

FLAME-GENERATED VORTICITY PRODUCTION IN PREMIXED FLAME-VORTEX INTERACTIONS

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INTRODUCTION

Theoretical analysis, experimental observations, and numerical simulations have all indicated that flame-vortex interactions play an important role in the propagation and extinguishment of turbulent flames in microgravity [1]. Most studies of flame-vortex interactions ignore the effects of gravity and experiments are usually conducted in Earth gravity. Recently, Sinibaldi et al. [2] and Driscoll and coworkers [3] have reported the results of drop-tower experiments that show that for some vortex strengths, the reduction in gravity can significantly alter the structure of the flame produced by the flame-vortex interaction. These studies found that the flame is much more wrinkled in microgravity conditions, attributable to the lack of the stabilizing effect of buoyancy.

In order to examine flame-generated vorticity (FGV), it is customary to look at the production and loss terms in the vorticity equation, that is, perform a vorticity budget. We will focus our attention on those terms that can increase or decrease the total vorticity in a region containing the flame. Terms that merely redistribute vorticity, such as convective terms, do not change the total vorticity and thus do not contribute to FGV. Only two terms in the vorticity equation can create vorticity where none was originally present before; these are the viscous term and the baroclinic torque term. The stretch term, cannot create new vorticity, but can amplify or attenuate the total vorticity.

The baroclinic production term is perhaps the most interesting and has been studied in detail (see for example Refs. 4-7). It has been presumed that the misalignment of the density gradient and the pressure gradient is a major cause of FGV. The density gradient across the flame is very large, and so any small misalignment of the gradients will produce FGV. In flame-vortex interactions, the flame is highly curved and the gradients get misaligned. In order to extract the effect of gravity, it is customary to separate the pressure into a hydrostatic pressure and a dynamic pressure. The baroclinic torque can be then separated into two parts: one due to the dynamic pressure and the other due to the gravity-induced hydrostatic pressure. The role of the latter term will determine the effect of gravity.

In this study, we use detailed time-dependent, multi-dimensional numerical simulations to investigate the relative importance of the processes leading to FGV in flame-vortex interactions in normal gravity and microgravity and to determine if the production of vorticity in flames in gravity is the same as that in zero gravity except for the contribution of the gravity term. The numerical simulations will be performed using the computational model developed at NRL, FLAME3D. FLAME3D is a parallel, multi-dimensional (either two- or three-dimensional) flame model based on FLIC2D [8], which has been used extensively to study the structure and stability of premixed hydrogen and methane flames.

OUR PREVIOUS WORK

In our previous work, we examined the effect of gravity on the flame-vortex interaction in lean methane-air flames [9]. All our simulations indicated that buoyancy controls the flame shape after the flame-vortex interaction. Gravity has the strongest effect on weak vortices with small Froude numbers. Figure 1 shows qualitative comparison of numerical and experimental results [3] for a downward propagating flame interacting with an intermediate strength vortex.

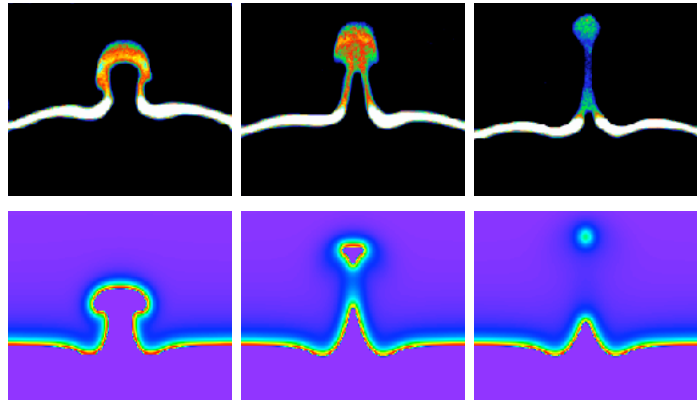


Figure 1. Experimental from U. Michigan (above) and numerical (below) comparison of OH concentration.

VORTICITY EQUATION

The vorticity equation is derived from the conservative form of the fully compressible, variable viscosity Navier-Stokes equation including the gravity source term. In our simulations, the axisymmetric form of the Navier-Stokes equation is used; thus only the ∇ -component of the vorticity is nonzero. The ∇ -component of the vorticity equation (after simplification) becomes:

$$\frac{D\nabla}{Dt} + \nabla(\nabla \cdot \mathbf{V}) = \underbrace{\frac{\mathbf{F}_v}{\rho}}_{\text{viscous}} + \underbrace{\frac{1}{\rho^2} [\nabla \nabla \nabla P]}_{\text{baroclinic}} + \underbrace{\frac{\nabla v_r}{r}}_{\text{stretch}}$$

where ∇ is the ∇ -component of the vorticity, \mathbf{V} is the velocity, ρ is the density, \mathbf{F}_v is the viscous force. Note that gravity does not appear explicitly anywhere. In order to extract the effect of gravity, it is customary to separate the pressure into a hydrostatic pressure and a dynamic pressure $P = p_H + p_D$, where the hydrostatic pressure, is given by: $p_H = \int_0^z \rho g dz$. With this decomposition, the baroclinic torque term can be written (after simplification) as:

$$\frac{1}{\rho^2} [\nabla \nabla \nabla P] = \underbrace{\frac{1}{\rho^2} [\nabla \nabla \nabla p_D]}_{\text{dynamic}} + \underbrace{\frac{g}{\rho} \frac{\partial \nabla}{\partial r}}_{\text{hydrostatic}}$$

The first of these terms is the baroclinic torque due to the dynamic pressure and the second is the torque due to the gravity-induced hydrostatic pressure.

An alternate approach [5,6] that has been taken is to assume that the hydrostatic pressure is given by: $p_H = \int_0^z \rho_A g dz$. This leads to a gravity term of the form: $\frac{g \rho_A}{\rho^2} \frac{\partial \nabla}{\partial r}$. This approach assumes that the density is basically perturbed around the constant ambient value ρ_A . This assumption is quite good for non-reactive flows, but it is incorrect for our flame-vortex simulations with large burned and unburned regions of greatly differing density. We will stick to the earlier form that does not make such an assumption.

RESULTS AND DISCUSSION

We will examine the total production of vorticity within a large control volume that fully contains the initial vortex and regions downstream into which the vorticity may be convected. We will look at the vorticity production by an “intermediate” strength vortex (peak initial vorticity 600 s⁻¹, see Ref. 8 for details). The flame vortex interaction during upward flame propagation and propagation in zero gravity is qualitatively quite similar to downward propagation for “intermediate” strength vortices. We will examine the influence of gravity on the vorticity enhancing terms. The results show the production rate of vorticity integrated over the entire control volume versus time for the terms of interest.

Figure 2 shows the overall production of vorticity. The production rate remains mostly positive while the flame is being distorted by the vortex. Once the flame bubble created by the vortex is consumed and flame is no longer greatly distorted, the production rate becomes negative and total vorticity is destroyed. The curve for zero gravity propagation usually lies between the upward and downward propagation curves as might have been expected.

Figure 3 shows the partition of the baroclinic production of vorticity into the hydrostatic component induced by gravity and the dynamic component. The hydrostatic components of the baroclinic torque in the upward and downward cases are essentially similar except for sign up to the point of bubble consumption. The dynamic components in all three cases exhibit the same features, but they are not identical. If the effect of gravity were limited only to the hydrostatic term, we would expect the dynamic component to be the same in all cases. Since this is not so, it is clear that gravity also affects the dynamic component indirectly.

Figure 4 shows the contribution to FGV from the viscous term. This contribution, though smaller than from the other terms is far from negligible. Thus, the usual assumption that has been made that this term can be neglected [4] or is identically zero [5-7] is not valid.

Vorticity is greatly enhanced by stretch while the flame is greatly distorted by the vortex. The vorticity enhancement by stretch varies by a factor of three in upward, downward, and zero-

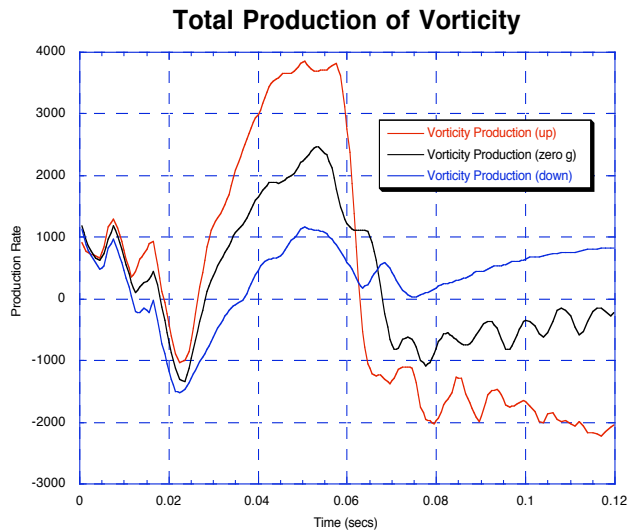


Figure 2 Total vorticity production.

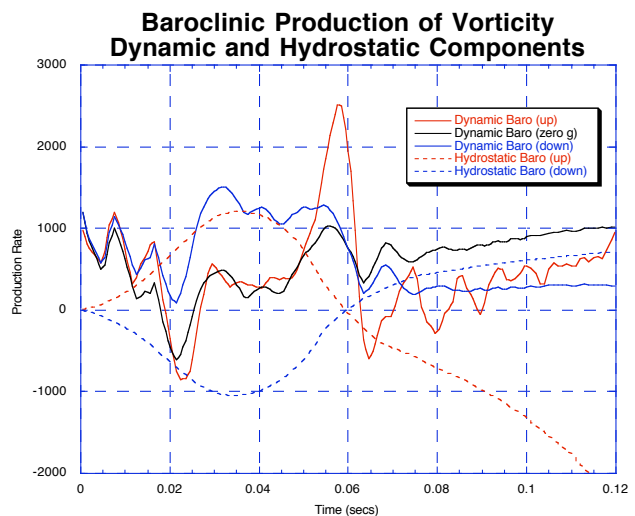


Figure 3. Hydrostatic (gravity) and dynamic components of the baroclinic production term.

gravity cases, indicating that gravity is significantly affecting this term, indirectly via the flame shape.

CONCLUSIONS

It is incorrect to presume that gravity's effect is fully explained just by the gravity term; the role of gravity is far more complex. All terms involved with vorticity enhancement are greatly dependent on the flame shape. Though the flame shape is quite similar in upward, downward, and zero gravity propagation, it is the subtle differences that cause the effect of gravity to be felt in the other terms as well. Thus it does not appear possible to isolate the effect of gravity on FGV to the one term in which it explicitly appears.

Several assumptions made about the vorticity production terms have been examined. The common assumption that the viscous term does not contribute to FGV was shown to be incorrect.

Acknowledgements

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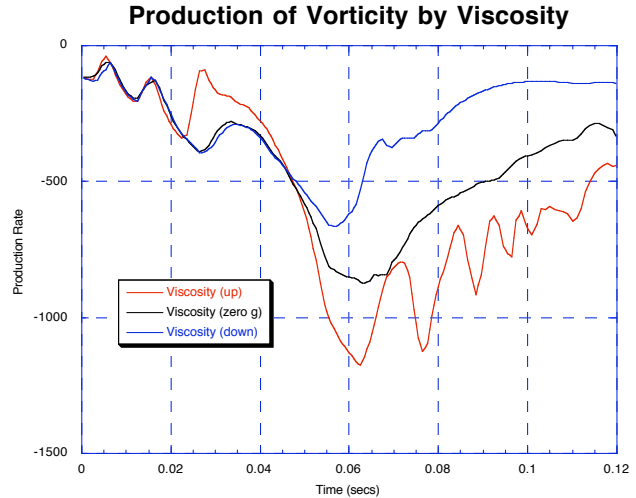


Figure 4. Viscous term.