IMPORTANCE OF INCLUDING THERMAL RADIATION IN DESIGNING DISCHARGE CONCENTRATION OF GAS PROTECTION SYSTEMS

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ABSTRACT

Radiation is the most important mode of heat transfer for transition from a small room fire to flashover. Ignition of combustibles, flame spread, and heat release rate in well-developed fires all depend on that.

The design concentrations of agents for total flooding gas protection systems should be determined based on the fire size and heat transfer. It is essential to analyze the radiative heat transfer in the fire environment for designing such system. This refers especially to those clean agents, such as substituting heptafluoropropane for halon, where the extinguishing mechanisms might be due to physical cooling. There are always queries on the performance of those systems as chemical inhibition effects are normally not significant. Full-scale burning tests are sometimes required to demonstrate that they can extinguish, or at least suppress, the fire scenario concerned.

The main concepts of radiation heat transfer will be introduced in this paper. Both emissivity and absorption of smoke for accurate predictions of the fire environment are discussed. Several radiation heat transfer models commonly used are reviewed.

1. INTRODUCTION

Because of the potential damage to the ozone layer in the upper atmosphere, the use of the effective fire extinguishing agent halon is prohibited and its production stopped completely by 2005. Many new clean agents have been developed for substituting halon [e.g. 1], heptafluoropropane (C_3HF_7) is an example. This agent is harmless to the protected objects and gives no residue after extinguishment. However, there are concerns on their performance [2]. Those systems were not popular before and so no historic track record is kept at the moment. The agent mainly cools the flame temperature, though some free radicals will be generated to disturb the chain reactions. In addition, a toxic gas hydrogen fluoride HF is decomposed as a by-product at high temperature. The concentration can be 2 to 10 times higher than that from halon [3]. Experiments by Su and Kim on assessing the performance of different agents in extinguishing fires indicated that hepta-fluoropropane would give the most hazardous environment among all the halocarbon agents tested. High HF concentration up to 7000 ppm was produced [4]. The formation of HF depends on the fire temperature, spraying time and concentration.

The design concentrations of the agent, activating time of the system, and the volume of the agent required depend on the fire size and heat transfer. The heat transfer in room fires should be included in designing the right concentration of agent.

Thermal radiation is the key mode of heat transfer in room fires [1,5] where radiation exchange plays a very important role. The radiative heat transfer from the flames to the fuel surfaces will exceed convective heat transfer when the characteristic fuel length is greater than 0.2 m [5]. A large fraction of heat transfer from the flame to the fuel and to the surrounding takes place by thermal radiation. Ignition of combustibles, flame spread, heat release rate and time to flashover all depend on that [6-8]. Radiation will affect the fire temperature and has direct threat to humans. Blocking of radiation heat by an agent such as water mist is an important fire suppression mechanism [e.g. 9]. But in many fire studies, the modeling of radiative transfer is often treated in a simple way or even ignored. This may give significant errors in the predictions.

Many studies on engineering radiative transfer originated from furnaces research. Models are developed to calculate thermal radiation in a furnace [e.g. 10,11], but not for studying fires [e.g. 12]. Such developed models for furnace application are commonly applied in fire simulations. But in contrast to a furnace, the combustion products in a fire depend on the fuel, ventilation and environment. Smoke is considered a mixture of entrained air, unburnt fuel such as soot and combustible products such as carbon monoxide (CO), carbon dioxide (CO_2), water vapour (H_2O) and others. The absorption and emissivity of smoke are very important for predicting thermal radiation in a fire.

In this paper, the basic concepts of radiation are reviewed first. The properties of smoke, including gas and soot, are then introduced. Several radiation models widely used in fire simulations are also described.

2. BASIC CONCEPTS OF RADIATION

Thermal radiation in terms of electromagnetic wave would be emitted from objects at non-zero temperature [e.g. 13-16]. The radiation flux E_∞ radiated from an object per unit time per unit area is proportional to the fourth power of its temperature T through the emissivity ε, radiation flux for a black body E_b and the Stefan-Boltzman constant σ:

$$E = \varepsilon E_b = \varepsilon \sigma T^4 \tag{1}$$

The fundamental quantity of radiation transport is the spectral intensity I_λ, which is defined as the radiant energy per unit time per unit wavelength interval passing per unit surface area normal to the direction Ω into a solid angle $d\Omega(\theta, \omega)$ centered around Ω as in Fig. 1. The intensity $I_{\lambda,\theta}$ across a surface of an arbitrary orientation θ is:

$$I_{\lambda,\theta} = I_\lambda \cos\theta \tag{2}$$

The total net radiative energy flux E is:

$$E = \int_0^{4\pi} I_\lambda \cos\theta \, d\Omega \tag{3}$$

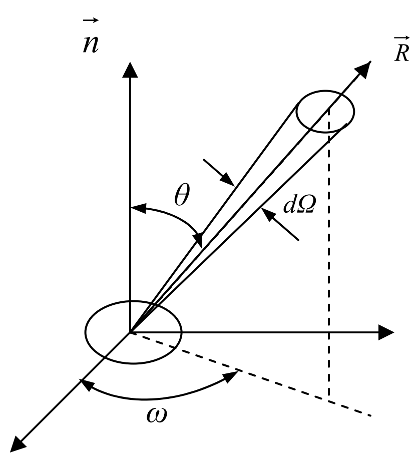

Fig. 1: Coordinate system for radiation intensity

Planck's Law can be applied to a perfect emitter or absorber to calculate the energy spectrum of the radiation emitted from a surface using quantum theory. For a blackbody radiator with a small opening from an enclosed cavity, the spectral intensity of blackbody radiation, $I_{b\lambda}$, also known as the Planck function, is given by [1]:

$$I_{b\lambda} = \frac{2hc^2}{n^2\lambda^5[\exp(hc/n\lambda kT)-1]} \tag{4}$$

In the above equation, c is the speed of light, n is the index of refraction for the medium and k is the Boltzman constant.

The total radiant intensity for a blackbody, I_b, can be obtained by integrating over all wavelengths according to Stefan-Boltzman law, giving

$$I_b = \int_0^\infty I_{b\lambda} d\lambda = \frac{n^2 \sigma T^4}{\pi} \tag{5}$$

The variation of radiation intensity for a real object will not follow the Planck's Law. The Krichhoff's Law can be applied to study the emissivity and absorption of a real object:

$$\varepsilon_{\lambda,\theta,T} = \alpha_{\lambda,\theta,T} \tag{6}$$

Under steady temperature, the monochromatic emissivity from a certain direction is equal to the absorption from the same direction.

When the incident radiation is independent of the incident angle (diffuse reflect) and has the same spectral proportions as a blackbody radiator (gray body), the Krichhoff's law can be revised as:

$$\varepsilon_T = \alpha_T \tag{7}$$

This equation is applied in many radiation heat transfer engineering models for participating media in fire applications.

3. RADIATION PROPERTIES OF GASES AND SOOT

At the early stage of a room fire, there are two layers of hot smoke and cold air. The smoke layer is composed of soot, CO, CO_2, H_2O, and entrained air. Diatomic gas molecules with symmetric structure (such as oxygen O_2 and nitrogen N_2) would have very little absorption and emission, considered as transparent. But for gas molecules with diasymmetric structure such as CO_2 and H_2O, there are higher absorption and emission. In a smoke layer, CO_2, H_2O and soot would give over

95% of radiant absorption and emission [17].

For a monochromatic beam of radiation with an initial intensity $I_{\lambda 0}$ passing through a gas layer of thickness L and extinction coefficient K_λ, the intensity of the radiation beam $I_{\lambda L}$ is [1,13-16]:

$$I_{\lambda L} = I_{\lambda 0} \exp(-K_\lambda L) \tag{8}$$

The absorption α_λ of the layer to the monochromatic beam is:

$$\alpha_\lambda = \frac{I_{\lambda 0} - I_\lambda}{I_{\lambda 0}} = 1 - exp(-K_\lambda L) \tag{9}$$

For an arbitrary shaped gas with volume V and area of the boundary surface A, the mean beam length L can be estimated by:

$$L = 3.6V / A \tag{10}$$

An emissivity chart for CO_2 and H_2O based on experimental data was formulated by Hottel and Sarofim [13]. The total emissivity charts were summarized by Edwards for water vapour and carbon dioxide [14]. The emissivity depends on the pressure, temperature and the mean beam length. These charts are only suitable for use at one standard atmospheric pressure, and have to be corrected at other pressures. For the mixtures of these two gases, an additional band overlap correction factor is needed. The equivalent gray gas emissivity ε_g for a mixture of CO_2 and H_2O is [1]:

$$\varepsilon_g = C_{CO_2}\varepsilon_{CO_2} + C_w \varepsilon_w - \Delta\varepsilon \tag{11}$$

In the above equation, C_{CO_2} and C_w are the pressure correction factors of carbon dioxide and water, respectively; ε_{CO_2} and ε_w are the emissivities of CO_2 and H_2O at 1 atm respectively; and $\Delta\varepsilon$ is the band overlap correction factor for the mixture. In most fire engineering applications, the pressure correction factor is taken as 1, and the band overlap correction is about half of the emissivity of CO_2. The total emissivity for a mixture of CO_2 and H_2O is:

$$\varepsilon_g = 0.5\varepsilon_{CO_2} + \varepsilon_w \tag{12}$$

Soot particles are produced from incomplete combustion. The soot particles inside the smoke and flame are at higher temperature, their radiation spectra are continuous, and depend on their temperature, size and shape. The emissivity equation for soot is similar to the absorption of monochromatic beam as follows:

$$\varepsilon_s = 1 - \exp(-K_s L) \tag{13}$$

Note that K_s is the mean absorption coefficient for soot, which is proportional to the temperature T and fraction f_v of soot in the smoke:

$$K_s = 3.72 \frac{C_0}{C_2} f_v T \tag{14}$$

C_0 is a constant lying between 2 to 6 and might depend on the soot refraction index [18]. C_2 is the Planck's second constant, taking a value of 1.44×10^{-2} mK.

The total emissivity of a gas-soot mixture can be approximated by using the empirical correlation:

$$\varepsilon = 1 - \exp(-K_s L) + \varepsilon_g \exp(-K_s L) \tag{15}$$

In calculating the total emissivity, the emissivities of CO_2 and H_2O are obtained through charts. This is not convenient and so for many engineering applications, simplified methods [19] are used.

$$\alpha = \alpha_g + \alpha_s \tag{16}$$

The absorption coefficients for gas phase α_g may be approximated using the following correlation [17,19]:

$$\alpha_g = 0.28 exp(-T / 1135) \tag{17}$$

The soot absorption and emission is proportional to the soot volume fraction, f_v. If the scattering of radiation by soot particles is negligible, the absorption coefficient for soot may be obtained from the Planck mean absorption coefficient data [1,19]:

$$\alpha_s = 1264 f_v T \tag{18}$$

Another expression for the absorption coefficient of soot produced by ethylene diffusion flame was proposed by Kent and Honnery [20] as follows:

$$\alpha_s = 1862 f_v T \tag{19}$$

Putting in the Smith's model [21], the overall absorption coefficient for the soot and gas mixture is:

$$\alpha = \alpha_g + \alpha_s - \alpha_s \alpha_g \tag{20}$$

4. HEAT FLUX FROM THE SMOKE LAYER

The smoke layer temperature might be heated up to 1000 K in a room fire. High heat flux will be radiated downward to act on the fire, walls, and other combustibles. Furniture and other items might be ignited to give flashover. Therefore, it is very important to calculate radiation from the smoke layer.

The surfaces of wall and smoke layer can be considered as diffuse gray surfaces. The lower face of the smoke layer is assumed to be an isothermal surface. Radiative energy exchange between the smoke layer and other surfaces in the enclosure can be calculated by the concept of radiosity and irradiation. The irradiation, G_i, being the radiative flux reaching the ith surface per unit time and per unit area [1] is:

$$G_i = \sum_j F_{i-j} J_j \qquad (21)$$

In the above equation, F_{i-j} is the view factor from surface i to surface j, J_j is the surface radiosity defined as the total radiative flux leaving the jth surface.

If radiation cannot transit through the surface transmitted, the radiosity is:

$$J_i = \varepsilon_i E_{bi} + (1-\varepsilon_i) G_i \qquad (22)$$

From equations (21) and (22), the radiative heat fluxes to and from each surface in the enclosure are obtained by solving the set of 2i simultaneous equations. The net loss of energy by radiation for surface i is given by:

$$Q_i = (J_i - G_i) A_i \qquad (23)$$

5. RADIATIVE HEAT TRANSFER MODEL

The equation of heat transfer describes the variation in intensity of a radiant beam $I_\lambda(s)$ at any position s along its path in a medium of spectral extinction coefficient k_λ including both absorption and scattering effects. The radiative transfer equation (RTE) is expressed as [1,18]:

$$\frac{dI_\lambda(s)}{ds} = k_\lambda I_{b\lambda} - k_\lambda I_\lambda(s) \qquad (24)$$

For a non-scattering gray medium, the RTE is revised as:

$$\frac{dI(s)}{ds} = \alpha I_b - \alpha I(s) \qquad (25)$$

Thermal radiation in a fire can be modeled with different levels of accuracy.

The simplest calculation is based on the observation that the flame radiates a roughly constant proportion of the total heat release rate. This simple but less accurate approach is widely used in studying jet and buoyant flames [e.g. 22,23].

A simple soot-band emission model was used by Tamanni [24] which assumed that the only radiation emission originated from a thin layer of soot located on the fuel size of the flame zone. This method is good only for small-scale jet flames, but not for large-scale pool fires in open air or enclosed space.

Traditional models widely used in simulating the radiative heat transfer of flames and fires can be divided into two kinds:

- directional equation methods including the discrete transfer method, the multi-flux method, the discrete ordinate method, and the weighted sum of gray gas method;
- the net energy balance methods including the Monte Carlo method (statistical method), and the finite-volume method.

The main disadvantage of the directional method is that the predicted results are sensitive to angular discretization [18]. Ignoring angular resolution will give inaccurate results if the radiative heat flux from a localized source to a remote surface must be included. The Monte Carlo method takes the advantages of being not affected by the media optical thickness and anisotropy. It is not sensitive to angular discretization. However, the method requires a longer computing time. Therefore, it is not widely used even in combustion modeling. This technique has just been used in modeling flashover [18] and fire zone models [25].

Three radiation models widely used in simulating radiation heat transfer will be reviewed in this paper. They are the discrete transfer method, the multi-flux method and the weighted sum of gray gas method.

6. DISCRETE TRANSFER METHOD (DTM)

In the DTM proposed by Lockwood and Shah [26], the medium and its boundary are subdivided into isothermal volumes and surface elements with constant material properties. The integrated directional equation is solved along the rays of radiation through a computational domain. The path along a ray is discretized using the sections formed from breaking the path at volume boundaries. Throughout each direction, the intersection of the ray and the boundary is used as the origin point. The total radiative flux is calculated by integrating the energy contribution along the rays emanating from the radiative source and pointing to any selected direction. The number and directions of rays from each point are chosen prior to providing a desired level of accuracy.

For the rays through the volume cell having uniform properties, such as temperature, absorption and scattering coefficients, the radiation equation can be integrated from a cell entry to cell exit to yield the relation [12,17]:

$$I_{n+1} = I_n \exp(-\alpha s) + \frac{\sigma T^4}{\pi}[1 - \exp(-\alpha s)] \qquad (26)$$

I_n and I_{n+1} are the intensities of the ray at the cell entry and cell exit respectively, and s is the length of the ray along the direction in the cell.

The net radiant energy in each volume cell is calculated based on the number of rays crossing the volume.

The DTM method is considered a more fundamental and accurate model by combining the features of the zone, Monte Carlo, and the flux models. The physics of the problem is retained with relatively simple mathematics. The desired accuracy can be achieved by increasing the number of rays and volume cells [12]. It can be easily extended to non-gray problems by dividing the spectrum into bands, applying the relations of the type in equation (26) for each band and then summing them up [17]. However, this model requires a surface model to describe the geometry; carefully shaped control volumes; and positioning of the rays to yield accurate predictions [12]. It is sensitive to the soot volume fraction and so might give problems on accurate calculations of radiation properties of the medium [17].

7. FLUX MODEL

The flux methods are based on the discrete representation of the directional variation of radiative intensity. Numerical solution of the radiation problem is obtained by solving the integrated directional equation of radiative transfer for a set of discrete directions spanning over the total solid angle range 4π. The method was developed originally as a two-flux model [16]. The solid angle subtended at a given location is divided into two directions within which the directional dependence of the intensity is assumed. As the solid angles are divided into more than two directions within which the directional dependence of the intensity is assumed, the method is known as the multi-flux method. The six-flux method extended by Patankar and Spalding [27] to six fluxes in three-dimensional Cartesian coordinates is employed extensively.

In the six-flux method, the radiative flux comes from only six directions, parallel and antiparallel to the three coordinate directions. Second-order differential equations are derived by addition and subtraction of the first-order terms describing the variation of the individual fluxes with distance. For example, the equation in the x-direction is [12,17]:

$$\frac{d}{dx}\left(\frac{1}{\alpha + \sigma^s}\frac{dR_x}{dx}\right) = (\alpha + \sigma^s)R_x - 2\alpha\sigma T^4 - \frac{\sigma^s}{3}(R_x + R_y + R_z) \qquad (27)$$

R_x, R_y, R_z are the composite radiative fluxes in the x-, y-, and z-directions respectively. σ^s is the scattering coefficients for a gray medium. Each of the differential flux equations expresses the attenuation of a flux with distance as a result of absorption and scattering and its augmentation by emission and scattering from other directions.

In this method, simple assumptions for the angular variation of radiant intensity allow the exact integro-differential radiation transfer equation to be reduced to a system of approximate equations. It is easy to understand, readily applicable and fast, but has limited accuracy. This model retains the important effects relevant to the fire scenarios, although radiation is assumed to be transmitted along the coordinate directions only. It has been applied successfully in simulating many fire scenarios. It solves directly on the flow spatial grid, and needs no special description of the geometry. It is quite accurate for optically thick media, but might yield inaccurate results for thinner media, especially near boundaries for anisotropic radiation field [12]. This method cannot be applied to complex geometries such as those with large openings.

8. WEIGHTED SUM OF GRAY GASES MODEL (WSGGM)

The concept of the WSGGM was first presented by Hottel and Sarofim [13] within the framework of the zonal method. This model may be applicable to arbitrary geometries with varying absorption coefficients, but is limited to non-scattering media confined within a black-walled enclosure.

In this model, the absorption of non-gray gases is approximated by the sum of component gray gas absorptions weighted with a temperature dependent factor. The WSGGM was further developed by Modest [15] to give a more elaborated technique with spectral properties of thermal radiation. The non-gray gas is replaced by a number of gray gases, for which the heat transfer rates are calculated independently [18,28].

$$\frac{dI_i}{ds} = \alpha_i (k_i I_b - I_i) \qquad (28)$$

The subscript i denotes the gases, and k_i means the temperature-dependant weighting factors, the sum of them is unity. The total flux is then found by adding the fluxes of the gray gases after multiplication with certain weight factors.

$$I = \sum_i I_i \qquad (29)$$

This model may be used in conjunction with any spectral model up to any desired accuracy. As the spectral flux is not evaluated, the computing time is reduced significantly up to three orders of magnitude.

9. CONCLUSIONS

Thermal radiation is the key mode of heat transfer in room fires at higher temperature. It plays a very important role in real room fires by contributing significantly to ignition, flame spread and flashover. Thermal radiative heat flux is hazardous to humans. Therefore, good modeling of thermal radiation in simulating room fires would give more accurate results in providing safety.

In order to have a good understanding of radiation heat transfer, the basic concepts of radiation are reviewed in this paper. The thermal radiation properties of smoke are then introduced. Three radiation models, DTM, FM and WSGGM widely used in fire simulations are described. All the above illustrated that further in-depth studies on thermal radiation should be carried out.

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