Experimental Thermal and Fluid Science 73 (2016) 87–93

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

# A burner to emulate condensed phase fuels

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ARTICLE INFO

*Article history:*
Received 22 September 2015
Accepted 22 September 2015
Available online 30 September 2015

*Keywords:*
Burner
Emulating
Pool fires

ABSTRACT

A gas-fueled burner with heat flux gages embedded in its porous surface is used to emulate condensed fuel flames. The measured heat flux, the flow rate of the fuel/inert mixture, and the burner surface temperature allow the emulation of the burning characteristics of condensed fuels. The burner is named the Burning Rate Emulator (BRE). It can burn a gaseous fuel at an effective heat of gasification matching the actual heat of gasification of condensed-phase fuels. It also can match other characteristics of the condensed-phase fuel by careful selection of certain properties of the gaseous fuel. These properties are the heat of combustion, the effective heat of gasification, the surface temperature, and the laminar smoke point. The BRE is shown to reasonably emulate steady burning of methanol, heptane, polyoxymethylene (POM) and polymethylmethacrylate (PMMA) burning in 50 mm diameter pools. It also can be used to emulate ignition and extinction. The results can be used to predict behavior at other conditions, such as burning with external radiant heating. The BRE can be extended to emulate steady burning under diverse conditions. The plausibility of the BRE is demonstrated and its limitations and difficulties are discussed. In particular, the difficulty of dealing with the actual surface heat flux distribution is examined. In general, the paper intends to demonstrate the attributes of a BRE.

## 1. Introduction

This study seeks to establish the burning conditions for condensed fuels using a gaseous burner. The burner conditions represent those of steady burning with the heat of gasification of the material as the principal fuel property. In addition three other properties are put forth to complete an emulation. They include the heat of combustion needed to control flame extent, re-radiation heat flux governing surface heat loss, and flame radiation represented by the laminar smoke point. These properties are hypothesized to establish the physical identity of the fuel its chemistry is not directly considered.

We seek to define the burning rate in terms of these four properties by using an emulator having a controlled gaseous fuel supply. The chemical nature of the gas is not modeled in respect to the real fuel's chemical composition. The Burning Rate Emulator (BRE) can be operated to simulate a condensed-phase fuel in steady burning. The results will depend on size, orientation, and, environmental conditions; however, we will examine primarily burning in air.

The theory of steady burning for an evaporating condensed fuel is considered as the basis of the BRE. Although steady burning is not practical for many condensed fuels, the BRE can still give valuable insight on average. In other words, as wood would have a non-steady burning signature due to charring, its peak or overall average burning rate can be represented by an appropriate (usually a high) value for the heat of gasification. Steady burning (rate per unit area or burning flux) can be formulated in terms of a heat of gasification ($L$) as

$$\dot{m}'' = \frac{\dot{q}_f'' - \dot{q}_{rr}'' + \dot{q}_e''}{L}, \tag{1}$$

where the quantities are defined in the nomenclature. The heat of gasification for liquids is a thermodynamic property defined as

$$L = h_{vap} + c_p(T_v - T_\infty), \tag{2}$$

where $h_{vap}$ is the heat of vaporization, $c_p$ is the specific heat, $T_v$ is the surface vaporization temperature, and $T_\infty$ is the ambient temperature. The heat of gasification of polymers will involve more phases and transitions. As stated even charring materials, in time-average burning, can be couched in terms of a relatively high value of $L$.

The flame heat flux is controlled by convective and radiative components, and the surface re-radiation heat flux by the temperature of the vaporizing surface. In the case of the BRE, it is the

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http://dx.doi.org/10.1016/j.expthermflusci.2015.09.025

**Nomenclature**

| | |
|---|---|
| $B$ | $B \equiv [Y_{ox}\Delta h_c/r - c_p(T_v - T_\infty)]/L$ (dimensionless) |
| $c_p$ | specific heat of gas (J/g K) |
| $h_c$ | convective heat transfer coefficient (W/m$^2$ K) |
| $\Delta h_c$ | heat of combustion (kJ/g) |
| $h_{vap}$ | heat of vaporization (kJ/g) |
| $\dot{m}''$ | burning rate (g/m$^2$ s) |
| $L$ | heat of gasification (kJ/g) |
| $\dot{q}''_e$ | incident external radiative heat flux (kW/m$^2$) |
| $\dot{q}''_f$ | incident flame heat flux (kW/m$^2$) |
| $\dot{q}''_{rr}$ | surface radiative loss heat flux to ambient (kW/m$^2$) |
| $r$ | stoichiometric mass oxygen to fuel ratio (g/g) |
| $T_v$ | vaporization temperature (K) |
| $T_\infty$ | ambient temperature (K) |
| $Y_{ox}$ | ambient oxygen mass fraction (g/g) |

burner surface temperature that gives the surface re-radiation. Heat flux gages in the burner surface record the flame heat flux, which includes both incident radiation and convection to the surface. With the measured gas flow rate of the burner, values of $L$ can be determined from Eq. (1). While such values might seem simplistic, an effective $L$, which includes external heating, can define the enhancement conditions needed for that $L$ to burn. By varying the gaseous fuel–inert mixture, the heat of combustion and the radiation character (specifically the laminar smoke point) can be varied. For a given configuration, a wide range of burning conditions can be readily established with the emulator (BRE).

But the development of the required net heat flux of Eq. (1) can present a challenge, and the control of a burner's surface temperature can be difficult. While the dilution of a gaseous fuel with an inert gas might match the heat of combustion and the smoke point of the emulated fuel, complete matching may only be approximately achieved.

The use of a burner to emulate combustion of solids and liquids has been used previously examined. Orloff and de Ris [1], Kim et al. [2], and de Ris et al. [3] pioneered the use of sintered metal burners for studying the steady burning of a planar condensed phase. Their burner used water cooling to obtain the needed heat flux, and thus the surface temperature was low. The water cooling also led to long equilibrium times. They examined mainly convective burning through the Spalding $B$ number. For a given ambient condition, the $B$ number is principally a function of the heat of gasification, $L$. The burning rate per unit area in purely diffusive or convective burning is also principally a function of the $B$ number. Flame radiation and surface re-radiation disturb this simple dependence. However, the relatively simple dependence could be emulated by the de Ris burner, and is shown to follow laminar pure convective flame theory [1–3].

The use of a burner is imperfect, as it generally maintains a uniform velocity over its surface. Boundary layer or pool burning, even for pure convection, will have a distribution of heat flux over the surface, and thus a variable surface velocity. The good agreement with theory suggests that the fuel velocity at the burner face quickly equilibrates to proper diffusional flows in the flame.

Bustamante et al. [4] presented another validation of burner emulation by comparing the flame standoff distance in the laminar region for burning of inclined flat plates. Results showed the similarity in the flame shape for a flat surface oriented at various angles. Even the onset of turbulent unsteady flow was approximately matched.

## 2. Experimental design and testing

Inspired by the de Ris burner, a BRE burner was designed and constructed. Its size was selected to replicate small pool fires. This BRE burner has a face diameter of 50 mm. Its internal features allow for a mixing plenum for the incoming fuel stream, an array of glass beads to provide uniformity to the flow, and a top brass plate with uniform holes having a high overall porosity. Two heat flux sensors are used anticipating heat flux variation over the surface. They are needed to compute the heat of gasification. Two thermocouples on the operating face record the surface temperature so that the re-radiation heat flux can be computed. Fig. 1 shows the BRE burner with two heat flux sensors, one at the center and the other between the center and edge. The "edge" sensor is at a radius of 3.2 mm. The sensors are 1/8-in. diameter water-cooled Medtherm thermopile devices, operated at about 65 °C to avoid a condensation error. The required heat fluxes needed in Eq. (1) are computed from these temperatures and heat flux measurements. A distribution needs to be postulated to give the integrated average radial heat flux. Also corrections are applied to address the differences in the sensor and plate temperatures. These corrections are generally small, and details will not presented here.

A series of tests were performed to assess the burner's ability to emulate particular condensed-fuel combustion. The procedure was to measure a steady burning rate for the condensed fuel, then select a gaseous fuel mixture with this same flow rate to best match (1) the heat of combustion, (2) the heat of gasification, (3) the surface temperature, and (4) the laminar smoke point of the original condensed-phase fuel. The heat of combustion and the smoke point could be matched as close as practical by selecting a mixture of pure gaseous fuel and an inert diluent; nitrogen was used.

Several condensed-phase fuels were selected for study: two liquids and two solids. Two of the fuels burn with negligible soot. The four properties were matched as closely as practical, and the burning rates, flame size, character, and color were compared. The burning rate of the condensed fuel is determined by a load-cell measurement of a 50 mm pool fire, and used to fix the BRE flow rate. The liquids were burned in a 50 mm diameter glass vessel. Although the liquid fuel was not refilled during the burning, we have reached the stable burning rate. Literature values are established for the four fuel properties as listed above [5–7]. Two of the four properties – heat of combustion and laminar smoke point – are best matched by selecting the proper gaseous fuel and nitrogen mixture. The other two properties – heat of gasification and surface temperature – are found from the BRE measurements. As the burner surface temperature is not controlled, this matching depends on the burner thermal properties. As long as the surface temperatures are not too out of line, this is not considered a serious defect to the emulation.

The four fuels selected are methanol, heptane, PMMA and POM. The liquids easily ignite and quickly establish steady burning. The solids need to be encouraged to burn, but eventually reach steady conditions.

Methanol was examined first. The mass loss rate of methanol was measured and the flame was photographed. To match the methanol with the BRE we would need to use a gaseous fuel with the same flow rate. To match the flame height, the fuel must have the same heat of combustion. In addition, consideration of the soot