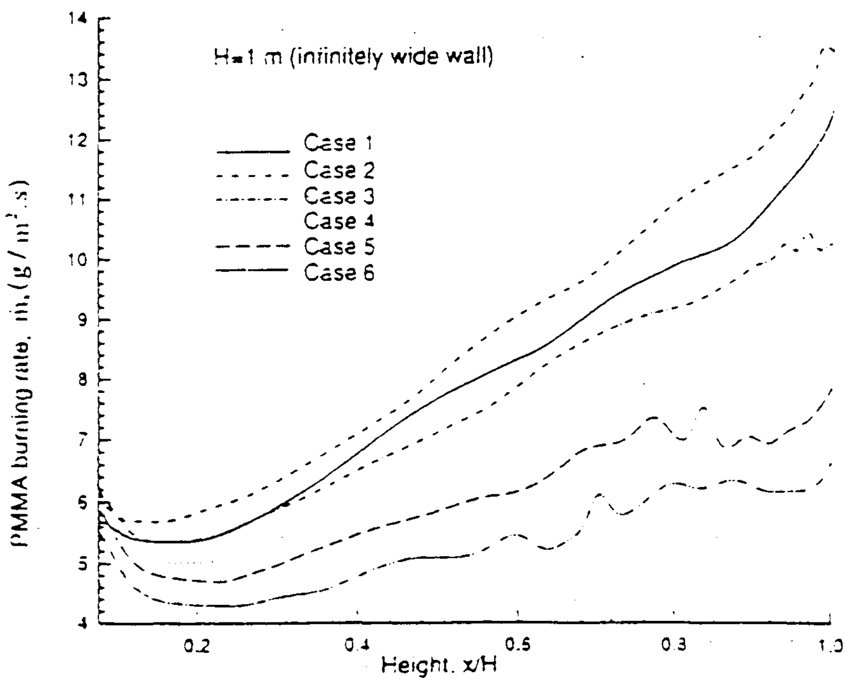


Figure 13: PMMA mass burning rate along the burning walls for different spacing

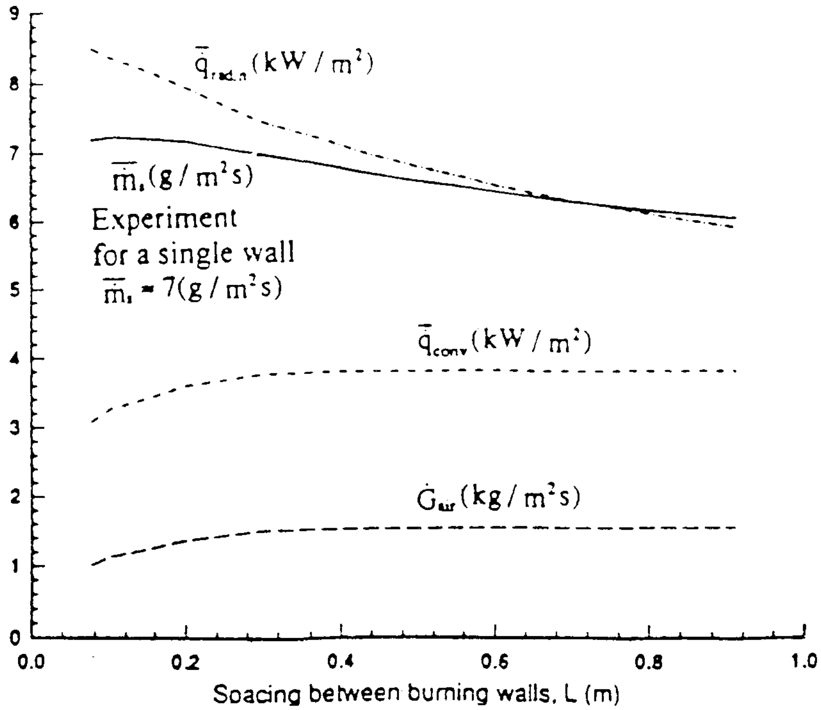


Figure 14: Influence of wall spacing on the average convective flux, radiative flux, burning rate and buoyancy induced air mass flow rate.

CONCLUSIONS

The use of the fully elliptic form of the three-dimensional model allows to quantify the flame shape and flow field resulting from a vertical burning wall adjacent to a rectangular pool fire that were previously predicted from a single vertical wall or a pool fire but not readily describe by a mathematical analysis. It is very interesting to notice that in the presence of pool fire, the flame thickness at the base of the vertical wall is initially important and remains practically constant all along the vertical burning wall. Consequently, as the buoyancy effects at the base of the burning wall are important, the flow is drastically accelerated upward up to 1.75 m/s only 0.1 m above the leading edge. Of course, at the different downstream locations, the acceleration of the flow rises progressively with the velocity vectors parallel to the burning surface. Moreover, the recirculating flow over a large area, just above the horizontal burner surface, greatly stabilizes the diffusion flame anchored at the corner between the pool and the vertical wall. However, the rapid broadening of the buoyant gas column, far downstream, away from the pool fire, seems responsible for the strong narrowing of the buoyantly induced plume.

A more elaborate version of the code has been able to predict the convection/radiation flux and the mass burning rate in the case of a fire-induced flow between vertical parallel PMMA surfaces. The flame structure and velocity vector field in parallel configuration have provided fundamental information about processes that were previously predicted from a single wall fire but not readily described by a rigorous mathematical analysis. The buoyancy induced air mass flow rate increases first with the wall spacing and then, remains later almost constant once a critical spacing is reached. Three characteristic flame structures, such as merging, transition and separation, as a function of the spacing have been identified. The flame in merging or transition case can maintain a high radiation flux, and the flame in the separation case results in a remarquable decrease of the flux. Of particular interest is the higher contribution by radiation to fuel vaporization at the lower part of the channel. Moreover, only for the moderate increase of L, a decrease of the radiative flux can be compensated by an increase of the convective contribution. In general the burning rate decreases once the spacing/height ratio exceeds 0.1.

More work is currently under progress in order to predict the mechanism generating the buoyant instability and the transition to turbulence. It becomes increasingly evident that success in describing the flame behavior in both case, and especially far downstream after the merging of the diffusion flames, depends on a realistic treatment of the coupling between turbulence and reaction kinetics. An other ongoing work is considering the laminar flamelet concept in turbulent diffusion flame. The relatively good trends in predicting the flame shape, the mean velocity and temperature fields, the mass burning rate and the different fluxes clearly underlined the capability of our approach and its relevance for future developments.

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