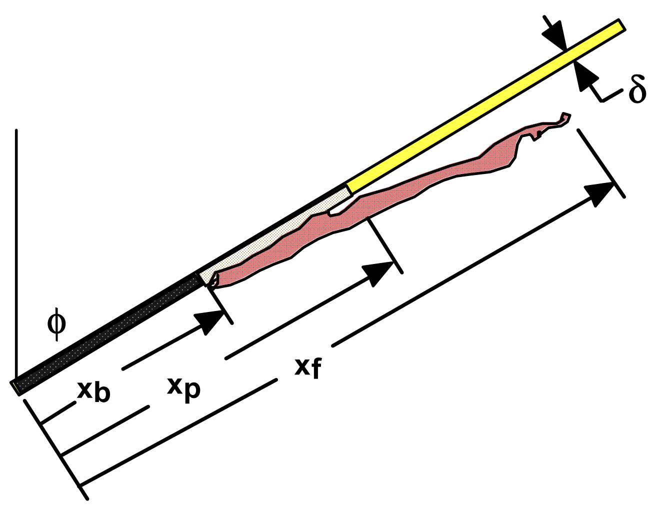
Fire Spread on Walls and Ceiling to Flashover

James G. Quintiere
Department of Fire Protection Engineering
University of Maryland
College Park, MD 20742

Flame spread speed on surfaces has been successfully modeled using a simple engineering formula that relies on knowledge of flame heating length and the corresponding heat flux. The flame spreads if the heat flux is sufficient to bring the material to its ignition temperature. This heat transfer process depends on the thermal properties of the material. To apply this formula, the material properties must be known. For practical applications, the material properties must easily be measurable, and consistent with a model. The flame heat flux and its extent of heating depend on orientation, direction of spread, and ambient conditions. These flame features are presently beyond the capability of fundamental prediction. The difficulties that prevent accurate prediction are the ability to resolve the reaction region, radiation heat transfer, and turbulence effects. Consequently, I have relied on correlations and measurements, for the most part, in estimating these flame parameters. The basic formula is presented below:

$$v_p = \frac{dx_p}{dt} = \frac{x_f - x_p}{t_{ig}}$$



The figure illustrates the process of flame wind-aided spread with a burnout region, x_b. The heat flux and thermal properties enter the time to ignite, t_{ig}, which is given by a thermally thin or thick formulation.

$$\text{Thin}: t_{ig} = \rho c \delta (T_{ig} - T_o) / \dot{q}''$$

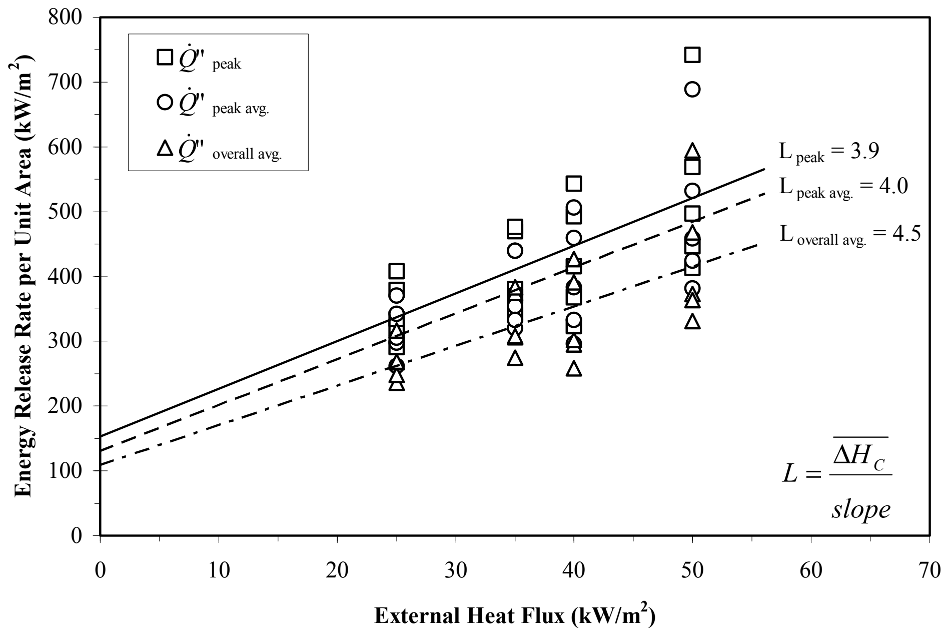
$$\text{Thick}: t_{ig} = (\pi / 4) k \rho c \left[(T_{ig} - T_o) / \dot{q}'' \right]^2$$

For upward or wind-aided spread, the flame extent, x_f-x_p, depends on the power output of the fire. A simple formula is used for the fire power which accounts for the flame heat flux and the material combustion properties, namely, heat of combustion and heat of gasification. This assumes quasi-steady burning which instantly adjusts to the heat flux applied. External heat flux from the surroundings is added to the flame flux, and re-radiation from the surface is computed at the ignition temperature. The formula for fire energy flux is given as:

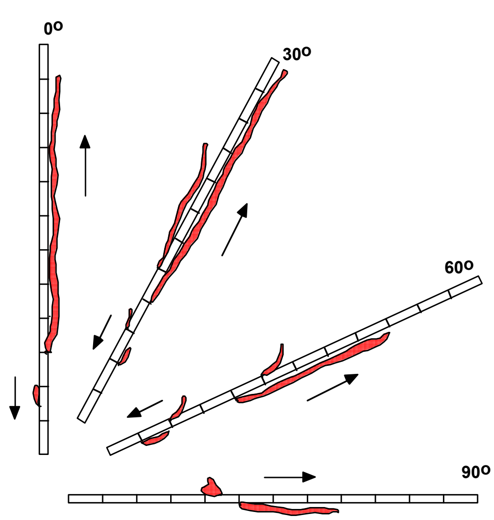
$$\dot{Q}'' = \dot{q}''_{net} \frac{\overline{\Delta H_C}}{L}$$

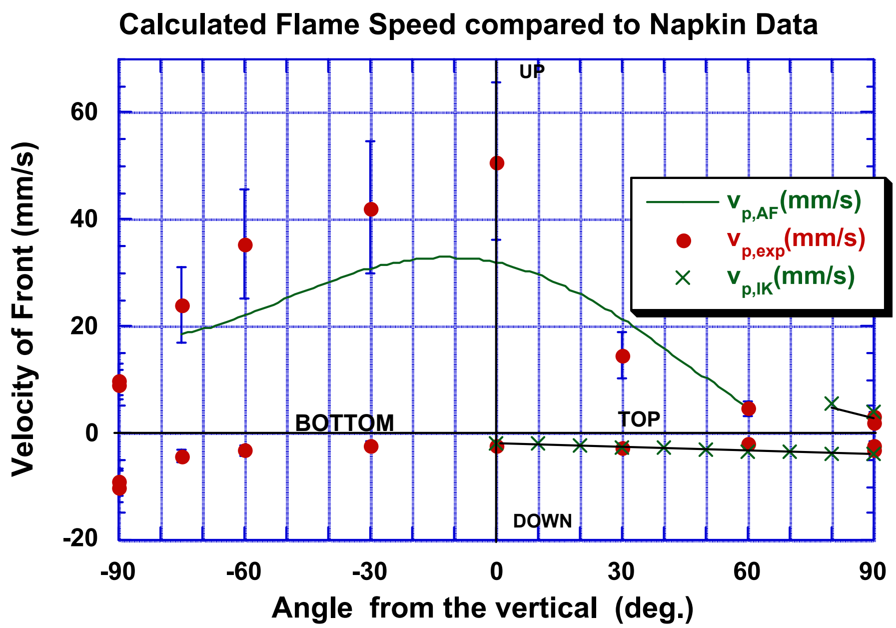
The combustion properties are derived form Cone data:

$$\Delta H_C(t) = \frac{\dot{Q}''(t)}{\dot{m}''(t)}$$



Results have been computed for thin paper at various angles, top and bottom, and up and downward spread. Here values for the flame heating and its extent have been taken from the works of Kashiwagi for opposed flow, and Faeth for upward conditions. The predictions are shown below:

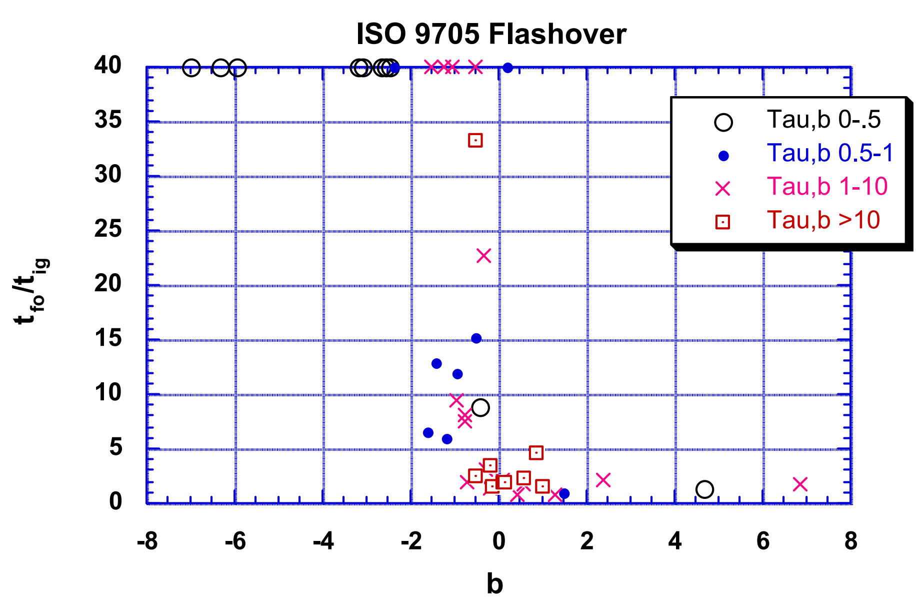




The same formulation has been a key part of global model for fire spread on wall and ceiling surfaces in the standard ISO room-corner test. About 45 materials have been modeled, and a single parameter has been found to significantly control flashover in the room. The parameter arises from the critical condition for accelerating upward flame spread. It represents the flame extension, and above a critical value the flame will accelerate. For the simple theory used here this parameter for the ISO room case is give by b:

$$a = k_f \dot{Q}'' - 1$$
$$b = a - t_{ig} / t_b$$

The results of 45 tests are shown below and depict a critical condition for flashover. For thick



materials, ($T_b - t_b/t_{ig}$), this value is about –0.5. It is found that the critical flame heat flux needed for flashover (where k_f is 0.01 m^2/kW) can then be computed as roughly:

$$\dot{q}''_{f,critical} = \sigma T_{ig}^4 + \left(\frac{L}{\Delta H_c}\right)\left(50 + 100\left(\frac{t_{ig}}{t_b}\right)\right), \text{kW/m}^2.$$

The heat flux from the ignition burner in the room corner test is about 60+/-20 kW/m^2. The initial fire spread will be driven by this ignition flux, and spread is likely to develop to flashover if the wall and ceiling material properties yield a critical flux less than the ignition burner flux. The properties given below, with the exception of 3 and 4, enter in to this critical condition.

	Material Property	Symbol	Test Method
1.	Ignition Temperature	T_{ig}	Cone or LIFT
2.	Thermal Inertia	$k\rho c$	Cone or LIFT
3.	Minimum Surface Temperature for Lateral Flame Spread	$T_{s,min}$	LIFT
4.	Lateral Flame Spread Parameter	Φ	LIFT
5.	Effective Heat of Combustion	ΔH_C	Cone
6.	Effective Heat of Gasification	L	Cone
7.	Total Energy per Unit Area	$\dot{Q}''$	Cone

We have also been studying the NIST FDS model to assess its applicability to directly compute flame spread. Here we compare the model with wall heat flux measurements by Back et al.