Characterizing Flammability of Corrugated Cardboard Using a Cone Calorimeter

K. J. Overholt*, M. J. Gollner†, A.S. Rangwala
Department of Fire Protection Engineering
Worcester Polytechnic Institute
Worcester, MA 01609

Abstract

In warehouse storage applications, it is important to classify the burning of cardboard because it provides a source of flaming combustion and is usually the first item to ignite and sustain flame spread. This study develops a methodology to obtain a non-dimensional mass transfer number (or Spalding's B-number) by using the mass loss measurements from a cone calorimeter. The small-scale experimental measurements are used to model upward flame propagation on a 20-30 foot high rack-storage warehouse commodity packed in corrugated cardboard boxes. Good agreement is observed between the simple model and large scale experiments during the initial stages of fire growth.

Introduction

When a warehouse is involved in a fire incident, the negative effects are felt in many different areas. From a business aspect, materials or products are lost and the operations may be stopped while various processes are restored, often resulting in losses on the order of millions of dollars [10]. Economically, insurance premiums are increased as a result of the fire and lost time can never be recovered. From a safety aspect, the lives of workers and firefighters are endangered resulting in injuries or death. The potential for a large fire in a warehouse is high due to the means of dense packing, large amounts of hazardous materials such as papers and plastics, and the presence of flammable packaging materials [9].

Currently, warehouses and storage areas are protected by prescriptive fire and building codes which differ according to the industry. The commodities stored in warehouses are ranked by hazard in NFPA 13, the Standard for the Installation of Sprinkler Systems, based on free burn tests and then classified in categories of Class I-IV and Groups A, B, and C. The numerous recent fire incidents in warehouses [4, 10] indicate that a more scientific approach is needed to quantify the hazard presented by different commodities.

Previous work by Pagni and Shih [12] has shown that upward turbulent flame propagation is a function of both the B number and the mass consumption number (r). Furthermore, for the specific application of large stacks of commodity, the B-number is the controlling parameter. This study strives to better classify stored and packed commodities based on their material properties and flammability rankings using a scalable, dimensionless mass transfer number known as the B number. The B number is a measure of thermodynamic efficiency and is representative of the amount of chemical energy released versus the energy required to vaporize a given amount of fuel. The benefit of using the B number when ranking flammability is that it is dimensionless and scalable to larger and more complex geometries. The parameter is also a more precise quantification than existing peak heat release rate (HRR) data, and is directly related to the suppression and extinction properties of a material as an application.

Specific Objectives

Previous work on flame spread in warehouse fires performed by Grant and Drysdale [9] has successfully modeled flame spread during the growth stages of a fire along cardboard and PMMA using boundary layer flows and pyrolysis length correlations. The work described in this paper focuses on a more fundamental approach to flammability ranking and result in a more scalable, simple model by utilizing the dimensionless B number. In this study, the B number was determined experimentally using small-scale samples and a cone calorimeter. The results were utilized in a vertical flame spread model for corrugated cardboard as an applied approach of the B number. Corrugated cardboard was chosen in this analysis because it usually is the first source of flaming combustion to sustain flame spread in a warehouse fire.

The objective of this study was to develop a simple model to describe the flame spread along a cardboard face. This work was performed in conjunction with experiments performed by Michael Gollner at the University of California, San Diego [8]. Gollner conducted tests at Worcester Polytechnic Institute (WPI) in 2008 at the intermediate-scale in which a fully packed commodity of 125 polystyrene cups was burned under a large hood.

*Corresponding author: koverholt@wpi.edu
†University of California, San Diego

Nomenclature

a	Equation 9
B	Mass transfer number, Spalding number (-)
c_p	Specific heat ($J/g \cdot K$)
$\dot{m}_F''$	Burning Rate (g/s)
Gr	Grashof number (-)
ΔH_c	Heat of combustion (J/g)
ΔH_g	Heat of gasification (J/g)
h_c	Convective heat transfer coefficient ($W/m^2 \cdot K$)
k	Thermal conductivity ($W/m \cdot K$)
L	Heat of gasification (J/g)
Nu	Nusselt number (-)
Pr	Prandtl number (-)
r	Stoichiometric parameter $Y_{O,\infty}/Y_{F,\tau,v_s}$ (-)
T_m	Mean temperature (K)
T_∞	Ambient temperature (K)
v_s	Stoichiometric oxygen-fuel mass ratio (-)
x_f	Flame height (cm)
x_p	Pyrolysis length (cm)
Y_{O_2}	Mass fraction of oxygen (g/g)

Greek Symbols

α	Thermal diffusivity (m^2/s)
ρ	Density kg/m^3
v	Kinematic viscosity (m^2/s)
Φ	x_f/x_p (Equation 7)
χ	Radiative fraction (-)

Subscripts

F	Fuel
f	Flame
g	Gas
m	Mean
p	Pyrolysis
∞	Ambient
s	Solid

Abbreviations

CB	Cardboard
FM	Factory Mutual
HRR	Heat release rate

Theoretical Background

The B number was applied as a boundary condition at the fuel surface by Emmons [6] in solving for forced flow flame spread over a liquid and is given in its complete form [15] as

$$B = \frac{(1-\chi)Y_{O_2,\infty}(\Delta H_c/r) - c_p(T_p - T_\infty)}{\Delta H_g + Q}, \quad (1)$$

where χ is the radiative portion of energy released by the flame, ΔH_c is the heat of combustion, r is the stoichiometric parameter, c_p is the specific heat of air, T_v is the vaporization or pyrolization temperature of the fuel, and T_∞ is the ambient temperature.

The B number is useful in classifying the hazard level of a fuel since it is dependent on a ratio of the heat available from the fuel to the heat required to gasify the fuel. A higher B number signifies a fuel with more energy available that is more hazardous [8]. During the early stages of a fire involving a commodity, the primary fuel consists of corrugated cardboard only as the flame spreads up the face of the stored commodities. This study ignored the effects of radiation and convection by assuming that the dominant mode of heat transfer for upward flame spread in this case is convection [13] and the excess pyrolyzate that is burned above the pyrolysis zone serves to preheat the samples to their ignition temperature to facilitate flame spread [12]. Therefore, the following derivations of the governing equations will focus on convective heat transfer to a vertical plate.

The B number can be written as an average mass loss ($\dot{m}_F''$) or burning rate per unit area by [14]

$$\dot{m}_F'' = \frac{\bar{h}}{c_p} \ln(1+B). \quad (2)$$

The heat transfer coefficient ($\bar{h}$) can be defined for convective and radiative heat transfer. It will be defined here as a convective heat transfer coefficient (h_c) using the Nusselt number for turbulent flame spread on a vertical plate, which represents the vertical cardboard face, and is given by

$$Nu = 0.13(Gr \cdot Pr)^{1/3}. \quad (3)$$

The Prandtl number (Pr) will be assumed to be 0.7 as for an ideal gas. The Grashof number is defined as [2]

$$Gr = \frac{g \cdot \beta \cdot l(T_f - T_\infty)}{v_g^2}, \quad (4)$$

where g is acceleration due to gravity, β is the volumetric expansion coefficient which is $1/T_m$ for an ideal fluid, T_f is the flame temperature, T_∞ is the ambient temperature, and v_g is the kinematic viscosity of air.

Rearranging for B, we can use the mass loss rates obtained from the cone calorimeter to obtain the mass transfer number experimentally resulting in

$$B = \exp\left(\frac{c_g \dot{m}_F''}{h_c}\right) - 1. \quad (5)$$

Expanding equation 5 with equations 3 and 4 results in an expression that will be used to determine an average B number from experimental mass loss data and results in

$$\bar{B} = \exp\left(\frac{\dot{m}_F''}{(\rho_g \alpha_g 0.13)((g(T_f - T_\infty)/T_g v_g^2) \cdot 0.7)^{1/3}}\right) - 1. \quad (6)$$

In the case of vertical flame growth, the ratio of pyrolysis heights (flame height over pyrolysis front height) is given for natural convection by [3]

$$\Phi = \frac{x_f}{x_p} = 0.64(r/B)^{-2/3}. \qquad (7)$$

To find the length of the pyrolysis front in the case of natural convection [3] , equation 8 is given by

$$(x_p^{1/2} - x_{p,0}^{1/2}) = \left(\frac{4(1 - 1.25(r/B)^{1/3}}{\pi} \right) *$$

$$\left(\frac{a_0^2}{\rho_s c_{p,s} k_s (T_g - T_\infty)^2} \right) * (t - t_0), \qquad (8)$$

and this equation along with equation 7 is later used to predict the flame height (x_f) as a function of time.

Within the expression for the length of the pyrolysis front, the term a_0 is dependent on various fuel and gas properties and is given by [3]

$$a_0 = 0.27 \frac{B^{7/4}}{(B+1)^{1/4}} r^{0.19} \frac{\Delta H_g \rho_s v_s (g \Delta H_c / v_s^2 c_{p,g} T_\infty)^{1/4}}{Pr^{1/2} \ln(B+1)}, \qquad (9)$$

where ΔH_g is the heat of gasification, v_s is the stoichiometric oxygen-fuel mass ratio, and ΔH_c is the heat of combustion.

Experimental Setup

The following section describes tests performed at the WPI Fire Science Laboratory. A total of 4 tests were performed in which 5 cm (width) x 20 cm (height) samples of cardboard and polystyrene were ignited uniformly across the base in the cone calorimeter. The 5 cm x 20 cm sample size was chosen since vertical flame spread is the primary focus of this study. The tests were performed in a cone calorimeter with the load cell lowered such that a 20 cm high sample could be placed in the apparatus. Figure 1 shows a schematic of the experimental setup. Photographs were taken from the side of the samples with a digital SLR camera and video was recorded from a front view of the samples with a digital video camera. The measured quantities from the cone calorimeter are the mass loss rate and heat release rate, and this data will be used to calculate a time-averaged B number for each test.

The corrugated cardboard used in these tests is identical to the type that is used to store commodities and of the same type used in the concurrent intermediate-scale tests being performed by the authors [8] for full size commodities. The dimensions of a standard cardboard carton used to store a commodity measures 0.53 m x 0.53 m x 0.51 m and consists of a single wall of corrugated cardboard. The cardboard samples are type F flute with a nominal thickness of 3 mm and 160 flutes per meter width [5], although
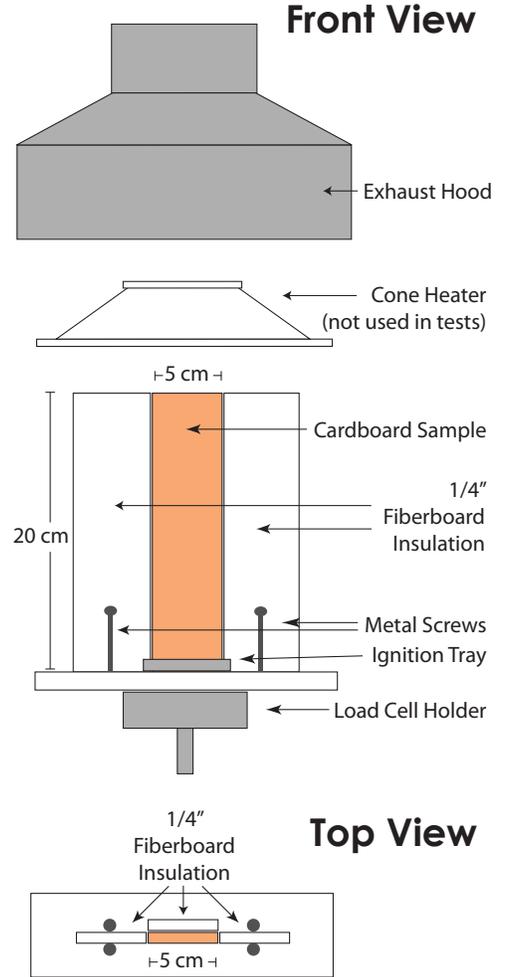

Figure 1: *Schematic of experimental setup*

shipping and handling may deform the cardboard packaging. All tests were performed with the flutes aligned in the vertical direction, similar to the orientation of the flutes on an upright commodity box.

The mode of ignition for these tests was a small aluminum tray, measuring 5 cm x 0.5 cm x 0.5 cm, placed at the base of the samples containing a thin strip of fiber insulation soaked with n-Heptane; this was to ensure an even flame along the entire base of the test sample. Test 1 used 0.75 mL of heptane, however this amount was reduced to 0.25 mL for tests 2-4. Table 1 contains details on all tests that were performed.

The vertical samples were insulated on the back and sides with 1/4 in (0.64 mm) thick Kaowool fiberboard insulation to isolate burning to the front face of the samples only. The insulation was attached to the samples in tests

Table 1: Experimental setup for vertical test samples

Test Number	Test Name	Description	Heptane Used
1	CB1	Cardboard	0.75 mL
2	CB2	Cardboard	0.25 mL
3	CB3	Cardboard	0.25 mL
4	CB4	Cardboard	0.25 mL

1-3 by aluminum tape on the back side. In test 4, it was not necessary to use the tape and instead the sample was held in by the outer pieces of insulation. Finally, all of the cardboard tests burned to completion and self-extinguished when the fuel was depleted.

Results and Discussion

During the tests, the mass loss rate and heat release rate were measured to observe the effects of upward flame spread as described in the experimental setup section. After initial ignition, the flame spread was seen to spread evenly in a vertical direction along the cardboard sample. As the excess pyrolyzate burned above the pyrolysis length, the cardboard region above was heated to ignition temperature and the flame spread quickly upwards [12]. Once the pyrolysis zone reached the top of the sample, the heat release rate quickly decayed from the peak. Figure 2 shows the heat release rates from the 4 tests performed and figure 3 depicts a visual time history of vertical flame spread along the cardboard sample in test number 3 (CB3). Good repeatability of the mode of burning was seen in the test series as the HRR curves are similar. From two of the tests (CB2-CB3), the vertical growth rate of the flame height was approximately 0.86 cm/s and 0.94 cm/s upward. Table 3 summarizes the various results from the 4 tests performed.

Using the acquired mass loss data and the properties of cardboard from Table 2, an average B number was found for each test by using equation 6. The average B number values obtained by this method are seen in Table 3 with values ranging from 1.21 to 2.47. The average B number from all 4 cardboard tests is 1.77.

Figure 4 shows the predicted flame heights calculated by the model versus the small-scale flame heights from the experiments. Two tests are used (CB2, CB3) because the additional amount of fuel in test CB1 may have skewed the flame heights and no video was available for test CB4.

To compare the results from the flame spread model to real-world phenomena, experimental flame heights were obtained from videos showing three large-scale commodity fire tests that were performed at the FM Global Research Campus in West Glocester, Rhode Island [7]. Commodities were packed in corrugated cardboard boxes that were stacked between 20 and 30 feet in height (6.1 m to 9.1 m)
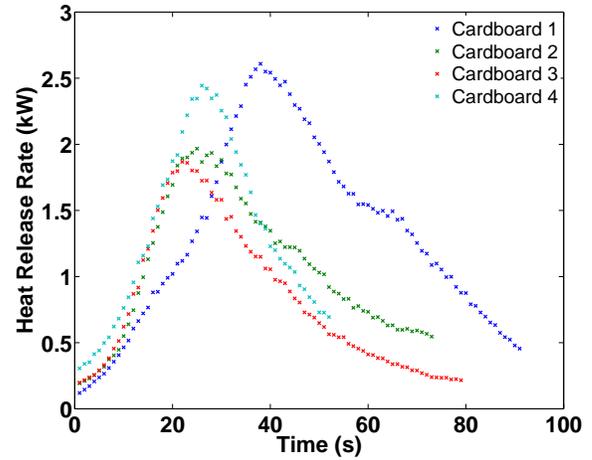

Figure 2: *Heat release rates from vertical flame spread tests in cone calorimeter*
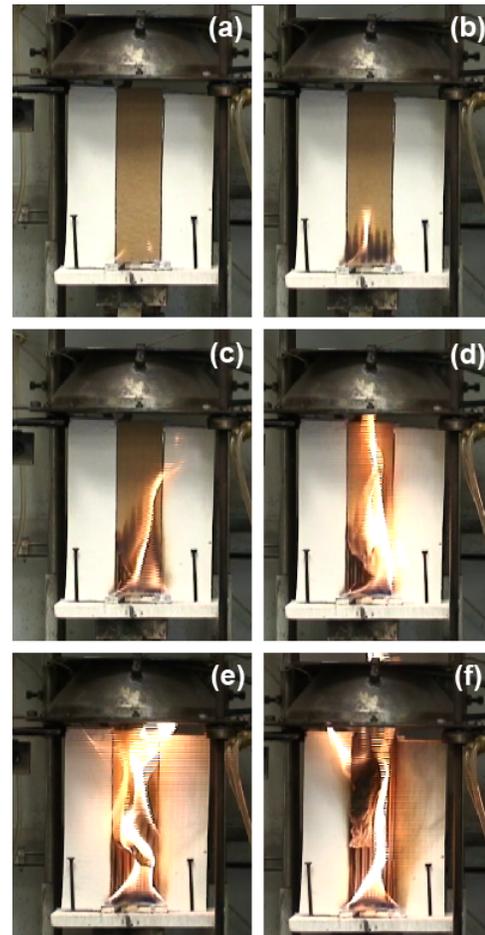

Figure 3: *Time history of test 3 (CB3) - Vertical flame spread along cardboard. (a) Ignition time - 0 seconds (b) 6 seconds (c) 14 seconds (d) 17 seconds (e) 21 seconds (f) 30 seconds*

4

Table 2: Physical properties for corrugated cardboard

Property	Value and Reference
k	$0.064\ W/m \cdot K$ [1]
ρ_s	$689\ kg/m^3$ [11]
ΔH_c	$13200\ kJ/kg$ [1]
ΔH_g	$2200\ kJ/kg$ [1]
r	0.194 [2]
T_g	$573\ K$ [2]
v_s	1.18 [2]

Table 3: Results from vertical flame spread experiments performed in the cone calorimeter

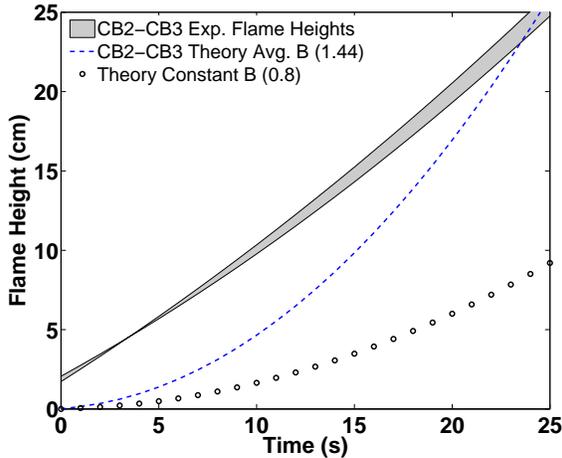| Test name	Total Energy Released (kJ)	Average HRR (kW)	Mass lost (g)	Average B number
CB1	120	1.3	6.2	1.77
CB2	78	1.1	4.7	1.67
CB3	65	0.8	3.9	1.21
CB4	70	1.3	3.9	2.47

Figure 4: *Flame heights measured in the small-scale tests are compared to the predicted flame heights calculated by the model. The shaded area represents the flame heights from the small-scale tests. The dashed line shows the predicted flame heights from the model using an average B number from 2 of the cardboard tests (CB2-CB3). The dark circles represent the predicted flame heights using a B number from previous literature (0.8) [3].*
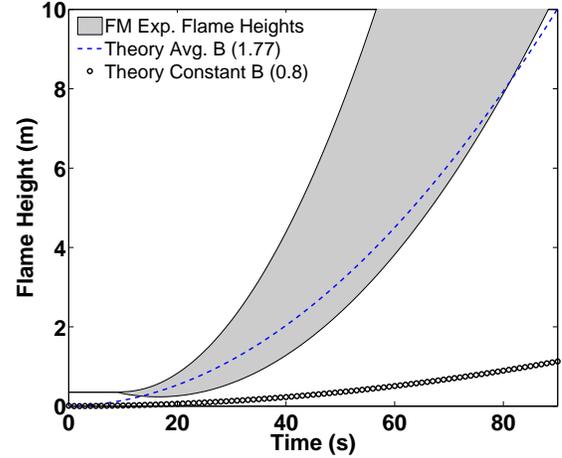

Figure 5: *Flame heights from the FM experiments are compared to the predicted flame heights calculated by the model. The shaded area represents the flame heights from the FM tests. The dashed line shows the predicted flame heights from the model using an average B number from the 4 cardboard tests (CB1-CB4). The dark circles represent the predicted flame heights using a B number from previous literature (0.8) [3].*

and placed on racks. The cartons were ignited on the bottom and flame height data was collected visually from the videos as a function of time.

To predict a flame height as a function of time, equations 7 and 8 were used iteratively in MATLAB to first find the length of the pyrolysis front (x_p) and then the turbulent flame height (x_f) by incorporating the average B numbers found experimentally from the small-scale vertical flame spread tests. Figure 5 shows a comparison between the flame heights predicted by the model and large-scale flame heights from the FM tests.

Conclusions

A method for experimentally determining the B number in order to rank the fire hazard of a material using a cone calorimeter has been shown and a model for predicting vertical flame spread along cardboard has been presented. Inaccuracies in the determination of the B number may be a result of spurious fluctuations in mass loss data during the test burns. Discrepancies in the predicted flame heights may be due to the fact that the model only accounts for convectively driven heat transfer and ignores radiation, which becomes important as the fire grows in size.

The model shows good agreement with the large-scale experimental flame heights (20-30 foot high rack storage) by using the average B numbers that were determined experimentally from the small-scale tests. The measured burning rates of cardboard resulted in a time-averaged B

number ranging from 1.21 to 2.47 for cardboard. The average B number for the 4 cardboard tests (CB1-CB4) was found to be 1.77 and was used to calculate predicted flame heights. The predicted flame heights are in good agreement with the large-scale experimental flame heights as seen in Figure 5.

Future Work

Future work includes performing additional tests to vary the volume fraction of the polystyrene backing to study the effects of fuel volume fraction on the B-number and flame spread. This will allow the comparison of the experimentally determined small-scale B numbers to the large-scale commodity setup in an attempt to model the commodities using the method described in this study. Once the B numbers for different materials have been identified from further tests, a small-scale, 2-cell setup representative of an actual commodity will be tested in a similar fashion.

Finally, additional analysis will be performed to link this small-scale work with the intermediate-scale tests performed by Michael Gollner so that this model can be applied to real world fire protection applications. Numerous additional commodities will be tested using this same method in order to assess the flammability ranking across a spectrum of fuels in order to establish a hazard and flammability ranking.

References

[1] *SFPE Handbook of Fire Protection Engineering*. National Fire Protection Association; Society of Fire Protection Engineers, Quincy, MA.; Bethesda, MD, 2002.

[2] K. Annamalai and M. Sibulkin. Flame spread over combustible surfaces for laminar flow systems Part I: Excess fuel and heat flux. *Combustion Science and Technology*, Jan 1979.

[3] K. Annamalai and M. Sibulkin. Flame spread over combustible surfaces for laminar flow systems Part II: Flame heights and fire. *Combustion Science and Technology*, Jan 1979.

[4] C. M. Bidgood and P. F. Nolan. Warehouse fires in the UK involving solid materials. *Journal of Loss Prevention in the Process Industries*, 8(1):11–16, 1995.

[5] D. Drysdale. *An Introduction to Fire Dynamics*. Wiley, Chichester; New York, 1999.

[6] H.W. Emmons. The film combustion of liquid fuel. *ZAMM-Zeitschrift fur Angewandte Mathematik und Mechanik*, 36, 1956.

[7] J. Golinveaux and D. LeBlanc. Is the code right? New warehouse fire test experience. Presentation. 2008 World Safety Conference & Exposition, June 2008.

[8] M. J. Gollner, T. Hetrick, A. S. Rangwala, J. Perricone, and F. A. Williams. *Controlling Parameters Involved in the Burning of Standard Storage Commodities: A fundamental approach towards fire hazard classification*. 6th U.S. National Combustion Meeting, 2009.

[9] G. Grant and D. Drysdale. Numerical modelling of early flame spread in warehouse fires. *Fire Safety Journal*, Jan 1995.

[10] J. L. Harrington. Lessons learned from understanding warehouse fires. *Fire Protection Engineering*, Winter, 2006.

[11] F. P. Incropera. *Introduction to Heat Transfer*. Wiley, Hobokenm NJ, 2007.

[12] P. J. Pagni, T. M. Shih, and Fire Research Group. *Excess Pyrolyzate*. University of California, Fire Research Group, 1976.

[13] Y. Pizzo, J. L. Consalvi, P. Querre, M. Coutin, L. Audouin, B. Porterie, and J. L. Torero. Experimental observations on the steady-state burning rate of a vertically oriented PMMA slab. *Combustion and Flame*, 152(3):451–460, 2008.

[14] J.G. Quintiere. *Fundamentals of Fire Phenomena*. John Wiley, Chichester, 2006.

[15] A. S. Rangwala, S. Buckley, and J. L. Torero. Analysis of the constant B-number assumption while modeling flame spread. *Combustion and Flame*, 152(3):401–414, Feb 2008.