Application of a Zone Model to Smoke Control in a Compartment with Exhaust Fan: Comparison with Field Modelling and Experimental Results

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ABSTRACT

In the French research programme F.I.S. (Feu, Incendie, Sécurité) devoted to the development of scientific approaches of smoke control in buildings, an experimental study was executed at L.E.T. on a scale model (W = 1m, L = 2m, H = 1m) with a gas burner (28 kW to 70 kW) and a door of adjustable height with natural or forced ventilation (1). A number of numerical computations have been performed with a field model (at L.E.T.) (1) and a zone model (at C.S.T.B.). The objective of this paper is to present and comment the results obtained from the zone model, compared to the experimental results and to the field model results. In a fire situation in which the flow pattern is poorly described by the zone model, we found that the zone model could nevertheless provide useful approximate results for fire safety design.

KEYWORDS : Fire modelling, Zone model, Field model, Smoke control.

INTRODUCTION

The confinement of fire products inside the compartment of fire origin is a major objective of fire safety. An efficient system of smoke control, in a shop for example, has to prevent smoke movements towards the spaces which communicate such as corridors, staircases, an atrium, etc ... The applicability of analytical methods for fire safety design has to be further assessed by evaluations of the adequacy of the computer models to allow sufficiently accurate predictions. The so-called zone models and field models have produced - for more than fifteen years - very encouraging results in a number of applications. References e.g. (7, 8, 9, 10 , 15) give a general view of the situation. The work presented in this paper concerns smoke control of a compartment with an open door and an exhaust fan located above the ceiling. The practical objective of the research programme F.I.S. is to give information to the French Ministry of Interior, Direction de la Sécurité Civile, in order to elaborate more founded technical requirements for the protection of people in buildings open to the public. Over the last years, C.S.T.B. has been active in the analysis of natural and mechanical ventilation in case of fire with zone models (2, 4, 12, 13, 14). We present here recent results issued from a cooperative work between L.E.T. and C.S.T.B., in which three approaches were carried on : experiments on a scale model (L.E.T.), field modelling (L.E.T.), and zone modelling (C.S.T.B.). Experiments on compartments of reduced size enable to carry out accurate measurements on the characteristic phenomena of the fire, and can provide quantitative information for the full scale if the proper adimensional groups of significant variables are kept constant. If radiative transfers are not predominant, useful results can be obtained for smoke control problems from scale models (5, 6).

Many experimental results were collected on the L.E.T. scale model with natural or mechanical ventilation. In this laboratory, experimental results were compared to the results obtained from the field model SIMEC (1), with a good agreement. We decided at C.S.T.B. to evaluate the accuracy of the predictions of zone models (FISBA and BS), based on the L.E.T. results. Though the field models are based on a fine description of the variables over space and time and then should give a precise description of the fire phenomena, some theoretical problems still remain and a considerable limitation of their widespread utilization is the requirement of computer means and practice. Zone models, on the other hand, necessitate small or mediumsized computers, but are built on rougher assumptions (large control volumes, quasi-steady equations on some points). The definition of a practical guide to help users to choose one of these two kinds of models to solve a given problem with a suitable accuracy is still to be elaborated. So, comparisons of results from a field model and a zone model are of interest.

- The field model S.I.M.E.C. has been developed at L.E.T. for years. It emphasizes the mere fluid dynamic aspects of the physical problem. More details on this model can be obtained from the above mentioned L.E.T. researchers.

- The C.S.T.B. zone model FISBA has been described previously (2, 12). In the FISBA version considered in this study, we assume that the temperature of the lower gas layer is constant and equal to the ambiant air temperature.

- This scale model (figure 1) is a compartment which is 1m x 2m and 1m high. Is is opened by means of a vertical door, 1m wide, whose height ranged from 30 cm to 100 cm. The power output of the fire source (a gas burner) ranged from 28 kW to 70 kW. The release of fire products from the compartment was carried out by mechanical exhaust on a horizontal vent above the ceiling with a volume flow rate between 0 and 0.35 m^3/sec. A more precise description of the experiments is given in (1).

EXPERIMENTS ON THE SCALE MODEL : THEIR PARTICULAR FEATURES, COMPARED TO THE ZONE MODEL ASSUMPTIONS

The experiments are described at reference (1). The observations show that the flow pattern is 2 - dimensional inside the compartment and 3 - dimensional in the vicinity of the exhaust vent. The phenomena of these fire conditions seem to be dominated by the fluid dynamic aspects.

The experimental conditions are not favourable to the zone approach, because of the following particular features:

- The horizontal vent is not far from the door (≃ 40 cm). In the zone model, the mass flow rates through the door are calculated via integrations of the differences between the vertical pressure field in the compartment and the vertical pressure field in the communicating space. The pressure fields are described by the law of statics of gases. In the scale model, the flows in the compartment between the door and the exhaust vent are directly influenced by the fan action.

- When the imposed volume flow rate of the fan increases, a suction of the fresh air in the lower layer occurs, giving rise to a mass transfer (and an associated heat transfer) from the lower layer, not described in the zone model. The importance of this "funnel" effect increases with the velocity across the horizontal vent.

- Because of the velocities of the opposed flows entering and leaving the compartment, a mixing layer is created by the shear forces between these flows. This intermediate "zone" is not considered in the zone model.

- Much is known about air entrainment in flames and plumes from pool fire. In the present situation, we have a line source 10 cm from the back wall. A simple and precise modelling of this configuration is not easy. We chose an expression of the mass flow rate entrained by flames and plumes for the lower layer, proposed by ZUKOSKY and KUBOTA (3) Though we found that adjustment of a multiplicative coefficient could lead to a better agreement with experiments than the predicted results presented below, we kept the values of the formula from (3), as we had no theoretical reasons to choose another expression.

VARIABLES CHOSEN FOR THE COMPARISONS

- TMEX is the mass flow rate leaving the compartment through the ceiling vent under the pressure difference imposed by the fan.

- TMS is the mass flow rate leaving the compartment through the door. In a real fire situation, this variable has to be small or close to zero, for an efficient protection of the spaces around the compartment.

- TMIN is the mass flow of fresh air entering the compartment through the door.

  The previous variables are evaluated both on the scale model and by computation. Other variables come from the zone model only:

  . Tu: temperature of upper layer

  . ZI: height (from floor level) of the assumed interface between lower and upper layers.

  Computed values of Tu and ZI, from the zone model, can be compared only the average values of the results obtained from the scale model or from the field model.

. DV, the volume flow rate drawn out by the fan, is a parameter.

RESULTS FROM ZONE MODEL

Under steady state conditions, mass balance implies:

TMIN + TMF = TMS + TMEX, (where TMF is the injected mass flow rate of the combustible gas, small as compared to TMIN) and: TMIN = TMENTR, where TMENTR is the entrained mass flow rate.

As steady state conditions were established in the scale model after a few minutes, the presented results come from BS, a steady state version of FISBA (algebraic equations instead of differential equations), each run of BS requiring a computer time of about one second on a work station, and leading to the same steady state results as FISBA's.

We found that in this situation the influence of heat transfer by radiation and convection between the hot gases and the walls was not important, within the realistic limits of exchanges coefficients. Varying the convective heat transfer coefficient h from 1 to $5W.^{-2}.K^{-1}$, or global coefficient K of light attenuation in upper layer from 0 to 1 m^{-1} gave rise to variations of a few percent on the calculated mass flow rates. For the results presented here, h = 5 $W.m^{-2}.K^{-1}$, k = 0. The radiation fraction of energy from the flames received in value of 0.1 but its variation between 0 and 0.2 did not have much influence.

The results shown on figures 2 to 7 are relative to the extreme conditions of the experiments: lower heat output (28 kW) and higher heat output (70 kW), lower soffit (50 cm) and higher soffit (100 cm). We can see on figures 2 to 4 that the value of DV at which TMS = 0 is very high as compared to the volume of the compartment (2 m^3). This observation is entirely in conformity with what we obtained from other computations on smoke control in shops: a very high flow rate has to be imposed by a fan for big fires in full scale to get TMS = 0 (for example, DV = 12 m^3/s for a 100 m^2 x 2.5 m shop with a 1.4 m x 2 m open door and a fire of 4 MW).

COMPARISONS OF ZONE MODEL RESULTS WITH MEASUREMENTS AND FIELD MODEL RESULTS

- The agreement on TMEX values is very good (a few percent), and is not represented by means of curves. This agreement is due to the fact that DV is imposed and that the predicted density of the upper layer was in good agreement (a few percent) with the average measured or field modelled values.

- The comparisons of the predictions of TMIN and TMS from zone and field models show larger discrepancies, between a few percent to about thirty percent. The observed changes in the slopes of TMIN correspond to the value of DV where TMS = 0. The general trend of the zone model results is to underestimate these mass flow rates.

Among the phenomena listed above that are not well considered in the zone approach and are the cause of the observed discrepancies, let us mention two important points:

. Entrainment into flames and plume: the zone model leads to TMENTR = TMIN under steady conditions. Accurate measurements and computations at L.E.T. showed that TMENTR was almost independent of DV, whereas TMIN is not. The influence of the computed values of

TMENTR (by zone model) on TMS is shown on figure 6, and on TMEX on figure 7. The slopes of these curves should be more vertical, according to L.E.T. results.

- Suction of fresh air from lower layer: a simple approach from energy conservation (2) show that the phenomenon can occur at TMEX $\simeq$ 0.2 - 0.3 kg/sec with Tu $\simeq$ 100 °C - 200 °C and the height of the lower layer ZI = 50 cm, these latter values of Tu and ZI being realistic. The modelling of the suction phenomena was carried out by L.E.T. with field modelling. This is out of the range of zone modelling, which can nevertheless roughly estimate the critical values DV at which the phenomenon occurs (2).

The reasons that can explain the relative quality of the predictions of the zone model approach are not very clear. We can only say that the included assumptions of the zone model do not counter the global balances on heat and mass transfer in the compartment, even if local flow features are badly represented.

CONCLUSIONS

From experiments dominated by the fluid dynamic phenomena, in which the flow pattern is not simple, we showed the capabilities and limitations of a zone model approach. The results from the whole work done by L.E.T. and C.S.T.B. add information to the debate about the use of field or zone models. If we think of the great practical advantages of the zone approach (small computer, quick computations), maybe we can accept it for fire safety design, keeping in mind that the accuracy is not excellent but that its use provides correct estimations that one can improve with field models.

We found that the threefold approach: scale model, zone and field model, was very instructive and fruitful: one can both derive from it simple correlations and evaluate the capabilities of computer models.

NOTE: Room is missing here for the description of the FISBA zones model. FISBA's basic assumptions are quite similar to the ones on which the NIST zones models, for instance, were elaborated. Details on FISBA are given in references (11) et (12).

The SIMEC field model has been used at L.E.T. for years for computations concerning 2-D or 3-D convection problems. SIMEC is based on the Navier-Stokes equations and several numerical algorithms. More precise information on SIMEC can be provided by L.E.T.

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FIGURES

Figure 1 : The scale model (longitudinal section)

Figures 2 to 7 : Results

- Units:

  Ox, 10-2 kg/sec (10 g/sec)
  Ox, 10-2 kg/sec (10 g/sec)

- Symbols:

  . solid or dashed lines: zone model
  . + : TMIN from field model
  . X : TMS from field model
  . O : TMIN from experiments
  . * : TMS from experiments

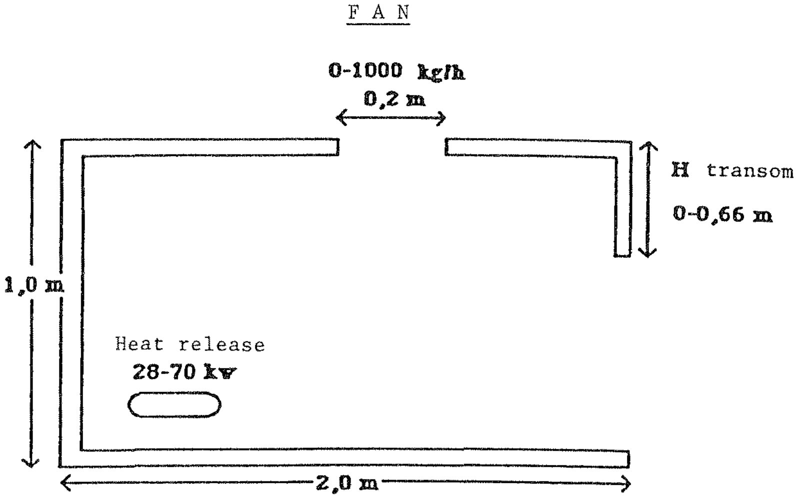
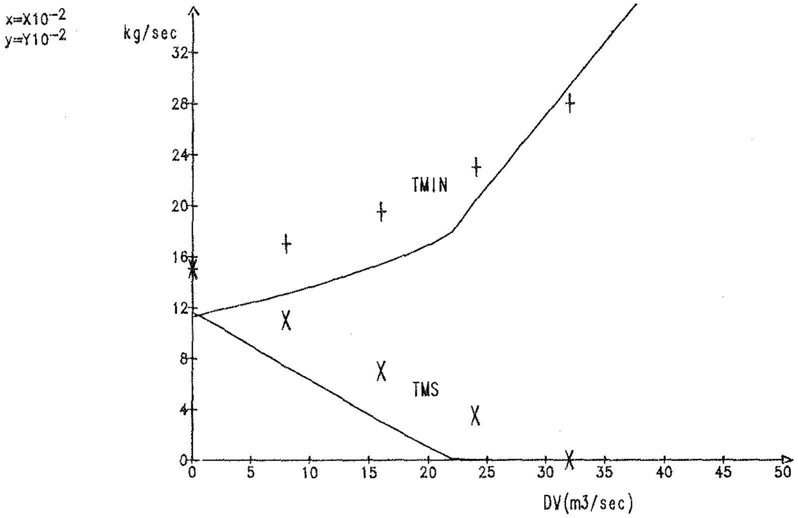
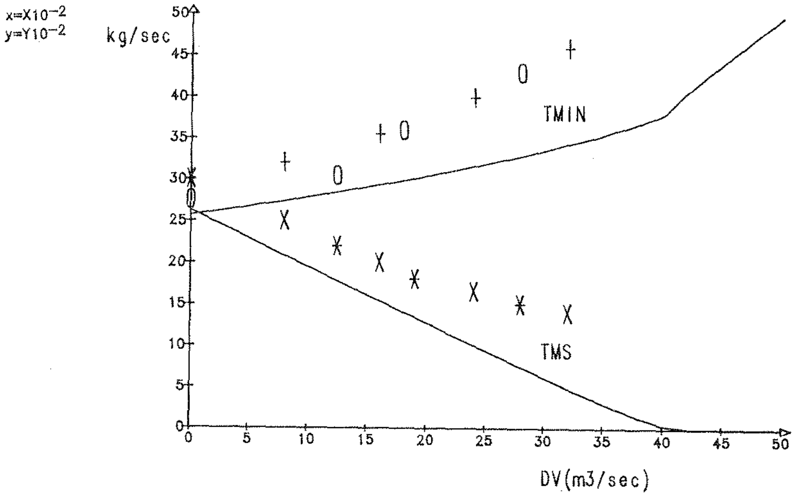


FIGURE 1



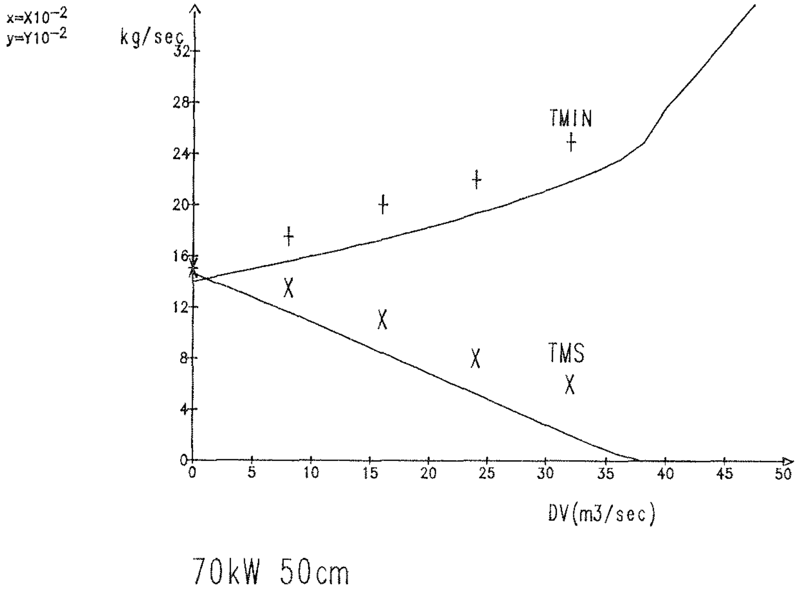
28kW 50cm

FIGURE 2



28kW 100cm

FIGURE 3



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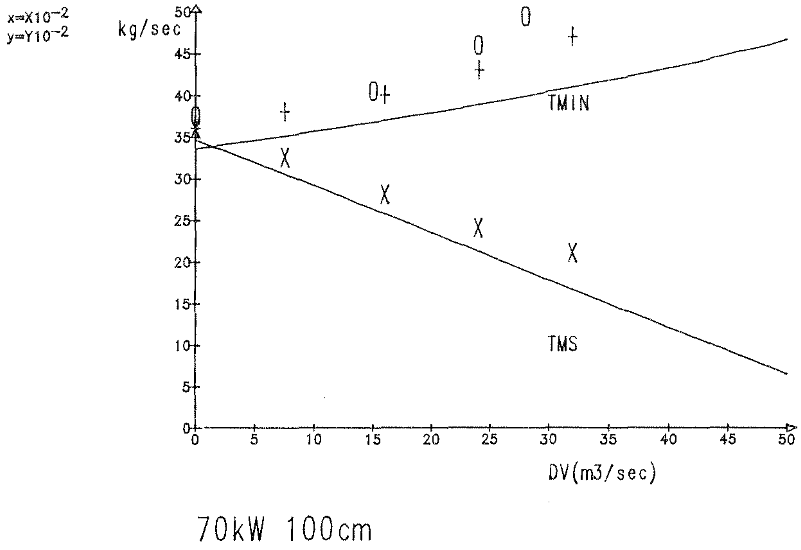

FIGURE 5

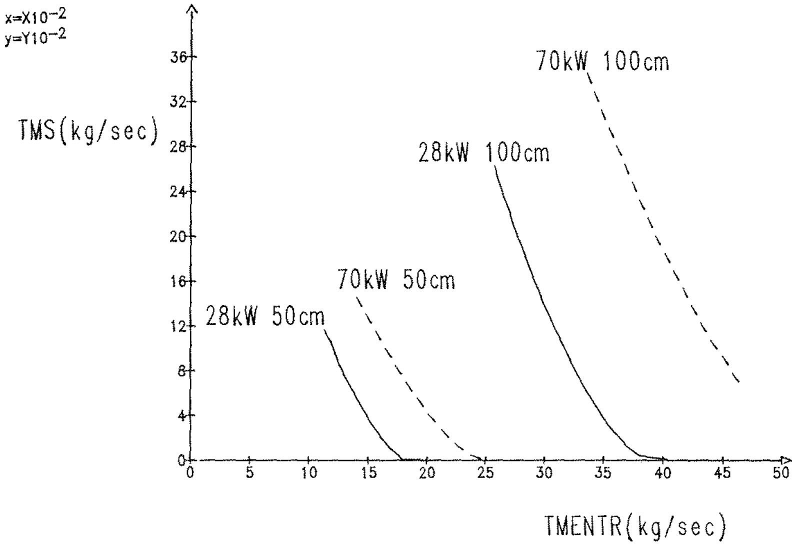

FIGURE 6

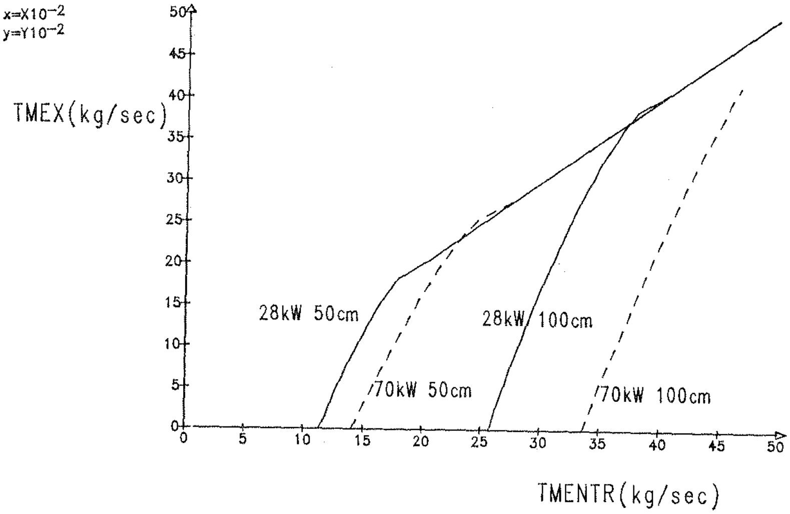

FIGURE 7

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