Modeling Flame Structure in Wildland Fires Using the One-Dimensional Turbulence Model

David O. Lignell
Chemical Engineering Dept., Brigham Young University, 350 CB, Provo, UT, USA, davidlignell@byu.edu
Elizabeth I. Monson
Chemical Engineering Dept., Brigham Young University, 350 CB, Provo, UT, USA, zidah03@gmail.com
Mark A. Finney
USDA Forest Service, Missoula Fire Sciences Laboratory, 5775 Highway 10 West, Missoula, MT 59808, mfinney@fs.fed.us

Abstract
The mechanism of flame propagation in wildland fire fuel beds is of critical importance for understanding and quantifying fire spread rates. Recent observations and experiments have indicated the dominance of flame propagation by direct contact between flames and unburnt fuel, as opposed to propagation via radiative heating alone. It is postulated that effects of radiative heating are offset by convective cooling associated with the turbulent, buoyant flames drawing in surrounding air, resulting in fuel surface temperatures too low to achieve ignition. Propagation via direct flame bathing occurs at the interface between burning and unburnt fuel particles where the flame is highly turbulent and intermittent. Quantifying this mode of flame propagation requires a detailed description of this intermittent, turbulent flame interface.

Detailed descriptions of turbulent flames are complex and difficult to obtain either experimentally or computationally. Turbulent flames are characterized by a wide range of length- and time-scales, spanning individual flamelets, to the full-scale fire. Full resolution of turbulent combustion in computer simulation is not possible for even the largest supercomputers because of the costs of full resolution in three dimensions. An attractive alternative to existing approaches, which resolve large-scale motions, but must model flame structures, is the one-dimensional turbulence (ODT) model. ODT represents a notional line-of-sight through a fire. The model fully resolves the transient evolution of the diffusive-reactive flame structure in one spatial dimension, and is computationally affordable, allowing many parametric simulations.

In ODT, turbulent advection is implemented stochastically by introducing mapping processes representing eddies on the domain in a manner consistent with turbulent scaling laws. ODT has been successfully applied to a wide variety of turbulent flows. Here, ODT is extended to the problem of flame propagation in fuel beds representative of wildland fires. In this paper, we review the problem of flame propagation in fuel beds, and introduce ODT as a promising model for investigation of this phenomena. The ODT model formulation is discussed and validation of the model is presented by comparison to data from canonical flows. Our initial investigations, consisting of simple gaseous fuels such as ethylene in buoyant pool and wall fire configurations, and our current progress in modeling these configurations is presented.

Keywords: Flame propagation, Fire spread, Modeling, Simulation, One-dimensional turbulence

1. Introduction

Understanding and quantifying the mechanism of fire spread rates in wildland fires is important for predicting fire behavior and in developing accurate models. Flames spread by two important mechanisms: (1) radiative heat transfer from flame zones to surrounding fuel; and (2) convective heating of surrounding fuel by direct flame contact. Recent observations and experiments have indicated the dominance of the second mode of flame spread over the first in many fire environments. This dominance is due, in part, to a convective cooling effect of objects that are not in direct flame contact but are heated by radiation. This cooling occurs as air is drawn inward towards buoyant flame zones past nearby fuel being radiatively heated at a distance from the flames.

The description of flame propagation by direct flame bathing is complicated by many factors. Turbulent flames exhibit a wide range of time and length scales from large-scale fluid motions that are determined by environmental constraints such as terrain, fuel concentration and orientation, wind, etc., down to processes that occur at small dissipation scales where turbulent kinetic energy is dissipated and molecular mixing occurs in individual flamelets. The description of the flame itself is complicated in that flames involve many, differentially-diffusing chemical species, whose identity may be unknown. Soot formation is an additional complexity which significantly affects radiative fields.

Here, we are interested primarily in the prediction, through simulation of properties of a turbulent flame brush to provide fundamental insight into processes occurring at the flame interface, to augment experimental investigations, and to validate combustion models. To capture flame propagation via direct flame contact, the turbulent flame itself must be resolved. The only simulation approach that can capture the full range of scales in a turbulent flow is direct numerical simulation (DNS). However, DNS is prohibitively expensive for all but the simplest configurations. For example, state-of-the-art DNS of turbulent combustion is being performed on centimeter size domains for millisecond run times, on tens of thousands of processors at a cost of 3-4 million CPU-hours [1]. Cost-effective simulations are performed using Reynolds averaged Navier-Stokes (RANS), or large eddy simulation (LES) approaches. These models are computationally efficient as the resolve only time averaged, or spatially-filtered unsteady flow fields, respectively. These approaches cannot, however, capture small-scale motions involving individual flames and the effects of these so-called subgrid-scale processes are modeled, with no direct accounting for spatially and temporally evolving chemico-diffusive structures. Since a representation of these structures is what we seek, an alternative simulation approach is used.

The one-dimensional turbulence (ODT) model [2] is being applied to this problem to bridge the gap between unaffordable DNS, and under-resolved LES/RANS. ODT solves the unsteady reactive flow equations with full resolution of all scales, but in a single dimension representing a line-of-sight through a flow-field. Mass, momentum, energy, and chemical species fields are evolved on the line. Turbulence development through vortex stretching processes requires three dimensions. The modeling compromise in ODT is that turbulent advection must be modeled. This is done stochastically in a manner consistent with turbulent scaling laws. ODT has been successfully applied to a wide range of turbulent reacting and nonreacting flows. Here, we extend the model to application of fires. This is part of an ongoing study to examine the flame interface in fires including statistics of the heat fluxes, and temperature and velocity fields. Here, we introduce the ODT and its implementation. We present validation of the model in channel flow, turbulent jet flame, and buoyant plume configurations. Our initial investigations of an ethylene wall fire configuration, being studied experimentally are also discussed. This configuration is being used to investigate flame variability and expansion in a configuration analogous to a deep fuel bed.

2. One-Dimensional Turbulence Simulation

ODT is a stand-alone model that solves flow equations for mass, momentum, energy, and chemical species in a single dimension, with turbulent advection modeled through domain mapping processes termed *eddy events*, which are implemented through so-called *triplet maps*. ODT consists of two concurrent advancement processes: (1) implementation of stochastic eddy events; and (2) solution of diffusion equations. There are two formulations of ODT, a temporal formulation in which all processes are advanced in time, and a spatial formulation in which boundary layer assumption are used to advance the ODT line in a spatial direction perpendicular to the ODT line. Equations are given for the temporal formulation with a subsequent discussion of the spatial formulation. The ODT formulation is based on a Lagrangian finite volume method in which cell faces move with the mass average velocity when flow dilatation through combustion occurs. The resulting constraint for continuity is $\rho\Delta x = c$, where ρ is density and c is a constant. Scalar equations for chemical species, velocity, and enthalpy are given by

$$\frac{d\phi}{dt} = -\frac{1}{\rho\Delta x}(f_e - f_w) + \frac{S_\phi}{\rho},$$

where ϕ is a species mass fraction, enthalpy, or a velocity component, f denote a property flux, and S_ϕ source term (e.g., chemical reaction source for species, or a pressure gradient source for momentum. Subscripts e, and w denote east and west cell faces. Note the absence of a convective term in the Lagrangian formulation. Property fluxes are given by Newton's law of viscosity, Fourier's law of conduction, a form of Fick's law for species diffusion, and heat flux due to species diffusion. These equations are solved to yield an unsteady, resolved flow field with full, one-dimensional resolution of flame and flow structures.

The spatial formulation of ODT follows from a formal derivation using the Reynolds transport theorem with standard boundary-layer assumptions. The result is the same as that for the temporal formulation, given above, but with time *t* replaced with space *y*, and the right hand side of the equation divided by the local streamwise velocity. The formulation is similar to that provided in [3].

During the diffusive advancement, stochastic eddy events occur that represent the effects of turbulent advection. These eddy events occur at a given location x_0, of size l, and with frequency $\lambda(x_0,l)$. Eddies events regions are implemented through triplet maps in which three copies of all profiles in the eddy region are created. The domain of each copy is compressed by a factor of three, the domains are lined up, and the center copy domain is reversed. **Erro! A origem da referência não foi encontrada.** shows a schematic illustration of the triplet map. The Kelvin-Helmholtz instability is a fundamental feature of

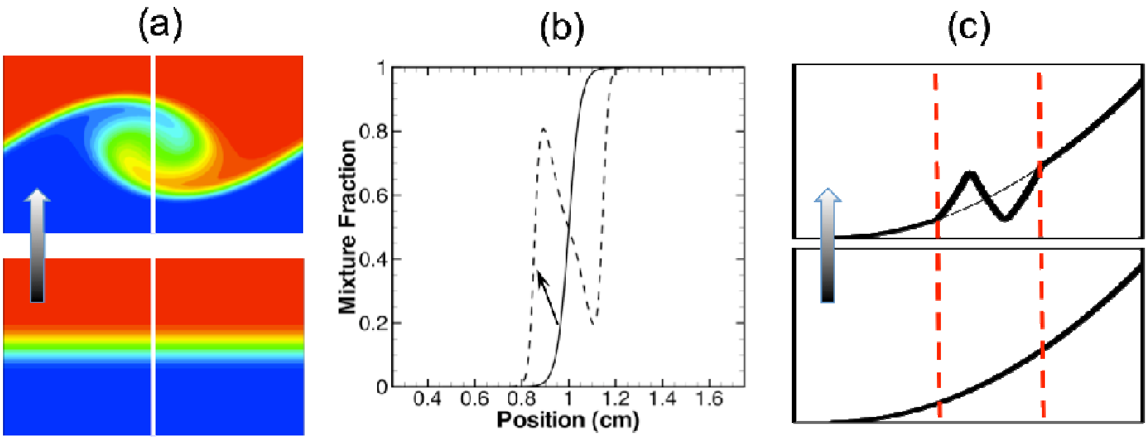

Figure 1. Illustration of the triplet map. (a) mixture fraction field in a Kelvin-Helmholtz instability before and after an eddy; (b) the corresponding profile through the indicated line-of-sight; (c) a schematic of the triplet map in ODT.

shear-driven turbulence. The figure shows a simulation of a single eddy in a Kelvin-Helmholtz instability. The mixture fraction (mass fraction originating in the fuel stream) is shown. In plot (b) the mixture fraction profile before and after the eddy is shown, and the triplet map process is shown in plot (c). Note the similarity of the triplet map to the effect of a turbulent eddy on a property field. The triplet map maintains key aspects of the turbulence cascade in that it is conservative of properties; profiles remain continuous; it is compressive, increasing scalar gradient which increases diffusive mixing; and it is local. As triplet maps occur, the eddy rate in the eddy region increases, resulting in an acceleration of triplet maps towards the diffusive scale, so that ODT reproduces the turbulent energy cascade process.

The eddy rate is specified by scaling arguments and a measure of the kinetic energy in the eddy region. The eddy rate expression is given by $\lambda = 1/l^2\tau$, where τ is an eddy timescale given by

$$\frac{1}{\tau} = C\sqrt{\frac{2}{\rho l^3}\left(E_{kin} - Z\frac{\nu^2\rho}{2l}\right)},$$

where ν is the kinematic viscosity, E_{kin} is the local kinetic energy, and *C*, *Z* are model parameters. The second term under the radical is a viscous penalty for eddies that cannot overcome viscous forces. Eddies (x_0, l) are sampled from an approximate eddy distribution $P(x_0,l)$ at times Δt_s (which are sampled from a Poisson distribution with mean Δt_m), and accepted with probability $P_a = \Delta t_s \lambda / P(x_0,l)$. This approach is accurate makes use of the rejection and thinning methods [4,5].

3. Results and Discussion

Here we discuss verification studies of the application of the ODT model to several flows including channel flow, planar jet flames, and buoyant plumes, along with initial investigations into an ethylene wall fire configuration.

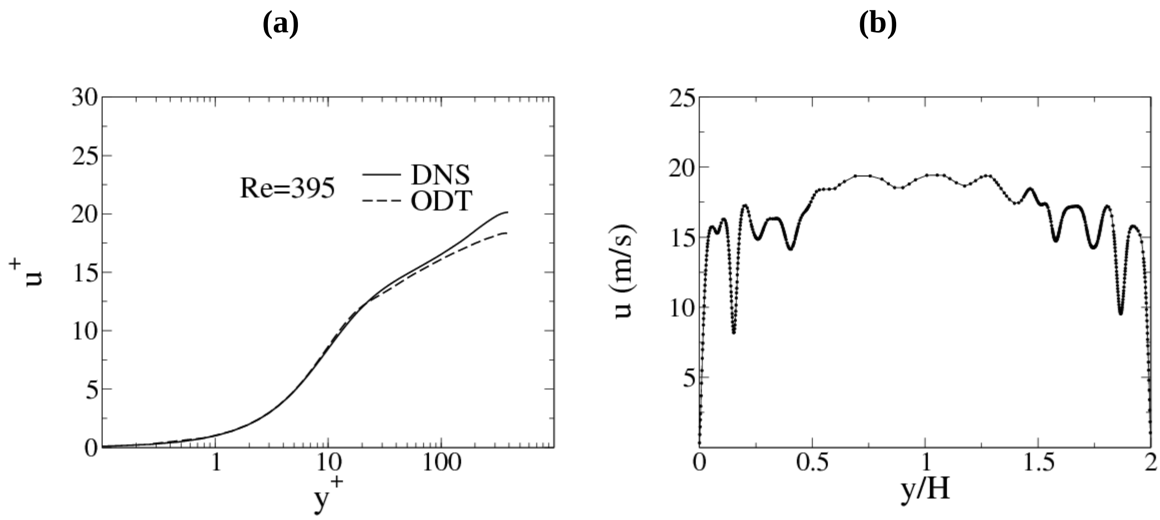

Figure 2. ODT of channel flow at Re=395. Plot (a) compares the scaled mean velocity profile with DNS; (b) shows an instantaneous realization of the upward-directed streamwise velocity field.

Erro! A origem da referência não foi encontrada. shows results of ODT simulation of a channel flow configuration. The Reynolds number of this simulation is 395, and comparison is made to DNS at the same Reynolds number [6]. Plot (a) compares the scaled mean velocity, with excellent agreement. ODT is able to capture the essential elements of near-wall flow including the viscous sublayer, and the log-law region. Plot (b) shows the instantaneous streamwise velocity profile. The ODT code uses an adaptive grid, and this is evident in the spacing of grid points in the velocity profile, with a high concentration of points in regions of high gradients. Convergence of statistics for this case occurs in approximately 30 minutes on a single processor.

The ODT code has been validated against a reacting ethylene jet flame. A variable density formulation of ODT [3] has been implemented and applied to the problem of combustion. The simulation is compared to recent DNS [7]. The configuration is a temporally-evolving, planar, ethylene jet flame. A fuel core of an ethylene/nitrogen mixture is surrounded by oxidizer. The fuel and oxidizer streams flow axially in opposite directions, with periodic boundary conditions in the axial (streamwise) and spanwise directions, and outflow conditions in the cross-stream direction. Figure 3 shows a schematic of the flow configuration. The Reynolds number of the jet is 5120, and a detailed chemical mechanism with 19 transported and 10 quasi-steady-state species is employed. Composition- and temperature-dependent thermochemical and transport properties are computed using Cantera [8]. Temporal ODT is ideally suited to this configuration, and the ODT line is oriented in the cross-stream direction. Since eddy events in ODT are stochastic, to recover statistics (such as means and variances), on the order of one hundred ODT realizations are performed.

The DNS simulations were performed to study the effects of flame extinction and reignition. These phenomena are particularly challenging to model with existing approaches. **Erro! A origem da referência não foi encontrada.** shows a comparison between the ODT and DNS simulations. Plot (a) shows the evolution of the jet as the full width at half maximum of the mixture fraction profile. The agreement with the DNS is excellent and highlights the ability of the ODT model to capture the turbulent flow processes occurring, even though the model is solved in only one dimension. This remarkable property is a consequence of the selection and implementation of eddy events determined dynamically as the flow evolves. Plots (b) and (c) in the figure show the mean temperature conditioned on the mixture fraction, as a function of the mixture fraction. Plot (b) shows results from the ODT, and plot (c) shows results from the DNS. The ODT and DNS are in good qualitative, and quantitative agreement. The stoichiometric mixture fraction in this flame is 0.17, and temperatures peak at mixture fractions somewhat greater (richer) than stoichiometric. The temperature profiles begin high, then decrease as flame extinction occurs, then rise again as flame the flames recover through reignition. A total of 128 ODT realizations were performed, and the somewhat fluctuating profiles shown in the figure indicate that results would be improved by considering additional realizations. The agreement with the DNS is excellent here, and is a result of the direct resolution of unsteady diffusive flame structures, without the requirement for complex combustion models. The cost of the DNS simulation was approximately 1.5 million CPU-hours, while that for 1000 ODT realizations would be approximately 250 CPU-hours. This reduction in computational cost is immense, and while DNS is naturally more accurate and involves the full range of physics, the low cost of ODT combined with good representation of key flow effects cannot be ignored. ODT can easily be validated against DNS, then used to simulate flows at scales that DNS cannot approach. Additionally, many simulations with varying parameters and flow regimes can be investigated. These benefits motivate our extension of ODT to the simulation of fires for the purpose of investigating the flame interface.

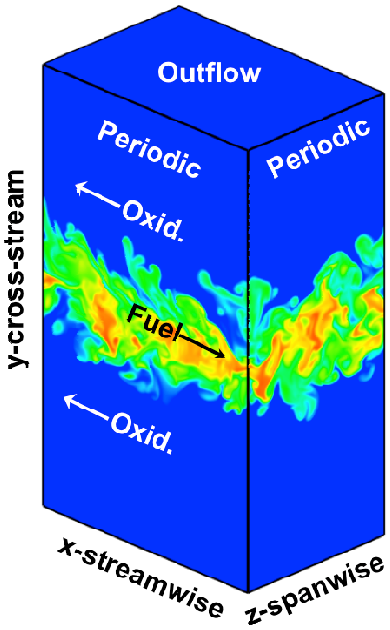

Figure 3. Configuration of DNS of an ethylene jet flame.

Erro! A origem da referência não foi encontrada. shows results of a single ODT realization of a one meter ethylene pool fire. Contours of temperature are shown in the plot at right. Here, the spatial formulation of the model is being employed. This necessitates using boundary layer assumptions that neglect elliptic effects such as vertical pressure gradients and axial diffusion. Also, three-dimensional flow structures are not captured in

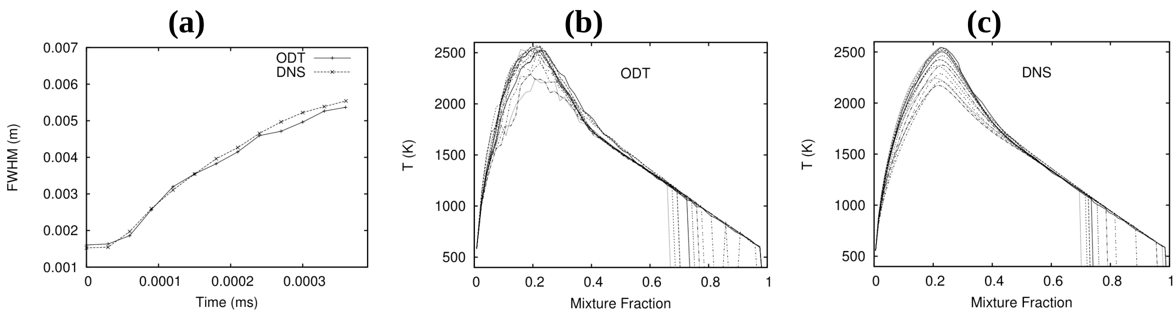

Figure 4. Comparison of ODT and DNS for a turbulent ethylene jet flame. Plot (a) full width at half maximum of the mixture fraction profile. Plots (b) and (c) are conditional mean temperature as a function of mixture fraction at evenly spaced times during the simulation.

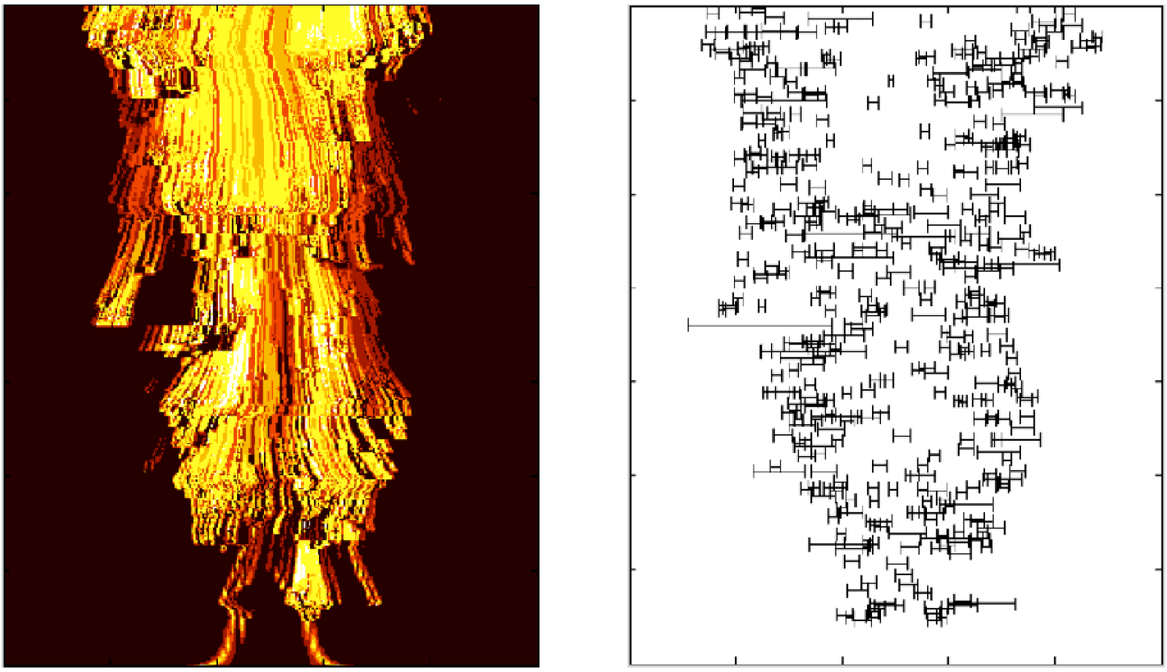

Figure 5. ODT realization of an ethylene pool fire showing contours of temperature (right) and location and sizes of eddies (left).

the model. Buoyant acceleration is included, however, through the Boussinesq approximation. Here, we observe the effects of eddy events by which the plume expands, coupled to the upward acceleration causing a contraction as fluid is drawn in from the horizontal boundaries. The large eddies serve to engulf air, and these eddies subsequently break down as fuel and air and combustion products mix together. The left-hand plot shows the size and location of eddies that occur through the particular realization. Note that many small eddies are observed downstream of particularly large eddies as the turbulent cascade is modeled through the eddy selection dynamics. The stochastic nature of the simulations is evident as the eddies occur randomly according to the local kinetic energy fields. These simulations can be used to compute single- and multi-point statistics of the flame properties.

Our most recent application of the model is to an experimental investigation of an ethylene wall fire. The purpose of these experiments is to study variability of flame edges in fires representative of those of varying fuel bed depths. Flame interfaces in fires are affected by the depth of the fuel bed through buoyant forces and through flame expansion, whose cumulative effects grow with flame height. Fire spread is related to the shape of the flame edge, which is positively inclined in the direction of the flame propagation. Experimental measurements with a neutrally-buoyant fuel, ethylene, are conducted in order to maintain a well-controlled configuration with known boundary conditions. The configuration is a vertical, porous panel through which fuel is uniformly injected. The flow is turbulent, but attains a statistically-stationary state. These experiments are elaborated on in another paper presented at this conference, by Mark Finney et al. The burner panel is 0.61 m wide, by 1.83 m tall; the porous burner consisting of a ceramic foam 2.5 cm thick with 17.7 pores per cm. The ethylene flow rate through the burner varies between 115 and 470 L/min. A photograph of the configuration is illustrated in Figure 6.

Thermocouple rakes are positioned at four vertical heights, and six horizontal positions spaced by 2 cm at each height. Temperature measurements were taken at a sampling rate of approximately 200 Hz.

This configuration is well-suited to ODT simulation since the configuration is planar in the spanwise direction, and the flow represents a buoyant, turbulent boundary layer, which is consistent with assumptions inherent in the spatial formulation of ODT. The ODT model is configured with a horizontal line perpendicular to the wall. The simulation is advanced by marching up the wall, beginning with a laminar boundary layer profile with a low velocity, and a flame initialized using products of complete combustion, with an assumed mixture fraction profile. The sensitivity of results to the initial conditions chosen will be studied. An outflow boundary condition is used at the ambient-free stream end of the line away from the wall, and a fuel inlet condition is used at the wall. The ODT line moves vertically with implied species mass fluxes through the local velocity profile. The inlet flux of ethylene, then is used to specify the flux of ethylene on the line in the computational cells near the wall. Optically thin, and two-flux radiation models have been implemented, and combustion chemistry is currently treated with a simplified one-step mechanism, that is in good agreement with detailed mechanisms for flames that are not significantly strained, as occurs here. A soot model is currently being implemented so that a more accurate treatment of radiative heat transfer effects may be incorporated. However, our primary interest is the investigation of statistics at the flame interface.

Figure 6. Photograph of ethylene wall flame experiment.

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4. Conclusions

A modern ODT code has been developed that is capable of simlating turbulent flows simple configurations using a temporal or a spatial formulation. The model has demonstrated and successfully applied to two temporal configurations: channel flow, and a turbulent ethylene jet, with detailed chemistry and non-trivial transport. Agreement with DNS data was shown to be excellent. The spatial formulation of the model has been applied to a buoyant ethylene plume. Investigation of an ethylene wall fire are underway and preliminary results

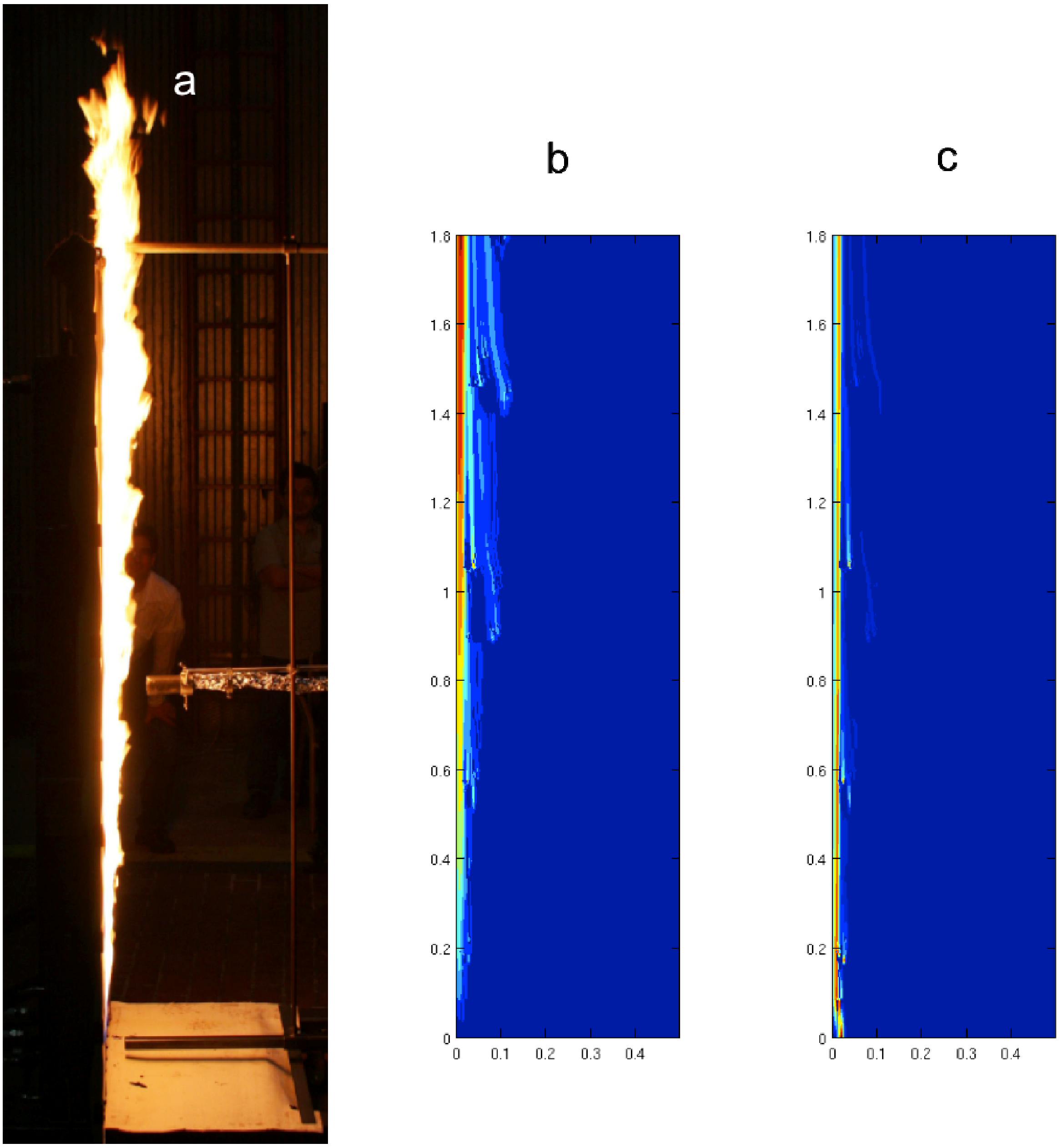

Figure 7. (a) Ethylene wall flame experiment; (b) and (c) are a preliminary ODT simulation of velocity (b) and temperature (c) fields, respectively, for a single realization.

are promising. The full resolution of fine-scale turbulent flow structures, including flames, in a cost-effective manner, is a significant advantage over other simulation approaches such as RANS and LES. The accuracy of the ODT model and the ability to capture multi-point, multi-time flow statistics is allows use of this tool in conjunction with experimental studies of the details of the turbulent flame interface. These studies will provide insights into fundamental processes of flame propagation in wildland fires, and provide a platform for data acquisition and model development and verification.

Acknowledgement

This work is supported by the USDA Forest Service Rocky Mountain Research Station.

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