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Large Eddy Simulation of Transient Ceiling Jet in a Compartment Fire Environment

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Abstract

Development of a ceiling jet is a primary feature of a compartment fire. This phenomenon is caused by the buoyant fire plume hitting the ceiling of the compartment and spreading along it.

In the present study, jet front propagation along the ceiling is predicted using the Large Eddy Simulation (LES) method. The predicted propagation rate is in good agreement with the available experimental data. Results of LES simulation are also compared with the conventional Reynolds-Averaged Navier-Stokes (RANS) predictions and correlations based on dimensional analysis.

Introduction

Ceiling jet flow occurs virtually always in any compartment fire scenario. Hot products of combustion ascend to the ceiling in the form of a fire plume. As the plume reaches the ceiling of the compartment, it flows along the ceiling, and eventually reaches side walls of the compartment.

Investigation of ceiling jets is of primary interest in fire safety for the two main reasons. First, the rate of ceiling jet spread controls the smoke filling rate in a compartment, and eventually determines level of fire hazard to occupants. Second, activation of sprinklers and smoke detectors rely on temperature or smoke concentration rise in ceiling jets. Therefore, knowledge of fluid mechanics characteristics of ceiling jets is essential for design of fire control systems.

Most Computational Fluid Dynamics (CFD) studies conducted on ceiling jets have been concerned with quasi-steady flows. Motevalli [12] presented calculations based on fire field model. However, the velocity profile in the ceiling jet was taken from empirical correlation and introduced into the model as an input parameter. Field models of ceiling jets have also been reported by Sato [14] and Chow [3], but they have not been substantially validated against experimental data.

However, unsteady behavior is of great interest in large buildings where there is substantial time delay before ceiling jet propagates to the side walls of compartment. Recently, Liu *et al.* [7] proposed a non-dimensional correlation for ceiling jet front propagation. They also made CFD simulations using the PHOENICS code.

In the present study the behaviour of an unsteady ceiling jet is of primary interest. However, steady-state ceiling jet is also analysed since CFD analysis of the problem that has been made so far is still insufficient. In particular, no attempt to make Large Eddy Simulations has been made. Comparisons are made to the two sets of experiments [5,13], as well as to RANS predictions and non-dimensional correlations.

Mathematical model

The mathematical model introduced by Baum *et al.* [1,9,10], along with their computational code – "Fire Dynamics Simulator", is used to perform calculations.

The governing equations for weakly compressible flow with prescribed rate of heat release are written as:

$$\frac{\partial \rho}{\partial t} + \nabla \rho \vec{U} = 0$$

$$\rho\left(\frac{\partial \vec{U}}{\partial t} + \frac{1}{2}\nabla\left|\vec{U}\right|^2 - \vec{U}\times\vec{\omega}\right) + \nabla p - \rho\vec{g} = \nabla\tau$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + \vec{U}\cdot\nabla T\right) - \frac{dp_0}{dt} = \dot{q} + \nabla\left(k\nabla T\right) \tag{1}$$

$$p_0(t) = \rho R T$$

where p, ρ, $\vec{U}$, T are gas pressure, density, velocity and temperature, respectively. Other notations are as follows: t - time, $\vec{\omega}$ - vorticity, $\vec{g}$ - acceleration due to gravity, τ - viscous stress tensor, c_p - specific heat, $\dot{q}$ - volumetric heat release rate, k - thermal conductivity. The background pressure p_0, present in the energy equation (1), may generally vary with time (for example, for tightly sealed compartments).

Additional assumption made in the momentum equation is that the vorticity generation due to the baroclinic effect is negligible compared with its generation due to buoyancy.

Sub-grid scale (SGS) effects on the flow are modeled using the Smagorinsky model [15], which suggests the linear relationship between SGS Reynolds stress, τ_{ij}^s, and strain-rate tensor of the resolved scales:

$$\tau_{ij}^s - \frac{1}{3}\tau_{kk}^s\delta_{ij} = \mu_s\left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i}\right) = 2\mu_s\overline{S}_{ij} \tag{2}$$

where an overbar denotes filtered resolved quantities.

SGS eddy viscosity is given by the Smagorinsky model [15] as

$$\mu_s = C_s^2\rho\Delta^2\left|\overline{S}\right| \tag{3}$$

where Δ is the filter length scale, C_s is the model parameter.

This model is essentially an analogue of Boussinesq modelling for Reynolds stress tensor in RANS models.

Further details of the model are available in [1,9,10].

Experimental data

Two sets of experimental data are considered for comparison.

The first is due to Motevalli and Marks [13] who studied steady-state flow. A schematic of their experiment is presented in Figure 1. The fire plume is produced by a small burner; convective heat release of the fire is 2 kW.

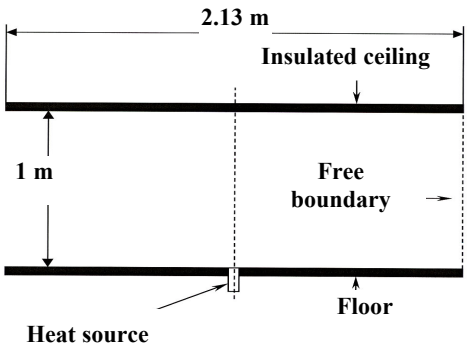

Figure 1. Experimental set-up by Motevalli and Marks [13] to investigate steady-state ceiling jet.

Fukutani *et al.* [5] studied ceiling jet front propagation, i.e. essentially unsteady ceiling jet flow. Another major difference from the experiments [13] was that hot smoke was delivered to the ceiling using an insulated pipe (Figure 2). This means that cooling of the smoke in the fire plume did not occur.

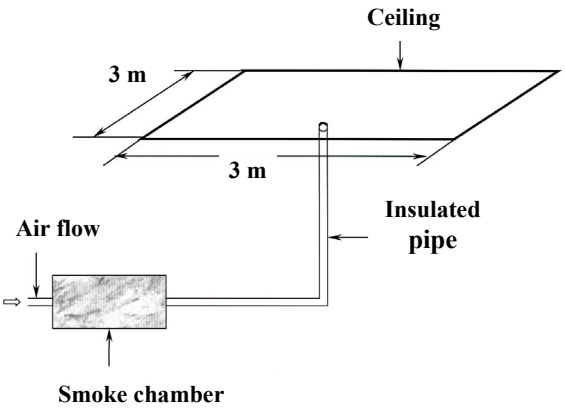

Figure 2. Experimental set-up by Fukutani *et al.* [5] for investigation of unsteady ceiling jet front propagation.

Computational details

In both cases (Figures 1,2) one quarter of the domain is considered. Therefore, symmetry conditions are enforced on two side faces of the computational domain. Free boundary conditions are set on another two side faces.

Base grid for all runs consists of 32 x 32 x 72 cells. The grid of 54 x 54 x 108 cells is considered as a refinement test.

The base choice for the Smagorinsky constant is $C_s = 0.14$ as suggested in [10]. The filter width is taken to be equal to the grid size.

The results of LES computations are time-averaged before comparison with the experimental data.

Results and discussion

Statistically stationary flow is achieved in computations in order to make a comparison with Motevalli and Marks [13]. The averaged flow is, therefore, steady-state. A snapshot of instantaneous temperature field is presented in Figure 3.

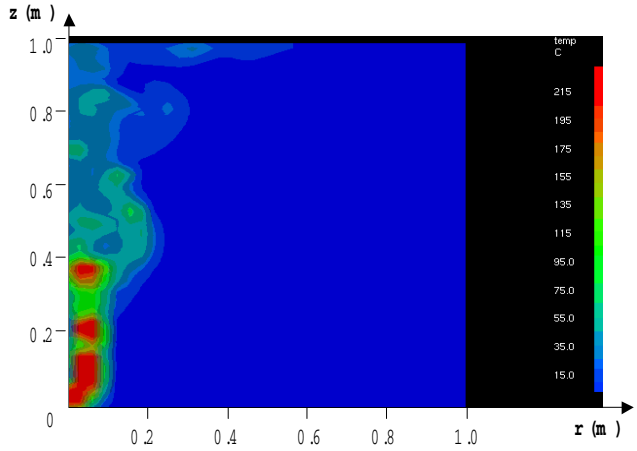

Figure 3. Snapshot of ceiling jet calculation corresponding to Motevalli and Marks [13] experimental conditions. Different temperatures from the indicated scale (right) are represented by different color intensity.

The primary variables of interest for a steady-state ceiling jet are velocity and temperature distributions. These are compared with the measurements at two different distances from the symmetry axis: $r/H = 0.26$; $r/H = 0.75$ (H is a ceiling height) (Fig. 4,5).

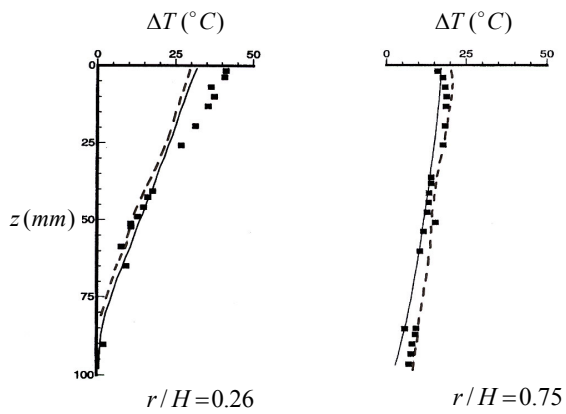

Figure 4. Comparison of excess temperature profiles between LES simulations and Motevalli and Marks [13] data.
T - temperature rise above ambient. z - distance from the ceiling.
■ - experimental measurements.
——— RANS predictions [11]. - - - - LES predictions.

Generally, the two methods (RANS and LES) give similar predictions for the temperature distributions (Figure 4). Both models under-predict the temperature close to the ceiling at $r/H = 0.26$. However, fire detection / suppression devices are usually located a few centimetres below the ceiling. In this region predictions shown in Figure 4 are reasonably accurate. Further from the fire source along the ceiling temperature profiles are in a good agreement with the measurements.

Velocity predictions are generally in a good agreement close to the ceiling (Figure 5). LES results are better at $r/H=0.26$ where they correctly reproduce velocity behavior far from ceiling.

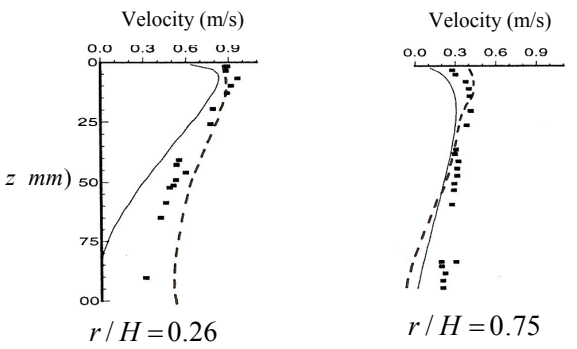

Figure 5. Comparison of absolute velocity profiles between LES simulations and Motevalli and Marks [13] data.
■ - experimental measurements. z - distance from the ceiling.
——— RANS predictions [11]. - - - - -LES predictions.

The next set of computations is made to predict the ceiling jet spread data of Fukutani *et al.* [5]. Two temperatures of released smoke are considered: 100 °C and 65 °C. Ambient temperatures for these cases are 10 °C and 14.1 °C, respectively. The ceiling is insulated in these cases.

The dynamics of the smoke front is presented in Figures 6,7. It is emphasized here that for these Figures the time origin $t=0$ corresponds to the instant of smoke impact on the ceiling. The time required for fire plume to hit the ceiling is not reported in [5], therefore, comparison for this quantity has not been made.

There is generally good agreement for both cases, although for the lower smoke temperature (Figure 7) predicted front propagates faster than in the experiments. However, the accuracy of predictions is sufficient for practical fire modeling calculations.

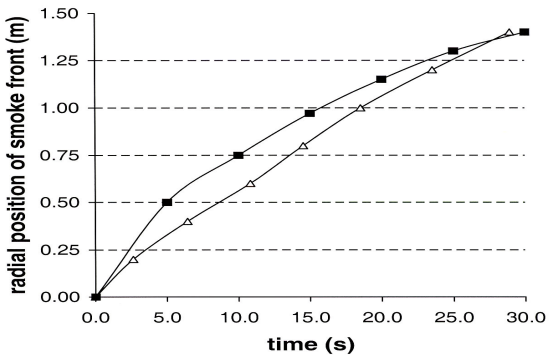

Figure 6. Comparison of jet front propagation along the ceiling between LES simulations and Fukutani *et al.* [5] data. Smoke temperature 100 °C.
■ - experimental measurements.
△ – LES predictions.

As a comparison, a non-dimensional correlation [2] is also presented in Figure 7. This correlation has the form:

$$\frac{r}{\left(A\cdot\dot{Q}_c\right)^{1/4}t^{3/4}}=0.75 \qquad (4)$$

where r denotes position of the leading edge of the jet, t is time, $\dot{Q}_c$ is convective heat release rate of fire. The parameter A is defined as $A=g/\left(c_p T_0 \rho_0\right)$ where T_0 and ρ_0 are ambient temperature and density, respectively.

Alternative correlation has been proposed by Liu *et al.* [7] in the following form:

$$1+\frac{r}{H}=\left(\frac{4}{p+3}\right)^{3/5}\left(\frac{A^{1/4}\cdot\dot{Q}_c^{1/4}\cdot t^{3/4}}{H}\right)^{4/5} \qquad (5)$$

where H is ceiling height, p is fire growth constant ($p=0$ for steady fires considered in the present paper).

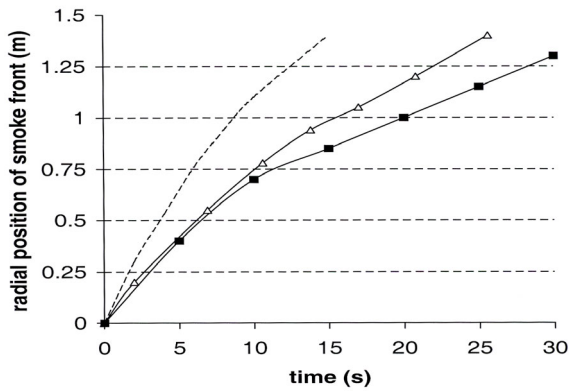

Figure 7. Comparison of jet front propagation along the ceiling between LES simulations and Fukutani *et al.* [5] data. Smoke temperature 65 °C.
■ - experimental measurements.
△ – LES predictions.
- - - - -Correlation (4)

Apparently, use of the correlation (4) results in significant overprediction of smoke spread rate. The main reasons for this are neglecting wall friction and ceiling height effects.

Unfortunately, the direct comparison with the correlation (5) is impossible since the height H is not provided in the paper [5]. According to [7], the correlation (5) gives reasonably good agreement with various experimental data in the range $r/H<10$ as the ceiling height effect is included.

In the LES simulations (Figure 7), the front propagates slightly faster at later stages than in the experiments.

In order to investigate the sensitivity of LES predictions to computational parameters, additional runs were made with different values of the Smagorinsky constant C_s (equation (3)), and also with the refined grid.

Generally, the parameter C_s has been adjusted differently for different types of flows. For example, Lilly [6] determined that $C_s=0.23$ for homogeneous isotropic turbulence. In the presence of mean shear, however, Deardorrf [4] reduced the estimation to $C_s=0.1$. Mason and Callen [8] used the value of $C_s=0.2$ while Piomelli *et al.* [16] found that $C_s=0.1$ give better results on very fine meshes. Generally, it is reasonable to vary this parameter in the range $0.1\le C_s\le 0.2$.

The results of calculations for different values of the Smagorinsky constant, as well as grid refinement test are presented in Figure 8. It is easily seen that the results are quite sensitive to the choice of the Smagorinsky constant. Large values of this parameter (close to 0.2) give slower propagation rate, especially at later stages. Values close to the lower limit (0.1) overestimate the front speed. The best results are obtained with $C_s=0.14$, which is in fact the default value in the FDS code [10]. This value has been producing consistently good results through the range of fire engineering applications [1,9,10].

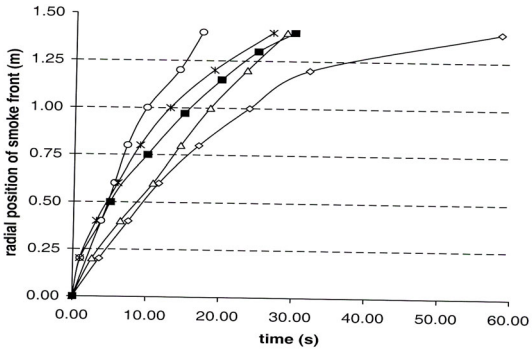

Figure 8. Effects of Smagorinsky constant variation and grid refinement on the base case solution.

■ - experiments, Fukutani *et al.* [5], 100 °C smoke.

△ – base case LES predictions.

○ – $C_s = 0.1$.

◇ - $C_s = 0.2$.

∗ - refined grid 54 x 54 x 108.

A refinement test is made on the 54 x 54 x 108 grid. With a realistic subgrid model, the solution should become independent of the grid after a certain resolution is achieved. A small change in the solution has been observed on a refined grid, compared with the base solution, which suggests reasonable subgrid modeling and grid refinement.

The formal requirement for LES simulations is that the cut-off of subgrid scales is made in the *inertial subrange*. The refined grid, mentioned above, is slightly coarser, but close to this requirement.

Overall, LES simulations performed in the present study agree reasonably well with the available experimental data for both steady-state and transient ceiling jets. Obviously, the technique is much more expensive computationally than the conventional RANS simulations. For a typical transient case considered in the present paper the ratio (CPU time)/(real simulated time) was about 400 using 1.4 MHz (Pentium 4) computer. This means about 3-4 hours of calculation to follow 30 seconds of real time ceiling jet front propagation. This is a practically acceptable time for doing fire research calculations in important cases where RANS models or empirical correlations may fail.

It follows from the results presented above that in many cases steady-state or unsteady behavior of ceiling jets can be reasonably well predicted by non-dimensional correlations or RANS models. However, the present study is considered in the context of application LES simulations to more complicated problems, where direct treatment of turbulence will become critical. One such problem is interaction between ceiling jet and fine water mist upon activation of fire suppression system. In such two-phase system, the life time for fine droplets is likely to become comparable with the turn-around time of large-scale eddies in the flow. In such a situation, application of the averaged equations is likely to produce significant errors in the prediction of the droplet evaporation rates.

In the view of future applications, it is important that LES models are validated on relatively simple "test" cases and their abilities and limitations are well understood. Some of such cases (steady-state and transient ceiling jets) have been reproduced reasonably well by the present study.

Conclusions

The present paper has presented Large Eddy Simulations of steady-state and transient ceiling jets developing in a compartment fire environment. Two sets of experiments were considered for comparison, and the results of predictions compare favorably with the available data.

Predictions of ceiling jet front propagation are sensitive to the choice of the Smagorinsky constant, however the value providing the best predictions is consistent with the values required for other fire safety applications.

Required computational times are acceptable for practical fire modeling calculations. Most significant advantage of LES modeling is likely to be seen in complex fire modeling problems, such as the problems involving multi-phase flow, turbulent combustion and toxic species production in fires.

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