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# Assessment of Radiation Solvers for Fire Simulation Models Using RADNNET-ZM

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## Abstract

The paper presents a neural-network based zonal method (RADNNET-ZM) for the analysis of radiative heat transfer in an arbitrary Cartesian enclosure with an isothermal, inhomogeneous, non-gray medium. The model accounts for the non-gray effect of absorbing species in a combustion environment and the geometric effect of any three-dimensional enclosures. The model is verified against benchmark solutions. Maximum local error is observed to be less than 4 %. Prediction accuracy of an existing zonal radiation solver is assessed. Results demonstrate that RADNNET-ZM can provide substantial improvement to zone fire simulation models for the prediction of radiative heat transfer without a significant increase in computation cost.

*Keywords:* Neural network, zonal method, non-gray, multi-dimensional, fire simulation model

## Nomenclature

$a_\lambda$	local absorption coefficient
$A_i$	elemental area $i$
$D$	grid size of discretization
$e_{\lambda b}$	Planck function
$f_v$	soot volume fraction
$F_{ij}$	view factor between $A_i$ and $A_j$
$F_{ss,xx}$	generic exchange factor ( $xx = pd, pp$ )
$L_{ij,xx}$	center-to-center distance between $A_i$ and $A_j$ ( $xx = pd, pp$ )
$L_{pd,x}$	mean beam length between two perpendicular elemental areas ( $x = soot, gas$ )
$L_{pp}$	mean beam length between two parallel elemental areas
$n_x, n_y, n_z$	dimensionless distances for $A_j$ relative to $A_i$
$P_{CO_2}$	partial pressure of $CO_2$
$P_{H_2O}$	partial pressure of $H_2O$
$P_g$	total pressure of an $N_2/H_2O/CO_2$ mixture
$\dot{q}''_g$	incident heat flux due to emission of mixture medium
$\dot{q}''_w$	incident heat flux due to emission of wall
$ss$	surface-surface exchange factor
$SS$	total surface-surface exchange factor
$T_g$	gas temperature
$T_w$	wall temperature
$X_{CO_2}$	mole fraction of $CO_2$
$X, Y, Z$	dimensions of an enclosure
<i>Greek symbols</i>	
$\alpha$	total absorptivity (sum of soot and gas absorptivity)
$\alpha_s$	soot absorptivity
$\Delta\alpha$	gas absorptivity
$\beta_{xx}$	normalized mean beam length ( $xx = pd, pp$ )
$\lambda$	wavelength
$\varepsilon$	emissivity of gas mixture
$\sigma$	Stefan-Boltzmann constant
<i>Subscripts</i>	
$pd$	perpendicular
$pp$	parallel

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## 1. Introduction

A significant amount of research has been conducted in both computational techniques for multi-dimensional radiation heat transfer and the understanding of spectroscopic absorption properties of different combustion gases over the past 30 years. To account for the geometric effect, there are zonal methods [1], discrete ordinate methods [2], discrete transfer methods [3], and many others [4]. To simulate the spectral effect, there are narrow band models [5], k-distribution models [6], and weighted sum of gray gas models [7]. In recent years, simulation methods to simultaneously account for both the spectral and geometric effect have also been developed [8]. Despite these efforts to deal with the non-gray multi-dimensional aspects of radiative heat transfer, few have been utilized in any significant degree by the engineering design and fire safety community in the areas of combustion and fire, where in many cases the effect of radiation is known to be not only important, but dominant. The primary difficulty is the mathematical complexity.

The evaluation of radiative heat transfer with the presence of a participating medium consisting of typical combustion products ( $H_2O$ ,  $CO_2$ , and soot particulate) at low pressure (i.e., one atmosphere) in a three-dimensional enclosure is numerically complex. For a one-dimensional isothermal homogeneous medium, the absorptivity is a complicated function of six independent variables (optical thickness of  $H_2O$ ,  $CO_2$ , and  $CO$ , source temperature, mixture temperature, and soot volume fraction) [9]. To obtain an accurate evaluation of the spectral behavior of the gas mixture, a direct numerical integration using realistic spectral data (i.e., the narrow band model) is required to be carried out. For the evaluation of radiative heat transfer between surfaces and the gaseous medium, the geometric effect is significant and another direct numerical integration is required. In a typical calculation, such as to simulate the transient thermal environment within a fire resistance furnace, previous work [10] indicates that more than 60 million numerical evaluations are needed to determine the exchange factors. Since the condition within the furnace is continuously changing, the exchange factors are required to be re-evaluated for every time step in a simulation. This level of computational effort is clearly not feasible for practical engineering applications. For this reason, many existing zone fire models, such as CFAST (Consolidated Fire And Smoke Transport [11]), and CFD codes, including FDS (Fire Dynamics Simulator [12]) and FLUENT [13], implement approximate radiation solvers which rely on empirical charts/correlations to enhance computational efficiency.

The objective of this paper is to present a generalized radiation solver that has the capabilities to simulate accurately the realistic effect of radiation heat transfer in any arbitrary three-dimensional fire/combustion environment efficiently. The radiation solver, RADNNET-ZM (RADiation Neural NETWORK-Zonal Method), is a generalization of the zonal method using the concept of the generic exchange factor (GEF) [14]. The GEFs have been demonstrated to be an efficient approach for the evaluation of radiative heat transfer in a multi-dimensional gray medium. In a recent work [15], the GEFs are expanded to account for the non-gray effect of a  $H_2O/CO_2$ /soot mixture medium by using a neural network correlation, RADNNET [9]. To improve the computational efficiency in the evaluation of the GEFs, the concept of mean beam length (MBL) is utilized. Additional neural networks are generated for the MBLs to characterize the non-gray absorptivity and emissivity of the medium bounded by the elemental surfaces. Using superposition, total exchange factors between arbitrary surfaces can be determined for the evaluation of radiative heat transfer within an enclosure accurately and efficiently.

In the following sections, the mathematical formulation of RADNNET-ZM is presented. Model verification for RADNNET-ZM is provided. Comparison with results generated from the radiation solver used in CFAST [11] is made. Note that the development of the GEFs is described with details in [14, 15]. Therefore, only the features related to the incorporation of the GEFs in the solution algorithms are addressed below.

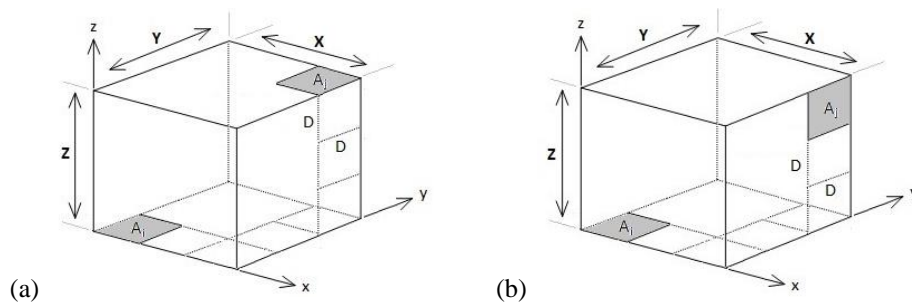


Fig 1. Geometry for (a) parallel surface-surface GEF,  $F_{ss,pp}$  and (b) perpendicular surface-surface GEF,  $F_{ss,pd}$ .

## 2. Mathematical formulation

Consider a one-zone enclosure filled with a mixture of water vapor, carbon dioxide, and soot particulate with arbitrary dimensions of  $X$ ,  $Y$ , and  $Z$  as shown in Fig. 1, the analysis of radiative heat transfer to the bounding surfaces requires the evaluation of surface-surface exchange factors. Mathematically, the surface-surface exchange factors between two surfaces,  $s_i s_j$ , can be evaluated from the following integration [8]

$$s_i s_j = \frac{1}{\sigma T_w^4} \int_{A_i} \int_{A_j} \int_0^\infty \frac{e_{\lambda b}(T_w) e^{-a_\lambda(T_g)S} \cos \theta_i \cos \theta_j}{\pi S^2} d\lambda dA_j dA_i \quad (1)$$

where  $T_w$  is the surface temperature of the source area  $A_i$ ,  $T_g$  is the gas temperature,  $S$  is the line-of-sight distance between the two integration area elements,  $dA_i$  and  $dA_j$ ,  $\theta_i$  and  $\theta_j$  are the angles between the line-of-sight and the unit normal vector of the two differential area elements,  $\sigma$  is the Stefan-Boltzmann constant,  $e_{\lambda b}$  is the blackbody emissive power, and  $a_\lambda$  is the local absorption coefficient. To achieve good accuracy, approximately 60 million numerical evaluations of Eq. (1) are required for one time-step in a typical fire simulation.

Using the concept of GEF, the expression for the evaluation of the surface–surface exchange factors is reduced into a simple form and the exchange factors can be determined from existing neural network correlations such that the numerical evaluations of Eq. (1) will no longer have to be performed during the actual calculation. Specifically, the surface-surface exchange factor for two parallel elemental areas,  $s_i s_{j,pp}$ , as shown in Fig. 1a is

$$s_i s_{j,pp} = D^2 F_{ss,pp} (T_w, T_g, P_g D, X_{\text{CO}_2}, f_v D, n_x, n_y, n_z) \quad (2)$$

where  $D$  is the grid size for the discretization and  $F_{ss,pp}$  is the GEF. For simplicity, the mathematical formulation is described under the assumption that the boundary of the enclosure can be subdivided into square elements. Additional treatment is required to handle conditions with imperfect discretization and they will be presented in future publications. ( $n_x = S_x/D$ ,  $n_y = S_y/D$ ,  $n_z = S_z/D$ ) are the non-dimensionalized locations of the receiving area  $A_j$  relative to the source area  $A_i$ .  $S_x$ ,  $S_y$ , and  $S_z$  are the scalar components of the vector connecting the center points of the area elements. As an example,  $(n_x, n_y, n_z)$  is  $(3, 3, 3)$  for the two parallel elemental areas being shown in Fig. 1a. Based on Eq. (2),  $F_{ss,pp}$  is a function of geometry and five combustion parameters: surface temperature ( $T_w$ ), gas temperature ( $T_g$ ), optical thickness ( $P_g D$ ), mole fraction of  $\text{CO}_2$  ( $X_{\text{CO}_2}$ ), and soot volume fraction ( $f_v$ ). The total pressure of the gas mixture is given as

$$P_g = P_{\text{H}_2\text{O}} + P_{\text{CO}_2} \quad (3)$$

and the mole fraction of  $\text{CO}_2$  is

$$X_{\text{CO}_2} = \frac{P_{\text{CO}_2}}{P_{\text{H}_2\text{O}} + P_{\text{CO}_2}} \quad (4)$$

Using the concept of mean beam length (MBL), the GEF can be written in a one-dimensional form

$$F_{ss,pp} = F_{ij} (n_x, n_y, n_z) \left[ 1 - \alpha (T_w, T_g, P_g L_{pp}, X_{\text{CO}_2}, f_v L_{pp}) \right] \quad (5)$$

where  $F_{ij}$  is the view factor between the two elemental areas,  $\alpha$  is the total absorptivity of the sooty gas mixture, and  $L_{pp}$  is the MBL accounting for mixture absorption. The numerical evaluation for the view factor is costly when the two areas are close to each other (i.e.  $n_x \leq 5$ ,  $n_y \leq 5$ ,  $n_z \leq 5$ ). For numerical efficiency, view factors are tabulated for  $(n_x \leq 5, n_y \leq 5, n_z \leq 5)$  and the tabulated view factors are used to obtain the generic exchange factor. When  $n_x$ ,  $n_y$ , or  $n_z$  is larger than 5, the center-to-center distance between the two elemental areas is used as the MBL for the evaluation of the view factors analytically and numerical experiments show that the error associated to the approximate view factor (using the center-to-center distance) is less than 1%.  $\alpha$  is obtained from RAD-NNET, a neural network correlation that predicts the one-dimensional total absorptivity for a  $\text{N}_2/\text{H}_2\text{O}/\text{CO}_2/\text{soot}$  mixture [9]. Given a combustion environment which can be described by the five combustion parameters, the neural network correlation provides the corresponding total absorptivity through “look-up tables”. The absorptivity data are generated using RADCAL [4] for 550 discrete values of  $P_g D$ , 11 discrete values of  $X_{\text{CO}_2}$ , 10 discrete value of  $f_v D$ , and 18 discrete values of  $T_w$  and  $T_g$ , respectively, corresponding to a set of over 19 million data points. The ranges of input variables are

$$\begin{aligned} 0 &\leq P_g D \leq 1000 \text{ kPa}\cdot\text{m} \\ 0 &\leq X_{\text{CO}_2} \leq 1 \\ 0 &\leq f_v D \leq 10^{-6} \text{ m} \\ 300 &\leq T_w, T_g \leq 2000 \text{ K} \end{aligned} \quad (6)$$

As shown in [9], the relative error associated with RAD-NNET is less than 5% for absorptivity or emissivity values larger

than 0.01. Thus, RAD-NNET is expected to have the same order of accuracy as compared to RADCAL. It should be noted that the RAD-NNET prediction capability for the total absorptivity can continuously be improved with the inclusion of more numerical data. For the determination of the MBLs, Yuen et al. [15] demonstrate that the effect of combustion parameters is minor. For  $(n_x = 1, n_y = 1, n_z = 1)$  where the effect of combustion parameters to the MBL is observed to be the largest, the absolute values of the MBL vary about 9 % as a function of the combustion parameters as shown in Eq. (6). An average MBL is shown to be sufficient to yield an accurate value for the GEF in a specific dimensionless distance. For that,  $L_{pp}$  is given as

$$L_{pp} = L_{ij,pp} \beta_{pp} \quad (7)$$

where  $\beta_{pp}$  is the average normalized MBL for  $(n_x, n_y, n_z)$  and  $L_{ij,pp}$  is the center-to-center distance between the two parallel elemental areas. As an example,  $\beta_{pp}$  for two parallel areas  $D^2$  separated by a distance  $D$ , which is being denoted as  $(n_x = 1, n_y = 1, n_z = 1)$ , is determined to be 1.10.

The surface-surface exchange factor for two perpendicular elemental areas,  $s_i s_{j,pd}$ , as shown in Fig. 1b can be expressed in a similar form of Eq. (1)

$$s_i s_{j,pd} = D^2 F_{ss,pd} (T_w, T_g, P_g D, X_{CO_2}, f_v D, n_x, n_y, n_z) \quad (8)$$

with

$$F_{ss,pd} = F_{12} (n_x, n_y, n_z) \left[ 1 - \alpha_s (T_w, f_v L_{pd,s}) - \Delta\alpha (T_w, T_g, P_g L_{pd,g}, X_{CO_2}, f_v L_{pd,g}) \right] \quad (9)$$

where  $F_{ss,pd}$  is the GEF for two perpendicular elemental areas and the total absorptivity,  $\alpha$ , is separated into a soot component,  $\alpha_s$ , and a gas component,  $\Delta\alpha$ . It is observed from numerical experiments conducted in [15] that the mathematical behavior of the MBL for perpendicular areas,  $L_{pd}$ , is more complex and  $L_{pd}$  varies strongly with the combustion parameters. For  $(n_x = 1, n_y = 1, n_z = 1)$ , the MBL varies more than 65 % over the entire range of combustion parameters. For that, two MBLs, a soot MBL ( $L_{pd,s}$ ) and a gas MBL ( $L_{pd,g}$ ), are needed to account for the corresponding absorption characteristics accurately.  $L_{pd,s}$  is tabulated for  $(n_x \leq 4, n_y \leq 4, n_z \leq 4)$  as a function of the product of surface temperature and soot concentration. If  $n_x, n_y,$  or  $n_z$  is out of range, the center-to-center distance between the two perpendicular elemental areas can be used. For  $L_{pd,g}$ , a neural network, MBLG-NNET (Mean Beam Length Gas – Neural Network), is generated for the ranges of the five combustion parameters. Geometrically, both MBLs are proportional to the center-to-center distance between the two areas and they are given by

$$L_{pd} = L_{ij,pd} \beta_{pd} \quad (10)$$

where  $\beta_{pd}$  is the corresponding normalized MBL for soot/gas mixture and  $L_{ij,pd}$  is the center-to-center distance between the two perpendicular elemental areas.

In summary, with the use of the neural network correlations (RAD-NNET and MBLG-NNET), the numerical evaluations for solving Eq. (1) are not needed. Furthermore, it can be demonstrated that the exchange factors for any parallel/perpendicular elemental areas can be efficiently determined for any finite surfaces at any arbitrary locations in an enclosure with an isothermal, inhomogeneous, non-gray medium.

Utilizing the method of superposition, the total exchange factors between finite surfaces can be determined by summing over the generic exchange factors for all elemental areas. For any finite surface  $A_i$  in an enclosure, the incident radiative heat flux consisting of emission from the surrounding walls,  $\dot{q}''_{w,i}$ , and emission from the sooty gas mixture,  $\dot{q}''_{g,i}$ , are given by

$$\dot{q}''_{w,i} = \sigma T_{w,j}^4 \left( 1 - \sum_{j=1}^N F_{ji} \alpha_{ij} (T_{w,j}, T_g, P_g R_x, X_{CO_2}, f_v R_x) \right) \quad (11)$$

$$\dot{q}''_{g,i} = \sigma T_g^4 \sum_{j=1}^N F_{ji} \alpha_{ij} (T_g, T_g, P_g R_x, X_{CO_2}, f_v R_x) \quad (12)$$

where  $N$  is the total number of bounding surfaces and  $R_x$  is the corresponding MBL for the different surfaces. Note that the details of the summation procedure and indexing associated with the superposition to the generic exchange factors in obtaining the total exchange factors in between two surfaces at arbitrary locations within an enclosure are demonstrated in [15]. For that, the details will not be provided in this paper. Readers can refer to the literature for detailed descriptions.

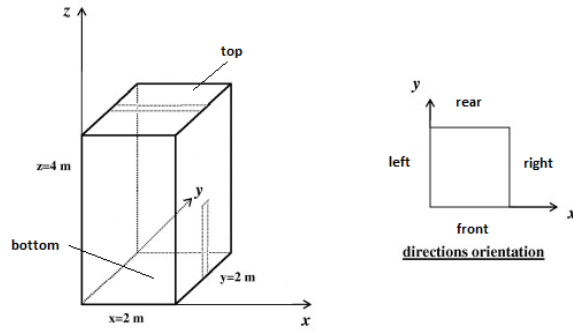


Fig. 2. Schematic of the considered geometry.

### 3. Results and discussion

#### 3.1. Verification case: comparison between RADNNET-ZM and benchmark results

The predictive accuracy of the model described above is investigated. RADNNET-ZM is applied to a radiative heat transfer problem in a three-dimensional enclosure containing non-gray gases. Solutions for this problem were generated by Liu [16] using a statistical narrow band model (SNB) for the determination of the gas radiative properties and a ray tracing method [2] to solve for the radiative transfer equation (RTE). This benchmark problem has been used to verify newly developed/modified spectral models and/or solution methods [17]. Due to its reliable accuracy, the benchmark results will be used as the exact solutions for the verification process.

Fig. 2 shows the geometry being considered in this verification study. It is a three-dimensional rectangular enclosure with the dimensions of 2 m by 2 m by 4 m. The surrounding walls are assumed to be black. Surface temperature for all walls is maintained at 300 K. The total pressure of the gas mixture is kept at 1 atm. The temperature for the gas mixture is assumed to be isothermal and is maintained at 1000 K. The composition of the gas mixture is assumed to be homogeneous and contains pure water vapor. The verification conditions are summarized in Table 1.

The verification case is calculated using uniform grids of 11 by 11 by 11 and 16 by 16 by 16. Numerical results from RADNNET-ZM are generated. The predicted incident heat flux to various locations in the x-direction at the center of the y-direction on the top surface, denoted as  $(x, 1 \text{ m}, 4 \text{ m})$ , and the predicted incident heat flux at different locations in the z-direction at the center of the y-direction on the right surface, denoted as  $(2 \text{ m}, 1 \text{ m}, z)$ , are obtained. Comparing the benchmark results generated by Liu, relative errors associated with RADNNET-ZM are determined. Due to symmetry condition of this problem, only half of the incident heat flux to the right surface will be presented. As shown in Fig. 3, it can be observed that the predicted results are in very good agreement with the benchmark results. The maximum local error is approximately 4 % and the large errors appeared at two ends (i.e.  $x = 0 \text{ m}$  and  $x = 2 \text{ m}$  as shown in Fig. 3a) are probably due to the angular discretization being used in Liu's study. For that, RADNNET-ZM solutions are possibly more accurate near the end of the wall. Overall, the results demonstrate that the RADNNET-ZM is capable to simulate both the spectral and geometric effect accurately.

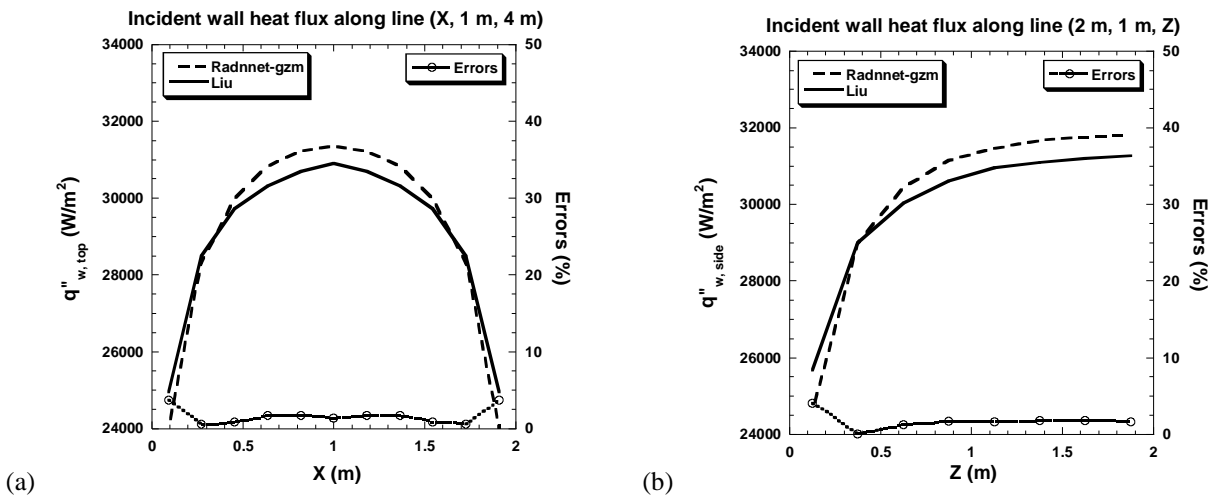


Fig. 3. Incident wall heat flux along lines (a)  $[x, 1 \text{ m}, 4 \text{ m}]$  and (b)  $[2 \text{ m}, 1 \text{ m}, z]$  obtained from RADNNET-ZM and Liu [13] together with the error associated with RADNNET-ZM.

### 3.2. Assessment of CFAST radiation solver using RADNNET-ZM

CFAST [14] is a fire simulation model that divides compartments into two zones. Each zone includes a gas mixture/soot medium bounded by a ceiling or a floor, and four surfaces. Thermal conditions of each zone are assumed to be uniform. When there is a fire, a hot layer will form and the medium can be divided into an upper layer and a lower layer. If the fire persists, the upper layer, consisting of combustion by-products such as H<sub>2</sub>O, CO<sub>2</sub>, and soot particulate, increases in depth and the upper layer temperature increases. At high temperature, thermal radiation becomes the dominant mode of heat transfer between surfaces and the medium. For that, accurate evaluation of the radiative heat transfer for a participating medium in a three-dimensional enclosure becomes crucial. However, since the absorption behavior of real gases, such as H<sub>2</sub>O and CO<sub>2</sub>, is a strong function of wavelength, temperature, and species concentrations, brute force numerical evaluation to account for the effect of absorption and geometry is required as discussed in Ref. [10]. Yet, this approach is not feasible for practical engineering calculations. For this reason, in many zone fire models, including CFAST, simplifications are made to their radiation solvers for the evaluation of radiative heat transfer. To account for the non-gray spectral effect of real gases, a 1-D empirical correlation known as the Hottel's emissivity chart [1] is typically used. To account for the geometric effect, a constant MBL, based on some ad-hoc length scales without mathematical validation, is used. The application of these simplifications for the evaluation of radiative heat transfer in multi-dimensional non-gray media has not been validated. Therefore, the prediction accuracy associated with these radiation solvers is uncertain.

In the following section, the prediction accuracy of the radiation solver from CFAST is assessed. In the discussion given below, the CFAST radiation solver will be denoted as the "approximate approach". It should be noted that with the implementation of the generic exchange factor, bounding surfaces can be subdivided even in a one-zone calculation. It can also be demonstrated that RADNNET-ZM is able to capture local radiative heat transfer effect in a 3-D enclosure with an isothermal, inhomogeneous, non-gray medium accurately.

#### 3.2.1. Test case 1: localized incident heat flux to surfaces (RADNNET-ZM vs. radiation solver using a constant MBL)

This case, identical to the verification case as shown in section 3.1, is simulated using the approximate approach. Target devices are specified on the top surface along (x, 1 m, 4 m) and the surface on the right along (2 m, 1 m, z) such that the corresponding incident heat flux can be obtained. Prediction generated from the approximate approach is compared to that obtained from RADNNET-ZM. Comparing RADNNET-ZM, relative errors associated with the approximate approach are also determined. As shown in Fig. 4, the approximate approach over-predicts the incident heat flux to the surface by as much as 28 %. This error is caused by the simplification used in the determination of mean beam length.

#### 3.2.2. Test case 2: radiative properties of gas mixture (RADNNET-ZM vs. radiation solver using 1-D emissivity expression)

For black surfaces, the emissivity of the gas mixture, radiating to surface  $A_i$ , can be obtained from the solution to the analysis of an emitting medium and non-emitting wall [10] as

$$\varepsilon_g(T_g, T_g) = \frac{Q_i}{A_i \sigma T_g^4} ; \quad Q_i = \left[ A_i - \sum_{j \neq i} S_i S_j (T_g, T_g) \right] \sigma T_g^4 \quad (13)$$

where  $Q_i$  is the radiative heat flux to surface  $A_i$  due to emission from the hot medium.  $S_i S_j$  is the total exchange factor and it can be determined by summing over the generic exchange factors for all elemental areas. With identical wall temperature for all surfaces, the mixture absorptivity due to wall emission is given to be

$$\alpha_g(T_w, T_g) = \frac{1}{A_i} \sum_{j \neq i} \left[ A_j F_{ij} - S_i S_j (T_w, T_g) \right] \quad (14)$$

A series of numerical experiments is conducted to investigate the effect of wall temperature ( $T_w$ ) to the radiative properties of the gas mixture. The wall temperature varies from 300 K to 1500 K. The gas temperature is maintained at 500 K and the remaining test conditions are identical to that used from the previous test case as shown in Section 3.2.2. A summary of test case 2 is provided in Table 1.

Fig. 5 shows the emissivity (a) and the absorptivity (b) of the gas mixture along the line (x, 1 m, 4 m) on the top surface for different wall temperatures (300, 500, 1000, or 1500 K) with the gas temperature maintained at 500 K. For gas emission, the approximate approach over-predicts the emissivity by approximately 8 % to 37 %. For mixture absorptivity, the results show that absorptivity can vary significantly depending on the wall temperature. In Fig. 5b, it can be seen that the mixture absorptivity is decreasing with increasing wall temperature. When the wall temperature is identical to the gas temperature, the emissivity equals the absorptivity. This observation agrees well with the findings in [8, 10]. However, since the approximate approach does not account for the wall temperature in the determination of the radiative properties, the

absorptivity is identical to the emissivity. As shown in Fig. 5b, the maximum discrepancy associated with the absorptivity predicted by the approximate approach can be different from that predicted by RADNNET-ZM by more than 100 %.

Test cases	Wall conditions		Gas medium conditions		
	Temperature	Emissivity	Temperature	Composition	Pressure
Case 1	300 K	1	1000 K	Water vapor	1 atm
Case 2	300/500/1000/1500 K	1	500 K	Water vapor	1 atm

Table 1. Test conditions for different test cases.

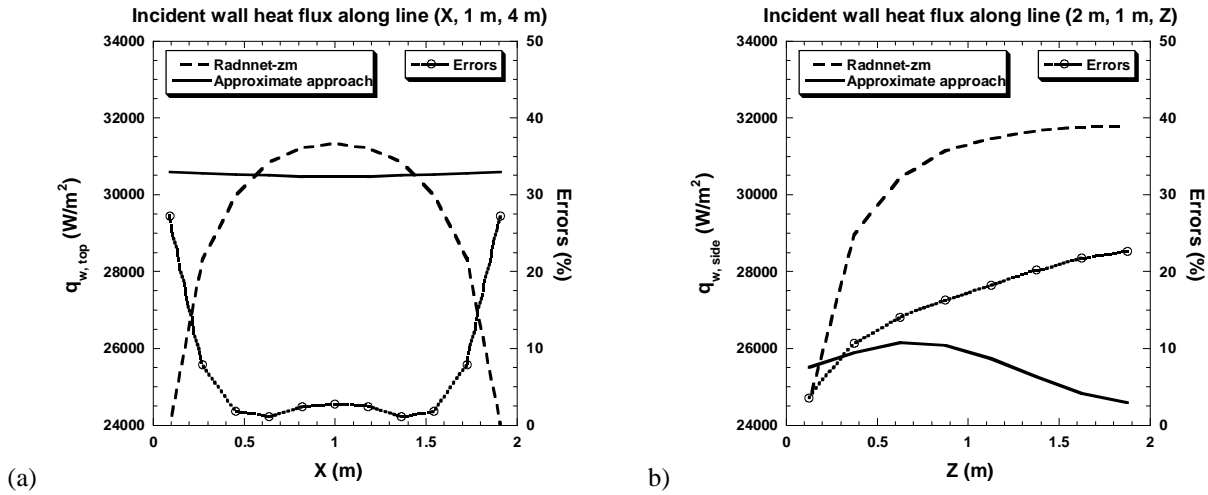


Fig. 4. Incident wall heat flux along lines (a) [x, 1 m, 4 m] and (b) [2 m, 1 m, z] obtained from RADNNET-ZM and the approximate approach together with the error associated with the approximate approach.

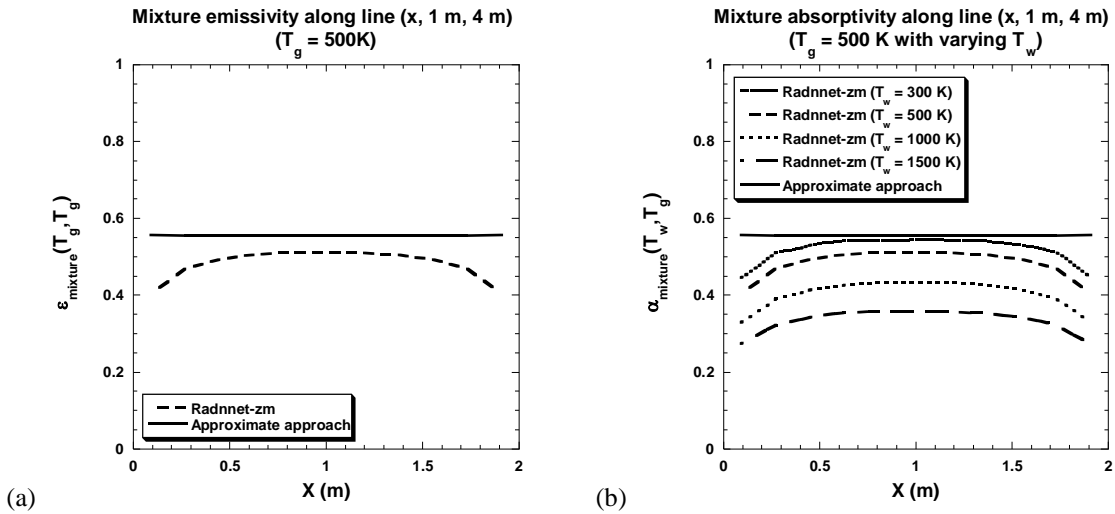


Fig. 5. (a) Mixture emissivity [ $T_w = T_g$ ] and (b) mixture absorptivity [ $T_w \neq T_g$ ] obtained from RADNNET-ZM and the approximate approach.

#### 4. Conclusions

The mathematical formulation of the neural network based generalized zonal method (RADNNET-ZM) is presented. Using the concept of generic exchange factor and the method of superposition, the radiative heat transfer to bounding surfaces in an arbitrary Cartesian enclosure with an isothermal, inhomogeneous, non-gray medium can be evaluated.

For an isothermal medium with pure water vapor emitting at 1000 K, errors associated with RADNNET-ZM predictions are within 4 %. For the approximate approach that is used in CFAST, the errors associated with the predictions are within 28 %.

The effect of wall temperature on the evaluation of the radiative properties has been investigated. Mixture emissivity is generally not equal to mixture absorptivity. Given a fixed gaseous concentration, it can be shown while emissivity is a strong function of the gas temperature, absorptivity varies significantly for both wall and gas (absorbing) temperature.



Results show that the use of the Hottel's emissivity chart is ineffective and highly inaccurate for the determination of the radiative properties in an enclosure with non-gray gases. Comparing the results generated by RADNNET-ZM, the approximate approach over-predicts the emissivity by approximately 8 % to 37 %. For absorptivity, the discrepancy between two radiation solvers can be more than 100 %.

Even though the current work focuses on isothermal homogenous media, RADNNET-ZM can be readily used to accurately simulate the radiative absorption effect for different mixtures involving species (i.e., H<sub>2</sub>O, CO<sub>2</sub>, and soot particulate). Solutions generated by RADNNET-ZM can be used as benchmark results to verify other radiation solvers from other commercial/CFD codes, such as FDS. For non-isothermal conditions, the concept of mean temperatures as referenced in [18] can be implemented to expand RADNNET-ZM to account for the radiative heat transfer effect in an enclosure with non-isothermal, inhomogeneous, non-gray media. This work is currently underway and results will be presented in future publications.

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## References

- [1] Hottel, H. C., & Sarofim, A. F., 1967. Radiative transfer. McGraw-Hill.
- [2] Fiveland, W. A., 1987. "Discrete ordinate methods for radiative heat transfer in isotropically and anisotropically scattering media." *Journal of Heat Transfer* 109, no. 3, pp. 809-812.
- [3] Carvalho, M., Farias, T. and Fontes, P., 1991. "Predicting radiative heat transfer in absorbing, emitting, and scattering media using the discrete transfer method." *Fundamentals of radiation heat transfer* 160, no. 1, pp. 17-26.
- [4] Grosshandler, W. L. RADCAL: A narrow-band model for radiation calculations in a combustion environment. Gaithersburg, MD: National Institute of Standards and Technology, 1993.
- [5] Mazumder, S., & Modest, M. F., 2002. "Application of the full spectrum correlated-k distribution approach to modeling non-gray radiation in combustion gases." *Combustion and Flame*, 129(4), pp. 416-438.
- [6] Cumber, P. S., Fairweather, M., & Ledin, H. S., 1998. "Application of wide band radiation models to non-homogeneous combustion systems." *International Journal of Heat and Mass Transfer*, 41(11), pp. 1573-1584.
- [7] Choi, C. E., & Baek, S. W., 1996. "Numerical analysis of a spray combustion with nongray radiation using weighted sum of gray gases model." *Combustion science and technology*, 115(4-6), pp. 297-315.
- [8] Yuen, W. W., Tam, W. C., & Chow, W. K., 2014. "Assessment of radiative heat transfer characteristics of a combustion mixture in a three-dimensional enclosure using RAD-NETT (with application to a fire resistance test furnace)." *International Journal of Heat and Mass Transfer*, 68, pp. 383-390.
- [9] Yuen, W. W., 2009. "RAD-NNET, a neural network based correlation developed for a realistic simulation of the non-gray radiative heat transfer effect in three-dimensional gas-particle mixtures." *International Journal of Heat and Mass Transfer* 52, no. 13, pp. 3159-3168.
- [10] Tam, W. C. Analysis of heat transfer in a building structure accounting for the realistic effect of thermal radiation heat transfer. Ph.D. Thesis, the Hong Kong Polytechnic University, Hong Kong, China, 2013.
- [11] Peacock, R. D., McGrattan, K. B., Forney, G. P., & Reneke, P. A. CFAST—Consolidated Fire And Smoke Transport (Version 7) Volume 1: Technical Reference Guide. Technical Note, NIST, Gaithersburg, Maryland, 1, 69-71, 2015.
- [12] McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., & Overholt, K. Fire dynamics simulator technical reference guide volume 1: mathematical model. NIST special publication, 1018(1), 175, 2013.
- [13] Fluent, A. N. S. Y. S. Ansys fluent theory guide. ANSYS Inc., USA, 15317, 724-746, 2011.
- [14] Yuen, W. W., and Takara, Ezra E., 1997. "The zonal method: A practical solution method for radiative transfer in nonisothermal inhomogeneous media." *Annual review of heat transfer* 8, no. 8.
- [15] Yuen, W. W. & Tam, W. C. "RADNNET-ZM – The generalized zonal method for radiative transfer in multi-dimensional non-gray media." In preparation.
- [16] Liu, Fengshan, 1999. "Numerical solutions of three-dimensional non-gray gas radiative transfer using the statistical narrow-band model." *Journal of heat transfer* 121, no. 1, pp. 200-203.
- [17] Coelho, P. J., 2002. "Numerical simulation of radiative heat transfer from non-gray gases in three-dimensional enclosures." *Journal of Quantitative Spectroscopy and Radiative Transfer* 74, no. 3, pp. 307-328.
- [18] Yuen, W.W., 2014. "Development of the concept of mean temperatures in the analysis of radiative heat transfer in an inhomogeneous non-isothermal non-gray medium." *International Journal of Heat and Mass Transfer*, 68, pp.259-268.