Modelling of Thermoelectric Power Generation by Porous Media Burner

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A system for converting combustion heat into electric power is proposed in this work on the basis of super-adiabatic combustion in a thermoelectric porous element. A lean gas mixture is introduced into the porous medium, where the gas flow rate changes at a regular interval of time. As a result, the combustion front remains at a predetermined region of the porous medium. A steady state temperature distribution is established along the flow direction, resulting in a steep temperature gradient in the thermoelectric porous element. Numerical simulation showed that the total thermal efficiency reaches 4.6 %, almost equal to the conversion efficiency of the thermoelectric element itself. Consequently, using the proposed system, the chemical energy can be effectively converted into electric power.

1. Introduction

Porous media burners can provide a number of advantages compared to conventional combustion systems due to the heat recirculation provided by the solid matrix such as large power variation range, high efficiency, compact structure with very high transport area, extremely low CO and NO_x emission over a wide range of thermal loads and stable combustion at different equivalence ratios, $0.4 < \Phi < 0.9$ (Mößbauer et al., 1999). One of the most important problems of porous media burners is flame stabilization in a specific zone of the inert porous medium (Bubnovich et al., 2011, Bubnovich et al., 2009). The motion of the combustion zone results in positive or negative enthalpy fluxes between the reacting gas and solid porous media (Babkin, 1993). As a result, observed combustion temperatures can significantly differ from adiabatic predictions. Upstream wave propagation, countercurrent to the gas flow, results in subadiabatic combustion temperatures while downstream propagation of the wave leads to combustion in the superadiabatic regime with temperatures much in excess of the adiabatic temperature (Contarin et al, 2003, Bubnovich and Toledo, 2005). This has been used to burn extremely lean mixtures either in porous burners as well as in combustion engines, in converting methane to hydrogen (Toledo et al., 2006).and in direct energy conversion

Recently, a new system for converting combustion heat into electric power was proposed by Hanamura et al. (2005) on the basis of reciprocating-flow super-adiabatic combustion in a catalytic and thermoelectric porous element. The total thermal efficiency obtained in his work reaches 4.7% using low calorific gas mixtures. In this work, a strong temperature gradient is generated within the porous media, changing input flow rates, at a regular interval of time, defined by analyzing the combustion wave dynamic curves. As a result, the combustion front holds oscillating around of a confined position adjacent to the thermoelectric elements which have a maximum allowed temperature of 1000 K.

2. Problem Formulation

The burner is a quartz tube of length L= 50 (cm), outer diameter d_t = 76 (mm), filled with alumina spheres of diameter d_0 = 4.8 (mm), giving volumetric porosity m = 0.4. Combustion wave confinement is achieved by periodically changing flow inlet velocity. Using $FeSi_2$ as thermoelectric elements with 5% efficiency.

2.1 Governing equations

Inside the porous media burner, temperature and composition profiles are assumed one-dimensional. Chemical reaction of combustion (CH_4/Air) is homogenous and presented in a one-step kinetics model: $CH_4 + 2\Phi^{-1}(O_2 + 3.76N_2) \rightarrow \text{PRODUCTS}$. Ideal gas behavior is assumed due to operating conditions of low pressures (1 atm) and high temperatures (1000 – 1800 K) in the combustion zone.
Continuity, mass fuel conservation, gas and solid phase energy equations are presented:

$$\frac{\partial(\rho_g \cdot u_g)}{\partial z} = 0 \tag{1}$$

$$\rho_g \frac{\partial w_i}{\partial t} + \rho_g \cdot u_g \frac{\partial w_i}{\partial z} = \frac{\partial}{\partial z} \rho_g \cdot D \frac{\partial w_i}{\partial z} + r_i \tag{2}$$

$$\rho_g \cdot Cp_g \left(\frac{\partial T_g}{\partial t} + u_g \frac{\partial T_g}{\partial z} \right) = \frac{\partial}{\partial z} \left(\lambda_g \frac{\partial T_g}{\partial z} \right) - \frac{\alpha_{vol}}{m} \cdot (T_g - T_s) - r_i \cdot \Delta h_c \tag{3}$$

$$(1-m) \cdot \rho_s \cdot C_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \left(\lambda_{eff} \frac{\partial T_s}{\partial z} \right) + \alpha_{vol} \cdot (T_g - T_s) - \beta \cdot (T_s - T_{ext}) \tag{4}$$

Where u_g filtration velocity of gas mixture, ρ_g gas density, w_i methane mass fraction, D_g gas diffusivity, c_p heat capacity, λ_g conductivity of gas mixture, α_{vol} volumetric heat transfer coefficient between solid and gas phases, Δh_c lower heating value of reaction, T_0 initial temperature, T_s solid temperature, λ_{eff} solid effective thermal conductivity corrected by radiation, β as the volumetric energy losses coefficient. Physical properties of gas mixture are available at Bubnovich et al. (2009).
Using an Arrhenius model for the fuel reaction rate:

$$r_i = -K_0 \cdot w_i \cdot \rho_g \exp\left(-E / R \cdot T_g\right) \tag{5}$$

Frequency factor and activation energy are $K_0 = 2.6 \cdot 10^8$ (1/s), E/R = 15643.8 (K).

Initial and boundary conditions are:

$$t = 0: \quad T_g = T_s = T_0 = 300\ \text{K}, \quad w = w_0 = \left(1 + 17.16 \cdot \Phi^{-1}\right)^{-1} \tag{6}$$

$$z = 0: \quad T_g = T_s = T_0, \quad u_g = u_0, \quad w = w_0 \quad \text{and} \quad z = L: \quad \frac{\partial T_g}{\partial z} = \frac{\partial T_s}{\partial z} = \frac{\partial w}{\partial z} = 0 \tag{7}$$

2.2 Numerical solution of equations

Mathematical model are discretized by finite differences method through implicit scheme and its solution reached by TDMA algorithm. Uniform grid with 1001 nodes and time step Δt = 0.01 (s) gave solution independence.

3. Problem Solution

3.1 Dynamic curves

A strong temperature gradient is generated within the porous media, switching input flow rate, at a regular interval of time, within intervals defined by analyzing the dynamic curves presented in Fig. 1, determining combustion front speed value and direction. As a result, the combustion front holds oscillating around of a preset porous media position where the thermoelectric elements are inserted. The study was centered in 3 different cases which are presented in table 1.

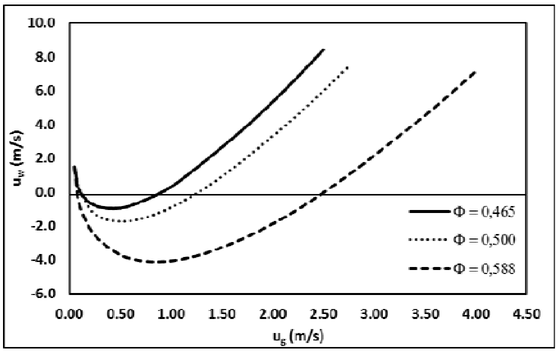

Figure 1: Dynamic curves for the porous media burner.

Table 1: Velocities inside combustion burner for different equivalence ratios

Φ	Low Velocity	High Velocity
0.588	1.25	3.25
0.500	0.5	1.7
0.465	0.5	1.7

3.2 Solid phase temperatures

Simulations were performed using 15 cycles considering a cycle is completed when filtration gas velocity magnitude is modified. We have considered even cycles when the flame is traveling countercurrent to the gas flow and odd cycles when the flame is flowing co-current with the gas mixture. Temperatures in even and odd cycles appear in Figure 2. At odd cycles superadiabatic temperatures were reached while at even cycles subadiabatic temperatures were observed in the burner.

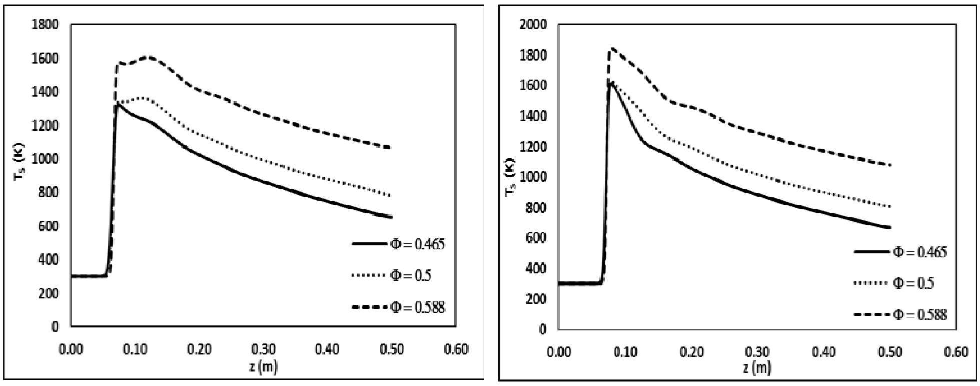

Figure 2:a) Solid matrix temperature at even cycles. Flame position is at x=0.0695 (m). b) Solid matrix temperature at odd cycles. Flame position is at x=0.0745 (m).

3.3 Thermal efficiency

Thermal efficiency is defined as the ratio of electrical power generated from the thermoelectric element and inlet gas combustion energy. Electrical power is evaluated at the maximum allowed temperature gradient and thermoelectric element efficiency:

$$\eta_t = \frac{W_e}{\rho_m \cdot u_f \cdot \Delta h_c} = \frac{\eta_{elec} \cdot \left| \lambda_s \cdot \frac{\partial T_s}{\partial z} \right|_{\max}}{\rho_m \cdot u_f \cdot \Delta h_c} \quad (8)$$

Where: η_{elec} thermoelectric element efficiency, W_e electrical power generated, η_t thermal efficiency, ρ_m fuel density, u_f superficial inlet velocity. Maximum temperature allowed by the thermoelectric element is considered at 1000 K, thus maximum temperature gradient will be chosen accordingly to that condition.

The thermoelectric element was considered fixed in one position of the burner regardless if the cycle was odd or even. Consequently, thermal efficiency was estimated as an average of both cycles with the results presented in table 2.

4. Conclusions

The electric power generated by super-adiabatic and sub-adiabatic combustion in the thermoelectric porous media burner has been estimated through numerical simulation.

Average thermal efficiencies reach a maximum of 4.64 %, almost equal to the conversion efficiency of the thermoelectric element itself. This means that 92.8 % of the combustion heat flows through the thermoelectric element by conduction.

Table 2: Total thermal efficiency for different equivalence ratios

Φ	η_t
0.588	2.85 %
0.500	4.64 %
0.465	3.68 %

Total thermal efficiency increases with poorer feeding mixtures but in the case of equivalence ratio equal to 0.465 combustion wave velocities where different between cycles and therefore the combustion wave moved faster co-current than counter-current which means that the thermoelectric element was exposed with super-adiabatic temperature less time than sub-adiabatic temperatures.

Consequently, using the system proposed here, the chemical energy of combustion can be effectively converted into electric power in this type of burner where heat recirculation is enhanced by the presence of a porous matrix.

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5. Nomenclature

5.1 List of symbols

c	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
d_0	Particle diameter (m)
D_g	Molecular diffusivity coefficient ($m^2 \cdot s^{-1}$)
E	Activation energy ($J \cdot mol^{-1}$)
K_0	Frequency factor (s^{-1})
L	Tube length (m)
m	Porosity
R	Universal gas constant ($J \cdot mol^{-1} \cdot K^{-1}$)
r_i	Consumption rate of methane ($kg \cdot s^{-1} \cdot m^{-3}$)
t	Time (s)
u_g	Gas filtration velocity ($m \cdot s^{-1}$)
u_f	Inlet superficial gas velocity ($m \cdot s^{-1}$)
u_w	Combustion wave velocity ($m \cdot s^{-1}$)
$\mathrm{W_e}$	Electric power ($kW \cdot m^{-2}$)
w_i	Mass fraction of methane
z	Axial direction (m)

5.2 Greek letters

α_{vol}	Volumetric heat transfer coefficient between phases ($W \cdot m^{-3} \cdot K^{-1}$)
β	Volumetric energy losses coefficient to the environment ($W \cdot m^{-3} \cdot K^{-1}$)
ρ	Density ($kg \cdot m^{-3}$)
Φ	Equivalence ratio
λ	Thermal conductivity ($W \cdot K^{-1} \cdot m^{-1}$)
Δh_c	Specific reaction heat of methane ($kJ \cdot kg^{-1}$)
η_t	Thermal efficiency
η_{elec}	Thermoelectric element efficiency

5.3 Subscripts

w	Relative to combustion wave
max	Maximum
m	Relative to methane
s	Medium porous
g	Gaseous Mixture
0	Initial

References

Babkin V. S., 1993, Filtrational combustion of gases. Present state of affairs and prospects, Pure & Applied Chemistry, 65, 335-344.

Bubnovich V. and Toledo M., 2005, Analytical Modelyng of Filtration Combustion in Packed Bed, Chemical Engineering Transactions, 7, 273-278.

Bubnovich V., Henriquez L., Diaz C. and Maiza M., 2011, Diameter of alumina balls effect on stabilization operation region for a reciprocal flow burner, International Journal of Heat and Mass Transfer, 54, 2026-2033.

Bubnovich V., Henriquez L., Diaz C. and Avila E., 2009, Stabilization Operation Region for a Reciprocal Flow Burner, Recent Advances in Applied and Theoretical Mechanics, Proceedings of the 5th WSEAS International Conference on Applied and Theoretical Mechanics, 114-119.

Contarin F., Saveliev A. V., Fridman A. A. and Kennedy L. A., 2003, A reciprocal flow filtration combustor with embedded heat exchangers: numerical study, International Journal of Heat and Mass Transfer, 46, 949-961.

Hanamura K., Kumano T. and Iida Y., 2005, Electric power generation by super-adiabatic combustion in thermoelectric porous element, Energy, 30, 347-357.

Kaviany M., Park C.W., 2000, Combustion-Thermoelectric Tube, Journal of Heat Transfer, ASME Transactions Journals, 122, 721-729.

Mößbauer S., Pickenäcker O., Pickenäcker K. and Trimis D., 1999, Application of the Porous Burner Technology in Energy and Heat – Engineering, Fifth International Conference on Technologies and Combustion for a Clean Environment, 1, 519-523.

Toledo M., Bubnovich V., Saveliev A. and Kennedy L., 2006, Filtration Combustion of Methane, Ethane, and Propane Mixtures with Air, WSEAS Transactions on Heat and Mass Transfer, 1, 283 – 292.