OUTWARDLY PROPAGATING TURBULENT FLAMES

Allocation: Illinois/80 Knh
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EXECUTIVE SUMMARY

The research team's objective is to simulate the evolution of centrally ignited flames in order to assess the roles played in their propagation of hydrodynamic and thermo-diffusive instabilities as well as background turbulence. The simulations were conducted within the framework of the hydrodynamic theory, which has been systematically derived using a multiscale asymptotic technique [1] and is thus free of turbulence-modeling assumptions and/or *ad hoc* adjustment parameters. The flame devolves into a well-defined moving interface that separates the burned products from the unburned mixture. The flame propagation relative to the flow depends on the local stretch rate, which combines the effects of surface geometry and hydrodynamic strain rate. The stretch rate is modulated by a mixture-sensitive parameter known as the Markstein number, which mimics the effects of diffusion and chemical reactions occurring inside the thin-flame zone. This eliminates the necessity for explicit reaction-chemistry modeling, thereby alleviating mesh size and timestep restrictions that render direct numerical simulation studies impractical.

RESEARCH CHALLENGE

Combustion is and will in the foreseeable future remain the primary mode of power generation. The process is inherently complex, involving the interdiffusion of a large number of chemical species (nearly 5,000 for real fuels) that interact chemically as well as the generation of heat that affects the density of the mixture and modifies the underlying flow field.

Flames encountered in most applications are turbulent in nature. Turbulence adds a stochastic, time-dependent, three-dimensional aspect to this intricate problem. While fundamental processes such as reaction chemistry, molecular, and energy transport are reasonably well known, it is still a major challenge to integrate these components with a highly turbulent flow field to produce practical computational results for the description of turbulent combustion. Additional complexity arises from intrinsic flame instabilities associated with thermal expansion and/or the disparity between the diffusion rates of the different species and of mass and energy, which are known to distort the flame even under laminar conditions.

The hydrodynamic theory adopted in this work is formulated in an intrinsic coordinate system [2] that requires a parametric description of the flame surface. The flame's evolution is described in terms of surface differential operators. The numerical solution of such an equation on an arbitrary, time-dependent surface is still an active area of research. Constructing an intrinsic coordinate system is nontrivial and computationally expensive, particularly for an evolving highly corrugated surface. The frequent need for remeshing renders this problem computationally intractable.

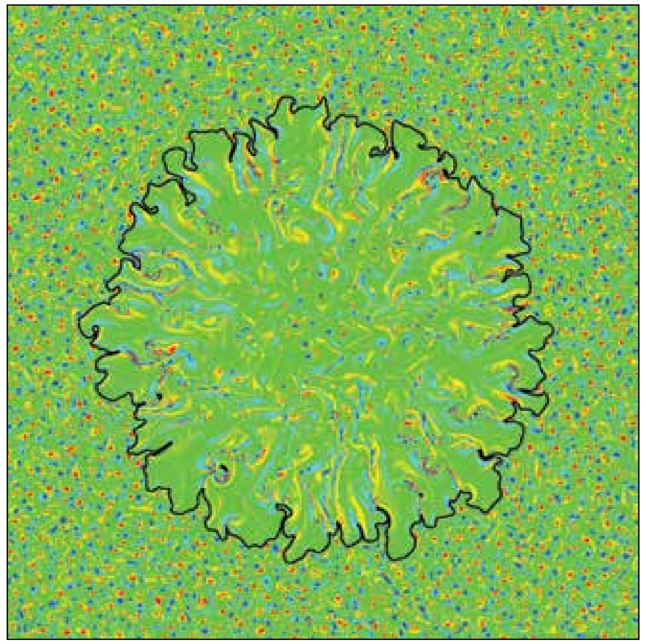

Figure 1: The structure of an expanding flame (black curve) in a turbulent medium; the wrinkled flame separates burned gas from the highly vortical flow of unburned gas (blue/red correspond to clockwise/counterclockwise vorticity). The highly wrinkled surface results from intrinsic combustion instabilities and the underlying turbulence; the lower-intensity turbulence in the burned gas is owing to gas expansion that results from the heat released during combustion.

The research team uses a new class of embedding methods to extend the surface differential equation into Cartesian space such that when the solution is restricted to the surface, the solution to the original problem is recovered. This embedding method also allows the researchers to solve the partial differential equations using Cartesian operators instead of surface differential operators, further reducing execution time. The implementation appropriates concepts from computational geometry and has been used to study a diverse array of applications including image-processing.

METHODS & CODES

The computations were made possible by coupling the embedded manifold approach with an adaptive mesh, variable-density incompressible Navier–Stokes solver. It is built on AMReX, an open source framework, to write massively parallel, block-structured adaptive mesh refinement applications [3]. The code underwent restructuring to improve efficiency and reduce memory demands for the nearly 30 million particles that constitute the turbulent spherical flame surface. Sample calculations illustrating a wrinkled flame front interacting with eddies of different sizes are depicted in Fig. 1.

RESULTS & IMPACT

The major contribution of this work was to develop a scalable, hybrid partial differential equation-based Cartesian embedding method for moving surfaces. This method is capable of handling multivalued and disjointed flame surfaces to simulate a complex, turbulent premixed flame. The methodology was used to investigate influences of the hydrodynamic, or Darrieus–Landau, instability on early and long-time flame kernel development in turbulent flows. The hydrodynamic instability resulting from the gas expansion is responsible for the corrugated appearance of the flame surface even in the absence of significant perturbations such as boundaries, obstacles, and/or turbulence. The instability is known to induce acceleration and enhance the flame propagation speed. The most practical outcome of this work includes the derivation of scaling laws for the turbulent flame speed in terms of flow and physicochemical characteristics. Its importance is in estimating fuel-burning rates in internal combustion engines and other similar applications.

WHY BLUE WATERS

Access to the Blue Waters system has been instrumental to this study; not only did it afford the research team access to extensive computing power, it also made available large memory nodes that were capable of processing the large number of particles on the flame surface.

PUBLICATIONS & DATA SETS

M. Matalon, "The ramifications of the Darrieus–Landau instability in turbulent premixed flames," in *SciTech Forum, Proc. AIAA SciTech 2019 Forum*, San Diego, CA, U.S.A., Jan. 7–11, 2019, doi: 10.2514/6.2019-0182.