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Leading points and heat release effects in turbulent premixed flames

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Abstract

This paper presents an investigation of the role of leading points in the propagation of turbulent premixed flames. The long time behaviors of turbulent flame speeds, brush thickness, and flame surface density are analyzed using direct numerical simulation (DNS) data for statistically stationary planar flames in homogeneous isotropic turbulence. Results suggest the existence of a regime where the leading points dynamics controls premixed flame propagation in homogeneous isotropic turbulence, which supports the viewpoint that under certain conditions, the processes near the leading edge determine the propagation speed of turbulent premixed flames. It is found that the enhanced apparent propagation speed due to heat release effects contributes to the dominant role of the leading points in the unity Lewis number flames investigated here.

Keywords: Turbulent premixed flames; Leading points; Heat release effects

1. Introduction

Premixed flame propagation in turbulent flows is of relevance to many practical applications and natural phenomena. Turbulence is known to enhance the burning rates of premixed reactants and thus increase the overall propagation speed of the flame until extinction can be significant. Extensive studies performed during the past several decades have revealed not only underlying physical mechanisms, but also the complexity of the process, leading to a consensus that turbulent flame speed is not well parameterized using local turbulence properties, ahead of a flame brush, scaled with laminar flame quantities [1–6].

Statistically planar flames propagating into homogeneous isotropic turbulence are considered a canonical problem to study turbulence-flame interactions. It is argued that in this configuration, isolating the geometry or boundary effects [4,7], a well-defined turbulent flame speed can exist at a statistically steady state and can be parametrized with a small number of parameters. Along the line, during the past decades, many theoretical and numerical studies have been performed for this one-dimensional flame configuration [8–14]. In most of the direct numerical simulation (DNS) studies, however, either growing or substantially fluctuating turbulent consumption speed was observed in contrast to the expectation. In this paper, the

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question of identifying a mechanism for such characteristics is addressed by investigating the long time behaviors of flame evolution and propagation speeds in DNS of premixed flame propagation in homogeneous isotropic turbulence. An approach to perform DNS of such statistically steady planar flames in a well-controlled and computationally efficient way is presented for the long time simulation.

2. Direct numerical simulation

2.1. Coordinate transformation

Consider a premixed flame propagating into homogeneous isotropic turbulence. Assuming low Mach number, single-step chemistry, unity Lewis number, and adiabatic conditions, all thermochemical properties are uniquely determined by the progress variable, typically defined as the normalized temperature or mass fraction of a deficient reactant [5]. The governing equation for the progress variable can be written as

$$\frac{\partial \rho C}{\partial t} + \nabla \cdot (\rho \mathbf{u} C) = \nabla \cdot (\rho D \nabla C) + \rho \omega_C, \tag{1}$$

where ρ is the density, $\mathbf{u}$ is the fluid velocity, D is the molecular diffusion coefficient, and ω_C is the chemical reaction source term. The equation of state is given as

$$\frac{1}{\rho} = \frac{1}{\rho_u} + C\left(\frac{1}{\rho_b} - \frac{1}{\rho_u}\right), \tag{2}$$

where ρ_u and ρ_b are the density of unburned mixture and of burned mixture, respectively. The dynamics of the premixed flame is described by the progress variable equation and the variable-density, low Mach number Navier–Stokes equation, together with the continuity equation.

Consider a finite-size box, Ω, which contains the premixed flame. Integration of the equation for $1 - C$ over the box leads to

$$\int_\Omega \frac{\partial \rho (1-C)}{\partial t} dV = \rho_u S_t A_P - \Gamma_{\text{out}} A_P - \int_\Omega \rho \omega_C dV, \tag{3}$$

where S_t is the mean velocity at the inflow boundary, Γ_{out} is the mass flux of the unburned mixture at the outflow boundary, and A_P is the area of the inflow and outflow boundaries. To maintain the total mass of the unburned mixture inside the box, the mean inflow velocity should be given as

$$S_t = \frac{1}{\rho_u A_P} \int_\Omega \rho \omega_C dV + \frac{\Gamma_{\text{out}}}{\rho_u}. \tag{4}$$

Assuming all reactants burn in the computational domain, i.e., $\Gamma_{\text{out}} = 0$, the usual definition of the consumption speed is obtained. In turbulent flames, the consumption speed is time-dependent in general and the thickness of a flame brush fluctuates. To keep the flame from touching the inlet boundary of the computational domain, the following inflow velocity is proposed:

$$U_t = S_t - \alpha \frac{S_t}{l_0}(x_{\text{le}} - x_{\text{le},0}), \tag{5}$$

where x_{le} is the location of the leading edge, $x_{\text{le},0}$ is a desired location of the leading edge, l_0 is a reference length on the order of the flame brush thickness, and α is a relaxation parameter. x is the coordinate in the direction of the mean inflow, with the origin at the inflow boundary.

The propagation speed of the turbulent flame in a finite-size computational box fluctuates in general. Let $\overline{U_t}$ be the turbulent flame speed defined as the time average of the consumption speed evaluated for a finite-size domain:

$$\overline{U_t} = \frac{1}{T} \int_0^T S_t(\tau) d\tau, \tag{6}$$

where the time interval T is much larger than the integral time scale. Taking an inertial frame moving with the speed of $\overline{U_t}$ and a reference frame moving with the speed of U_t, the following coordinate transformation is introduced:

$$x = x' + \int_0^{t'} (U_t(\tau) - \overline{U_t}) d\tau, \tag{7}$$

$y = y'$, $z = z'$, and $t = t'$. The (x, y, z, t) represents the coordinate system in the reference frame, while (x', y', z', t') in the inertial frame. When U_t is time-independent, the transformation is Galilean and the governing equations are not changed. Since the reference frame is not inertial in the present cases, the momentum equation in the reference frame is modified to read

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot \left[\mu\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right)\right] + \rho \mathbf{f} + \rho \frac{\partial U_t}{\partial t} \mathbf{i}, \tag{8}$$

where p is the pressure, μ is the dynamic viscosity, $\mathbf{f}$ is the body force per unit mass, and $\mathbf{i}$ is the unit vector in the direction of inflow (the x direction). The body force $\mathbf{f}$ is set to be zero here. The last term is the acceleration term due to the speed change of the frame.

2.2. DNS cases

The momentum equation, Eq. (8), and the progress variable equation, Eq. (1), together with the continuity equation and the equation of state, are solved to simulate premixed flame propagation in homogeneous isotropic turbulence. The equations are solved using the second-order semi-implicit finite difference method [17]. The velocity and pressure fields are discretized using a centered second-order scheme, while the fifth-order Weighted Essentially Non-Oscillated (WENO) scheme [18] is used for scalar advection.