Large-eddy simulation of buoyant plane plumes

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LARGE-EDDY SIMULATION OF BUOYANT PLANE PLUMES

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Abstract. In the present study a turbulent plane plume is examined by means of numerical simulations. Results are compared with experiments and results from integral models based on an entrainment assumption. The objective of this research is to determine whether a Large-Eddy Simulation can be applied in this case and what subgrid scale model performs best.

1. Introduction

In the present study the usefulness of a large eddy simulation for convection plumes is studied, where in particular the attention will be focussed on transition from laminar to turbulent flow conditions. There are two types of spatial transition in a plume. First there is the laminar/turbulent transition from the ambient flow to the turbulent core of the plume. Second there is a transition in the downstream direction when the width of the heat source and the heat flux are small enough, so that the initial Reynolds number is small. The latter transition is accompanied with dipolar structures that are shedded to alternate sides. This is illustrated in fig. 1 where a transitional laminar plume is shown.

In continuation of previous research [1], this paper describes a comparison between numerical simulations and results obtained by use of an

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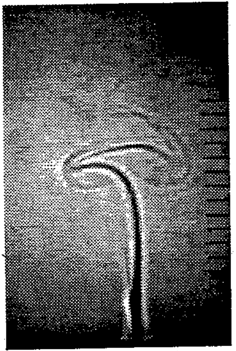

Figure 1. Shadowgraph of the transition of the laminar plane plume

integral model for the fully turbulent plume in a quiescent surrounding. The entrainment hypothesis which is needed in this model states that the mean inflow velocity across the edge of a turbulent flow is proportional to the time-averaged maximum velocity in the core. An overview of the use and succes of the integral model is given by Turner [8]. The goal of the present study is to determine if a large-eddy simulation (LES) can solve the flow. Once the LES model is validated it is possible to determine from the simulation results important quantities, e.g. occurence of temperature extrema and distributions of it in time and space, together with it's probability.

2. Numerical Method

Our numerical code used is based on the Navier-Stokes equations using the Boussinesq approximations. It is a finite volume method with second order upwinding. A similar approach can be found in Schmidt and Schumann [6].

The effects of subgrid-scale motion is modeled by applying a functional relation between the subgrid scale stresses τ_{ij} or temperature fluxes h_j and the resolved scale variables. The simplest and most commonly used model is based on gradient diffusion: $\tau_{ij} = 2\nu_T S_{ij}$ and $h_j = \nu_H \partial T/\partial x_j$, where ν_T is the eddy viscosity and ν_H the eddy diffusivity. The resolved scale deformation rate tensor S_{ij} is defined by: $S_{ij} = \frac{1}{2}\left(\partial u_i/\partial x_j + \partial u_j/\partial x_i\right)$ (an overbar denotes filtered variables).

The eddy coefficients ν_H and ν_T depend on the local intensity of the subgrid energy. To determine the eddy viscosity a model proposed by Smagorinsky [7] in which the eddy viscosity is set proportional to the local resolved velocity gradient is widely used: $\nu_T = (C_s\Delta)^2 S$ where $S = \sqrt{2S_{ij}S_{ij}}$ and C_s is a constant. The length scale Δ, which in principal is proportional to the filter width, is usually set equal to the average grid size.

A somewhat more complicated model has been used by Nieuwstadt et al. [5] for atmospheric convection in the planetary boundary layer. They define the turbulent viscosity in terms of the subgrid energy e: $\nu_T = C_\mu \Delta \sqrt{e}$. For e a separate differential equation has to be solved (see [5]).

In the Germano approach [2], one usually takes the Smagorinsky subgrid model, but the constant C_s is computed dynamically. It is a model developed to simulate intermittent and non-homogeneous flows as occurring in transition. An alternative is the structure-function model, a subgrid model which was proposed by Métais and Lesieur [4].

The subgrid heat fluxes are generally modeled analogously to the subgrid stresses. The exchange coefficients are related to each other with the turbulent Prandtl number: $Pr_T = \nu_T/\nu_H$. Here we take $Pr_T = 1/3$.

3. Results

In an integral model one satisfies the momentum and buoyancy equation averaged over the plume cross section. To close these equations one needs an entrainment hypothesis which prescribes the inflow in the plume. The entrainment assumption, which uses a constant ratio α of time mean entrainment velocity to vertical velocity at the core, results in a linear spread of the plume width. Additional measurements by several researchers have demonstrated that the lateral profiles of vertical velocity and temperature are approximately Gaussian. With these assumptions the velocity and temperature field can be determined to be:

$$w = \left(\frac{\gamma+1}{2\alpha^2\gamma}\right)^{1/6} B^{1/3} e^{-(x/b)^2} \tag{1}$$

$$g\beta\Delta T = \frac{1}{2}\left(\frac{2\gamma(\gamma+1)^2}{\alpha^4}\right)^{1/6} B^{2/3} z^{-1} e^{-\gamma(x/b)^2} \tag{2}$$

with $b = (2\alpha/\sqrt{\pi})z$ the plume width and γ accounting for the difference in width between velocity and temperature profile. The buoyancy flux is given by $B = g\beta Q/\rho c_p$ and x is the lateral direction. The heat flux per unit length Q in the situation that we considered was 570 W/m and the medium was water at about 300 K. The values of α and γ have been measured to be 0.157 and 1.281, although List [3] reports measurements in which the midplane velocity was determined to be $1.66B^{1/3}$. In figure 2 the time mean vertical velocity as obtained by a 3-D LES with the energy equation model [5] at some arbitrary height is given together with the Gaussian profile obtained with height according to List. The resolution of the simulation was $128 \times 64 \times 64$ in the (x, y, z) direction. The left plot of figure 2 shows the integral model result with the latter midplane velocity, compared to the simulation. The differences next to the plume are due to the recirculation because of the confinement of the flow. In the right plot of figure 2 the mean vertical velocity (non-dimensionalized by $B^{1/3}$) is displayed against the height of the container, represented in the form of a local Grashof-number $Gr_{Qx} = g\beta Q x^3/\rho c_p \nu^3$. Also laboratory experiments using Laser-Doppler anemometry are plotted in this figure. There is a reasonable agreement between experiment and simulation. There is some deviation from theory in the region near the source and near the roof of the container. This is to be expected since theory does not fulfil the correct boundary conditions for a closed container.

The rising speed of the initial dipole is plotted in figure 3. It is compared to observations of the rise of a thermal plume using dye. The rising speed in both cases seems to be constant until the turbulent dipole collides with the top wall.

The 2-D calculations (performed on a 64 × 32 grid) show more or less the same results as the 3-D simulations. In contrast to the other models the Germano model shows clearly more dynamics, as could be observed by larger energy contents of fluctuating quantities, smaller structures, a localized large turbulent diffusivity and an overall larger standard deviation of the turbulent diffusivity. These features were also found in (short) 3-D runs with the different models.

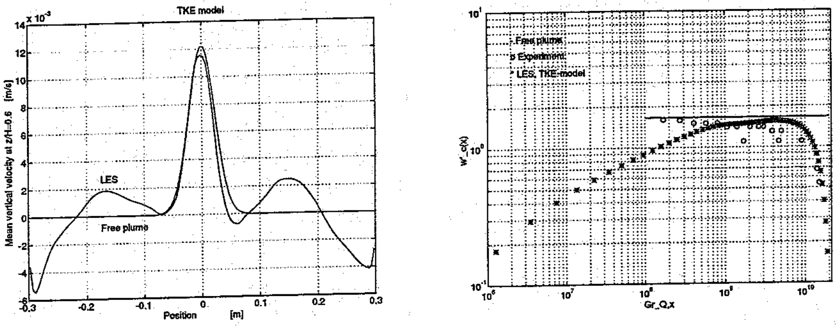

Figure 2. Time-averaged velocity profiles in horizontal (left) and vertical (right) cross section, compared to measured Gaussian distributions

4. Conclusions

The behaviour was investigated of thermal plumes above a small sized heat source inside a cavity with adiabatic side walls and cold top and bottom walls. Experimental results were compared to numerical solutions obtained by LES in which different subgrid scale models were used. It was found that numerical solutions obtained with the turbulent energy equation model

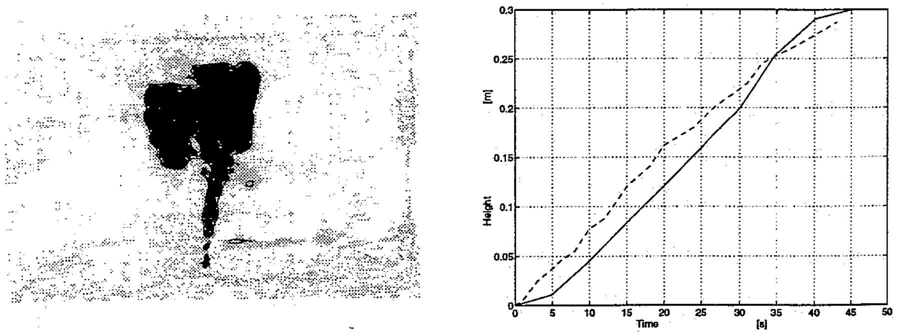

Figure 3. Rising of the initial dipole, left: experiment, right: experiment, ---; LES, —

gave good results compared to theory and measurements, when using a sufficiently high resolution grid. Simulations using the Smagorinsky model and the structure function model gave comparable results. The Germano model yielded a stronger dynamical behaviour.

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