Turbulence and ‘Self Accelerated’ Combustion

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In most practical combustion applications, flames burn in the presence of a very turbulent flow. For example, the mixture of air and gasoline in a car engine churns chaotically, helping to completely mix the fuel and air during intake and compression by the piston. Then the same turbulence enhances the spread of combustion throughout the cylinder after ignition. The air being drawn through the intake of a jet engine is also very turbulent, serving the same purposes.

Generally, the interactions between combustion and turbulent fluctuations in the burning fluid are not yet well enough understood for us to model the process predictively. In large fires, such as those in buildings, explosions, and detonations (both planned and accidental) the *chemical reaction itself*, through the addition of heat and flame products behind the flame appears to produce the fluctuations that ultimately result in turbulent combustion. An interesting example of such an explosion (this time nuclear!) is that of a supernova, a remnant of which is shown in the figure. Observations of supernova events, in conjunction with indirect evidence based on the elemental mass distribution of the universe, constrain supernova evolution scenarios in a manner that suggests the existence of thermonuclear flame self-acceleration effects of unknown origin. We can isolate an important part of this fundamental question in this way: Does a flame traveling through a fuel-air mixture move at a constant speed, or does it continuously speed up (i.e. Is it ‘self accelerated’ by flame-generated turbulence?), in a manner analogous to the increase in a bank account due to compounded interest?

This is one of the fundamental unanswered questions standing in the way of a predictive understanding of a wide range of important phenomena, including stellar explosions (supernova), premixed turbulent combustion burning rates, and transitions from burning to detonation in explosions. New understanding of this problem therefore has implications for a wide range of science and engineering. Supernova are the principal "measuring sticks" for the size, age, and cosmology of the universe. The gasoline engine in every automobile, and the low-NOx gas turbine electric generators all depend on turbulent premixed combustion, but must be designed in a cut-and-try approach. The transition from deflagration to detonation (DTD) is one of the unsolved problems in combustion and affects our understanding of explosion prevention as well as our use of explosions for weapons.

Terrestrial experiments cannot easily address this issue, because the effect cannot be isolated in containment devices. Uncontained experiments have been performed, but it has not been possible to instrument them well enough to isolate flame-generated turbulence from the wide range of physical phenomena that occur. For this reason, numerical simulations provide a promising avenue for isolating specific effects, as well as offering more complete data than can be obtained from experiment, and on a scale not possible in experiments. In the specific case of turbulent flames in stars, simulations are the only possible data source. Also, successful simulation codes can provide a basis for testing new engineering designs and identifying roles of competing processes (such as flame instabilities).

Current computing resources only permit combustion simulations with a very limited degree of turbulence. This is because turbulence is an inherently three-dimensional phenomena which operates over a wide range of length scales. Three-dimensional simulations with resolutions of several thousand grid points in each direction ($>10^{10}$ grid points) are therefore needed to achieve a turbulent simulation that contains enough dynamic range in length scale. Simulation of a spherically expanding combustion front in the final stages of turbulence development would also require solution of the governing equations for several thousand time steps. Initial simulations with a simple reaction model and an adaptive mesh would be expected to exceed a week on a 20-TFlop computer, and would be expected to provide the first clear and detailed view into ‘self acceleration’ in a turbulent flame. For comparison, simulations to date are either two-dimensional or have resolutions of only a few hundred grid points in each of three dimensions. New computational facilities would thus enable the first simulations which can truly investigate the impact of turbulence on flames and vice versa, including the self-acceleration question. This research would pave the way to a broad range of research, using even larger computers, to further investigate more strongly turbulent flames, explosion and detonation dynamics, and the interesting properties of super-novae in the more distant future.