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Research Paper

High efficiency high temperature heat extraction from porous media reciprocal flow burner: Time-averaged model

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HIGHLIGHTS

- High temperature heat extraction from a porous reciprocal flow burner is studied.
- A fast 1-D time-averaged model is developed for parametric studies.
- The heat extraction efficiencies above 90% are predicted after optimization.

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ABSTRACT

The high temperature heat extraction from a porous media reciprocal flow burner (RFB) is studied numerically. In RFB, the air/fuel mixture flow direction is switched periodically to contain and sustain combustion. High temperature heat extraction is essential for the efficient operation of small electrical and thermal systems based on thermoelectric generators, Stirling engines and micro-turbines. In this paper, the efficiency of the heat extraction is studied for different extraction locations, temperatures and equivalence ratios. An 1-D time-averaged model is developed and validated to represent a RFB and to further predict the behavior of the burner. Optimization on the burner's geometry is also performed to increase the heat extraction efficiency.

1. Introduction

The development of small-scale and portable energy generators based on thermoelectric devices and Stirling engines requires high temperature sources capable to operate with high energy efficiency. Hydrocarbon fuels have high energy densities and remain preferable primary energy sources to supply high temperature loads. However, the low high-temperature efficiencies of conventional burners and the urge to decrease pollutant released by combustion motivate the development of more effective burner designs. One of the designs is porous media reciprocal flow burner (RFB). Compared to conventional burner, RFB allows gaseous fuel to burn in a wide range of equivalence ratios, has a higher efficiency in terms of energy extraction, and generates lower NO_x and CO emissions [1,2].

Porous media burners takes advantage of the strong interaction between solid and gas phase. The solid matrix absorbs and stores the energy released from combustion and transfers it to low temperature fuel/air mixture for preheating and ignition. The solid matrix generally has a high heat capacity, allowing it to keep a high temperature, thus sustaining the flame, resulting in a much wider range of flammability than combustion in free space.

Porous media reciprocal flow burner, as its name suggests, changes flow direction periodically. Unlike conventional burner, RFB stabilizes a gaseous flame in a porous media using a self-adjusted heat recuperation process. In RFB, the combustion temperature of air/fuel mixture is independent of the adiabatic combustion temperature. The former could be lower (underadiabatic) or higher (superadiabatic) than latter. In superadiabatic or excess enthalpy combustion, as described by Weinberg [3], energy from burnt gas is 'borrowed' to pre-heat unburnt air/fuel mixture. The flame containment is attained by switching the direction of premixed combustible flow periodically, using the thermal energy stored in the solid phase during last cycle to preheat and ignite the flow. The efficient regeneration of thermal energy in solid phase paves way to achieving high thermal extraction efficiencies.

The performance of RFB is influenced mainly by three aspects, the design of reactor, the efficiency of heat extraction and the properties of air/fuel mixture [4]. The performance of packed bed reactors depends on material and structure of the porous medium [5–7], the geometry and properties of combustion chamber and the presence of catalyst [8]. The heat extraction can be performed with an intermediate heat

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Nomenclature

A	Arrhenius pre-exponential factor
c	specific heat
C	mole fraction
D_{ax}	axial dispersion coefficient
d	packed bed pellet diameter
E_a	activation energy
F	radiative heat exchange factor
H_{chem}	heat of chemical reaction
h_v	volumetric heat transfer coefficient
k	thermal conductivity
L	length
LHV	low heating value
$\dot{m}$	mass flow rate
$\dot{Q}_e$	heat extraction rate
T	temperature
v	velocity
x	axial coordinate
y	mass fraction
W	volumetric products production rate

Greek symbols

β	heat exchange coefficient
γ	mass fraction of CH_4 in unburned stream
ϵ	porosity
ρ	density
σ	Stephan–Boltzmann constant
ϕ	equivalence ratio

Subsripts

e	extraction
g	gas
i	initial
p	product
s	solid
0	room
1	upper channel
2	lower channel

exchanger [9] or directly with a thermoelectric energy converter [10].

A number of numerical models have been developed to study the behavior of RFB. One-dimensional and two-dimensional models are very common in previous research. Contarin et al. [11] built a numerical one-dimensional model to study the efficiency of low temperature heat extraction. Bubnovich et al. [12] gave a one-dimensional analytical solution by dividing the reactor into three regions: the preheating region, the moving reaction region, and the region occupied by products. Laguerre et al. [13] compared two simulated temperature profiles, which were generated by commercial software Fluent and self-developed codes, respectively, with experimental results. Zheng et al. [14] used a two-dimensional Fluent model to study inclinational instability of porous flame. Three-dimensional models are rarely adopted, because of their heavy computational duties.

Porous media combustion has a variety of applications [15]. Other than a portable power source for small electronic devices, it can drive

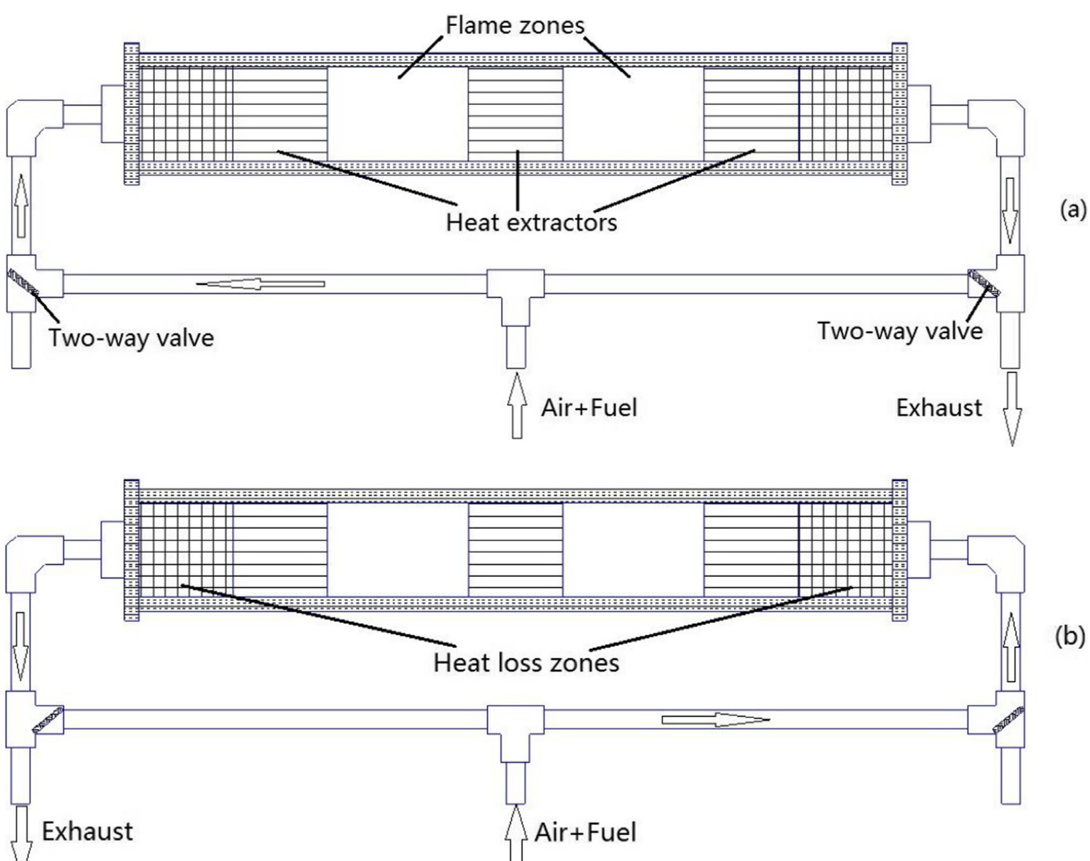

Fig. 1. Reciprocal flow burner (a) first half-cycle (b) second half-cycle.