A STUDY OF MECHANISM OF RADIATION IN LUMINOUS FLAMES

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ABSTRACT

The radiation of the luminous flame behaves differently from that of non-luminous ones in that the former can have a radiative energy 2-3 times as much as that of the latter. It then becomes important to determine, in a reasonable way, the influence of the soot particles in the luminous flame on the radiative properties of the flames. Based on the fundamental optical and electromagnetic theories, a new approximate approach is put forward in this paper for calculating the emissivity of flames with soot particles which can fit the accuracy of engineering requirement. the result can be helpful in the design of portable polychromatic flame bolometer.

KEY WORDS: LUMINOUS FLAME, NONLUMINOUS FLAME, SOOT, ELECTROMAGNETIC AND SCATTERING THEORY

INTRODUCTION

It is insufficient to calculate the radiative heat transfer by only considering the combustive constituents and geometrical form of the flame at the initial stage of combustion because the properties of the radiation are also related to the temperature, the velocity and the concentration in the flame, The currently used empirical method (not based on fundamental theory) for determining the radiation property of the flame of combustion system can not fit to the accuracy required in engineering. It is urgent in fire science study to solve the problem of mechanism of luminous flame, so as to understand how the radiation intensity varies with various factors.

Usually, flame can be divided into two main kinds, luminous and nonluminous . The nonluminous flame is blue and transparent. Its radiation property resembles that of the gases flame, i.e. , determined mainly by theradiation property of the triatomic gases in it (such as CO_2,H_2O) . Thus, to many phenomena of nonluminous flame, the calculation of radiative heat transfer can be done in terms of relevant gas flame radiation. Luminous flame is caused by the blazing and flaring soot particles (with an average diameter of 0.006-0.06 μm), which is caused by products of hydrocarbons pyrolysis. Large soot particle is not transparent to radiation beam. They behave like little black bodies in luminous flame, which make the flame's emissive power approaches to that of the black body's radiation. Whereas, small soot particle in flame is almost transparent to radiative beam. Thus the actual blackness of different luminous flame can differ greatly.

The characteristic of luminous flame is that it is accompanied with combustion possess. The energy creation and radiation make the temperature changes, as a result, the properties of radiation in the luminous flame and the radiated energy will be changed. Heat transfer will become complicated because the intermediate product produced by complicated chemical reaction will change the radiative properties of the final products. Soot particles, which are composed mainly of carbon, radiate continual spectra in both visible and infrared ranges, and its radiative energy is 2-3 times as larger as that of pure nonluminous radiation. How to determine the effect of soot particle on luminous flame remains to be a difficult problem up to now, because the number and size of soot particles are affected by the kinds of fuel, rate of combustion, shape and size of combustion space, quantity and component of air supply for combustion and many other complicated factors. This paper deals with the problem how to calculate the absorptivity (α) and emissivity (ε), make the method simple and practical to determine temperature of luminous flame and reach a certain level of accuracy. The author is enlightened much by some famous reserachers'(such as H.C.Hottel etc.) experimental dada and formulation, use interpolation or extrapolation method, select from some rough optical experimentaldata got by others and by myself and base the calculation on fundamental theory.

APPROXIMATE FORMULAS BASED ON FUNDAMENTAL THEORY

Assuming that the soot particles are spherical, with mean diameter D, projection area is $A=\pi D^2/4$, and absorption factor is E_λ, then the cross section area is $E_\lambda A$. Assuming N is the number of particles per unit volume, n, k are optical constants, with $n=f_1(\lambda)$, $k=f_2(\lambda)$, then for the limit condition of $\min(\pi D/\lambda)$, we have:

$$\alpha_\lambda = E_\lambda AN \quad \text{(Maxwell's Electromagnetic Theory)} \qquad (1)$$

$$\left.\begin{aligned} &= \frac{24\pi D}{\lambda} f(\lambda)AN \\ &= \frac{36\pi C}{\lambda} f(\lambda) \end{aligned}\right\} \qquad (2)$$

$$\alpha_\lambda/c = \frac{36\pi}{\lambda} f(\lambda) \qquad (3)$$

where

α_λ is single absorption;

λ is wavelength in μm;

C is volume concentration of soot particles, $c=\pi D^3 N/6$

$$\left.\begin{aligned} E_\lambda &= \frac{24\ \pi\ D}{\lambda} f(\lambda) \\ f(\lambda) &= \frac{nk}{(n^2-k^2+2)^2+4n^2k^2} \end{aligned}\right\} \text{(G.Mie Scattering Thery)} \qquad (4)$$

In infrared range, Mie's law can give simpler formula:

$$\alpha_\lambda = 1 + \frac{\ln[f(1)/f(\lambda)]}{\ln \lambda} \qquad (5)$$

Where, f(1), f(λ) is calculated by formula (4) from chemical constant n , k of soot particles in various wavelength.

If the change of n ,k with λ is not significant, we can take $\alpha_\lambda/C=k/\lambda$. Where k is a constant related to the kind of particle and can be obtained from α_λ/C value in λ=1μm.

The total emissivity ε of isothermal soot particle clouds, which have penetrated a distance of S and have homogeneous suspending distribution, can be got by using some theoretical formulas (such as Wien formula) and adopting some assumptions (such as suspended gas has no radiation effect, the emissivity is depend on soot particles and only at certain wavelengths)

$$\varepsilon = f(T,CS)$$

$$= 1 - \frac{1}{[1+(kCS/C_2)T]^4} \qquad (6)$$

where

T is average temperature of soot particles in K;
CS is the product of volumetic concentration of soot particles and the mean beam lengths in μm.

C_2 is the Second Plank Radiation Constant, $C_2=1.44\times10^{-2}m\cdot K$

We can take $k/C_2=350(m\cdot K)$ as the average value of soot particle in usual combustive temperature range.

The above formulation for calculating α and ε is based on fundamental theory. Some assumptions have been made during the derivation. It can supply technical data essential for the calculation or experiment of radiative heat transfer of flame when the optical constants n and k are known, this is indispensable when we study the model of heat radiation source.

In addition to the formula given above, we must also found a method for calculating the volumetic concentration C of soot particles by using fundamental theory, however what we can do only, at present, is to investigate flame by experiment to get the data of C or CS, or to investigate similar flame to get approximate property of them. What are introduced below is an ordinary method.

In this method , high temperature bolometer equipped with red and green filter should be used, when the brigthness of flame is equal to that of black body radiative source, the temperature is being measured. The temperature is measured by high temperature bolometer (The red and green filter should be used separately each time).

Assuming that T_r and T_g are temperatures of black body when the brigthness of flame is equal to the temperature using red and green filters, λ_r and λ_g are the wavelength of red and green light, so the blackbody's emissive power of red light (λ_r=0,665μm) and green light (λ_g=0,555μm) have the relationship as follows:

$$e_{\lambda br}=\varepsilon_{\lambda r}e_{\lambda brf} \qquad (7\text{-}1)$$

$$e_{\lambda bg}=\varepsilon_{\lambda g}e_{\lambda bgf} \qquad (7\text{-}2)$$

where

$$e_{\lambda br}=2\pi C_1/\lambda_r^5\exp(C_2/\lambda_r T_r) \qquad (8\text{-}1)$$

$$e_{\lambda bg}=2\pi C_1/\lambda_g^5\exp(C_2/\lambda_g T_g) \qquad (8\text{-}2)$$

$$e_{\lambda brf}=2\pi C_1/\lambda_r^5\exp(C_2/\lambda_r T_f) \qquad (8\text{-}3)$$

$$e_{\lambda brg}=2\pi C_1/\lambda_g^5\exp(C_2/\lambda_g T_f) \qquad (8\text{-}4)$$

where

$\varepsilon_{\lambda r}$ is monochromatic emissivity of red light;

$\varepsilon_{\lambda g}$ is monochromatic emissivity of green light;

C_1 is the First Planck Constant, $C_1=3.74\times10^{-16}W\cdot m^2$;

T_f is temperature of flame in K.

According to Hettel's experimental study, when path penetrating through flame for measurement is S, the empirical formula for calculating emissivity ε_λ is:

$$\varepsilon_\lambda = 1-\exp(-\frac{Ck_2s}{\lambda^{1.39}}) \quad (\lambda<0.8\mu m) \qquad (9\text{-}1)$$

$$\varepsilon_\lambda = 1-\exp(-\frac{Ck_1s}{\lambda^{0.95}}) \quad (\lambda>0.8\mu m) \qquad (9\text{-}2)$$

Substituting empirical formula (9-1),valid for light in visible range into (7) and rearranging it, we find:

$$\frac{1}{T_f}-\frac{1}{T_r}=\frac{\lambda_r}{C_2}\ln[1-\exp(-\frac{Ck_2s}{\lambda_r^{1.39}})] \qquad (10\text{-}1)$$

$$\frac{1}{T_f}-\frac{1}{T_g}=\frac{\lambda_g}{C_2}\ln[1-\exp(-\frac{Ck_2s}{\lambda_g^{1.39}})] \qquad (10\text{-}2)$$

With formulae (10-1) and (10-2), we can calculate T_f and Ck_2(k is a constant of experiment), then we can calculate ε using the below formulas:

$$\varepsilon_f C_0 (\frac{T_f}{100})^4 = \int_0^{\infty} e_{\lambda bf} \varepsilon_\lambda d\lambda \qquad (11\text{-}1)$$

$$\varepsilon_f = \frac{\int_0^{\infty} e_{\lambda bf} \varepsilon_\lambda \, d\lambda}{C_0 (\frac{T_f}{100})^4} \qquad (11\text{-}2)$$

where C_0 is Boltzmann constant, $C_0 = 5.67 w/(m^2 \cdot k^4)$

Assuming that there are three gradients which are carbon dioxide, water vapor and soot particles in flame, the total emissivity is the sum of the three gradients' emissivity minus modification terms of spectral overlap, the formula is:

$$\varepsilon = 1-(1-\varepsilon_c)(1-\varepsilon_w)(1-\varepsilon_s) \qquad (12)$$

NOTES

1. Attention must be paid to the condition of experiment because this condition is hard to be controlled accurately.

The change of optical constants n and k with wavelength λ can be measured by experiment. The method of preparing sample and squeezing it into species and the error of measurement make the values of n and k fluctuate considerable, so better method for measuring n and k is expected.

2. The spectral emissivity ε_λ and total emissivity are both related to α_λ, and α_λ is related to C. There is no satisfactory method for calculating C, it can be measured by instrument, and it is the key problem that puzzled one who wants to investigate the mechanism of luminous flame.

3. The main factors which affect the emissivity of luminous flames are the emissivity of soot particles and radiation property the gradient of fuel, number and size of soot particles. And the factors which affect number and size of soot particle are:

A. The chemical and physical property of fuel. For example, the greater the ratio of carbon to hydrogen (C/H)is, the larger the volume concentration of soot particles will be.

B. The quantity of air supply for combustion. when the air supply is not sufficient, the volume concentration of soot particles will increase.

C. The condition of mixing of air and fuel, and the temperature and pressure of combustion.

4. For the soot particles with bigger CS value, the radiative heat transfer take the main part of heat transfer. When $CS=10^{-4}$cm, $\varepsilon=1$.

5.The approximate formulas based on fundamental theory presented in this paper can be used to direct the design of portable polychromatic flame bolometer.

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