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# A methodology for estimation of local heat fluxes in steady laminar boundary layer diffusion flames

Ajay V. Singh, Michael J. Gollner *

*University of Maryland, College Park, Dept. of Fire Protection Engineering, College Park, MD 20742, USA*

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ABSTRACT

A unique methodology has been used for the estimation of local mass burning rates and flame heat fluxes over a laminar boundary layer diffusion flame with a high accuracy by utilizing micro thermocouple measurements in the gas phase close to the condensed phase surface. Both liquid and solid fuels were investigated. Convective and radiative heat feedback from the flames were measured both in the pyrolysis and plume regions by using temperature gradients near the wall. As expected, for small laminar flames, convective heating was found to be the dominant mode of heat transfer to the condensed fuel surface and accounted for nearly 85–90% of the total flame heat flux in both liquid and solid fuels. The total average incident flux to the condensed fuel surface was estimated to be approximately 22, 20 and 27 kW/m$^2$ for methanol, ethanol and Poly Methyl Methacrylate (PMMA) wall-bounded flames, respectively. The average convective heat flux from the flame to the wall in the pyrolysis zone was estimated to be 18.9, 17 and 22.9 kW/m$^2$ for methanol, ethanol and PMMA, respectively. The radiative component in these small flames was observed to be small, never accounting for more than 20% of the total wall heat flux. Temperature gradients normal to the wall, proportional to the dominant convective heat flux, were found to decrease from the leading edge towards the trailing edge in the pyrolysis zone, however they were found to remain relatively constant in the combusting plume region (~450 K/mm) until the tip of the flame was reached. Thereafter, they were found to decrease significantly downstream of the combusting plume. The work presented here also discusses the selection of transport properties at appropriate temperatures to calculate convective fluxes by using a crude approximation as opposed to detailed temperature measurements in such flames.



## 1. Introduction

In most problems related to fire safety, it is necessary to have a means of estimating the mass-burning rate over condensed fuel surfaces. The rate of flame propagation over any solid or liquid fuel surface, and its ultimate growth to a large fire primarily depends on the burning or mass-loss rate of the fuel and associated heat fluxes to unburnt fuel ahead of the pyrolyzing region. The burning rate also determines flame heights, rates of heat release, and smoke and CO emissions, which in turn determine the growth rate of the fire and its potential hazards. The burning rate and forward flame heat fluxes in turn depend on external conditions, such as the free-stream velocity (for the burning of fuel in a forced convective environment) and the fuel geometry such as the angular orientation of the combustible surface with respect to the normal gravity direction. The coupled nature of these properties makes them difficult to determine under mixed conditions.

The work presented here has utilized experimental data of steady laminar flames established over vertical condensed fuel surfaces to separate the convective and radiative components of heat feedback to condensed fuel surfaces. Accurately determining the convective and radiative components of flame heat flux is important for the study of laminar burning fuels and future numerical validation. Although this study only approaches laminar wall fires, smaller in scale than realistic unwanted fires, the laminar wall fire is a canonical fire research problem and serves as an important first step for future development of the techniques and numerical models of fire spread. Detailed high resolution temperature measurements were taken both in the pyrolysis and plume regions of boundary layer diffusion flames using both liquid and solid fuels. Temperature profiles were measured by using fine-wire thermocouples and time-averaged fuel consumption rates were measured using a load cell. The convective heat feedback to the wall was then determined by utilizing the detailed temperature measurements

* Corresponding author.
*E-mail address:* mgollner@umd.edu (M.J. Gollner).

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $B$ | B-number (Spalding mass transfer number) (–) |
| $c_p$ | specific heat at constant pressure (J/kg K) |
| $D$ | species diffusivity (m$^2$/s) |
| $d$ | diameter (m) |
| $g$ | gravitational acceleration (m/s$^2$) |
| $Gr$ | Grashof number (–) |
| $h$ | convective heat transfer coefficient (W/m$^2$ K) |
| $h_g$ | effective heat of gasification or vaporization (J/kg) |
| $k$ | thermal conductivity (W/m K) |
| $L$ | length of the condensed fuel surface (m) |
| $L_v$ | effective heat of vaporization (J/kg) |
| $\dot{m}_f''$ | mass-burning rate (mass flux) (kg/m$^2$ s) |
| $Nu$ | Nusselt number (–) |
| $Pr$ | Prandtl number (–) |
| $\dot{q}''_{net}$ | net heat flux (W/m$^2$) |
| $\dot{q}''_{fl,c}$ | convective heat flux (W/m$^2$) |
| $\dot{q}''_{fl,r}$ | radiative heat flux (W/m$^2$) |
| $\dot{q}''_{s,rr}$ | surface re-radiation heat flux (W/m$^2$) |
| $\dot{q}''_{s,i}$ | incident heat flux (W/m$^2$) |
| $\dot{q}''_{id,cond}$ | in-depth conduction into the solid (W/m$^2$) |
| $\dot{q}''_{id,r}$ | in-depth radiation into the solid (W/m$^2$) |
| $\dot{q}''_{hfg}$ | total heat flux from heat flux gauge (W/m$^2$) |
| $r$ | surface reflectivity (–) |
| $Re$ | Reynolds number (–) |
| $t$ | time (s) |
| $T$ | temperature (K) |
| $T^*$ | non-dimensional temperature (–) |
| $U_\infty$ | free-stream velocity (m/s) |
| $x$ | coordinate parallel to the condensed fuel surface (m) |
| $y$ | coordinate perpendicular to the condensed fuel surface (m) |
| $x^*$ | non-dimensional distance, $x/L$ (–) |
| $y^*$ | non-dimensional distance, $y/L$ (–) |
| $y_f$ | flame standoff distance (m) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity (m$^2$/s) |
| $\delta$ | surface regression of PMMA (m) |
| $\varepsilon$ | emissivity (–) |
| $\nu$ | kinematic viscosity (m$^2$/s) |
| $\rho$ | density (kg/m$^3$) |
| $\tau_s$ | shear stress at the surface (N/m$^2$) |

*Subscripts*

| | |
|---|---|
| ad | adiabatic |
| $f$ | film (mean properties) |
| fl | flame |
| $g$ | gas |
| hfg | heat flux gauge |
| id | in-depth |
| $\infty$ | ambient |
| $p$ | pyrolysis |
| $s$ | surface |
| tc, $b$ | thermocouple junction or bead |
| $w$ | wall/wire |

*Abbreviations*

| | |
|---|---|
| HFG | heat flux gauge |
| LBL | laminar boundary layer |
| PMMA | poly methyl methacrylate |

near the wall. Total flame heat flux was measured both in the pyrolysis and plume regions using a standard water-cooled heat flux gauge. By comparing both of these measurements with local mass-loss data from a new technique which utilizes local temperature gradients near the fuel surface [1], convective, radiative and net heat flux components can be extracted locally for this canonical fire research problem. This study therefore seeks to improve the accuracy and predictive capability of theoretical and numerical models while providing an experimental data set for local burning rates and various components of incident flame heat flux to the condensed fuel surface.

## 2. Literature review

Burke and Schumann [2] were one of the earliest research teams to present a theoretical analysis of a general diffusion flame from homogeneous reactants. Spalding [3] later addressed the problem of fuel pyrolysis due to energy transfer from a combustion zone. Emmons pioneering work in which he mathematically modeled a steady, laminar diffusion flame in a forced-flow airstream provided a framework for most fire safety studies and laminar diffusion flames [4]. The simplistic closed-form similarity solution presented by Emmons served as a starting point for further studies of steady [5,6] and spreading [7,8] laminar flames. The results of analyses in all configurations showed that the local burning rate per unit area was controlled by the fuel mass-transfer number, $B$ [9,10], and that it decreased with distance from the leading edge.

Experimental studies followed analytical work, investigating various aspects of non-spreading, steady, boundary layer type diffusion flames. One of the earliest experimental investigations on the aerodynamic structure and stability of diffusion flames stabilized over a fuel surface was reported by Hirano and co-authors [11,12], where gaseous fuels were injected uniformly through a porous flat plate into a parallel air stream. In their subsequent experimental studies, Hirano and Kinoshita [13] measured gas velocities and temperature profiles across a diffusion flame established over a liquid fuel surface with a free air stream parallel to the plate. Later, Andreussi and Petarca [14] carried out experiments similar to those by Hirano and Kinoshita [13] using ethyl alcohol as a fuel. Both authors studied the structure of the diffusion flame formed on a liquid surface with a parallel oxidizer flow experimentally, analytically or both. Gas velocity and temperature profiles were measured by Hirano and Kinoshita whereas Andreussi and Petarca measured the temperature and species concentration profiles across the boundary layer diffusion flame. However, both the authors did not measure the local temperature gradients at the surface of a condensed fuel and no attempt was made to measure the local fuel consumption rate. A recent study by the authors [1] utilized a first set of temperature measurements close to the fuel surface of methanol, ethanol and PMMA using a new technique to calculate local mass burning rates.

Several experimental investigations on forced convection boundary layer flames on Poly methyl methacrylate (PMMA) plates have also been reported. Krishnamurthy and Williams [15] investigated forced convective boundary layer flames on a PMMA plate. While there have been several relevant studies on the burning of polymethyl methacrylate (PMMA) slabs [16,17], only Ananth et al. [18] and later Ndubizu et al. [19] report both average burning rates and temperature profiles for steady and unsteady PMMA burning in a laminar forced convective environment.