ARTICLE IN PRESS

Energy xxx (2015) 1–13

Contents lists available at ScienceDirect

Energy

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

A numerical investigation of the entropy generation in and thermodynamic optimization of a combustion chamber

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ARTICLE INFO

Article history:
Received 4 August 2014
Received in revised form
10 December 2014
Accepted 17 December 2014
Available online xxx

Keywords:
EGM
Combustion chamber design
Optimization
Numerical
Exergy analysis

ABSTRACT

In this study, we are simulating the turbulent combustion of a mixed bluff-body swirl stabilized flame in a gas turbine combustion chamber and investigating the effects of different parameters, including the swirl number, distance between the air and fuel nozzle which is called bluff size, equivalence ratio, inlet fuel flow rate, and the inlet air velocity, on the entropy generation. We perform the process of the design of the combustion chamber by proposing the optimal value of each parameter based on the EGM (entropy generation minimization) method under the two maximum allowable temperature and size constraints. Two common methods of entropy generation calculation, one based on the overall entropy balance on a system and the other based on the local entropy generation rate calculation, are used and compared in this study. Our results show that the deviation between the total entropy generations calculated by the two methods is 6.4% in average which is an acceptable error in turbulent combustion simulations. Also, the two opposing factors, namely chemical reaction and heat transfer, have the main contribution to the total entropy generation.

1. Introduction

The efficient utilization of energy is a critical concern in today's design of energy systems. Scientists are trying to approach maximum efficiency in various industrial applications as much as possible. In other words, it is favorable to have minimum irreversibility. In order to achieve this goal, the exergy analysis and EGM (entropy generation minimization) method [1] can be applied to optimize the design of energy conversion systems. In this method, the design parameters of the system are changed and entropy generation is computed in each case. The optimum design corresponds to the case with the minimum entropy generation while some additional geometry and economic constraints should be satisfied. For the details of the method, one can consult the book by Bejan [1]. Bejan [2] also reported an extensive review on the applications of the EGM method in several thermal problems.

The EGM method is vastly incorporated by researchers in different applications. Li and Faghri [3] performed both the exergy balance analysis and the local entropy generation analysis to investigate the irreversibility within fuel cells. Mahian et al. [4] applied EGM to study the effect of using nanofluids on the entropy generation between two concentric rotating cylinders at constant heat flux boundary conditions. They found that the entropy generation decreases with the increase of volume fraction of nanoparticles. Makhanlall et al. [5] found an optimum optical thickness and an optimum tilt angle where the heat losses are minimized for gas filled solar collectors. Escandón et al. [6] determined the local and average entropy generation rates for the electro osmotic flow of a non-Newtonian fluid in a parallel flat plate micro channel.

EGM method has also been implemented in several heat transfer studies in pipes. For example, Ko and Ting [7] and Ko [8] reported different optimal parameters for fully developed flow in helical pipes at the constant heat flux. Jarungthammachote [9] investigated entropy generation for the pipes with different shapes of cross section, and Amani and Nobari [10,11] studied entropy generation in the entrance region of curved pipes both numerically and analytically.

EGM is extensively used for IC (internal combustion) engine problems. Caton [12] observed that, in general, availability destruction decreases when combustion temperature is increased. He [13] also examined the availability destruction in an adiabatic, constant volume combustion in a vessel. He discussed the effect of combustion temperature and equivalence ratio on the entropy

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http://dx.doi.org/10.1016/j.energy.2014.12.077
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Nomenclature

Latin symbols

A	area
C_p	specific heat
D	mass diffusion coefficient
E	energy
G_k	production of turbulent kinetic energy
h	enthalpy
J_i	diffusion flux of ith species
k	turbulent kinetic energy
M_i	molecular weight of ith species
P	pressure
Q	volume flow rate
$\overline{R}$	universal gas constant
R_i	mass rate of creation of ith species by chemical reaction
r	radial coordinate
S	swirl number, modulus of mean rate of strain, global entropy generation rate
S_{ij}	mean strain rate
Sc	Schmidt number
S'''	local entropy generation rate
s	specific entropy
T	temperature
u	velocity
V_a	mean air-inlet velocity
Y_i	mass fraction of ith species
Z	mixture fraction
z_i	mass fraction of ith atomic species
x	axial coordinate
X_i	mole fraction of ith species

Greek symbols

α	inverse effective Prandtl number
ξ	bluff-size ratio
ε	turbulent energy dissipation rate
Φ	equivalence ratio
λ	thermal conductivity
μ	dynamic viscosity
μ_i	chemical potential of ith species
ρ	density
τ	stress tensor

Subscripts

a	air
b	bluff body
ch	due to chemical reaction
eff	effective
f	fuel
gen	entropy generation due to all phenomena
h	due to heat transfer
i,j	species index, coordinate index
m	due to mass transfer
n	normal component
t	turbulent
v	due to viscous dissipation

generation. Rakopoulos and Kyritsis [14] Compared the entropy generation of the internal combustion engine operation for methane, methanol, and dodecane fuels. Nakonieczny [15] investigated entropy generation in the charge exchange system of a turbocharged, intercooled diesel engine and discussed the effect of various variables, such as the intercooler air temperature, air pipe length, and timings of inlet valve closure and exhaust valve opening, on the entropy production. Rakopoulos and Kyritsis [16] studied entropy generation during the combustion of the hydrogen-enriched natural and landfill gas. Finally, Rakopoulos and Giakoumis [17] presented comprehensive reviews of the studies on the availability analyses of IC engines published up to 2006. They reported fruitful conclusions about the availability destruction, heat transfer rates, and availability expelled with the exhaust gas. Also, they concluded that less availability is destroyed with lighter fuels such as methane and methanol compared to the longer-chain hydrocarbons which is attributed to the lower entropy generation of the decomposition of lighter molecules. Sieniutycz [18] investigated the relationship between entropy generation and some parameters, like fuel consumption and power generation, in an engine. The availability analysis of a spark ignition biogas–hydrogen engine during the closed part of the engine cycle was performed by Rakopoulos and Michos [19]. Knizley et al. [20] investigated the effects of the fuel type, reactant temperature, reactant pressure, fuel-air equivalence ratio and diluents on the entropy generation and availability destruction in a constant energy-volume (UV) combustion process.

In addition to IC engines, exergy analysis and EGM has been applied to other single- and multi-phase combustion processes. Dash and Som [21] investigated the transport processes and associated irreversibility of droplet combustion in a convective medium. In a later study, Dash and Som [22] analyzed thermodynamic irreversibility of the spray combustion process for different inlet pressures, temperatures, and swirls. Datta [23] studied the entropy generation of a confined laminar diffusion flame and the influences of the inlet air temperature, heat loss through the wall, and equivalence ratio on the total rate of entropy generation. Also, Nishida et al. [24] investigated the effects of these parameters on the entropy generation of both premixed and diffusion flames. Datta [25] extended his previous study [23] to account for the role of gravity on the entropy generation. He concluded that the entropy generation increases by decreasing gravity. Stanciu et al. [26] investigated the irreversibility in both laminar and turbulent diffusion flames. Two combustion models are used by them; the multi-species approach based on the eddy-break-up model for the mean reaction rate, and the assumed probability density function for a conserved scalar that relies on the flame sheet model. Yapici et al. [27–29] investigated the effects of oxygen fraction in the air, equivalence ratio, and swirl on the entropy generation in methane- and hydrogen-fueled combustion chambers. They also compared the local entropy generation for different fuels [30]. Entropy generation during burning of a spherical fuel droplet was calculated by Raghavan et al. [31]. Investigation of the influence of swirl angle on the irreversibility in a turbulent diffusion flame was performed by Stanciu et al. [32]. Som and Datta [33] performed a fundamental study on the thermodynamic irreversibility in the processes of combustion of gaseous, liquid, and solid fuels. They discussed the effects of the free stream velocity, particle diameter, ambient temperature, and gravity on the entropy generation rate in both upward and downward flows. They reported the decrease of the entropy generation by reducing the Froude number. Analysis of the entropy generation of laminar propagating hydrogen-enriched coflow methane-air triple flames was conducted by Briones et al. [34]. Chen [35] investigated the entropy generation of laminar premixed

Please cite this article in press as: Arjmandi HR, Amani E, A numerical investigation of the entropy generation in and thermodynamic optimization of a combustion chamber, Energy (2015), http://dx.doi.org/10.1016/j.energy.2014.12.077