INCORPORATION OF ACCELERATION EFFECTS INTO THE ONE-DIMENSIONAL-TURBULENCE MODEL, WITH APPLICATION TO TURBULENT COMBUSTION AND SHOCK-TURBULENCE INTERACTIONS.

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Abstract One-dimensional turbulence (ODT) is a stochastic simulation in which 3D turbulence effects are captured on a notional 1D line of sight by introducing instantaneous spatial re-arrangements (maps) that represent advection by notional turbulent eddies. These eddy events incorporate the possibility of kinetic-energy changes that are equal and opposite to changes of other forms of energy such as the gravitational potential energy change due to a re-arrangement of a vertical density profile. This illustrates that motion aligned with an applied force, in this case gravitation g, can be associated with energy change. Using this principle, we 1) present a model of turbulence interaction with the dilatational acceleration caused by thermal expansion in flames and show results for a turbulent counterflow flame with comparison to DNS and 2) present a model for shock-induced turbulence and show results for mixing width growth in a shock tube with comparison to experiments.

Keywords: turbulent flame, counterflow, shock tube, numerical simulation, one-dimensional-turbulence model

Einstein's equivalence principle [1] implies that effects of reference-frame acceleration can be formulated in the same manner as effects of the gravitational force. For 3D Navier-Stokes turbulence, there is neither a need nor any practical method to identify particular motions as reference-frame accelerations that are formally equivalent to body forces. In ODT, dilatational motion is implemented continuously in space and time, but as noted, vortical motions (eddy events) are instantaneous changes superimposed on this background motion. In this context, it is both valid and useful from a modeling viewpoint to treat time-varying dilatation as acceleration of eddy reference frames. Accordingly, an ODT eddy is deemed to be subject to an associated spatially varying acceleration, allowing the acceleration analog of gravitational potential energy change to be evaluated. Since the acceleration is not the result of a physical body force that can act as an external energy source, it does not change the total kinetic eddy, but it contributes to the determination of eddy occurrences as though there were a body force. In combustion simulations, this introduces the ODT analog of the Darrieus-Landau (DL) instability [3].

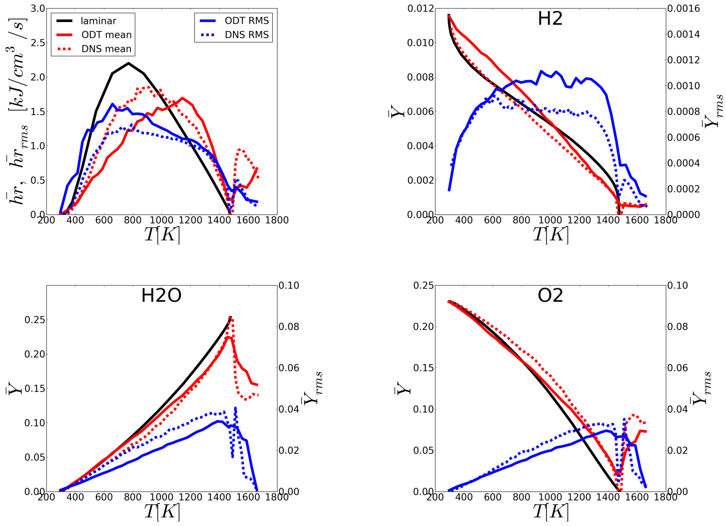

Figure 1. Premixed H_2/air reactant-to-product counterflow results [2]. Temperature conditioned mean (red) and RMS (blue) of heat release rate (top left) and major species H_2 (top right), H_2O (bottom left), and O_2 (bottom right). Solid lines: ODT, dotted lines: DNS. The black line represents results for the strained laminar flame with a strain rate of 2,400 s^{-1}.

The benefit of the DL model extension has been demonstrated in an ODT study of flame-wall interaction [4] and is further demonstrated in the present application to a premixed reactant-to-product counterflow flame [2]. The counterflow configuration consists of two asymmetric, opposed nozzles of internal diameter $D = 12.7$ mm separated by a distance $L_x = 12.0$ mm. The flow arrangement consists of a highly turbulent stream of premixed H_2/air reactants opposed against a laminar stream of hot combustion products in equilibrium. Fig. 1 shows comparisons between ODT and DNS mean and RMS plots conditioned on temperature for heat release rate and major species. For reference, the strained laminar flame results are also shown. ODT mean results compare well to DNS for temperatures above 1,000 K. For temperatures below 1,000 K, ODT underestimates the heat release rate. A possible explanation for this is that in low temperature regions, the flame is weaker and more sensitive to strain fluctuations. ODT through its instantaneous maps can induce momentarily artificially high strains which disrupt the preheating process. RMS profiles show good qualitative comparison to DNS throughout the temperature range. Comparison of major species results shows that ODT gives good qualitative results for both mean and RMS profiles. Additional comparisons (not shown here) of minor species conditioned on temperature and spatial mean and fluctuating velocity, temperature and major and minor species profiles shows that ODT results are in good agreement with DNS.

The reference-frame acceleration picture admits a further extension to shock-turbulence interaction. In this case, an eddy event is deemed to represent the completion of a notional eddy motion of finite duration, such that any shock that traverses the eddy interval during the prior period of eddy motion is deemed to either suppress or enhance the likelihood of eddy occurrence depending on the density profile. As in the DL treatment, the details are analogous to the ODT representation of buoyant stratified flow, except that shocks are net energy sources, so the associated kinetic energy changes are incorporated.

ODT simulation of high Mach number (Ma) flows utilizes the compressible gas-dynamic formulation described and demonstrated in [3]. The shock-turbulence interaction mechanism is incorporated into this formulation and applied to the Vetter and Sturtevant air/SF_6 shock tube experiments [5]. Comparison of results for mixing zone width as a function of time for Ma =1.24, 1.43, 1.50, and 1.95 are shown in Fig. 2. Results show that of the four different experiments simulated, all had good agreement with the observed growth rates of the mixing zone after the initial shock and after the reshock. Although there is a large degree of uncertainty in the initial condition of the air/SF_6 interface, the actual width of the ODT mixing zone also compares well to the experimental data. Shock speeds are captured accurately as seen by the arrival of the reshock which first compresses the mixing width before the mixing width begins to grow at a higher rate. This serves as further validation that the compressible gas-dynamic formulation is capable of accurately capturing shock propagation. The compression zone in the experimental data is not seen, as there are no data points there. The lines drawn in have been interpolated from the measurements. Additional testing of the shock-turbulence interaction model for inert gases with different Atwood numbers and for a reactive case are in progress.

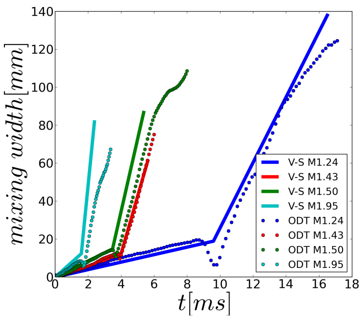

Figure 2. Air/SF_6 shock tube experiment of Vetter and Sturtevant (V-S) [5]. Plotted are the interface growth widths as a function of time for ODT (circles) and interpolated curve from V-S (solid) results at Mach numbers Ma= 1.24, 1.43, 1.50, and 1.95.

Implementation of the ODT formulations outlined here requires empirical inputs and parameter adjustments. Nevertheless, the presented results, and others not shown, demonstrate that these formulations have significant capabilities not previously attained by other forms of turbulence modeling. The results imply that the application of concept of reference-frame acceleration to the ODT eddy mechanism leads to useful extensions of ODT.

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