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# Optical thickness of emissivity for pool fire radiation

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## ABSTRACT

The evaluation of emissivity $\varepsilon = 1 - \exp(-\kappa L)$ is important for predicting fire radiation heat transfer, where the flame in many actual scenarios is neither optically thin nor optically thick. In this work, the mean optical length of soot emissivity was focused on. Firstly, the formula of the optical correction factor was deduced, which was dependent on burner size, flame shape, geometrical configuration, soot volume fraction, flame temperature, and radiation flux. Secondly, burner size and air pressure were shown to have coupling effects on soot volume fraction as $f_v \propto D^{0.4}p^{1.4+0.2n}$ ($\dot{m}'' \propto p^n$), which caused a high flame temperature and a low flame luminosity in a low air pressure for small-sized burners. Thirdly, in a low air pressure, the optical correction factor was indicated to be larger, which was dominated by the decrease in soot volume fraction. Finally, compared with the soot emissivities generated using the formula proposed in this work, the soot emissivities obtained using traditional formulas were larger. The overestimated difference increased with increasing burner diameter. In a low air pressure, soot emissivity was smaller mainly because of the decrease in soot volume fraction. The assumptions of optically thin would apply better for a small-sized burner in a low air pressure.

## 1. Introduction

A pool fire is a buoyancy-controlled diffusion fire burning above a horizontal pool, where fuel has a low initial momentum. Most of the oil storage tank and offshore installation fire scenarios can be classified as pool fires. The burner of pool fire may be of an arbitrary geometry, but for simplicity, most studies have considered a circular or square configuration characterized by a single geometrical scale, namely, the pool diameter (*D*).

Radiation is the main concern for the fundamental research about fire behavior and engineering applications on fire hazard. Combustion products from fires of hydrocarbon fuel generally consist of both gaseous products and unburned carbon particulates called soot. Gaseous radiation is concentrated in specific locations in the spectrum, thereby generating discrete band spectra. Soot particles emit continuum radiation throughout the visible and infrared, which mainly contributes to flame luminosity and fire radiation.

The thermal radiation in fires involves energy exchange between surfaces (i.e., walls, ceilings, floors, furniture, etc.), as well as emission and absorption by various gases and soot particles. Configuration factor *F* is the fraction of diffusely radiated energy from the radiating surface to the radiated surface, which is determined by such reciprocal configuration parameters as distance, position and angle. Spectral emissivity $\varepsilon_\lambda$ is the fraction of energy emitted to the blackbody emission at the same temperature for a gas volume, which is an important factor of flame radiation. Emissivity is typically in terms of the total emissivity as $\varepsilon = 1 - \exp(-\kappa L)$ integrated over all wavelengths, where $\kappa$ is the extinction coefficient, and *L* is the mean optical length that determines the simplified calculations of emissivity in optically thin and optically thick limits.

In previous studies about the radiation heat transfer of pool fires, a point model was often employed, and the changes in optical thickness caused by fire scales and ambient conditions were ignored [1–8]. de Ris [1] extended both narrow-band statistical and exponential wide-band models for optically thin luminous flames to predict the radiation of moderate-scale and large-scale fires. Comparative measurements of various non-charring plastic fuels show that flame absorption-emission coefficient is the principal fuel property controlling the burning rate of fuel at hazardous scales. Orloff [2] developed a convenient and widely accessible radiation model to simplify the calculations of radiant heat transfer from pool fires, in which fires were described by an equivalent homogeneous, isothermal, spectrally gray volume of flame gases defined by a composite flame shape. A point model was applied to calculate the radiation transfer to an external target, while an adjustable parameter of 0.95 was represented as a coefficient of emissivity to cover the optically thin and thick limits. In 2013, Hu et al. [5] found that the pool-scale effect on both flame radiation feedback fraction and accordingly mass burning flux differed when with and without a cross air

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**Nomenclature**

| | |
|---|---|
| $A$ | Surface area |
| $C$ | Optical correction factor |
| $C_0$ | Constant depended on the complex refractive index |
| $C_2$ | Planck's second constant |
| $C_m$ | $3.72C_0/C_2$ |
| $c_p$ | Specific heat at constant pressure |
| $D$ | Pool diameter or equivalent diameter |
| $E_f$ | Radiation flux of the flame |
| $F$ | Configuration factor |
| $f_v$ | Soot volume fraction |
| $g$ | Gravitational acceleration |
| $H$ | $R/r$ |
| $h$ | Flame height |
| $L$ | Mean optical length or $h/r$ in Eq. (4) |
| $L_0$ | Geometric beam length |
| $m$ | Complex refractive index of soot particle |
| $\dot{m}''$ | Mass burning rate per unit area |
| $p$ | Air pressure |
| $\dot{Q}$ | Heat release rate |
| $\dot{Q}^*$ | Dimensionless heat release rate |
| $\dot{q}''$ | Radiation flux from flame to the radiometer |
| $R$ | Center distance |
| $r$ | Pool radius, $D/2$ |
| $T$ | Temperature |
| $V_f$ | Flame volume |
| $X$ | $(1+H)^2+L^2$ in Eq. (4) |
| $Y$ | $(1-H)^2+L^2$ in Eq. (4) |

*Greek letter*

| | |
|---|---|
| $\Delta H_c$ | Heat of combustion |
| $\varepsilon$ | Emissivity |
| $\kappa$ | Extinction coefficient |
| $\kappa_m$ | Mean extinction coefficient |
| $\rho_\infty$ | Ambient density |
| $\sigma$ | Stefan-Boltzmann constant |
| $\tau_c$ | Chemical reaction time |
| $\tau_f$ | Flow time |
| $\Phi_{f-r}$ | Radiant heat from the flame to the radiometer |
| $\psi^{(3)}$ | Pentagamma function |

*Subscript*

| | |
|---|---|
| $f$ | Flame |
| $r$ | Radiometer |
| $\infty$ | Ambient condition |

flow. In 2014, Hu et al. [6] studied the optically thin flame radiation fraction of sooty buoyant turbulent jet diffusion flames in reduced and normal atmospheric pressures, as well as developed a global correlation with Reynolds number. In 2013, we investigated the effects of a low air pressure on radiation-controlled rectangular ethanol and n-heptane pool fires, in which $\kappa L$ was assumed to be invariant by Radiation modeling [7,9]. Raj and Prabhu [10] developed a refined methodology which makes use of the transmissivity of flame to determine the instantaneous spatial and temporal variation of emissivity in pool fires.

The evaluation of emissivity is important for predicting radiation heat transfer in fundamental research, engineering applications, and numerical simulations. The radiating gas in many actual fire systems is neither optically thin nor optically thick; thus, band theory should be used to calculate the mean absorption coefficient. To account for the influence of optical thickness on the prediction of emissivity, Tien et al. [11] emphasized that a correction factor should be employed for the mean optical length, which is dependent on the geometry of the fire body.

In this work, we re-visit the experiments about pool fires conducted in normal air pressure (Hefei, 99.8 kPa) and low air pressure (Lhasa, 66.5 kPa). Pool fire has various scales, and burning rate is dominated by the heat feedback of conduction, convection, and radiation. The objective is to give theoretical formulas about the correction factor of the mean optical length, which is dependent on the parameters of combustion characteristics and ambient conditions. The theoretical calculations based on the experimental results are then discussed and compared with other work.

## 2. Theoretical methods

In this study, we address the problems of the configuration factor of geometry and the correction factor of optical thickness. The assumptions are as follows: stoichiometric reaction applies; the cylindrical shape of flame prevails [11]; flame is equivalent homogeneous and isothermal; radiation heat is uniformly distributed in the flame body; for the fuel of n-heptane, soot production dominates the radiation of luminous flames [12,13].

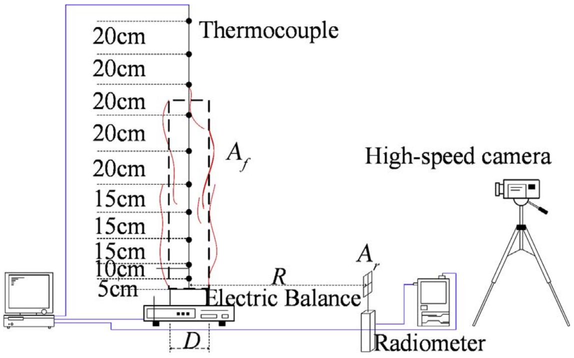

**Fig. 1.** Configuration of a cylindrical flame in the experiments. $R$ is equal to 5 times square burner inner side length.

### 2.1. Configuration factor of geometry

For the geometry configuration of a cylindrical flame and a radiometer with a vertical flat surface shown in Fig. 1, the center point of the horizontal burner surface is in the normal direction of the vertical radiometer surface in the center point. The radiation flux from the flame to the radiometer can be calculated as

$$\dot{q}'' = \Phi_{f-r}/A_r, \tag{1}$$

$$\Phi_{f-r} = F_{f-r}E_f A_f, \tag{2}$$

where $\Phi_{f-r}$ is the radiant heat from the flame to the radiometer (W), $A_f$ is the surface area of the flame (m$^2$), $A_r$ is the surface area of the radiometer (m$^2$), $E_f = \varepsilon\sigma T_f^4$ is the radiation flux of the flame, $\sigma$ is the Stefan–Boltzmann constant $5.67 \times 10^{-8}$ W·m$^{-2}$K$^{-4}$, and $T_f$ is the flame temperature (K), and $F_{f-r}$ is the configuration factor, which is defined as [11].

$$F_{f-r} = (A_r/A_f)F_{r-f}. \tag{3}$$

The configuration factor of $F_{r-f}$ can be calculated by the geometry as