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International Journal of Heat and Mass Transfer 51 (2008) 4276–4286
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Turbulent mixing of a passive scalar in confined multiple jet flows of a micro combustor

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Received 11 July 2007; received in revised form 7 November 2007
Available online 3 March 2008

Abstract

The turbulent mixing characteristics of multiple jet flows in a micro can type combustor are investigated by means of large eddy simulation (LES). The micro combustor can be used for a micro gas turbine which is hybridized with solid oxide fuel cell. Attention is paid for a micro combustor having a circular disk baffle plate with a fuel injection nozzle in the center and oxidant injection holes allocated annularly. Downstream the baffle plate, a complex flow is produced from the interaction of multiple jet flows and study is made for three different configurations of the baffle plates resulting in different mixing pattern. From the results, it is substantiated that the turbulent mixing is promoted by complex flow fields caused by the jet flows and large vortical flow regions in the micro combustor. This is effective to accelerate the slow mixing between fuel and oxidant suffering from low Reynolds number in such a small combustor. In particular, the vortical flow region formed downstream the fuel jet core region plays an important role for rapid mixing coupled with another flow recirculation region. Discussion is made for the instantaneous and time and space averaged flow and passive scalar quantities which show peculiar turbulent flow and mixing characteristics corresponding to the different flow structures for each baffle plate shapes, respectively.

Keywords: Large eddy simulation; Micro combustor; Recirculation; Turbulent mixing; Vortical flow

1. Introduction

Currently, a micro gas turbine (MGT) has been widely drawing attention as a distributed energy generation system for an individual household or a small community. In parallel to the progress of MGT technology, a fuel cell has been highlighted for its high efficiency and environmental advantages. For MGT, its efficiency can reach to 40% [1], but it seems to be difficult to achieve higher efficiency than 40%. However, the efficiency of solid oxide fuel cell (SOFC) for electricity generation recently becomes 50% or higher [2,3]. Therefore a method hybridizing MGT with SOFC is promising technology because the MGT/SOFC hybrid system can provide higher efficiency over 70% [4]. Several concepts of the hybrid system have been suggested to elevate the system efficiency [3–5]. Among the various hybrid systems, the present study is based on the MGT/SOFC hybrid system suggested by Suzuki et al. [3]. Especially, focus is given to the turbulent mixing characteristics of a passive scalar in an innovative micro cylindrical combustor with baffle plate providing multiple fuel and oxidant jets as illustrated in Fig. 1, which is proposed as a combustor for the MGT/SOFC hybrid system by Suzuki et al. [3]. This micro combustor is expected to secure zero emission of toxic gases like CO and a stable flame for burning the effluent of SOFC in an extraordinary fuel lean condition.

Combustion in a very small chamber may not simply resemble a scaled-down version of its large-scale counter-

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doi:10.1016/j.ijheatmasstransfer.2007.12.017

Nomenclature

CV	coefficient of variation, $\mathrm{CV} = \frac{1}{(F_i)_{cs}} \times \sqrt{\frac{\sum_{i=1}^{n}[F_i-(F_i)_{cs}]^2}{(n-1)}}$
D	diffusion coefficient, $D = \nu/Sc$
D_f	fuel jet diameter
D_o	oxidant jet diameter
D_{tube}	combustor tube diameter
k	turbulent kinetic energy, $k = \frac{1}{2}(\overline{u_i'u_i'})$
L	combustor length
p	instantaneous pressure
$\hat{p}$	filtered pressure
$\dot{Q}_i$	total volume flow rate of species i
Re_{tube}	Reynolds number based on combustor tube diameter
S_{ij}	strain rate tensor, $S_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2$
Sc	Schmidt number
Sc_t	turbulent Schmidt number
s_j	subgrid-scale scalar flux
t	time
u_i	instantaneous velocity
U_i	time mean velocity
u_i'	velocity fluctuation
$\widehat{u}_i$	filtered velocity
$\overline{u_i'u_j'}$	Reynolds stress
V_f	fuel jet velocity
V_o	oxidant jet velocity
f	instantaneous mixture fraction
F	time mean mixture fraction
$(F_i)_{cs}$	(y, z) cross-sectional averaged value of F_i
$\hat{f}$	filtered mixture fraction
f'	fluctuation of mixture fraction
f_{rms}	rms of mixture fraction fluctuation, $f_{rms} = \sqrt{\overline{(f-F)^2}}$

Greek symbols

ϵ_f	dissipation rate of scalar variance, $\epsilon_f = D\left(\frac{\partial f'}{\partial x_j}\right)^2 = \frac{\nu}{Sc}\left(\frac{\partial f'}{\partial x_j}\right)^2$
Λ_2	the second largest eigenvalue of $S_{ik}S_{kj} + \Omega_{ik}\Omega_{kj}$
ν	kinematic molecular viscosity
ρ	fluid density
τ_{ij}	subgrid-scale stress tensor
Ω_{ij}	vorticity tensor, $\Omega_{ij} = (\partial u_i/\partial x_j - \partial u_j/\partial x_i)/2$

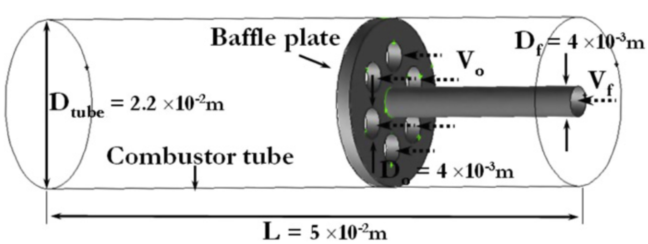

Fig. 1. Configuration of a micro can combustor for case A.

part. For example, such a small combustor may be suffering from incomplete mixing between fuel and oxidant, insufficient fuel residence time for complete combustion and high heat transfer rate to combustor outside because of high surface to volume ratio [6]. This is mainly due to the difference of geometrical dimension and Reynolds number. In the proposed micro combustor, Reynolds number based on the combustor tube diameter is very low [7–9]. Consequently, suffering from smaller residence time, mixing between fuel and oxidant is likely to become much slower, which may cause relatively longer and sooty luminous flame. In case of non-premixed combustion, to accomplish complete combustion the sum of characteristic mixing and chemical reaction time should be much smaller than residence time. Thus, the mixing enhancement is one of key factors in the development of such a small combustor satisfying another requirement to secure the flame stability. To overcome these problems, the forming of a flow recirculation region inside a combustor can be one of the solutions, which can help the scalar mixing and flame stability. However, according to Zhdanov et al. [10] if general mixing technique is used as does in a large commercial combustor, it may hard in such a small combustor to form a flow recirculation region. To solve these problems, a baffle plate with multiple jets for oxidant and fuel injections is introduced to intensify the mixing between fuel and oxidant and maintain flame stability, simultaneously. From the previous works by Choi et al. [7–9] and Woodfield et al. [11], it is seen that the proposed micro can combustor with multiple jets is very effective to meet the both requirements of mixing enhancement and flame stability.

In the present study, characteristics of turbulent flow and mixing fields in the proposed micro can combustor [3,7–9] are studied by applying the large eddy simulation (LES). Three different types of baffle plates, leading to different values of oxidant to fuel velocity ratio, are numerically tested and instantaneous and time mean quantities for the turbulent flow and mixing are scrutinized. As a result, peculiar characteristics of the turbulent mixing in the micro combustor are elucidated. Multiple recirculating flow regions appear downstream the baffle plate and these regions play an important role for the turbulent scalar mixing between oxidant jets and central fuel jet. Changing the baffle plate geometry, the shape and location of these recirculating flow regions are changed and this has a significant effect on the mixing phenomena.