Applied Thermal Engineering 29 (2009) 3506–3510

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Reduction of NO emissions in a turbojet combustor by direct water/steam injection: Numerical and experimental assessment

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ARTICLE INFO

Article history:
Received 10 November 2008
Accepted 2 June 2009
Available online 7 June 2009

Keywords:
NO_x reduction
Turbojet combustor
Water/steam injection

ABSTRACT

Numerical and experimental investigations are conducted to assess the benefits and drawbacks of both water (mist) and steam direct injection within the combustion chamber of a 200 N static thrust turbojet. For this purpose, a three-dimensional CFD model of the combustion process is implemented where pollutant emissions are calculated; in parallel, a test campaign on the turbojet at sea level static conditions is carried out. In both cases the refrigerant flow is injected directly into the combustor, outside the liner. The aim of the investigations is to evaluate the impact of increasing water and steam flows (ranging from 0% to 200% of the fuel mass flow) onto the emissions levels (NO and CO) of the engine.

1. Introduction and background

Pollutant emissions arising from oxidation processes in aeronautical combustion chambers have recently become of great concern due to their environmental impact. Emissions of nitrogen oxides from aircrafts, which affect men's health and contribute to the formation of ozone, have been of particular interest to many airport operators as a result of increasing air traffic.

Since the end of World War II water injection in aero-engines has been quite extensively studied [1–3], and was implemented mainly for thrust augmentation [4] even at supersonic flight conditions [5,6]. Such "old-style" water injection systems used on early Boeing 707 and 747 aircraft were unpopular with airlines because little benefit was readily seen while the drawbacks of servicing the system with water were observed every day. Since those times, interest regarding water injection in aero-engines has dropped down until the beginning of the new century.

Recently, the use of water injection has been again proposed as an effective tool to reduce emission levels, particularly NO_x, during taxiing and take-off operations [7–13]. The most comprehensive study was carried out at NASA Glenn Research Center to estimate the effects of water injection on a commercial turbofan engine to reduce specific fuel consumption (SFC), NO_x emissions, and engine hot-section temperatures while maintaining constant thrust [7]. According to these results, the subsequent reduction in hot-section temperatures could increase engine life and reduce maintenance costs. Water injection technique is very similar to the one employed in industrial gas turbine combustors, where water injection is currently used for power augmentation, turbine life saving and NO_x reduction during the hot seasons [13,14]. It consists basically in injecting finely atomized (misted) water into the engine's low pressure compressor or directly in the combustion chamber [15]. Water misting evaporates purified water to reduce the temperature of the engine inlet air and makes for a denser mixture. As opposed to old style water injection schemes, this approach has additional potential benefits of reduced Specific Fuel Consumption (SFC) and emissions, as well as greatly reduced turbine inlet temperature.

In an aircraft engine, the water can be conveniently carried on board in an appropriate tank and delivered only during the taxiing and take-off without paying too much in terms of extra weight for the overall aircraft. This is a consequence of the relative small mass necessary, which are of the same order of magnitude of the fuel needed during take-off. In the case of steam, some of the heat produced by the engine combustion could be employed in specific heat exchangers to generate the required amount of steam. As a matter of fact, almost all the engines could take advantage from this technique, from small to high by-pass turbofans and open rotor engines.

On the other hand, based on some experiments conducted in the past [16], Benini and Mistè have recently modeled the effect of steam injection directly within an aeronautical combustor in order to study its effect on both the liner cooling and combustion efficiency [17]. They also observed a significant shift toward lower values in the temperature distribution within the combustor, a phenomenon which could be conveniently exploited to reduce the thermal NO_x. More recently, Molnar and Marek [18] developed a mathematical model for the simulation of Jet-A and methane fuels including water injection to be used in numerical combustion codes, and ended up in a correlation that gives the chemical kinetic time of the fuels investigated. Although the main scope of their

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doi:10.1016/j.applthermaleng.2009.06.004

Nomenclature

A	Eddy dissipation model constant
B	Eddy dissipation model constant
Da	Damköhler number
g	acceleration of gravity = 9.8066 m/s^2
h	specific enthalpy
I, $[I]$	generic species, molar concentration of species I
$\bar{J}^z$	diffusive flux of chemical species z
k	turbulent kinetic energy per unit mass
N_c	number of chemical species
p	static pressure
Pr	laminar Prandtl number, Pr = $c\mu/\lambda$
Pr$_t$	turbulent Prandtl number, Pr$_t$ = $c\mu_t/\lambda t$
$\vec{q}$	heat diffusive flux
$\dot{Q}_{rad}$	radiative heat flux
R	universal gas constant
R_z	elementary reaction rate of progress for reaction z
Sc	Schmidt number
t	time
$\vec{u}$	velocity vector $\vec{u}{=}_1 + u_2 + u_3$
$\dot{w}_I$	mass reaction velocity of chemical species I
$\vec{x}$	position vector
Y_z	mass fractions of chemical species z
Greek symbols	
δ_{ij}	identity matrix or Kronecker delta function
ε	turbulence dissipation rate
λ	thermal conductivity
λ_t	turbulent thermal diffusion coefficient
μ	molecular (dynamic) viscosity
μ_t	turbulent viscosity
ρ	density
τ	viscous stress tensor
ϕ	generic quantity
$\tilde{\phi}$	Favre-average of generic quantity
ϕ''	random fluctuation of generic variable
v_{zI}	stoichiometric coefficient for component I in the elementary reaction z

work was to develop a numerical tool to better describe the kinetics of the burned fuels, they demonstrated how significant is the water injection in modifying the nature of the chemical reaction involved in the combustion and in reducing NO_x formation. Other relevant results on modelling combustion including water injection are given in [19–21].

In this paper, numerical and experimental studies are conducted to assess the potentialities of both water and steam injection in a small turbojet combustion chamber as far as NO reduction and cooling effect are concerned.

2. Mathematical model

A numerical model is applied to solve for the thermo-fluid dynamic flow field inside a generic combustor, where compressible and reactive phenomena, including heat transfer, occur. For this purpose, the ANSYS CFX© package is used. Equations implemented in the software are the following:

Conservation of mass (continuity):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad i = 1,2,3 \tag{1.1}$$

Transport of chemical species:

$$\frac{\partial(\rho Y_z)}{\partial t} + \frac{\partial(\rho Y_z u_i)}{\partial x_i} = -\frac{\partial J_i^z}{\partial x_i} + \dot{w}_z \quad z = 1,2,\ldots,N_c \tag{1.2}$$

Conservation of momentum:

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j \tag{1.3}$$

Conservation of specific enthalpy:

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho h u_i)}{\partial x_i} = -\frac{\partial q_i}{\partial x_i} + \frac{Dp}{Dt} + \tau_{ij}\frac{\partial u_i}{\partial x_i} + \dot{Q}_{rad} \tag{1.4}$$

The partial pressure of each species is calculated using Dalton's law for ideal gases:

$$p = \sum_z p_z \Rightarrow p_z = pY_z = \rho R T Y_z \tag{1.5}$$

while the viscous stress tensor is expressed using Newton's equation:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\left(\frac{\partial u_i}{\partial x_i}\right) \tag{1.6}$$

and the diffusive flux of chemical species z is expressed by the Fick's law:

$$\bar{J}^z = -\frac{\mu}{\mathrm{Sc}_k}\frac{\partial Y_z}{\partial x_i} \tag{1.7}$$

where Sc is the Schmidt number.

The generic source term q_i is modeled as:

$$q_i = -\frac{\mu}{\mathrm{Pr}}\left[\frac{\partial h}{\partial x_i} + \sum_{z=1}^{N_c}\left(\frac{\mathrm{Pr}}{Sc_z} - 1\right)h_z\frac{\partial Y_z}{\partial x_i}\right] \tag{1.8}$$

being Pr the Prandtl Number.

To solve for the turbulent flow, the Favre Averaged Navier–Stokes (FANS) assumption has been considered [22]. This is particularly suitable for reacting flows, where high density variations take place. In this approach, the general quantity is split into two components: its time-density- averaged value over a period of time T' and a component that fluctuates with time:

$$\phi = \frac{\int_{T'}\rho(t)\phi(t)dt}{\int_{T'}\rho(t)dt} + \phi'' = \frac{(\widetilde{\rho\phi})}{\tilde{\rho}} + \phi'' = \tilde{\phi} + \phi'' \tag{1.9}$$

Rewriting the equations of conservation, we obtain:

$$\begin{aligned}
&\frac{\partial\tilde{\rho}}{\partial t} + \frac{\partial\tilde{\rho}\langle u_i\rangle}{\partial x_i} = 0\\
&\frac{\partial\tilde{\rho}\langle Y_z\rangle}{\partial t} + \frac{\partial\tilde{\rho}\langle Y_z\rangle\langle u_i\rangle}{\partial x_i} = -\frac{\partial\tilde{\rho}\langle Y_z''u_i''\rangle}{\partial x_i} - \frac{\partial\widetilde{J_i^z}}{\partial x_i} + \widetilde{\dot{w}_z}\\
&\frac{\partial\tilde{\rho}\langle u_j\rangle}{\partial t} + \frac{\partial\tilde{\rho}\langle u_j\rangle\langle u_i\rangle}{\partial x_i} = \frac{\partial\tilde{\rho}\langle u_j''u_i''\rangle}{\partial x_i} - \frac{\partial p}{\partial x_j} + \frac{\partial\tilde{\tau}_{ij}}{\partial x_i} + \tilde{\rho}g_j\\
&\frac{\partial\tilde{\rho}\langle h\rangle}{\partial t} + \frac{\partial\tilde{\rho}\langle h\rangle\langle u_i\rangle}{\partial x_i} = -\frac{\partial\tilde{\rho}\langle h''u_i''\rangle}{\partial x_i} + \frac{D\tilde{p}}{Dt} - \frac{\partial\widetilde{J_i^z}}{\partial x_i} + \tau_{ij}\frac{\partial u_j}{\partial x_i} + \tilde{\dot{Q}}_{rad}
\end{aligned} \tag{1.10}$$

The viscous Reynolds stresses are modeled using the standard k–ε model [23].

The turbulent mass and heat fluxes are modeled using the gradient transport hypothesis: