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Full Length Article

A numerical study of NOx reduction by water spray injection in gas turbine combustion chambers

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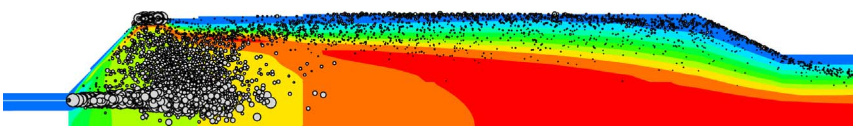
GRAPHICAL ABSTRACT



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ABSTRACT

An Eulerian-Lagrangian model is implemented to study the process of water spray injection inside gas turbine combustors. The validation of different parts of the model and the examination of the uncertainties introduced by different assumptions in this model are presented and discussed carefully. Then, the model is used to investigate the effect of different injection parameters; including position, direction, and mass flow rate, on the performance and emission of a gas turbine combustor at different swirl numbers. The results show that the interaction between spray droplets and the flow structures inside the liner plays the key role in the effectiveness of the injection process. The spray should be injected such that droplets are not trapped in the internal recirculating zone (IRZ) since they are pushed towards the colder flow near the liner walls. On the other hand, the droplet entrapment in the swirling vortex would be favorable since it increases both the droplet residence time inside the chamber and the proximity of droplets to the hot central gas regions. It is found that the best injection location satisfying these criteria is at the end of the primary zone rather than around the inlet nozzles and is targeted at the post-ignition region.

1. Introduction

Today, issues such as pollution and global warming are of the biggest concerns for human life. Attempts to improve the existing fuel combustion systems to reduce emissions have created one of the most important research fields in combustion science. With the widespread usage of gas turbines in power plants, strict laws are set in order to control their pollution. For example, based on EU law for gas turbines, the maximum amount of nitrogen oxides (NOx) and carbon monoxide (CO) emission allowed in dry mode is 25 PPMVD [1]. Natural gas is a good choice for a clean combustion because the percentage of the production of carbon dioxide (CO_2) resulting from the combustion of this fuel is very low [2]. However, NOx emission is the other obstacle to deal with since the greenhouse effect of NOx is even more than CO and CO_2 [3].

Recently, a lot of researches had focused on the emission and especially NOx reduction in gas turbines, e.g. Fichet et al. [4] generated a Reactor Network (RN) to model the NOx formation using the results of numerous studies on the influence of air humidity and load on NOx emissions. RN methodology can estimate the NOx emission in short time, high accuracy and low CPU usage. Cho et al. [2] tried to change the design of burners to obtain uniform mixing of fuel and air to reduce NOx. Ayed et al. [5] studied the dry-low-NOx hydrogen combustion chamber in gas turbines. Lee et al. [6] studied the nitrogen dilution effect in $H_2/CO/CH_4$ syngas flames on the NOx and CO emissions in a premixed gas turbine model combustor. They showed that the NOx reduction is related to temperature and residence time change in the hot combustion zone.

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One of the effective ways of reducing gas turbine NOx emission is using the wet cycles. NOx production has a direct relationship with the fuel-to-air ratio, air temperature and pressure, and an inverse relationship with the amount of moisture in the air [7]. The temperature profile of the incoming gas into the turbine blades is the main factor influencing the efficiency and emission characteristics of the system and its careful control should be adopted to achieve a high performance. The water injection technique has also been the focus of many studies on NOx reduction in internal combustion engines (ICE), especially in heavy-duty diesel engines, and their findings can improve the general knowledge of the effect of water injection in combustion chambers. In ICE chambers, water is introduced in several ways. The first method is the direct water injection (DWI) inside the cylinder. Mingrui et al. [8] used DWI in a gasoline direct injection engine and observed 35% NOx reduction with a water-to-fuel mass flow rate ratio, $\dot{m}_W/\dot{m}_F$, about 0.15 at low load. The alternative way is the injection of water before the cylinder. This method has been implemented for different kinds of ICEs, such as diesel [9], dual fuel spark-ignition [10], and reactivity controlled compression-ignition [11,12] engines. These studies reported considerable amounts of NOx reduction (about 50% in average) at the expense of slight decreases in the thermal efficiency at full load, however, by using different amounts of $\dot{m}_W/\dot{m}_F$ ranging from 0.4 to 2.6. Other techniques, like fuel-water emulsion [13,14], are also used in ICEs. An important question which should be addressed is the proper value of the water mass flow rate or $\dot{m}_W/\dot{m}_F$ since this parameter has been reported in a wide range in the literature and no unified conclusion can be made.

Water in the gas turbine can be recovered from the compressor cooling to reduce the pollution and increase the efficiency [15]. Water is used in gas turbines in different ways, including the injection of water, steam or humid air into the air flow. Liquid water and steam injection are done in different ways; a primary method is direct injection into the combustion chamber, and the other is steam or water injection in the compressor stages. There are numerous studies on the effects of water or steam injection in the compressor, e.g. White and Meacock [16] showed that water injection in compressor inlet can boost gas turbine output power and Roumeliotis and Mathioudakis [17] collected results of performance augmentation and engine operability with water injection in compressors. Cooling process with water evaporation can occur at the inlet or inside the compressor and with both cases, the discharge air temperature of the compressor is reduced and the power consumption of the compressor increases due to the decrease of air inlet temperature and increase of the air density. However, the net power output increases [18–20].

The other method is water or steam injection in the gas turbine combustor. Experiments show that with the steam injection at the rate of 2% of the total air flow, up to 50% of NOx emission can be reduced and with 4% injection, 75% NOx reduction is achieved [21]. Paepe and Dick [22] used steam as coolant to increases the efficiency by 3% (from 49% to 52%). The computations and measured results by Bhargava et al. [23] in the humid air turbines showed the 15% moisture addition reduces the NOx from 15 ppm to 3 ppm at the same exhaust temperature. This is attributed to the O-atom concentration decrease. Cardu and Baica [24] reported that with water/steam injection the output power increases from 38.5 to 43.5 MW and NOx emission decreases from 152 to 42 ppm. Recently, for a micro gas turbine, Paepe et al. [25] showed that by injecting water into the combustion chamber, fuel consumption decreases 18% and electricity generated by generator connected to it increases 7%.

An important question is the appropriate amount of water injection mass flow rate for the best performance. Different suggestions have been made in the literature. According to Lupandin et al. [26], the optimum injection rate for maximum NOx reduction was 150% of the fuel flow. In this case, the amount of NOx decreased to 24 ppm. Benini et al. [27] reported that with steam injection twice as fuel, NOx emission reduces by 16%. And by taking water instead of steam this amount is equal to 8%. Goke et al. [28] pointed out that steam injection should be optimized. They observed that by increasing steam injection to 20% of the air flow NOx emission decreases up to 10 ppm then the reduction trend stops with increasing the steam injection.

The other important questions are the proper location and direction of the injection. Furuhata et al. [29] revealed that when the steam is directly introduced into the ignition region (injected into the fuel spray or combustion air), the NOx formation is effectively reduced. Although the behavior of water droplet and steam injection is similar in the combustion chamber, water injection is more efficient to reduce NOx emission because of the latent heat of evaporation of water droplets. There are many parameters affecting the efficiency of the water injection inside the combustor, e.g. water spray must be injected into the maximum temperature region in the combustion chamber and the droplets must be atomized well [30]. Recently, Pugh et al. [31,32] used the water spray as a flame stabilizer in a swirling premixed syngas flame and showed that this technique offers a great potential to reduce NOx; first due to the thermal effect of water addition and second with the possibility to work at a leaner condition offered by reducing the lean blowoff stability limit.

In spite of the existence of some general guidelines on direct water spray injection in gas turbine combustors, many features of this process still remain unknown probably due to the fewer number of studies devoted to or published on this topic with respect to the water or steam injection in the compressor. The proper values of water injection mass flow rate, angle, and location at different operating swirl numbers encountered in gas turbines are of special interest. In this research, the effects of water spray injection in the combustion chamber on the combustor performance parameters are scrutinized and the best designs are introduced with a proper physical discussion and analysis of the flow and droplet dynamics in different cases to reveal some features of the process of water spray injection in the combustors.

2. Mathematical modelling

An Eulerian-Lagrangian formulation is incorporated to model the flow of combusting gas and water droplets in this study. Using Cartesian coordinate notation, all governing equations are given in this section.

2.1. Lagrangian droplet-phase equations

Considering the large density of the water droplets with respect to the gas phase, the equation of motion for each droplet can be written as [33]

$$\frac{dx_{p,i}}{dt} = U_{p,i} \tag{1}$$

$$\frac{dU_{p,i}}{dt} = \frac{U_{s,i}-U_{p,i}}{\tau_p} + \left(1-\frac{\rho}{\rho_p}\right)g_i, \quad \tau_p = \frac{1}{f_D}\frac{\rho_p d_p^2}{18\mu_m} \tag{2}$$

where, $x_{p,i}$, $U_{p,i}$, and ρ_p are the position vector, velocity vector, and density of a droplet, respectively, and g_i is the gravitational acceleration vector. ρ is the density of the gas mixture. In the droplet equations, the droplet properties are indicated with subscript p and the gas-phase properties without this subscript. The value of the properties of the gas phase in these equations are interpolated at the droplet position. τ_p is the relaxation time scale of the droplet, d_p the droplet diameter, and μ_m the dynamic viscosity of the gas mixture in the film layer around the droplet. The coefficient f_D is calculated by the Schiller and Naumann correlation [34].

In Eq. (2), $U_{s,i}$ is the fluid velocity seen by the droplet and is defined by

$$U_{s,i} = u_i + u'_{s,i} \tag{3}$$

where, u_i is the (mean) velocity of the gas phase governed by the