June 6-9, 2005, Reno-Tahoe, Nevada, USA

GT2005-69038

TOWARDS AN OPTIMIZATION OF TURBULENCE EFFECTS ON HEAT AND MASS TRANSFER IN EVAPORATING AND REACTING GAS TURBINE SPRAYS

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ABSTRACT

In this paper, the way towards an optimization of turbulence effects on heat and mass transfer in evaporating and reacting GT-sprays is outlined. It is based on an accurate consideration of coupling between turbulence and turbulence modulation, swirl intensity and non-equilibrium effects during the vaporization. This is achieved by including a physically consistent modelling of turbulence modulation phenomena that allows to better retrieve mass and heat transport effects on the droplet surface, and therefore improves the prediction of processes, like evaporation and combustion, which in turn affect the turbulence.

For this purpose, an Euler-Lagrangian method in conjunction with advanced models has been used in RANS-context and applied to the numerical study of a single gas turbine combustor configuration. a) To quantify, to control or to optimize the effects of turbulence along with the swirl intensity effects, a mixing parameter has been introduced. b) Under reacting conditions, it is shown how the evaporation characteristics, mixing rate and combustion process are influenced by turbulence. In particular, the turbulence modulation modifies the evaporation rate, which in turn influences the mixing and the species concentration distribution. It is demonstrated that this effect can not be neglected far from the nozzle for low swirl intensities ($Sw.Nu.<1$) and close to the nozzle for high swirl number intensities. All these findings can well be used to optimize turbulence effects in evaporating and reacting sprays.

INTRODUCTION

The success of some promising approaches, such as the LPP- or the RQL-concept strategies, that can help to limit gas turbine emissions, depends on a suitable homogeneity of the air-fuel mixture in the reaction zone. To achieve this goal by means of numerical simulations, an accurate determination of droplet and vapour spatial distribution and a reliable control of the interaction between the evaporating and reacting spray with the surrounding turbulent gas flow are prerequisite.

As pointed out in [1, 2] a considerable amount of works have been done including diverse parameter studies (e. g. [1-5, 8-15, 20-25, 34]. However, there are relatively few experimental and numerical results devoted to the effects of turbulence characteristics on spray combustion [2, 3, 4]. In internal combustion engines, a systematic consideration of the effect of the turbulent interactions between gas and droplets is rather rare [2], although the turbulence is one of the major factors controlling the droplet dispersion, evaporation and spray combustion along with the spray flame structure.

Available results deal solely with turbulence augmentation by additional injections of air or gaseous fuel or by adjusting the swirl intensity without investigating deeply the nature of modulation processes [5]. The latter, i.e. the modification of the continuous phase turbulence characteristics by droplets or by interface transport and the modification of interface transport by turbulence are confirmed by various experimental investigations [1, 3, 4] to have a decisive effect on the turbulent fluctuations, and therefore on the turbulent kinetic energy. An accurate capture of the turbulence characteristics, in particular of the turbulent kinetic energy is therefore determinant for an accurate prediction of the spray dispersion, evaporation and combustion characteristics.

Although in many recent works some numerical calculations have been performed in which the effects of the turbulence on droplet vaporization have been pointed out, they deal mostly with mono-dispersed sprays using numerical codes in which the standard *k-e* model was coupled to quasi-equilibrium evaporation models without a fully consideration of turbulence modulation processes [5, 10, 14]. Thereby no reliable prediction of the turbulence effect could be expected. This is also the case in *LES*, where only the standard dissipative expression for two-way coupling is really available in existing formulations of subgrid scale turbulent kinetic equation (e.g. [12, 13, 21]).

In this paper, the way towards an optimization of turbulence effects on heat and mass transfer in evaporating and reacting GT-sprays is outlined. It is based on an accurate consideration of coupling between turbulence and turbulence modulation, swirl intensity and non-equilibrium effects during the vaporization.

In this regard a single gas turbine combustor is used. It is a swirl stabilized combustor similar to that investigated by Wittig et al. [5] where we vary swirl intensities in the RANS simulation adopted.

Advanced models for turbulence, turbulence modulation, evaporation are combined in different manners. To demonstrate the ability of the model combinations employed in predicting the evaporating spray and droplet properties under turbulent conditions, respective results are compared with available experimental data. The qualified, accurate model combination is then coupled to the combustion model, and used to carry out the analysis of spray characteristics in non-reacting case and in reacting case, and to optimize some properties. In the next section the modelling and numerical procedure are presented. Then, the numerical configuration and boundary conditions are described. Finally, numerical results along with some parameter studies are provided before concluding.

NOMENCLATURE

ARSM	Implicit Algebraic Reynolds Stress Model
EARSM	Explicit Algebraic Reynold Stress Model
EDM	Eddy Dissipation Model
LRR	Launder, Reece and Rodi (implicit algebraic Reynolds stress Model)
k	Turbulent kinetic energy [m^2/s^2]
LES	Large Eddy Simulation
$\dot{m}_p$	Droplet evaporation rate [kg/s]
PDPA	Phase Doppler Particle Analyzer
RANS	Reynolds Averaging based Numerical Simulation
$S_{k,p}$	Particle source term for *k*-equation
$S_{u_i,p}$	Particle source term for momentum equations
Sw. Nu.	Swirl number
u_i (*u,v,w*)	Gas velocity components [m/s]
u_{pi}	Particle velocity components [m/s]
x,y,z	Position coordinates
r	Gas-phase density [kg/m^3]
$\overline{(\cdot)}$	Average value

MODELING AND NUMERICAL PROCEDURE

To account for instantaneous flow properties encountered by droplets, involving each droplet history starting from the injection into the flow, an Euler-Langrangian approach is adopted. Droplets are described by a Lagrangian transport through a continuous carrier gas flow which is captured by an Eulerian approach.

Governing Equations for Turbulent Gaseous Flow

The turbulent fluid phase is described following an RANS- modeling approach. The non-stationary, general form of the transport equation needed emerges as:

$$\frac{\partial(\bar{r}\bar{f})}{\partial t}+\frac{\partial(\bar{r}\bar{u}\bar{f})}{\partial x}+\frac{\partial(\bar{r}\bar{v}\bar{f})}{\partial y}+\frac{\partial(\bar{r}\bar{w}\bar{f})}{\partial z}-\frac{\partial}{\partial x}\left(\Gamma\frac{\partial f}{\partial x}\right)-\frac{\partial}{\partial y}\left(\Gamma\frac{\partial f}{\partial y}\right)-\frac{\partial}{\partial z}\left(\Gamma\frac{\partial f}{\partial z}\right)=S_f+\bar{S}_{f,p}+\bar{S}_{f,p,v}+\bar{S}_c \quad (1)$$

in which f may represent the mean value of mass, velocity, energy, turbulent kinetic energy, turbulent dissipation rate, and chemical species mass fraction (O_2, CO_2, vapor fuel), respectively. G represents an effective diffusion coefficient and S_f the well-known turbulence source term in single phase flow cases (e.g. [16, 26]). With regard to multiphase flow phenomena under study, further contributions appear. They may include source terms for phase exchange, $\overline{S}_{f,p}$, phase transition processes, $\overline{S}_{f,p,v}$ and chemical reactions, $\overline{S_c}$, respectively. These additional source terms characterize the direct interaction of mass, momentum, energy and turbulent quantities between the two phases and therefore account for the coupling between the fluid turbulence and the evaporating droplets moving in the turbulent flow. The first term , $\overline{S}_{f,p}$, expresses the classical two-way coupling in absence of evaporation and combustion. Details about these terms and their relationship can be found in [22].

For the turbulent gaseous flow, efforts to better capture streamline curvature effects and swirled flows phenomena are achieved by using the algebraic Reynolds stress models of Launder, Reece & Rodi [16] and of Gatski & Speziale [26] modified for two phase flow description by including additional source terms mentioned above. We additionally apply the standard *k-e* model for comparison. For simplicity, the heat flux vector in the energy equation has been postulated by means of a gradient ansatz.

Two-way Coupling and Combustion

Focused on phase interactions with regard to turbulent quantities such as turbulent kinetic energy of the gas phase, the

presence of small particles may attenuate the turbulence of the gasphase while big particles can augment it. In fact, an overbalancing of the particle-induced turbulence attenuation and production is observed which cannot be well captured by the state-of-the art approaches, as described in Crowe [6] who used the energy balance to attempt a first consistent description.

Because all the phenomena involved are thermodynamical processes, we use in this work, besides the standard expression for the two-way coupling, a model compatible with the second law of thermodynamics to better account for both particle-induced attenuation and production of continuous phase turbulence due the dispersed phase or to the interphase transport in internal combustion engines. The particle/droplet source term for the turbulent kinetic energy is given in this model by [22]:

$$S_{k,p} = b\left(\overline{u_{pi}S_{u_i,p}} - \overline{u_i}\ \overline{S_{u_i,p}}\right) + \left(\overline{u_i S_{u_i,p}} - \overline{u_i}\ \overline{S_{u_i,p}}\right) \qquad (2)$$

where

$$b = a' + \frac{(1-a')\left(\overline{u_{pi}S_{u_i,p}} - \overline{u_{pi}}\ \overline{S_{u_i,p}}\right)}{\left(\overline{u_{pi}S_{u_i,p}} - \overline{u_i}\ \overline{S_{u_i,p}}\right)} \qquad (2a)$$

is a model parameter. The parameter α' in Eq. (2a) depends on droplet properties, as shown in [22]. The second term in Eq. (2) represents the usual (dissipative) standard contribution, while the first term accounts for the production of the turbulent kinetic energy. So, this thermodynamically consistent model captures well both the enhancement and the diminution of the turbulence of the gas phase due to the presence of both big and small droplets in polydispersed sprays. Thus, transport equations of turbulent quantities in Eq. (1) have been modified by including this physically consistent consideration of turbulence modulation phenomena. Such a consistent approach is expected to improve the prediction of mass and heat transport processes involving evaporation and combustion, which in turn affect the turbulence.

For the reacting spray case, chemical source terms in the equations for O_2, CO_2 and vapor fuel must be provided. Although many efforts have been done in the last decade in combustion modeling (see e.g. [29-30]), we follow [10, 17] and choose for the complex swirled, reacting two-phase flow the Eddy dissipation model (EDM) to calculate the mean source terms. As well known, in modern low-emission gas turbine combustors characterized by high bulk flow velocities and short residence time as it is the case here, radiation that affects the temperature field of the reacting flow, and thus many other processes, like droplet evaporation, chemical reaction and pollution formation, plays a minor role on the temperature inside the combustor [27], although it still may influence the NOx emission. For comparative study of efficient numerical methods for radiation in gas turbine, see [27, 28]. To save computational time and because we do not focus on NOx, an approximate evaluation of the radiation contribution in the energy equation is given by solving differential equations for the radiant fluxes following the Four-Flux method [18]. The equations system of gas-phase, Eq. (1), is closed by the equation of state which determines the distribution of density for ideal gas.

Droplet Description, Evaporation and Dispersion Models

A Lagrangian approach is employed to compute properties of droplets moving in turbulent flow. Trajectories of various droplets classes are obtained from motion equations, where all external effects except drag, buoyancy and gravity forces are neglected [1, 2, 9-15, 20-25].

For evaporating droplets, two additional equations which give the rate of change of droplet diameter and temperature with respect to time are also needed (e.g. [8, 24, 25, 31-34).

To account for the 3D-evaporation of droplets, equilibrium [24, 25] and non-equilibrium models [8] are considered. For the equilibrium models usually used, the molar mass fraction χ_s is related to the saturation pressure through the Clausius-Clapeyron equation. In order to incorporate the effects of Stefan flow on heat and mass transfer, Abramzon and Sirignano [25] introduced modified Nusselt and Sherwood numbers. In the case of non-equilibrium evaporation model [8, 2], the molar mass fraction χ_s is determined by the following relation:

$$c_{s,neq} = c_{s,eq} - \left(\frac{L_K}{d/2}\right) b_L \qquad (3)$$

where

$$b_L = -\left(\frac{3\mathrm{Pr}_G\, t_d}{2}\right)\frac{\dot{m}}{m}, \qquad (3a)$$

represents the half of the blowing Peclet number. d is the droplet diameter, Pr_G is the Prandl number, L_K represents the Knudsen length and τ_d is the particle relaxation time. According to [8], corresponding modifications are performed in the Lagrangian equation describing the transient temperature.

To obtain the velocity fluctuations of gas occurred in the motion equation of droplets at droplet locations, a dispersion model following the Markov-Sequenz-ansatz (see in [2, 20, 22, 23]) is used. This model is based on the Langevin equation; it includes the calculation of Lagrangian and Eulerian correlations, and exhibits a high ability in calculating gas fluctuations.

Numerical Procedure

A three-dimensional CFD-code in which the equations for the gas phase are solved by finite volume method has been used. The time integration is achieved implicitly with the Crank-Nicholson method, the diffusion terms are discretized with central schemes on a non orthogonal block-structured grid. The velocity-pressure coupling is accomplished by a SIMPLE algorithm. The whole system is solved by the SIP-solver. The Lagrangian equations for droplets are discretized using first order scheme and solved explicitly. Source terms for the gas phase are computed in each cell with the contributions of all the relevant droplets [2, 20].

Numerically, the interaction between the continuous and the dispersed phases consists in couplings between two modules involved. After several iterations of gas phase alone,

the gas variables are kept frozen and all the droplets representing the entire spray are injected in the computational domain. High levels of under-relaxation factor were used on all main gas variables in order to obtain successful convergence. Due to the presence of droplets source terms, the conventional residuals are characterized by a jump of residuals after each coupling. To avoid it, an additional under-relaxation technique should also be employed for droplet source terms [2, 20].

$$S_{f\,p}^{i+1} = S_{f\,p}^{i} \cdot (1-g) + S_{f\,p(cal.)}^{i+1} \cdot g \qquad (4)$$

where $S_{f\,p}^{i+1}$ and $S_{f\,p}^{i}$ are the particle source terms appearing at $i+1$–th and i-th couplings, respectively. The under-relaxation factor g takes values in the interval [0,1].

The droplet injection is based on a stochastic approach by considering the droplet mass flux and the droplet size distributions obtained at the inlet near the nozzle exit from experimental measurements [5].

CONFIGURATIONS AND BOUNDARY CONDITIONS

A single gas turbine combustor investigated in [2, 5] is used. It consists of a radial swirl cup design dividing the inflow air into two primary and secondary co-rotating air flows with swirl intensities 0.45 and 0.85, respectively. A pressure swirl atomizer is mounted at the center of the swirl cup and supplies fuel to atomizer lip as illustrated in Fig. 1. The swirl cup is attached to a cylindrical duct where the combustion takes place. The geometry of chamber and details of operating conditions used as boundary conditions at the combustor inlet are summarized in Fig. 1. The combustor operates at atmospheric conditions (pressure=1 *bar*) and with a global equivalence ratio of Φ_{global}=0.5. The liquid fuel (dodecane) is injected into the combustion chamber from axially located nozzles as shown in Fig. 1. Droplet classes and velocities were chosen based on PDPA data.

In accordance with [5] properties of CH_4 were used for the fuel vapor. According to experimental data the droplet size distribution is determined from Gaussian distribution. Due to the symmetry assumption, half the domain is presented in computed results. The computational domain is represented by 128 × 64 cells in axial and radial directions, respectively. This was found to be sufficient.

RESULTS AND DISCUSSIONS

To evaluate the performance of the approach used, numerical and available experimental results are compared in both non-reacting and reacting cases. The results shown have been achieved by using different model combinations as summarized in Table 1.

First Case: Non-reacting swirled spray

First, the ability of different turbulence models employed has been judged through a comparison of the cross-sectional profiles of gas axial velocity component along the chamber with available experimental data, Fig. 2. It turns out that in the vicinity of inlet port all turbulence models deliver good agreement with experimental data without any considerable deviation from each other. In the second section where experimental data are still available, the comparison reveals a high performance of *EARSM* [26] in capturing well the velocity field of the turbulent swirling flow. For further investigations in this paper, this turbulence model has thus been adopted.

Table 1: Different model combinations used for simulations

Config.	Turbulence model	Evaporation model	Modulation model	Dispersion model	Chemis-try
Fig. 1	EARSM [26]	Equilibrium [25] Non-equilibrium [8]	Standard [20] Sadiki [22]	Markov-Sequenz [1]	EDM [17]
	ARSM [16]	Equilibrium [25] Non-equilibrium [8]	Standard [20] Sadiki [22]	Markov-Sequenz [1]	EDM [17]
	Standard k-ε [1]	Equilibrium [25] Non-equilibrium [8]	Standard [20] Sadiki [22]	Markov-Sequenz [1]	EDM [17]

In order to characterize phase transition processes ongoing on the droplet surface, and then to qualify the suitable evaporation model, the prediction of radial distributions of the droplet mass flux using equilibrium and non-equilibrium evaporation models is shown at different axial positions in Fig. 3. Generally, the concentration of droplets decreases while moving away from the nozzle due to evaporation. A comparison between equilibrium and non-equilibrium evaporation models does not reveal a prediction difference as long as big particles are involved (x=5mm). As expected, with decreasing droplet diameter non-equilibrium effects become predominant (x>20mm) and lead to an enhancement of droplet evaporation rate in accordance to [2]. This is also confirmed in Fig.4 which shows the droplet concentration zones inside the chamber obtained by using equilibrium and non-equilibrium models in comparison with experimental visualization. A qualitatively better agreement with experiment is achieved by using a non-equilibrium model delivering the correct spray penetration length. Therefore, the non-equilibrium evaporation model is retained for further investigations.

As pointed out in [2], a vaporization Damkoehler number appeared to be useful in characterizing the turbulence-droplet vaporization interaction regimes in non-reacting case. To highlight the influence of the turbulent kinetic energy on the vaporization rate along the axial direction, Fig. 5 reveals that there exists a critical number below which the turbulence energy is able to increase the mass transfer. For higher value of this number an inverse behavior is even observed. Focusing on the pure turbulence effect, this result confirms the experimental and numerical findings in [2, 3] where a so called vaporization Damkhoeler number, Da_v , has been introduced. For Da_v<1 the evaporation rate is increased with the increase of the turbulence intensity, while in the case Da_v >1 an inversed phenomenon can even be observed. For the mean droplet size used in

calculations, this behavior is observed independently from evaporation models.

To illustrate and optimize the influence of the swirl intensity on the spray dispersion, let us first consider the influence of the swirl intensity on the mixing process. For this purpose, we introduce a spatial mixing deficiency parameter (*SMD*) according to:

$$SMD = \frac{RMS_{plane}\left(\overline{Y_i}\right)}{Avg_{plane}\left(\overline{Y_i}\right)} \quad ; \qquad Avg_{plane}\left(\overline{Y_i}\right) = \frac{1}{m}\sum_{i=1}^{m}\overline{Y_i} \tag{5}$$

$$RMS_{plane}\left(\overline{Y_i}\right) = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(\overline{Y_i} - Avg_{plane}\left(\overline{Y_i}\right)\right)^2}\,. \tag{6}$$

In (5)-(6) Avg_{plane} is the average of the mean vapor mass fraction over a plane section having m cells, and RMS_{plane} is the corresponding root mean square. The *SMD* parameter describes the heterogeneity of the distribution of the fuel vapor mass fraction, Y_i, in the combustion chamber. A zero value indicates perfect mixing at a given plane. Figure 6 displays the influence of swirl number variations on the mixing process at different axial planes located at the positions between x=0 and 0.4 m nozzle downstream. It is shown that an enhancement in swirl intensity leads to a rapid and efficient mixing process providing a homogeneous mixture very close to the inlet port. This fact may be related to the presence of two (internal and corner) recirculation zones formed in the flow for high degrees of swirl (*Sw.Nu.*>0.6). As pointed out in [6], an increase in swirl number obviously enhances the size of the internal recirculation zones in radial direction.

Second Case: Swirled Reacting Sprays

In the reacting case, the temperature distribution affected by different swirl numbers has already been investigated in [2] along with the flow characteristics. We focus now on two swirl numbers in Fig. 7 for particular illustration. An increase in swirl number enhances the temperature and the size of the hot zone in chamber. The hot zone appeared at the outlet area (Fig. 7a) is shifted inside the combustor which leads to a homogenization of the temperature distribution in the combustion chamber (Fig. 7b). This is due to the modification of the flow and mixing dynamics according to Fig. 6 and 8.

In fact the influence of swirl intensity on the mixing process in reacting case is shown in Fig. 8. This figure shows that the mixing process evolution in presence of combustion is quantitatively different from that observed in non-combusting case (Fig. 6). The heterogeneity seems to be more persistent due to density and viscosity modifications of the flow. While the mixing is already homogeneous at x=0.06m in non-reacting case for swirl number Su.Nu.=1, it reachs an homogeneous state far away at x=0.18m in reacting case for the same swirl number.

To investigate the influence of turbulence modulation on some spray properties let us first show in Fig. 9 the variation of the turbulent kinetic energy in the flow due to different particle source terms in the turbulent kinetic energy equation. We achieve this by using different modulation models (no-model, standard approach and Sadiki & Ahmadi model) allowing different predicted values of the source terms along with different degrees of turbulence modification prediction. The results confirm findings observed in [22] where the standard approach always underestimates the turbulent kinetic energy. In Fig. 9, effects of the swirl number have also been pointed out in a very good agreement with observations made in Fig. 10 discused below.

In fact, regarding the vaporization rate in relation to both the modulation modelling and the swirl number intensity, Fig. 10 displays effects of the modulation modeling on the calculation of the droplet evaporation rate along the spray core. The influence of the swirl intensity can also be seen. For a given modulation model, a comparison between results for different swirl numbers shows that in contrast to the non-reacting case, the evaporation rate is arising at the beginning and reaches different maximum values while moving along the spray core. These values decrease with decreasing swirl numbers. That is due to the fact that in the combusting case the ambient temperature is much higher than that in non-reacting case and, this might additionally accelerate the vaporization rate. It can be also seen that the penetration length of spray increases with decreasing swirl intensity due to the absence of the internal recirculation zone and the relative reduction of gas temperature for *Sw.Nu.*=0.6 as shown in [2]. This gives rise on one hand to a longer droplet residence time so that the modulation effects become considerable and, on the other hand to a delay in the mixing process which can strongly affect the combustion (see also Fig. 8). For high degree of swirl number (*Sw.Nu.*=1), due to the high ambient temperature in the combustor, a fast evaporation of droplets in the vicinity of inlet port occurs, so that droplets/turbulence interaction becomes negligible far away from the nozzle (x>0.038m in Fig.10) where droplets are already evaporated. Only in the region close to nozzle where droplets are still present as illustrated by droplet source term effects in Fig. 9, droplet/turbulence interaction is considerable, and an accurate prediction is relevant for a reliable prediction and control of the mixing preparation process. In general for the same swirl number, it obviously appears in the reacting case that modulation models influence the prediction of the evaporation rate. Thus, besides the role of the temperature, the effect of the turbulence modulation is not negligible.

Figure 11 demonstrates clearly this analysis. It reveals the influence of the turbulence modulation modeling on the prediction of scalar distribution in swirled combusting sprays. Comparing the results of different modulation modeling strategies it appears that the model by Sadiki & Ahmadi causes a considerable reduction in predicting the chemical reactions approximately in the middle of combustion chamber exclusively for *Sw.Nu.*=0.6.

Due to the well-known reliability of the thermodynamically consistent modulation model by Sadiki and Ahmadi, it turns out that the prediction of turbulence interactions in spray achieved by this model may be considered as physically consistent. In addition, Fig. 11 shows the influences of swirl intensity on the concentration of oxygen and carbon dioxide along the centerline at the position r =10 mm. It can be observed that increasing the swirl intensity enhances the speed of chemical reaction in O_2-consumption and CO_2-creation in

combustion chamber. For low swirl intensities (*Sw.Nu.*=0.6) the oxidator is not consumpted entirely and can be observed at the outlet.

CONCLUSIONS

By including a physically consistent consideration of turbulence modulation phenomena that allows a better capture of mass and heat transport effects on the droplet surface, it could be shown that such a description improved the prediction of other processes, like evaporation and combustion, which in turn affect the turbulence**.** Especially, the combination of EARSM model for the turbulence, a non-equilibrium model for evaporation and the modulation model by Sadiki & Ahmadi provided an appropriate global model in studying evaporating spray dispersion properties. The turbulence-droplet vaporization interaction regimes could be characterized by means of a vaporization Damkoehler number that appeared to be useful in non-reacting cases. The use of the spatial mixing deficiency parameter allowed to quantify the mixing heterogeneity. This confirms that the increasing tangential motion of gas causes a more mixing rate of the fuel vapor and the ambient air which provides appropriate conditions for earlier ignition and complete combustion of the gas-fuel mixture.

Dealing with combustion, the coupling between modulation and swirl number effects lead to following observations: 1) For low levels of swirl intensity (*Sw.Nu.*.=0.6) the modulation effects are dominant still far from the nozzle. The modulation models affect significantly the calculated vaporization rates. This, in turn, affects the prediction of the fuel vapor distribution, the mixing process and consequently the chemical reactions. 2) For high degree of swirl number (*Sw.Nu.*=1), due to the fast evaporation of droplets in the vicinity of inlet port, the droplets/turbulence interaction becomes negligible far from the nozzle so that the turbulence modulation does not play a significant role in the results for chemical species concentrations in this region. All these findings can well be used to optimize the turbulence effects in evaporating and reacting sprays.

ACKNOWLEDGMENTS

The research reported in this paper is sponsored by the *Deutsche Forschungsgemeinschaft (DFG*) through the Sonderforschungsbereich SFB568 (TPA4) and the Graduiertenkolleg GK91.

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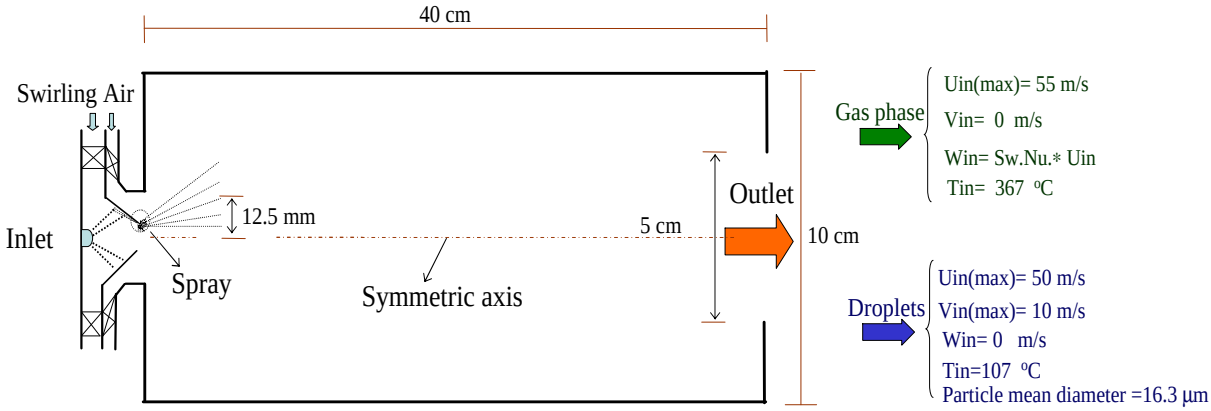

Figure 1: Cylindrical Combustion Chamber

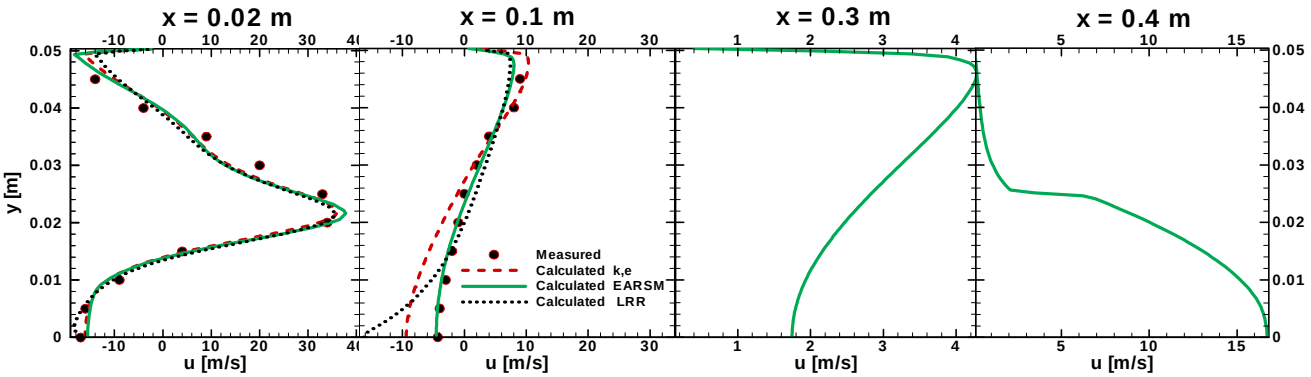

Figure 2: Cross-sectional profiles of gas axial velocity component along the chamber

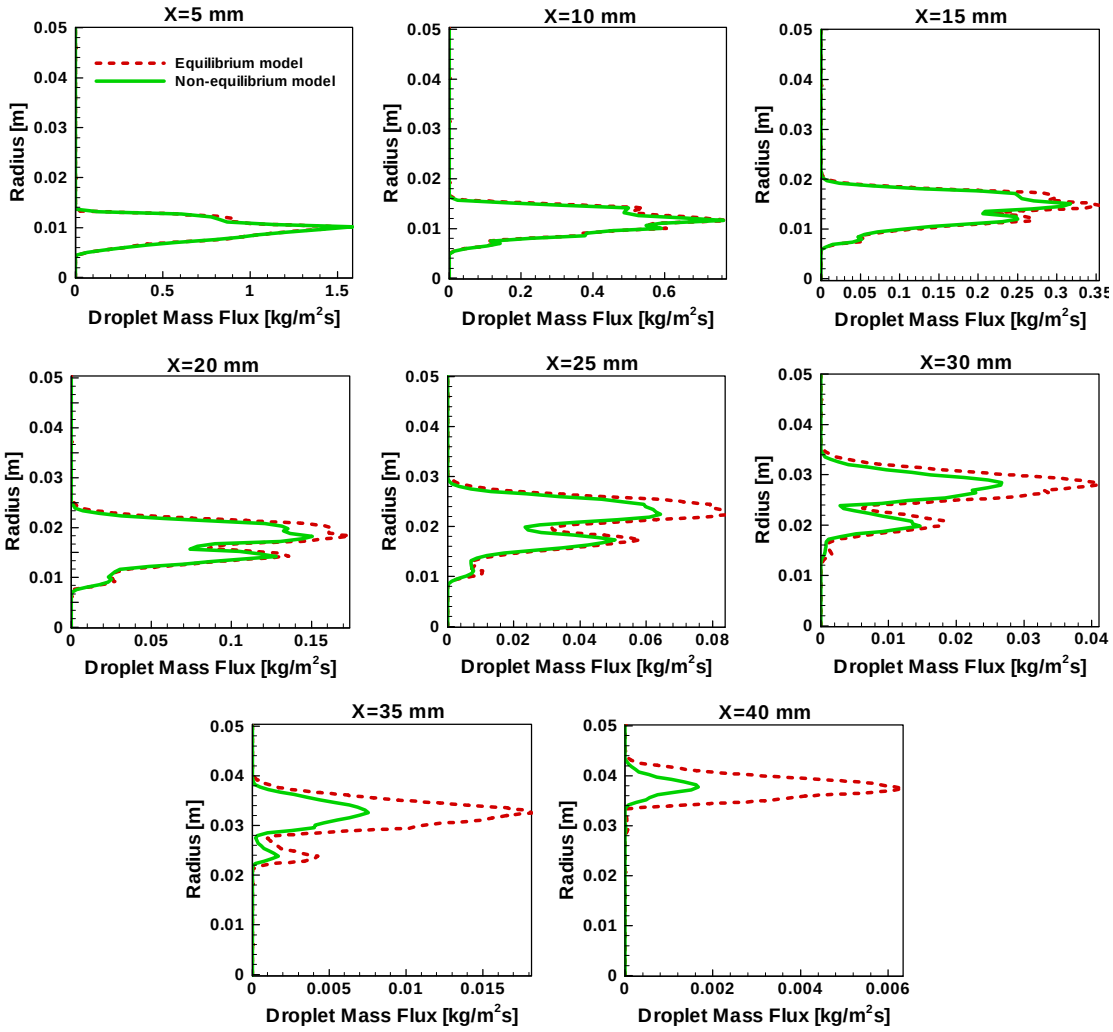

Figure 3: Droplet mass flux along the chamber: Comparison between results with equilibrium and non equilibrium evaporation models

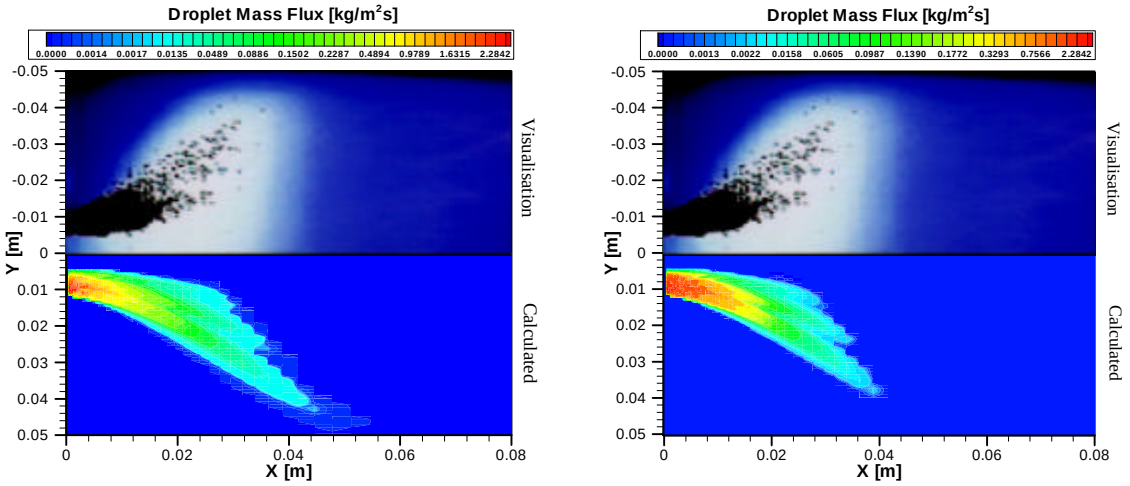

Figure 4: Droplets concentration zones in reacting case using non-equilibrium (right) and equilibrium (left)

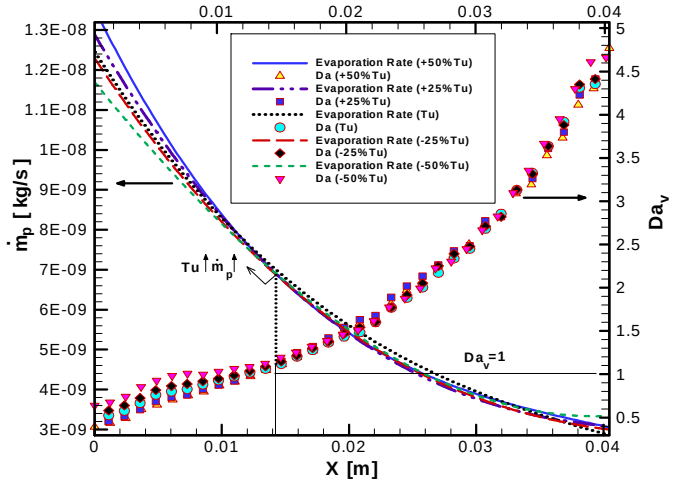

Figure 5: Influence of the turbulent kinetic intensity on the Evaporation rate of droplets and the evaporation Damkhoeler number (Da_v) along the spray core

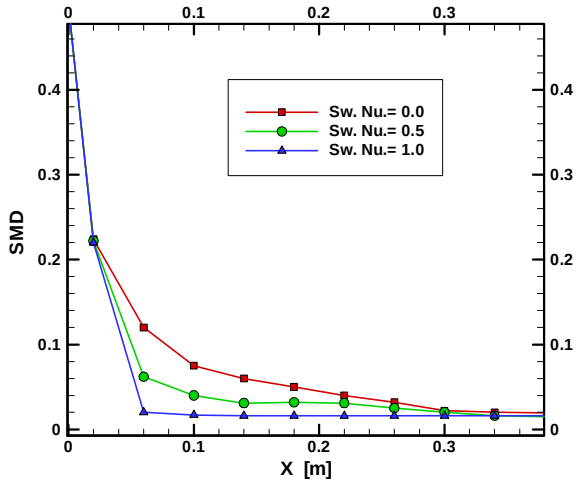

Figure 6: Spatial Mixing Deficiency (*SMD*) along the chamber (Non-reacting case)

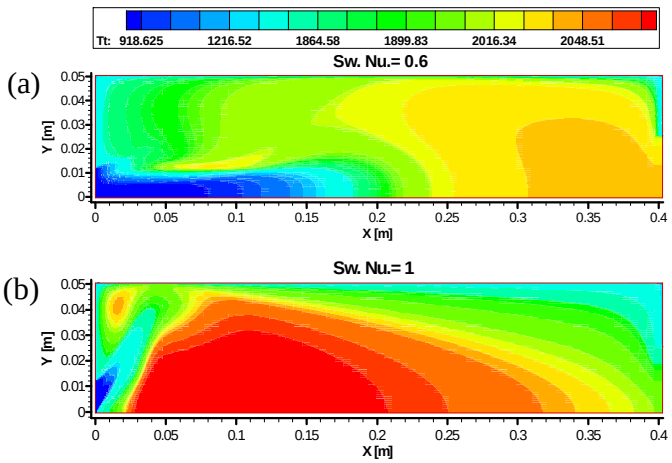

Figure 7: Effects of swirl intensity on temperature [K] distribution (reacting case).

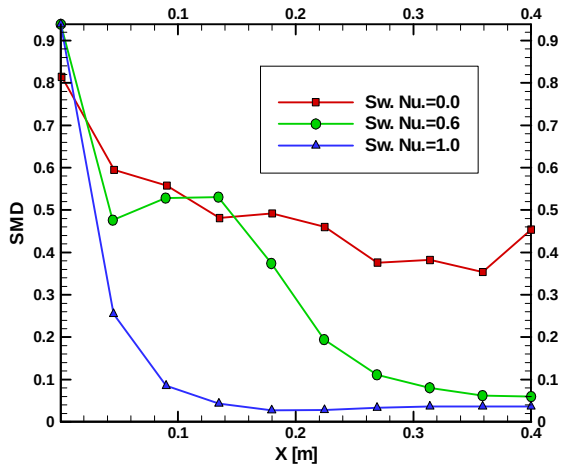

Figure 8: Spatial Mixing Deficiency (*SMD*) along the chamber (Reacting case).

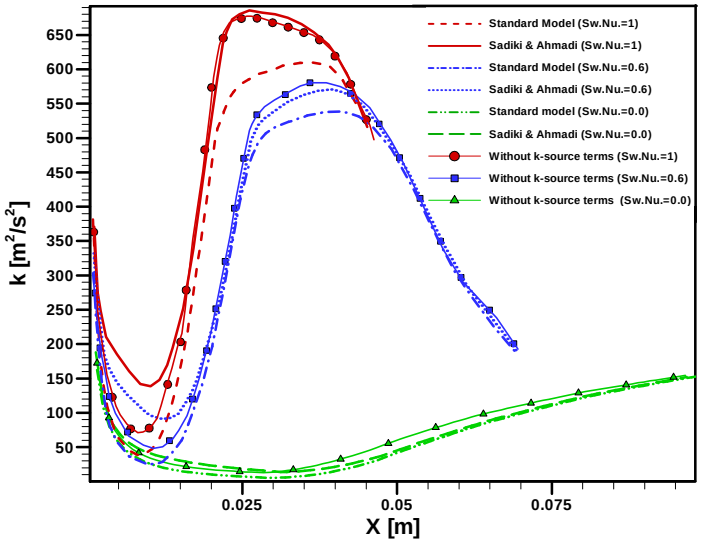

Figure 9: Effects of turbulence modulation on turbulent kinetic energy along the spray core using different modulation models along with comparison between different swirl numbers

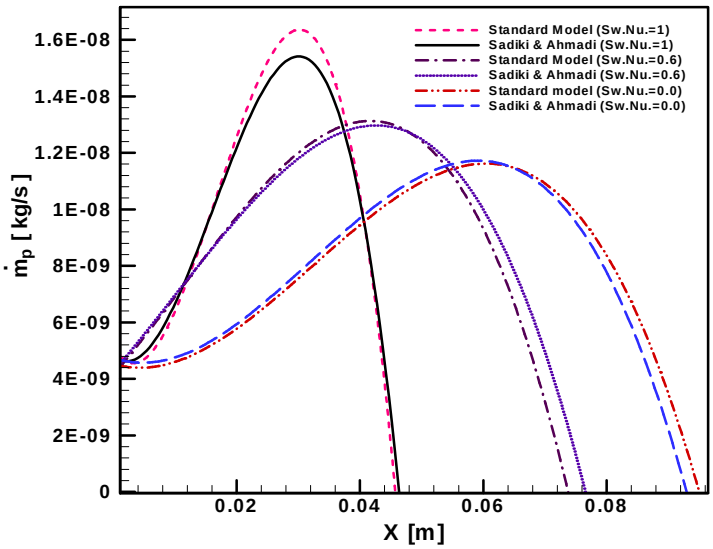

Figure 10: Effects of swirl intensity on evaporation rate along the spray core along with comparison between two different modulation models. (Standard model and model by Sadiki & Ahmadi)

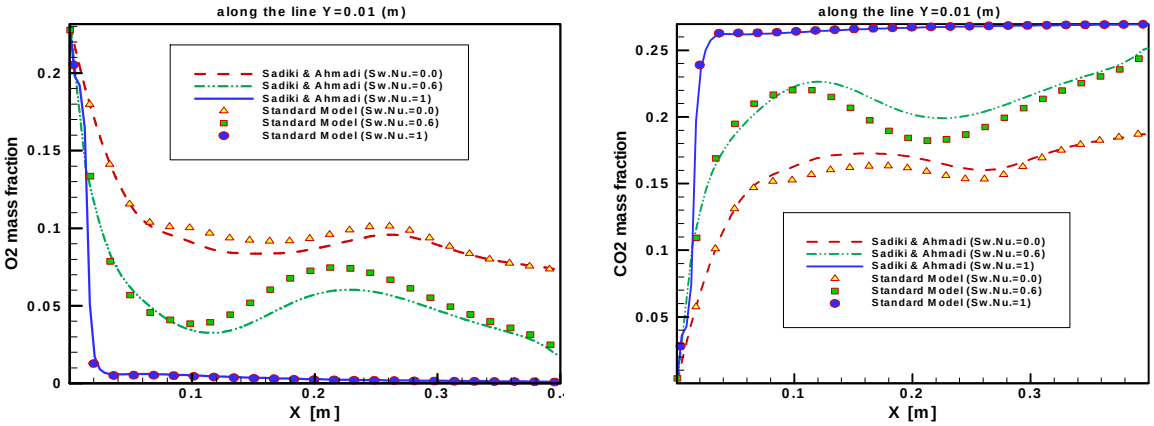

Figure 11: Effects of swirl intensity on concentration of O_2 and CO_2 along the combustion chamber along with comparing two different modulation models: Standard model and model by Sadiki & Ahmadi