

Scale Model Flames for Determining the Heat Release Rate from Burning Polymers

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Abstract

The utility of flame size for the assessment of the heat release rate of burning polymers has been studied. Six polymers were tested in the NIST cone calorimeter to determine their heat release rate, and their flame height, area, and volume. A reduced-scale burner was developed for producing non-flickering, laminar flames, and tests were conducted with four gases, three liquids, and three polymers; subsequent automated image analyses again determined the flame size. The scaling for the flame size was shown to be reasonably well described by Froude modeling for turbulent pool fires or by laminar jet diffusion flame theory.

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INTRODUCTION

The heat release rate of a burning object is important for quantifying fire growth and spread in a building [1]. To estimate the heat release rate of full-scale objects, small-scale samples of representative materials are subjected to controlled radiant heat fluxes, and the heat release is measured. Various methods have been developed to measure the heat release rate of the reduced scale samples [2][3], and they are accurate and effective, but unfortunately require expensive equipment and are relatively time consuming (0.5 h to 2 h per sample). If a less expensive, faster test method could be developed, heat release rate measurements might be more widely used by the polymer industry in their development of materials with lower flammability; such a method could also be used in high-throughput testing, allowing combinatorial techniques to be applied to the development of fire-safe materials.

The present paper investigates the potential of measurements of flame size as a surrogate for heat release [4]. As a first step, various polymer samples were burned in the NIST cone calorimeter and their heat release rate was determined. Simultaneously, the flame images were captured and then analyzed to determine the flame height, area, and volume. An image analysis procedure was developed which allowed flame size determinations from a large number of frames using an automated image analysis program with various filtering techniques. In the second set of tests, a new burner was designed which would limit the flames to the laminar regime. To achieve non-flickering, laminar flames, this burner used smaller samples, provided a co-flow of oxidizer, and the geometry was controlled. Flames of solid, liquid, and gaseous fuels were produced, and the heat release rate was determined from the measured fuel consumption rate and the calculated heat of combustion. This paper describes the scaling relationships observed for the flame height, surface area, and volume with respect to the heat release, and discusses the utility of these for estimating the heat release.

BACKGROUND

Our search for a correlation between flame size and heat release is motivated in part by the observation by Orloff and de Ris [5] that turbulent pool fires have an approximately constant heat release rate per unit volume of the flame, $\dot{Q}_c'''$ (1200 kW/m³). The scaling laws for pool burners have been investigated by many researchers, and good reviews exist [6-8]. While these investigations have been most interested in

turbulent flames typical of fires, they can also be applied to the present results obtained in the cone calorimeter. For the reduced-scale flames, however, it is more appropriate to use laminar flame theory, for which descriptions appear in the literature [9,10,10]. Although all of these mathematical descriptions employ significant simplifications, they are expected to provide useful scaling relationships for correlating and interpreting the present data.

EXPERIMENT

Two distinct sets of experiments were conducted. In the first, the NIST cone calorimeter [11] was used as the test bed for the burning polymer samples. This apparatus consists of a cone-shaped electric resistive heating element (hence the name), which provides radiant fluxes up to 100 kW/m² on a polymeric sample of dimensions typically 7.5 cm to 10 cm diameter. In addition to other parameters, the exhaust is tested for mass flow, and volume fraction of oxygen (CO volume fraction measurements were not available for the present experiments). From these, the heat release rate of the burning sample is estimated using oxygen consumption calorimetry (which is based on the approximation that the heat release is proportional to the mass of oxygen consumed, times a constant of 13.1 kJ/g [12]). In the present experiments, the cone heater was off, and the sample decomposition was due entirely to the heat provided by the flame radiation and convection to the sample surface.

A second experimental apparatus was specifically developed to reduce the transition to turbulent flow. For solid samples, a smaller sample was used (2.5 cm diameter, 2.5 cm tall), and it was positioned concentrically in a laminar co-flowing oxidizer stream of controlled velocity (16.7 cm/s). The configuration was a variant of the cup burner [13], and has been used previously in tests of halon replacements for suppressing solid-sample flames [14]. The gas and liquid fuels were tested in a separate cup burner, that has been described previously [15]. It consists of a cylindrical glass cup (28 mm diameter) positioned inside a glass chimney (53.3 cm tall, 9.5 cm diameter); glass beads and screens provide flow straightening for the fuel and oxidizer flows. For the liquid and gaseous fuels, the chimney was cut off at a point lower than the burner rim to avoid reflections from the flame image. Gas flows were measured by mass flow controllers (Sierra 860¹) which were calibrated so that their uncertainty is 2 % of indicated flow. For liquid fuels, syringe pumps (Yale Apparatus model YA-12) supplied the fuel at a known rate, which was manually adjusted to keep the fuel level flush with the edge of the cup rim. For the solid fuels, the mass consumption rate was determined with a laboratory scale (Mettler, PE-360). The syringe pump or the scale output was recorded with a computer.

The fuels used were methane (Matheson UHP, 99.9%), propane (Matheson CP, 99%), ethylene, propylene (Matheson, CP), methanol (Aldrich, 99.8 %), ethanol (Warner Graham), heptane (Mallinckrodt), trioxane (Aldrich, 99+%), and various commercially available polymers, including poly(methyl methacrylate) PMMA, polypropylene, paraffin, ethylene vinyl acetate (EVA), Nylon-12, and high density polyethylene (HDPE). The air was house compressed air (filtered and dried) which is additionally cleaned by passing it through an 0.01 µm filter, a carbon filter, and a desiccant bed to remove small aerosols, organic vapors, and water vapor.

The flame images for all tests were recorded with a digital color video camera (Sony, TRV-730) having a pixel resolution of 720 x 480 and framing rate of 30 Hz. The flame images were analyzed to determine the flame height, area, and volume using an automated image analysis system based on two software packages. The NASA image processing freeware program Spotlight 1.1 provided the flame outline from the color image (for PMMA and Nylon-12 in the cone, it was necessary to determine the flame outline manually, and a single, representative image was used). A custom-written code subsequently interpreted the outline and calculated the flame surface area and volume. In determining the flame outline, no attempt was made to distinguish between the yellow soot emission and the blue

¹ Certain commercial equipment, instruments, or materials are identified in this paper to adequately specify the procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment are necessarily the best available for the intended use.

emission from radicals in the reaction zone; both delineated the presence of a flame. The various filtering options in Spotlight were adjusted for each flame sequence so that the determined flame outline matched the visual luminous flame location.

For the small, non-flickering, laminar flames, estimation of the flame height and area from the flame outline was straightforward, obtained by measuring the flame tip location and cord width, and assuming axial symmetry, summing segments as described below. For the convoluted flames in the cone calorimeter, however, we used the method described by Orloff [16], in which the vertical flame is divided up into slices (determined by the vertical pixel resolution). Across each slice, the software determines the presence or absence of the flame, assumes that any segment of the cord containing the flame is a cylindrical disk, and sums the volume or area for each segment of the vertical slice. The total surface area or volume of the flame is the sum for all vertical slices. Using this approach for complicated turbulent flame shapes, Orloff was able to produce flame *locations* within about 5 % of those obtained from integration of the flame presence probability density function. Hence, we estimate that at the 95 % confidence level, the luminous flame area or volume for the cone flames are within about 10 %. For the small laminar flames which have very regular shapes, this uncertainty is less than 1 %. Note that in many of the figures which follow, if the uncertainty is shown on the data points, the error bars represent the standard deviation (66 % confidence level) for the variation in the flame area for the 30 frames of data. This uncertainty is much larger than that due to the flame area determination techniques described above.

An uncertainty analysis was performed, consisting of calculation of individual uncertainty components and root mean square summation of components. All uncertainties are reported as *expanded uncertainties*: $X \pm ku_c$, from a combined standard uncertainty (estimated standard deviation) u_c , and a coverage factor $k = 2$. Likewise, when reported, the relative uncertainty is ku_c / X . The expanded relative uncertainties for the theoretical heat release for the gaseous and liquid fuel flames are 4 % and 2 %. For the solid fuels, the theoretical heat release, determined from the mass loss rate and heat of combustion, varies according to how constant the heat of combustion is for that polymer. For PMMA, paraffin, and trioxane, the uncertainty is estimated to be 4%; for polypropylene, it is 10 %.

RESULTS

Fig. 1(a-c) show the measured flame height (a.), area (b.), and volume (c.) for the six polymers tested in the cone calorimeter; the dotted lines are linear least-squares fits to the data. The closed symbols are used for the samples for which automated image analysis could be performed (EVA, HDPE, PP, and trioxane), while the open symbols are used for Nylon-12 and PMMA, for which image analysis was performed manually. For data points determined automatically, each point shown is the average from 30 flame images, and the error bar is $\pm$ one standard deviation. As indicated, the standard deviation is around 18 %, 29 %, and 15 % for the height, area, and volume, respectively, for the flames in the cone. While there is significant scatter in the points representing the averaged data, the height, area, and volume of the flame are clearly correlated with the measured heat release.

Although the cone calorimeter would appear to be a good test apparatus for comparing the flame size with the heat release, several features make it less than optimum. Geometrical factors influence the flame shape; for example, the sample holder support is not optimized for smooth flow, causing the exhaust-induced air flow to be highly irregular and disturbing the flame. Also, the edge of the typical sample holder can trip the flow to turbulent flow [16,17], changing the flame size-heat release rate relationship. The typical sample size creates flames which are in-between laminar and turbulent flow, making them hard to describe analytically, and causing the oxygen transport rate to the flame to vary. If the conical heater element is being used, it can obstruct the view for tall flames. Finally, the flame images are highly irregular, making the determination of the flame area difficult. As a result, we conducted tests in the reduced-scale burner described above as the cup burner.

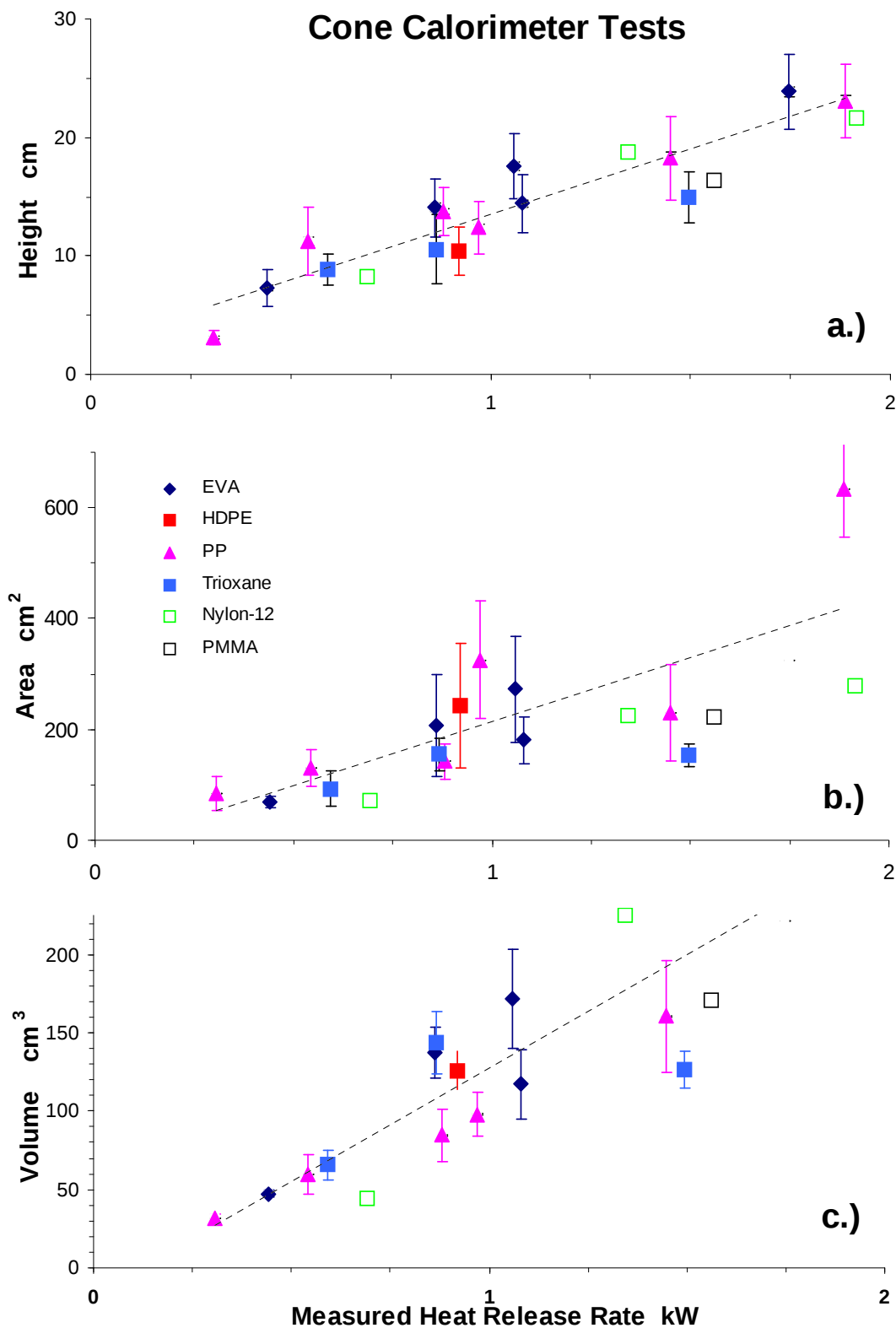


Fig. 1. Measured flame height (a.), area (b.), and volume (c.), as a function of heat release rate for polymers tested in the cone calorimeter. Open symbols denote manual image analysis; closed, automated; dotted lines are linear curve fits to the data.

For the cup-burner flames, the theoretical heat release of the flames was calculated from the measured fuel input rate and the heat of combustion of the gaseous reactants. An implicit assumption in the present work is that the combustion efficiency is high (>97 %). The polymers selected for the tests were those with relatively constant and known heats of combustion. Since we are interested in the oxygen demand of the gas-phase reactants, the heat of combustion used was for gas-phase reactants to gas-phase products. Fig. 2(a-c) shows the flame height, area, and volume as functions of the theoretical heat release. (Note that the heptane point is scaled by $\frac{1}{2}$ for both variables to put it on the same plot without expanding the scales.). It is clear from the figure that the gaseous flames (square symbols) have the least variation between images, and their flame height, area, and volume are very well correlated with the predicted heat release. The reduced-scale, cup burner produces flames which have little variation between images, typically 3 %, 6 %, and 10 %, for the gaseous, liquid, and solid fuels, respectively, regardless of whether height, area, or volume.

For turbulent diffusion flames above pool fires, Zukoski [6] outlines various theoretical scaling relationships which have been developed based on Froude modeling. These typically are power-law functions of the form $Z_f/D \sim Q^{*n}$, in which Z_f is the flame height (normalized by the burner diameter D), and Q^* is the non-dimensional square root of the Froude number expressed in terms of the heat release $Q^* = \dot{Q}_c / (\rho_\infty C_p T_\infty (gD)^{1/2} D^2)$, in which $\dot{Q}_c$ is the heat release in the flame, ρ_∞ , C_p , T_∞ , are the density, specific heat, and temperature of the oxidizer, and g is the acceleration due to gravity. Fig. 3 shows the normalized flame height Z_f/D as a function of Q^* for the gaseous, liquid, and solid fuels in the reduced-scale cup burner (solid symbols) as well as for the solid fuels in the cone calorimeter (open symbols). Also shown are the power law relations for Z_f/D suggested by Zukoski [6], each applicable in a range of Q^* , with a $Q^{*2/5}$ dependence for $Q^* > 1$, $Q^{*2/3}$ for $0.15 < Q^* < 1$, and Q^{*2} for $Q^* < 0.15$. The dotted black line is a linear curve fit to the data in the reduced-scale cup burner. The present data, from either burner, are clearly in the transition regime.

The laminar flame theory of Roper [10] for co-flow jet diffusion flames can also be used to predict the flame height in the reduced-scale cup burner flames. The calculated flame height from Roper's correlation is shown in Fig. 3. as the dotted red line, which indicates a Z_f/D variation with Q^{*1} , which is consistent with the curve fit through the reduced-scale cup burner data which also gives a Q^{*1} dependence. (The offset of the Roper prediction with the curve fit through the data is likely due to the wide burner used in the present flame, which gives a non-zero flame area at zero height).

Our ultimate goal in the present work is to relate the measured heat release to the measured flame size (height, area, or volume). Simple scale arguments of the type suggested by de Ris and Orloff [5] can be used to determine the predicted and actual scaling relationship between the heat release and the height, area, or volume. To do this, it is useful to plot the heat release normalized by the flame height, area, or volume, as a function of the heat release, as done in Fig. 4. From the power-law fits to the data, it is possible to extract the relationship between the heat release rate normalized by the height $\dot{Q}'_c$, area $\dot{Q}''_c$, or volume $\dot{Q}'''_c$, and the heat release rate. From these, we can then estimate the power-law relationship correlating the heat release with the height, area, or volume; e.g. $\dot{Q}_c \sim Z_f^{n_f}$, $\dot{Q}_c \sim A_f^{n_a}$, or $\dot{Q}_c \sim V_f^{n_v}$. Table 1 lists the power-law scaling coefficients n_f , n_a , n_v , for the heat release based on the measured flame height, area, or volume as observed in either the cone or the reduced-scale cup-burner flames; values are also given for the laminar flame theory prediction of Roper [10], as well as the turbulent flame theory predictions from Froude modeling as outlined by Zukoski [6]. As shown, the experimental results for the cone calorimeter flames are midway between the theoretical results for turbulent flames in the $0.15 < Q^* < 1$ and $Q^* > 1$ regimes. For the flames in the reduced-scale cup burner, the results are midway between the theoretical prediction of Roper for laminar jet flames, and the Froude modeling turbulent flames in the $0.15 < Q^* < 1$ regime.

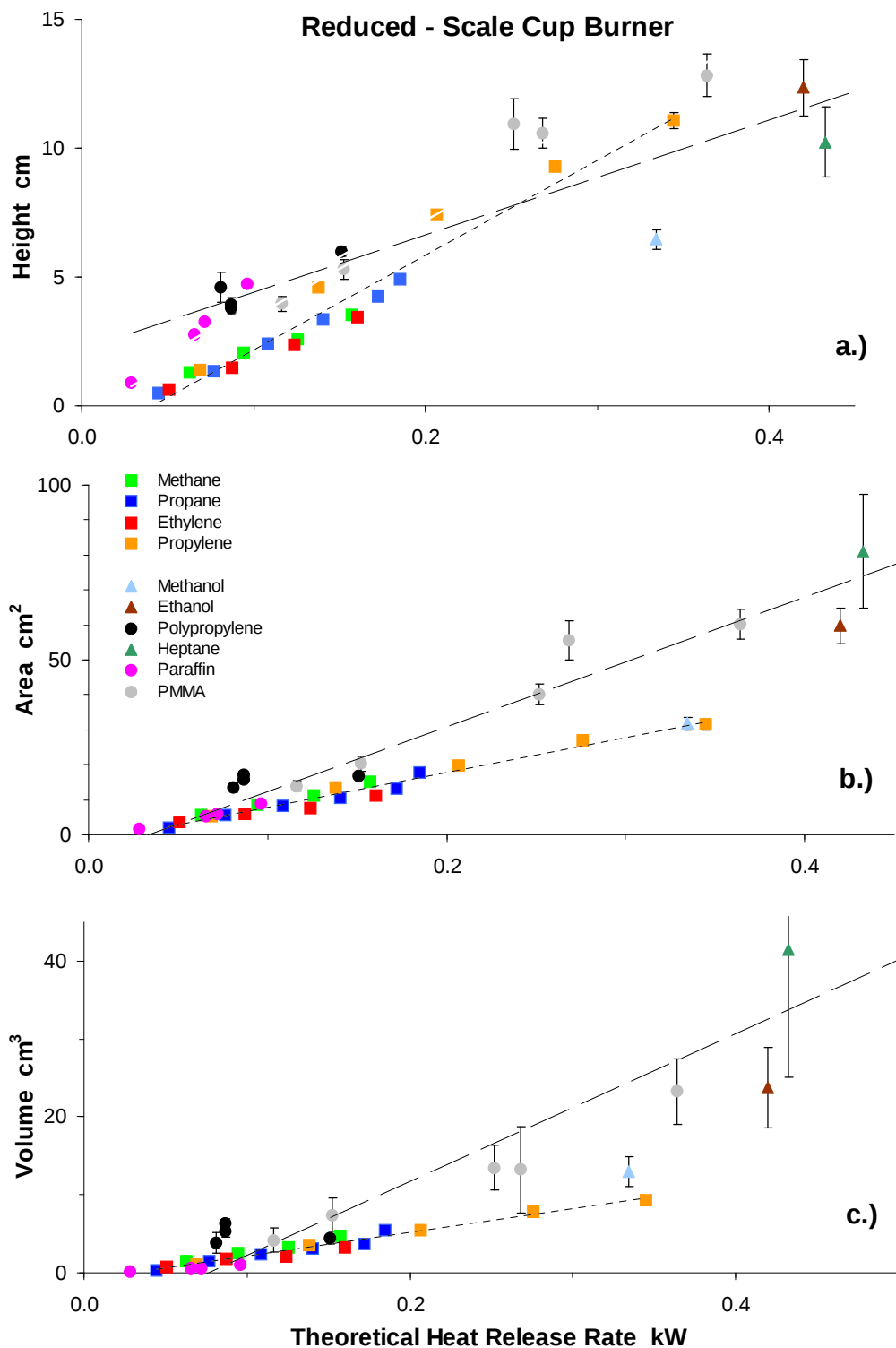


Fig. 2. Measured flame height (a.), area (b.), and volume (c.), as a function of heat release rate for solid, liquid, and gaseous fuels tested in the reduced-scale cup burner (both heptane parameters on all plots scaled by 2). Dotted lines are linear curve fits to the gaseous fuel data; dashed, to the solid and liquid fuels data.

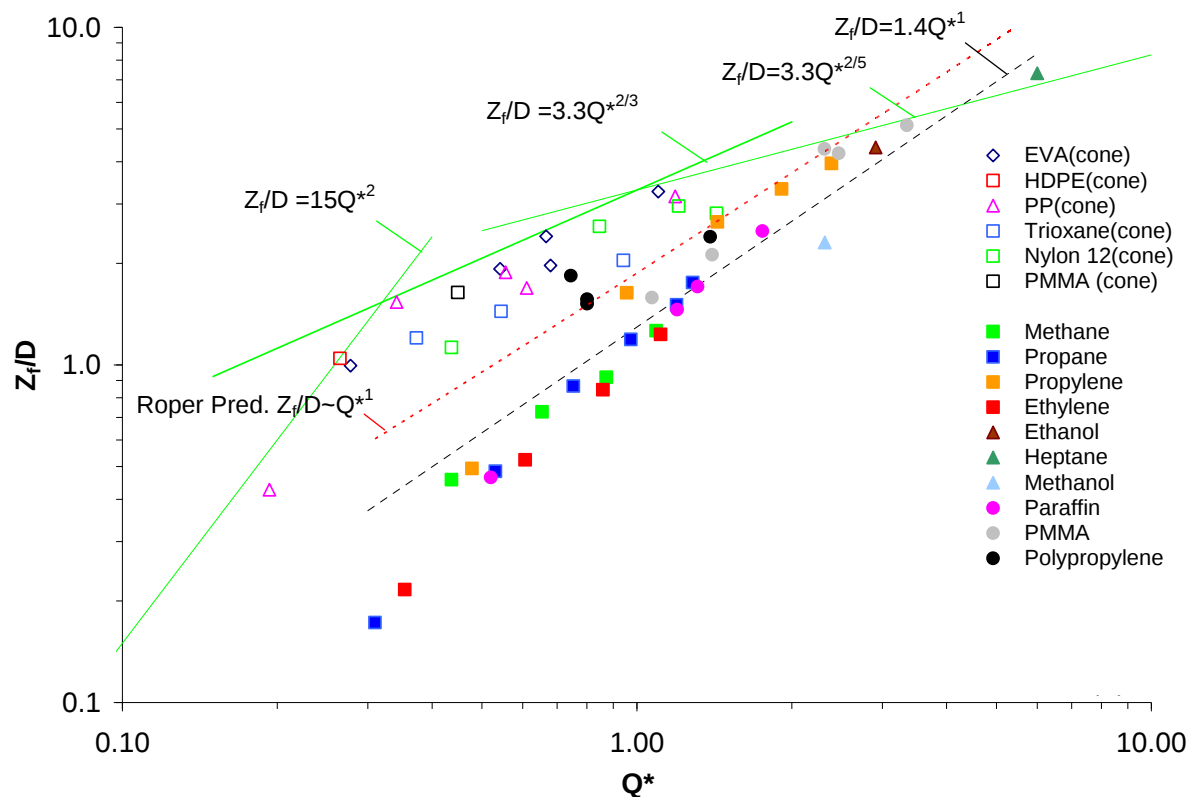


Fig. 3. Normalized flame height Z_f/D as a function of Q^* (cone calorimeter data, open symbols; reduced-scale cup burner, filled symbols).

Two additional features of the flames were observed to be important for the data analysis. First, the image recording and analysis used the visible image, which includes both the blue emission from flame radicals in the reaction zone, as well as the much stronger black body emission from soot particles. We observed the luminous flame shapes to be larger than the blue reaction zone flame shapes; other researchers have found the luminous shapes to be 10 % to 60 % larger [18,19]. Second, as the sample size gets smaller, the physical effects which may contribute to flame retardancy, for example, barrier layers on the burning polymer, can be affected by the small size.

CONCLUSIONS

Experiments have been performed to measure the heat release rate as well as the flame height, area, and volume of burning gaseous, liquid, and solid fuels. Flames from samples in the NIST cone calorimeter had relatively high variability in these measured parameters from image to image, and were reasonably well described by Froude modeling predictions for turbulent pool flames, but in a regime where viscous effects are starting to be important. A reduced-scale burner similar to the cup burner produced flames with much lower scatter and image to image variation. The variation of the height of these flames with heat release was well-predicted by the theoretical model of Roper. The small laminar flames showed scaling behavior of the heat release with respect to the height, area, and volume, midway between that of laminar co-flow jet diffusion flames and turbulent pool flames in the transition regime. Further research is necessary to determine if these measured parameters (flame height, area, and volume) can be determined accurately enough to be useful for predicting the heat release rate, especially for a wider range of test materials with actual heat release data based on oxygen consumption calorimetry.

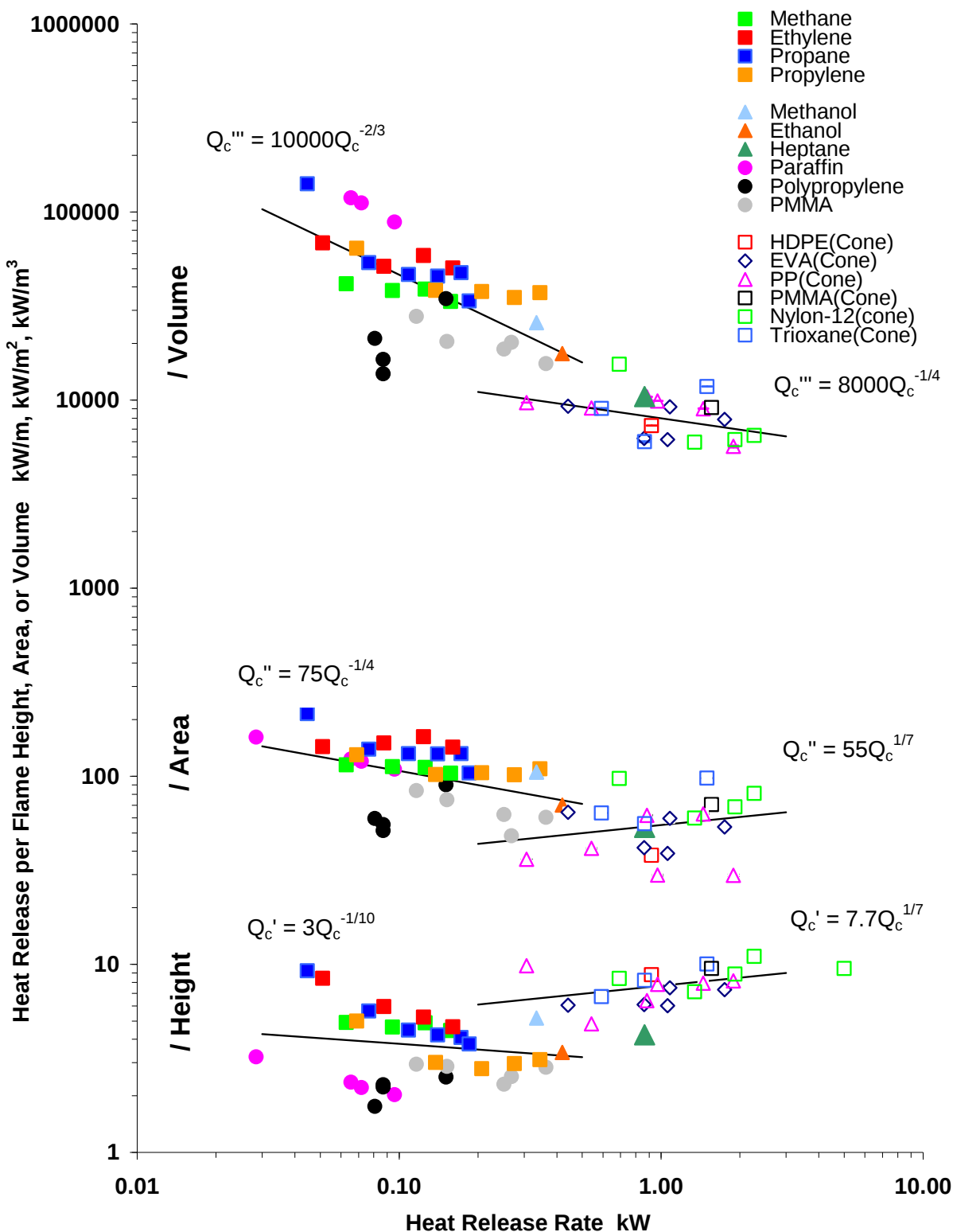


Fig. 4. Heat release normalized by the measured flame height, area, or volume as a function of the heat release rate for flames in the reduced scale cup burner (solid symbols) and the cone calorimeter (open symbols); the lines are the results of a power-law curve fit to the data, together with the equation.

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TABLE 1

Power-law scaling coefficient for the heat release from the measured flame height, area, or volume, as observed in either the cone or the reduced-scale cup-burner flames, as well as that predicted by theory.

Scaling Relationship	Power Law Scaling Coefficient, n_i				
	Observed		Theory		
	Cup Burner	Cone	Laminar Flame, Roper [10]	Froude Modeling [6] $0.15 < Q^* < 1$	$1 < Q^*$
$\dot{Q}_c \sim Z_f^{n_z}; n_z =$	0.91	1.2	1.0	1.5	2.5
$\dot{Q}_c \sim A_f^{n_a}; n_a =$	0.8	1.2	0.5	0.75	1.25
$\dot{Q}_c \sim V_f^{n_v}; n_v =$	0.4	0.8	0.25	0.5	0.83

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