



NUMERICAL SIMULATIONS OF THE EFFECT OF TURBULENCE IN THE THERMAL-RADIATION FLOW FIELD

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ABSTRACT

This paper investigates possible inherent modifications of the radiative heat source term due to the influence of turbulence in the thermal radiation field of a gas turbine combustor flame. Adapting a flame temperature of 2000[K], COMSOL Multiphysics software was utilized to numerically simulate the process, assuming a gray gas participating medium with absorption coefficient of 0.03[m⁻¹]. The analysis of the results for five (5) different radial cut sections of the simulated combustor chamber shows that turbulence-radiation interactions cause radiative heat losses from the flame, with the divergence of the radiative heat flux having a deviation factor of 3.48, and a 1.43% reduction in the local flame temperature, as observed at a critical radial section of the combustor chamber.

Keywords: Radiative heat source term, gas turbine combustor, flame temperature, turbulence-radiation interactions

1. INTRODUCTION

Radiation has a fourth-power dependence on temperature, making it a dominant source of heat transfer for very high temperature processes. Of enormous engineering and scientific importance are its numerous applications in almost all fields associated with high temperature, energy conversion processes, and particularly in the design of various thermal devices; the combustion process in gas turbine combustors is a common application. Most practical combustion devices, however, operate in turbulent flow conditions. The need to accurately model the combustion process is paramount, and cannot be overemphasized, as increasing regulations on emissions from combustion devices, higher efficiency considerations, and hence, energy conservations are global issues (Ian, 1997; Masataka *et al* 2019).

It should be noted that simulation has played significant roles in advancing progress in engineering and science. Consequently, it will continue to have great impact on all areas of engineering and scientific discovery because of its versatility (Babuska and Oden, 2004). In numerical simulations of high energy dependent processes, accurate treatment of radiation heat transfer is essential. The influence of turbulent fluctuations in the thermal radiation field is obvious from the fluctuations in the radiation intensity, which is a function of the scalar temperature field. Therefore, the fluctuations of the scalar field as a result of the turbulence flow field, causes a corresponding fluctuation in the thermal radiation field, resulting to modifications of the energy sources associated with the process; a phenomenon termed Turbulence-Radiation Interactions (TRI) (Li and Modest, 2003; Tessé, *et al.*, 2004; Modest, 2003). However, these interactions had until recently been ignored by virtually all investigations due to the complexities associated with the non-linear couplings between radiation and turbulence models. While the investigations on TRI was originated in the 1960's, the first numerical study was achieved in 1978 (Germano, 1978), TRI has received attention

in recent years (Li and Modest, 2002; Coelho, 2007). Reviews showed that accounting for TRI can increase radiative losses from a flame by factors more than two (2) (Faeth *et al*, 1989; Li and Modest, 2002). Many experimental and numerical results have also shown that neglecting TRI can result in underestimation of heat loss by factors up to three (3) (Townsend, 1958; Song, and Viskanta, 1987). Dos Santos *et al*, (2009) simulated the effect of TRI for a flame previously simulated by (Barve *et al*, 2006). They utilized a one-dimensional temperature profile predicted from the temperature of the simulated flame at just one cut section of the cylindrical chamber. They discovered that TRI contributed significantly to radiative flux especially at higher temperatures.

Despite the previous work, there is still a lot of unresolved issues especially the effect of turbulence flow field on TRI. Therefore, the present work which is adapting to the gas turbine combustor system focuses on the numerical study of the effect of turbulence in the thermal-radiation flow field taking into consideration the effect of TRI. The study will improve our understanding of the interaction in the flow field. The numerical simulation is performed using COMSOL Multiphysics software, incorporating advantages of flexibility in analysis for the comparison of five different cut sections of the combustor chamber, with flame temperature adapted from previous investigations on the adiabatic flame temperature in gas turbine combustors (Barths *et al*, 2000).

2. THEORETICAL BACKGROUND

Consider a 2-D cylindrical combustor chamber of height, 72m and radius 20m as shown in Fig. 1. Two identical nozzles of height 5m are placed symmetrically in the domain. With the aim, to investigate the influence of turbulent fluctuations primary for the estimation of the divergence of the radiative flux ($\nabla \cdot \mathbf{q}_R$), without necessarily considering the spectral effects of the radiation field and the chemical kinetics associated with the

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combustion process. The radiative intensity of the simulated flame is shown in Fig. 2.

To take into account the effect of the interaction between radiation and turbulence, a coupled model of both physics were treated. As a prerequisite for the simulation of the coupled process, a workable instance (converged solutions) of each of the two physics models is required.

The simplified form of the radiative transfer equation (RTE) in one dimension, eliminating complications concerned with the spectral effects, is given as:

$$\frac{dI}{dx} = -kI + kI_b \quad (1)$$

I = radiation intensity; I_b , = blackbody radiation intensity; K = absorption coefficient

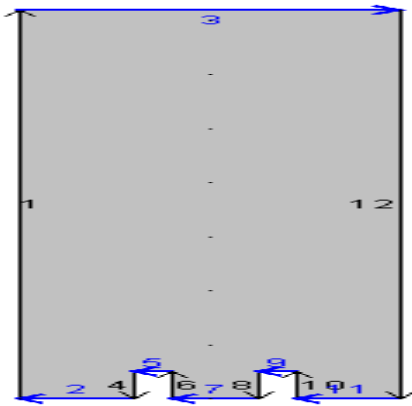


Fig. 1 The 2-D cylindrical domain

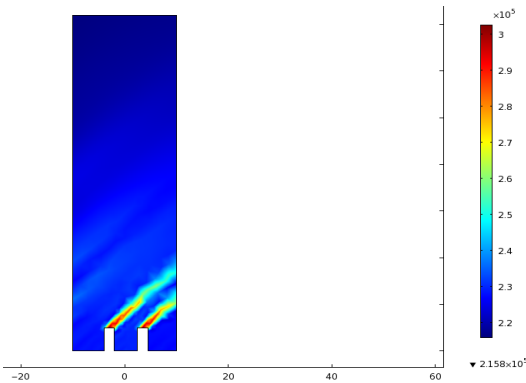


Fig. 2 Surface plot of the radiative intensity of the flame

The basic assumption of a gray gas participating medium, with absorption coefficient of $0.03 \text{ [m}^{-1}\text{]}$ (Dos Santos *et al*, 2009) is utilized. The turbulence model is based on the Reynold's Averaged Navier-Stokes equation (Riyadh *et al* 2019):

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u + \nabla \cdot (\overline{\rho u' \otimes u'}) = -\nabla p + \nabla \cdot \mu(\nabla u + (\nabla u)^T) + F \quad (2)$$

Where, u & u' = averaged and fluctuating velocity respectively; \otimes = outer vector product. The term $\nabla \cdot (\overline{\rho u' \otimes u'})$, is the interaction between the fluctuating velocities called Reynolds stress tensor.

A flame temperature of 2000[K] was utilized for the study, based on investigations on the adiabatic flame temperature in the gas turbine

combustors (Barths *et al*, 2000). This is the temperature of the hot gases after the oxidation process in the combustor.

The effect of turbulence in the thermal radiation field is noticeable from the radiative heat flux ($\nabla \times \mathbf{q}_R$), in simplified gray form is given as:

$$\nabla \times \mathbf{q}_R = k[4\pi I_b - \int_{4\pi} I d\Omega] \quad (3)$$

This term is required as a source term in the energy equation, accounting for the effect of radiation field for investigation of the total energy characteristics of the system.

2.1 Numerical modeling

The simulation study was performed using the COMSOL Multiphysics Version 4.0a software. The Radiative Transfer Equation (RTE) was solved using the built-in Discrete Ordinate Method (DOM) which involved independent discretization of spatial and angular domains. The RTE equation is replaced by a discrete set of equations for a finite number of directions, Ω_m , and each integral is replaced by a quadrature.

$$\Omega_m \frac{dI}{dx} = -kI + kI_b \quad (4)$$

Equation (4) is separated into two equations, one for positive direction and the other for negative direction, while the integral in Eq. (3) is replaced by a quadrature:

$$\Omega \frac{dI^+}{dx} = -kI^+ + kI_b \quad (5)$$

$$-\Omega \frac{dI^-}{dx} = -kI^- + kI_b \quad (6)$$

$$\nabla \times \mathbf{q}_R = 4\pi k I_b - 2\pi k \sum_{k=1}^M w_k [I^+ - I^-] \quad (7)$$

Where, w_k are the ordinate weights.

This angular approximation is used to transform the original integral-differential equation into a set of coupled differential equations. The discrete ordinate equations may then be discretized spatially after angular discretization has been performed using the finite volume method.

The physics used for the study are the heat transfer in participating media (*htpm*) and the turbulence flow, k-e (*spf*) model. It should be noted that the heat transfer in participating media interface provides the possibility to model radiative transfer inside a participating medium in conjunction with heat interaction in solids and fluids. The interface solves for radiative intensity and temperature fields. The turbulence flow interface provides the equations, boundary conditions, and volume forces for modeling turbulent flow, solving for the mean velocity field, the turbulent kinetic energy k and the rate of dissipation of turbulent kinetic energy, ϵ . Presented in Table 1 is the simulation model input.

2.2 Boundary conditions

Case 1: The domain is confined to the radiation field only, thereby neglecting the effects of the flow field on the radiation field.

Case 2: The turbulence field is introduced into the domain with the aim of investigating its effect on the radiation field

Case 1 Boundary conditions:

Walls 1-4, 6-8, 10-12 are assumed to be black walls

The radiation intensities,

$$I^-(x = -10\text{m}) = I_b(x = -10\text{m})$$

$$I^+(x = 10\text{m}) = I_b(x = 10\text{m}),$$

Case 2 Boundary conditions:

Walls 5 & 9 has inlet boundary condition with inlet velocity of 10m/s

Table 1 Simulation model input.

Name	Symbol	Unit	Value
Absorption coefficient	K	m^{-1}	0.03 (Dos Santos et al, 2008)
Scattering coefficient	σ_s	m^{-1}	0
Thermal conductivity	K	$W/(m.K)$	0.0257
Heat capacity	C_p	KJ/kgK	1.005
Dynamic viscosity	μ	$Pa.s$	1.79×10^3
Density	ρ	kg/m^3	1.23
Wall Temperature	T_w	K	293.15
Radiation intensity	I	W	Default (Inbuilt)
Surface radiosity	J	W/m^2	0
Inlet velocity	U_o	m/s	10
Flame temperature	T	K	2000(Barths et al, 2000)

2.3 Discretization and Meshing of the domain

A refine mesh of the entire geometry was performed using the regular refinement method. The mesh description is shown in Table 2.

Table 2 Mesh description.

Element type	Triangular	Edge	Vertex
Number of elements	996	N/A	N/A
Minimum element quality	0.8208	N/A	N/A
Average element quality	0.957	N/A	N/A
Element area ratio	0.07485	N/A	N/A
Mesh area	1420 m^2	N/A	N/A
Element length ratio	N/A	0.3043	N/A
Mesh edge length	N/A	204 m^2	N/A
Vertex elements	N/A	N/A	12

3. RESULTS AND DISCUSSION

The analysis of the temperature profiles and divergences of the radiative heat flux at five (5) different radial sections of the cylindrical combustor chamber with the purpose, to make comparison, and to study the behavior of the system along the transverse sections with and without the influence of TRI are presented in Fig.(3) ~ Fig.(7).

It is evidenced from the plots of the temperature profiles and the divergence of the radiative flux for the different cut sections presented that the results follow a similar trend. It should be noted that with the influence of turbulence, the divergence of the radiative heat flux increases considerably, with corresponding drop in the peak temperature levels of the local flame temperature. This may be as a result of greater emissions and increased heat loss from the heat source. However, these emissions may adversely affect the performance and efficiency of the combustor. For instance, it could result in possible damping of the exergy of the system, with some of the energy needed for effective work distributed to the surfaces of the combustor and thereby result in thermal loading of the system. This may lead directly to the deterioration of the material of the

combustor which eventually may result in premature failure of the combustor.

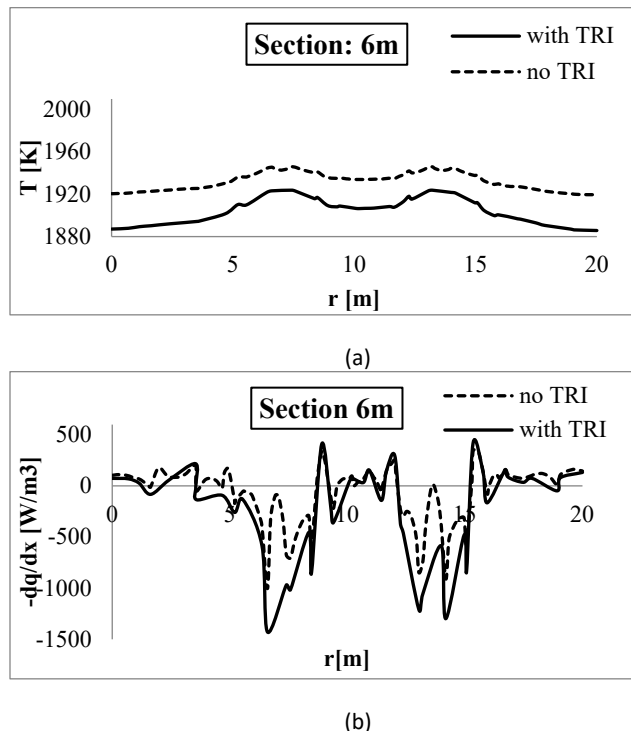


Fig. 3 (a) Temperature profile at section 6m, (b) Divergence of the radiative flux at section 6m.

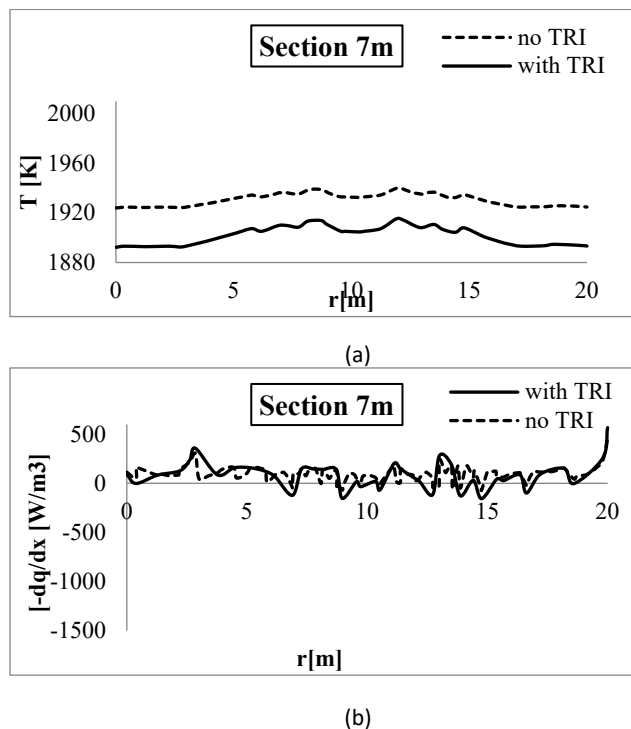
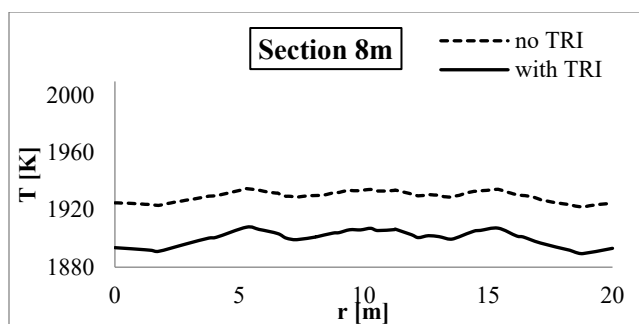
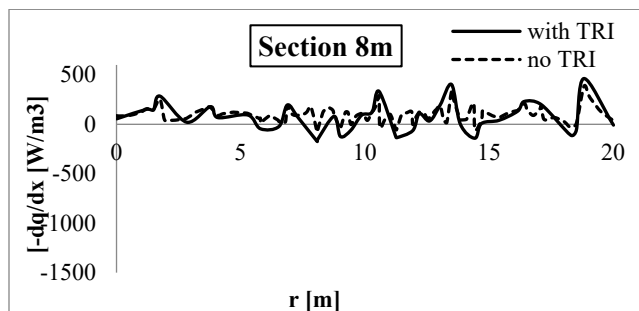


Fig. 4 (a) Temperature profile at section 7m, (b) Divergence of the radiative flux at section 7m.

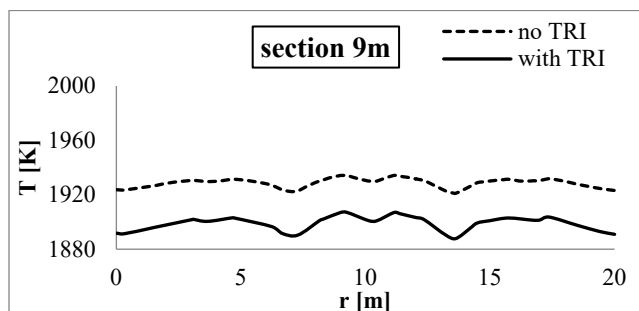


(a)

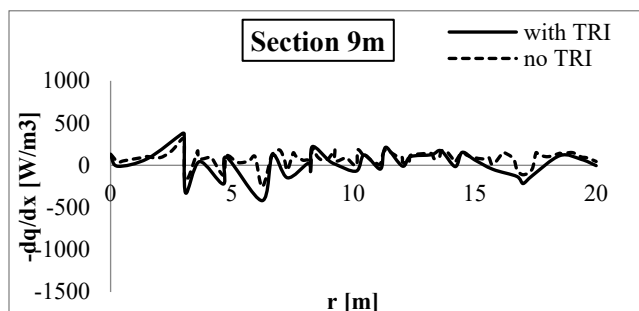


(b)

Fig. 5 (a) Temperature profile at section 8m, (b) Divergence of the radiative flux at section 8m.

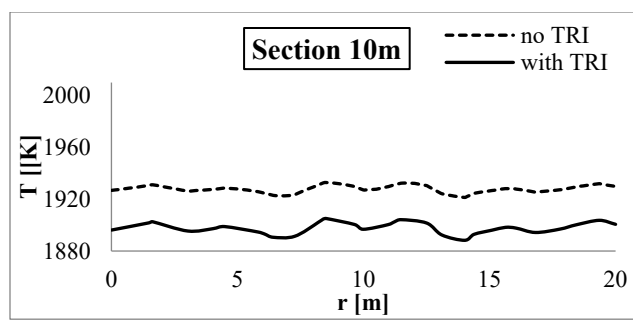


(a)

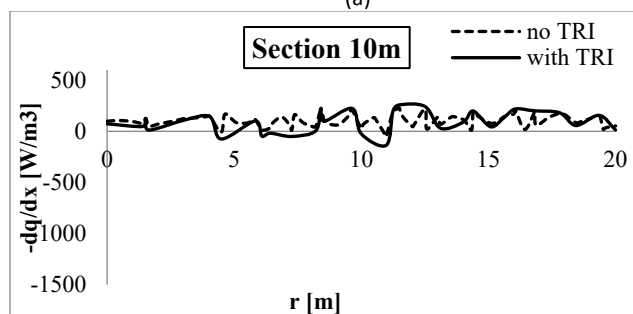


(b)

Fig. 6 (a) Temperature profile at section 9m, (b) Divergence of the radiative flux at section 9m.



(a)



(b)

Fig. 7 (a) Temperature profile at section 10m, (b) Divergence of the radiative flux at section 10m.

The magnitude of the fluctuating axial velocity across the chamber is shown to decrease significantly as shown in Fig. (8). From the upward half of the chamber, the axial velocity becomes fairly constant as the influence of the turbulence flow field degenerates due to spectral distributions of the turbulent kinetic energy which is at its maximum at the inlet, as shown in Fig. (9), then, gradually retarding uniformly towards the outlet of the chamber.

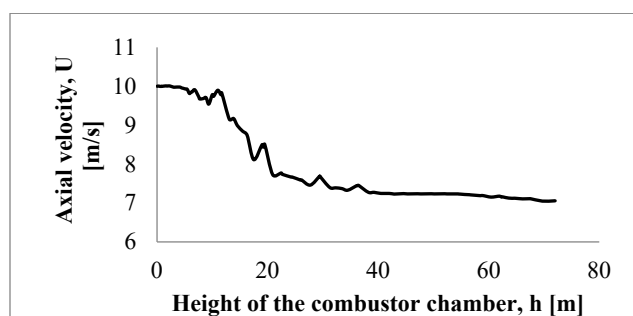


Fig. 8 Magnitude of the axial centerline velocity.

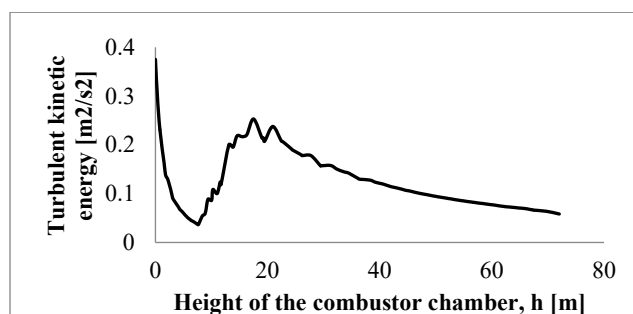


Fig. 9 Turbulent kinetic energy of the combustor.

Analysis of the result at the critical section of the combustor (6m) in order to investigate the critical factor for the deviation of the mean divergence of the radiative flux taking into consideration the effect of turbulence in the thermal radiation field is presented in Table 3. It can be inferred that turbulence-radiation interactions causes radiative heat losses from the flame, with the divergence of the radiative heat flux having a deviation factor of 3.48, and a 1.43% reduction in the local flame temperature.

Table 3 Mean divergence of the radiative flux at section 6m.

Cases	Mean Temperature [K]	Temperature difference [K]	Divergence of the heat flux [KW/m ³]	Deviation
Isolated radiation field	1932.81	-	50.29	-
Radiation coupled with turbulence flow	1905.23	-27.58 (1.43%)	225.48	+3.48

4. CONCLUSION

A numerical simulation of the effect of turbulence flow field in the thermal-radiation field has been studied using COSMOL Mutiphysics software by analyzing and comparing five different sections of the combustor chamber. The results showed that Turbulence-Radiation Interactions (TRI) increase the heat loss from the gas turbine combustor flame, leading to a reduction in the local flame temperature as observed from their profiles. Consequently, the radiation heat source term which is synonymous with the divergence of the radiative heat flux is increased. This term is an integral part of the total energy equation, inserted as a source term; though, often neglected in low temperature processes. Further, the magnitude of the fluctuating axial velocity across the combustor chamber decreases significantly, as the influence of the turbulence flow field degenerates due to spectral distributions of the turbulent kinetic energy.

Hence, the importance of taking into consideration the influence of turbulence in the thermal radiation field generated by the high energy, combustion process in a gas turbine combustor cannot be overemphasized. Analysis of the critical section of the combustor chamber resulted in deviation of the divergence of the radiative heat flux up to a factor of 3.48, with 1.43% reduction in the local flame temperature.

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