# Numerical Simulation of Wind-Aided Flame Spread over Horizontal Surface of Condensed Fuel in a Confined Channel

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### **1** Previous studies

The phenomenological analysis of wind-assisted flame spread has been made to gain insight into the mechanisms governing the flame spread rate. The flame spread rate is measured, and the flame-to-fuel surface heat fluxes are estimated from the existing flame spread theories [1]. By assuming that convective heat transfer can be neglected, a flame spread correlation over horizontal PMMA surface is also available [2]. A semi-empirical result derived for a turbulent wind-aided spread shows that the flame length is only a function of the heat release rate [2]. The flame shape (height/length) is also described mainly from sets of equations derived by applying Froude number preservation, combined with some experimental data [3]. The smoke movement is experimentally studied by using a horizontal model tunnel with propane gas burners as fire sources. Modeling or theoretical treatments are significantly simplified and must resort to large-scale fires to validate their assumptions.

## **2** Objective of this work

This work has focused on a rigorous analysis including the material properties, heat transfer to the condensed fuel, chemical kinetics, soot and turbulence effects. This is the first numerical study of turbulent wind-aided flame spread over a flat horizontal surface of a condensed fuel in a highly confined channel on a scale where radiation and buoyancy are significant. The time-averaged flame height/length, and flame-surface heat flux are compared with the experimental data [3] based on a fuel controlled fire, and a relatively good agreement is obtained. This approach to the field modeling of fire spread over condensed fuel surface emphasizes high enough spatial and temporal resolution. Predictions are provided of the transient mass loss, flame front, pyrolysis length and flame shape (length/height) at various wind velocities.

# **3** Theoretical analysis

Controlling mechanisms of three dimensional flow, combustion, soot production and radiation are coupled with a Large Eddy Simulation (LES). The basic idea behind the LES technique is that the eddies that account for most of the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid dynamics. Applying the filtering operation to each term in the conservation equations of mass, momentum, energy and species, and decomposing the dependent variables (u, v, w, p, etc) into resolved and subgrid components results in the filtered governing equations. The unresolved scale eddy motion can be crudely

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accounted by using Smagorinsky model for which the length scale of turbulent viscosity is tied to the grid and its time scale is determined by the local resolvable dissipation rate. The turbulent scalar flux is based on an eddy viscosity assumption. Combustion of the condensed fuel (PMMA) is described by a mixture fraction equation via a single irreversible step. The soot formation and its oxidation are incorporated into a turbulent flow calculation in two convection-diffusion equations for obtaining the precursor particles density and soot number density. The interaction between soot combustion and turbulence is modeled according to the Eddy-Break-Up concept. The radiation intensity is found by solving the radiative transfer equation without scattering through the use of a Finite Volume Method. The overall absorption coefficient for the soot and gas mixture is calculated in function of the temperature and concentration of combustion products. The mass loss rate of the condensed fuel is determined from the energy available for pyrolyzing fuel and the heat of vaporization. Flame radiation flux is computed from a discrete representation of the radiative intensity equation. The Couette flow is assumed to prevail near the wall surface, and the convective heat feedback is calculated from a wall function. The finite-difference technique is used to discretize the partial differential equations. All spatial derivatives are approximated by second-order central differences and the flow variables are updated in time using an explicit second-order Runge-Kutta scheme.

# 4 Validation from a model channel with an uniform fuel injection

In order to see the validity of the numerical model, comparison to the experimental data from a channel fire, as shown in Figure 1, is first presented. The predicted time-averaged flame height/length are determined from the predicted persistent flame, as shown in Figure 2, on the median plane (x-z, y=0.2 m), and compared with the experimentally-determined ones in Figure 3 as a function of the wind velocity varying from 0.5 to 2.5 m/s. Both the experiment and prediction show that the flame length progressively increases, and however, the flame height decreases with wind velocity. Comparison between predicted and measured mean flame-surface heat flux downstream behind the burner (x-x<sub>b</sub>>0), along the burning wall centerline (y=0.2 m) is presented in Figure 4. The predicted total heat flux closely follows the general behavior of the experimental data in a range of wind velocity from 0.7 to 2.5 m/s. Just downstream behind the burner (x-x<sub>b</sub><0.25 m), the total heat flux is found to decrease with an increase of the wind velocity due to reduction in the flame thickness (cf. Fig.2). Far away from the burner (x-x<sub>b</sub>>0.5 m), the total heat flux, as a whole, is proportional to the wind velocity mainly due to the increase of the flame length (cf. Fig.2). By taking into account an uncertainty of 10-15% during experiment due to buoyant instability, agreement between prediction and measurement is good, enabling a numerical study of flame propagation over a condensed fuel surface in a channel.



Fig. 1. Model channel fire, and the coordinate system for numerical simulation



Fig. 2. Predicted thermal field for the wind velocities of  $U_0=0.5$  and 2.5 m/s

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Fig. 3. Comparison between predicted and measured flame height/length



Fig. 4. Comparison between predicted and measured total heat flux

## 5 Results and discussion

The situation encountered in the present work is shown in Figure 1, where the PMMA is 1 m in length (L), 0.4 m in width and 2 mm in thickness (thermally thin sheet). The upstream edge of the PMMA is ignited under a heat flux of 20 kW/m<sup>2</sup> provided by a gas burner fire. The heat flux from the flame incident upon the unburned fuel surface is responsible for heating of the surface to the ignition temperature, causing the fire to spread. Figures 5 and 6 show variations of the flame length/height as a function of the pyrolysis front for the wind speeds between 0.5 and 2.5 m/s. The flame propagation over condensed fuel surface occurs in two successive modes. In the first mode ( $L_0/L<0.3$ ), when the flame is confined within a boundary layer, the flame is elongated in the downstream direction with an essentially constant flame shape  $(L_f \approx 2L_p, H_f \approx 0.2L_p)$ . Transition to the second mode, occurring earlier at low wind velocity ( $U_0 < 1 \text{ m/s}$ ) where the flame stands up to form a buoyant plume, characterized by a significant increase of flame height. For the wind velocity of 0.5 m/s, the zone with the oxygen mass fraction higher than 15% is reduced rapidly inside the channel, and therefore, we have a ventilation-controlled fire. In this case, the extent,  $L_f$ , of the visible flame (T>450 °C) is 4.5 times the pyrolysis length,  $L_p$ . The transition from the boundary layer to the plume mode is evident from a sharp rise in the slope of the curves, and is seen to occur at  $L_p/L=0.4$  where the ratio (Froude number) of the horizontal and the upward forces in the flow stream is low. However, for the strong wind velocity of 2 m/s, oxygen is still available in the large portion of the channel, and we have a fuel-controlled fire. The flame length increases with the pyrolysis front, reaching an asymptotic value of 2 times the pyrolysis length. Globally, the extent,  $L_{f}$ , of the visible flame (T>450 °C) for a ventilation-controlled fire is about two times that for fuel-controlled fire. The flame at low wind velocity is roughly six times thicker than that at high wind velocity mainly due to buoyancy and air entrainment.



Fig. 5. Predicted flame height for different  $U_0$ 



Fig. 6. Predicted flame length for different U<sub>0</sub>

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An expression for the flame spread velocity, defined as the pyrolysis front advancement rate, is derived in the following form,  $V_f=dL_p/dt$ , as shown in Figure 7.  $V_f$  appears to be generally higher for higher wind velocity. The predicted spread velocities are the same orders of magnitude (cm/s) as the measured spread rate over PMMA [1, 2]. The overall flame spread process can be divided into two modes. For the first boundary layer mode ( $L_p/L < 0.25$ ),  $V_f$  is essentially constant with the pyrolysis front. Transition to the second mode, a quick increases of  $V_f$  occurs up to a maximum value of  $3 \pm 0.5$  cm/s due to the constant total heat flux. Figure 8 shows variations of the spatial average fuel mass loss (pyrolysis) flux,  $\dot{m}_s$  (g/m<sup>2</sup>s), with the predicted pyrolysis front,  $L_p$ , at different wind speeds between 0.5 and 2.5 m/s. It is seen that  $\dot{m}_s$  increases quickly as the fire propagates up to  $L_p/L < 0.4$  and is generally higher at lower wind velocity. Beyond  $L_p/L>0.4$ , the fuel pyrolysis rate reaches an asymptotic value of approximately 25 g/m<sup>2</sup>s in spite of the wind speed variation.



Fig. 7. Flame spread velocity for different  $U_0$ 

Fig. 8. Predicted spatial fuel mass loss flux

## 6 Conclusion

The behavior of the large-scale, highly transient flame spread over noncharring solid fuel surface are reasonably well predicted by using Large Eddy Simulation. In a boundary layer mode, the fire spread rate is generally higher at stronger wind speeds. Transition to a plume mode, happening sooner at lower wind velocities, is marked by a rapid increase of the flame height. The flame tends to stand up and transfers heat to the fuel surface with a contribution by radiation higher than 60% of the total heat flux. For low wind velocity, the flame length is found to be roughly 4.5 times the pyrolysis length. The predicted maximum spread rate of  $3 \pm 0.5$  cm/s is essentially independent of air flow. Ongoing work is accounting for a dynamique subgrid-scale model of turbulence for the wind-aided flame spread in a channel.

### References

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