

LAGRANGIAN SIMULATION OF LARGE FIRE PLUMES

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The numerical simulation of large fire plumes poses an uncommon challenge due to (1) the multiplicity of the physical processes which contribute to the outcome of burning a pool of fuel in a windy environment, (2) the multiplicity of scales which arise as the flow, transport and chemical reactions interact requiring numerical resolution in time and space which exceed 10^6 in each dimension, and (3) the enormous demand on the computational power as one tries to accommodate such resolution. Large fires are controlled by buoyancy dynamics, heat and mass transport which includes a major contribution from radiation, and combustion chemistry in which soot formation and destruction plays an important role. The evolution of a turbulent flow within the bulk of a fire is nearly unavoidable no matter how small the fuelpool is, and as such leads to all the known complexity of turbulence, turbulence-combustion interactions, and turbulence-radiation interactions. Developing a predictive tool which can be used to study the impact and footprint of a large fire is clearly a daunting task.

We have initiated an effort to develop a flexible and efficient framework for numerical fire simulation which takes advantage of (1) the current understanding of the physics of turbulence, combustion and radiation to simplify the model used to incorporate each component, (2) a powerful set of Lagrangian, grid-free numerical schemes which optimize the effort by concentrating the computational elements where they are most needed, and (3) the most advanced class of parallel, scalable computers. At the heart of the approach is the integration of the unsteady Navier-Stokes equations, cast in their vorticity transport form, using the transport element method in which the vortex elements are tracked along their trajectories while their circulation is being updated due to the action of the pressure gradient and the gravity field. Moreover, the gradients of the species concentrations, density and temperature are also computed along the same trajectories to efficiently solve for the mixing and combustion field.

The combustion model used at this stage assumes fast chemistry and considers the combustion process to be diffusion limited. To the extent that one is interested in fuel consumption, this is a reasonable approximation. This simplification reduces the species and energy equations into a set of conserved scalar equations which can be readily solved in terms of a mixture fraction as the different scalars are properly normalized. The dynamic effects of combustion, the primary source of energy in a fire, is represented in two mechanisms: the generation of vorticity along the combustion front and the

volumetric expansion associated with the heat release. In our first attempt to model the fire plume we accounted only for the first mechanism and showed that the observed intermittency in fire plumes, known as puffing, is due to an intrinsic instability of the vorticity layer which forms along the rising column of hot mixture, forming primarily from hot fuel and products [1]. The simulations were used to gain a better understanding of the similarities and differences between nonreacting and reacting buoyant plumes in an effort to explain some of the reported experimental data and explore the possibility of simplifying the overall model [2]. We showed that using a hot nonreacting pool of gases one can produce a plume whose dynamics are qualitatively and under some conditions quantitatively similar to those observed in the fire plume. Baroclinic vorticity generation, being the mechanism by which the potential energy of the plume is converted into kinetic energy, is very similar in both cases since even in the fire plume the density gradient acts essentially in the radial direction (fuel heating by the flame produces a hot column resembling that of an isothermal plume).

In this paper, we focus on the effect of volumetric expansion on the dynamics, mixing and combustion within the fire plume. We should mention that in the current model the effective enthalpy of reaction is reduced by about 30% to account approximately for the effect of radiation which has not been modeled comprehensively in our simulation [3]. As such, and given the overall fuel lean environment of a fire, one might expect that the volumetric expansion in the fire zone is not significant. This is indeed borne out of the simulations. We find that most of the predictions of the zero expansion model are close to those obtained in the finite expansion model in as far as the observable dynamics, e.g. puffing frequency and its dependence on the pool diameter, the average flame height and overall shape of the quasi periodic plume. We find, however, that the finite expansion model leads to reduced entrainment into the large structures and as such reduced overall fuel burning rate. The entrainment is still sufficient to reduce the temperature within the burning zone and inside the plume such that the overall field maintains the approximate distribution of a nearly isothermal plume. The paper will include detailed comparisons between the two models and a discussion of the implications of the impact of volumetric expansion on the fire evolution.

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