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Studies on a heat-recirculating microemitter for a micro thermophotovoltaic system

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Abstract

A new microemitter (microcombustor) configuration for a micro thermophotovoltaic system in which thermal energy is directly converted into electrical energy through thermal radiation was investigated experimentally and computationally. The microemitter as a thermal heat source was designed for a 1–10 W power-generating micro thermophotovoltaic system. To satisfy the primary requirements for designing the microemitter (stable burning in the small confinement, maximum heat transfer through the emitting walls, but uniform distribution of temperature along the walls), the present microemitter is cylindrical with an annular-type shield to apply for the heat-recirculation concept. Results show that the heat recirculation substantially improves the performance of the microemitter: the observed and predicted thermal radiation from the microemitter walls indicated that heat generated in the microemitter is uniformly emitted. Thus, the present microemitter configuration can be applied to the practical micro thermophotovoltaic systems without any moving parts (hence frictional losses and clearance problems are avoided). Ratios of the inner radius of the shield to the gap between the shield and microemitter walls and the microemitter wall thickness substantially affect thermal characteristics.
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Keywords: Micro thermophotovoltaic system; Microemitter; Microcombustion

1. Introduction

Recently, the demand for light, fast-charging and long-lasting portable power sources to replace current lithium-ion batteries has been increasing due to advances in portable electronic devices such as laptop computers, cellular phones, and camcorders. Miniature or microscale (which will be called *micro* hereafter) power systems using combustion of hydrocarbon fuels are considered one of the alternatives, since they can contain more energy per unit mass than lithium-ion batteries and be quickly charged. Thus, various combustion-based micropower devices have been suggested [1].

Many combustion-based micropower systems are scaled down from macroscale heat engines such as gas turbine and rotary engines [1,2]. However, such micro heat engines involving moving parts seem to be impractical, since overcoming heat and friction losses and the difficulties of fabrication and assembly are considered technological challenges for miniaturizing the systems. In order to avoid such technological difficulties in developing micropower systems

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Nomenclature

A	pre-exponential factor
D	mass diffusivity
D_T	thermal diffusion coefficient
E	energy
E_a	activation energy
d_s	inner diameter of shield
d_w	inner diameter of microemitter
g	acceleration of gravity
h	enthalpy
h_c	heat transfer coefficient
$\vec{J}_i$	diffusive mass flux vector
k	thermal conductivity
l	length of main part of microemitter
$\dot{m}_f$	fuel mass flow rate
M_w	molecular weight
n	temperature exponent
N	number of chemical species in the system
p	pressure
Q	volume flow rate
R_i	net rate of production of species i by chemical reaction
r	radial coordinate
R_u	universal gas constant
Re	Reynolds number
S_h	heat sources
T	temperature
t	time
t_g	gap between shield and microemitter walls
t_w	microemitter wall thickness
$\vec{u}$	flow velocity vector
u_r	velocity component in the radial direction
u_x	velocity component in the axial direction
V	averaged microemitter inlet velocity
X_f	mole fraction of fuel
X_i	mole fraction of species i
x	axial coordinate
Y_i	mass fraction of species i
ϕ	fuel-equivalence ratio
γ	ratio of inner radius of shield to gap between shield and microemitter walls, $(d_s/2)/t_g$
μ	viscosity
ρ	density
τ	stress

involving moving parts, Ahn et al. [3] suggested a micro thermoelectric device that consists of a combustor connected with a heat-recirculating (Swiss-roll type) fuel–air mixture inlet and exhaust outlet assembly for reducing heat losses and thermoelectric elements. Maruta and co-workers also conducted experimental and computational studies on Swiss-roll type and radial microcombustor configurations [4,5]. Federici et al. [6] developed another type of micro thermoelectric device using catalytic combustion for stable burning in a relatively simple combustor configuration. Although the micro thermoelectric power systems could much improve the difficulties of fabrication and assembly, there are still technological challenges: complicated structure for homogeneous gas-phase combustion and a maintenance problem due to easily poisoned catalyst surface for catalytic combustion. Schmidt and co-workers developed radiant micro burners applying the heat-recirculation concept and catalytic combustion for reforming various fuels [7,8].

Considering the technological difficulties of the aforementioned combustion-based micropower systems, a novel micro device should be structurally simple and efficient without moving parts. Thermophotovoltaic (TPV) power generators in which photovoltaic (PV) cells generate electric energy from thermal radiation, similarly to solar cells converting the radiative energy of sunlight into electrical power, have been developed for house heating systems and power suppliers in remote areas and as range extenders in electric cars [9,10]. Due to their simple geometry with no moving parts, TPV power systems are expected to be easily scaled down for micropower generation. Recently, effects of major parameters, including the configuration, wall thickness, and materials of microcombustors and mixture compositions, on microcombustion for TVP energy conversion have been investigated [11]. The investigation, however, was carried out only for hydrogen–air mixtures in a simple cylindrical combustor with a backward-facing step. However, practical use of hydrogen for microcombustors is somewhat questionable due to the fuel storage problem, though hydrogen seems to experience less quenching than hydrocarbon fuels.

In the present investigation, a heat-recirculating but still structurally simple microcombustor (microemitter) for micro TPV power systems using hydrocarbons instead of hydrogen to improve volumetric energy density is suggested to guarantee stable burning in the small confinement while effectively transferring heat into the microemitter wall surface and then uniformly radiating into the PV cells. Identifying the structure of microflames in the microemitter,

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