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Research Paper

Effect of wall thermal conductivity on the stability of catalytic heat-recirculating micro-combustors

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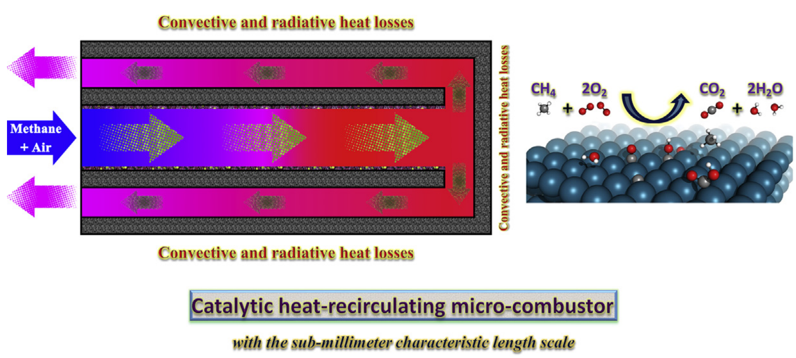
HIGHLIGHTS

- An effective thermal management strategy for heat recuperation was studied.
- The mechanism responsible for the enhancement of stability was explored.
- Heat recirculation has little effect on extinction but greatly affects blowout.
- Heat recirculation is effective only for low conductivity walls.
- Stability diagrams were constructed and design recommendations were made.

GRAPHICAL ABSTRACT



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ABSTRACT

Thermal management strategies for enhancing stability of catalytic micro-combustors via heat recirculation were studied for obtaining design insights. The stability of heat-recirculating systems utilizing catalytic combustion of methane-air mixtures was studied numerically. A two-dimensional computational fluid dynamics model including detailed chemistry and transport was developed to explore the underlying mechanism by which heat recirculation enhances combustion stability. Simulations were performed over a wide range of wall thermal conductivities and flow velocities in order to gain insight in combustion stability and identify suitable ranges of operating conditions, with special emphasis on heat recirculation as a means of understanding energy management at small scales. It was shown that the wall thermal conductivity plays a vital role in determining stability, especially for that of the inner walls. Heat recirculation has little effect on extinction but strongly affect blowout. The optimal design is obtained by the use of all walls with minimal thermal conductivity. For highly conductive walls, heat recirculation does not improve stability significantly, whereas heat recirculation is effective only for low-conductivity walls. The effect of heat recirculation becomes more pronounced with decreasing wall thermal conductivity. Engineering maps that delineate combustion stability were constructed and design recommendations were finally made.

1. Introduction

The rapid advances in micro-fabrication techniques have made possible the development of micro-chemical systems [1]. These systems has been intensely studied due to their fundamental and practical importance, notably their many distinct advantages over

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Nomenclature

$c_{p,k}$	specific heat capacity at constant pressure of the k-th gaseous species
d	gap size, i.e., distance between the plates
D_k^T	thermal diffusion coefficient of the k-th gaseous species
$D_{k,m}$	mixture-average diffusion coefficient of the k-th gaseous species
h	total enthalpy
h_k	chemical enthalpy of the k-th gaseous species
h_o	effective heat-loss coefficient
$k_{ad,k}$	adsorption rate constant of the k-th gaseous species
K_g	total number of gaseous species
K_s	total number of surface species
l	combustor length
m	total number of gaseous and surface species
p	pressure
q	heat flux
R	ideal gas constant
$\dot{s}_m$	heterogeneous molar production rate of the m-th surface species
T	absolute temperature
T_{amb}	ambient temperature
T_o	reference temperature
$T_{w,o}$	temperature at the external surface of the solid wall
u	streamwise velocity component
u_{in}	inlet velocity
v	transverse velocity component
$\vec{V}_k$	diffusion velocity vector of the k-th gaseous species
W_k	molecular weight of the k-th gaseous species
$\bar{W}$	average molecular weight of the gas mixture
x	streamwise coordinate
y	transverse coordinate
Y_k	mass fraction of the k-th gaseous species

Greek variables

Γ	surface site density
δ	thickness of the solid wall
λ	thermal conductivity
μ	dynamic viscosity of gas
ρ	density of gas
σ_m	site occupancy of the m-th surface species
$\dot{\omega}_k$	homogeneous molar production rate of the k-th gaseous species

Subscripts

amb	ambient
g	gas phase
in	inlet
i, j, k, m	species index
o	outer
rad	radiation
s	solid phase
w	wall
x	streamwise component
y	transverse component

large-scale reactors. Examples include extremely high energy densities [2], higher efficiency and selectivity for chemical production [3], inherent safety [4], and abatement of pollutants for energy production [5]. Micro-combustors, among others, are emerging as a powerful tool for portable production of energy [6,7]. They can serve as efficient heat sources for endothermic reactions in integrated micro-chemical systems for the production of hydrogen for fuel cell applications [8,9]. In general, the design of micro-chemical systems requires an in-depth understanding of the fundamentals in these devices.

Considerable progress has been made in understanding of these systems. The fluid-structure interaction within these systems is important [10,11], and heat losses become more significant [12,13]. Consequently, micro-chemical systems based on the existing design for large-scale devices may be impractical. The small scales of these systems make them significantly more prone to loss of combustion stability [14,15]. Therefore, understanding and improving the stability of these systems has attracted considerable interest, and the potential for system instability needs to be exploited for robust design. The importance of heat loss on stability has been illustrated both theoretically [14,15] and experimentally [16,17]. Loss of stability and high wall temperatures are main issues that require careful thermal management. Thermal management is important in minimizing heat loss, mitigating thermal quenching [18–20], and improving efficiency [21,22]. Consequently, these systems could substantially be improved if an effective strategy for heat recuperation is developed.

Less work has been devoted to thermal management in micro-chemical systems. It is often tacitly assumed that these systems are isothermal due to their small scales and large heat-transfer coefficients [23]. However, overall thermal management has been found to play a critical role in determining stability [24–26]. An important concept in the development of thermal management strategies is that of heat recirculation [27–29]. The mechanism of heat recirculation is originally discussed by Egerton et al. [30] and Weinberg [31]. The heat-recirculating combustor, first proposed by Weinberg [32,33], is an “excess enthalpy” burner, in which the hot combustion products are used to preheat the incoming reactants, using a counter-current heat exchanger for thermal management. Furthermore, heat-recirculating systems have been found to be effective, as they offer significant advantages with regard to efficiency [7,34,35], combustion intensity [36], and fuel conservation [37]. Enhanced heat recirculation without an increase in heat losses is essential for extending stability limits. There has been considerable interest in the development of such heat-recirculating systems, and various designs have been proposed [7,29]. Ronney and co-workers have extended this concept on spiral-wound “Swiss roll” heat-recirculating combustors [24,25], which are considered one of the most efficient systems. Increased stability arises from transverse heat recirculation between products and reactants [24,25]. While catalytic combustion benefits from the enhanced mass transfer and thus is advantageous for heat-recirculating systems, appropriate thermal management is of vital importance [23].

Since maximizing thermal efficiency is regarded as the most important criterion, the effects of design parameters on the stability of heat-recirculating systems have been studied theoretically [18,38,39] and experimentally [40–42]. The effect of wall thermal conductivity is very valuable to understand these systems, and its importance in heat recirculation has also been realized using several simplified models [24,25]. It has been demonstrated that the wall thermal conductivity plays a dominant role in heat recirculation [24,43,44], and thus is important in determining stability, which has been illustrated for “Swiss roll” type combustors [24].