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High temperature heat extraction from counterflow porous burner

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ABSTRACT

Energy extraction from an adiabatic regenerative porous burner is studied numerically. Steady state governing equations are solved to predict the fluid and thermal properties of the system. The temperature of heat extraction is varied from 300 K to 1300 K. The numerical simulation predicts the effect of efficiency of energy extraction on the location and extraction temperature of heat exchangers. Higher extraction temperatures tend to decrease the extracted energy and consequently raise the exhaust temperature of the burner. Two burner configurations are studied comparatively by changing the properties of the wall separating the incoming reactants from the exhaust gases. Out of the two materials used to study the effect of separation wall on energy extraction, the study predicts higher gains for alumina as compared to silicon carbide. The maximum heat extraction efficiency of 35% is reported for extraction at 1300 K when silicon carbide separation wall is used in the burner. Whereas for porous burner with alumina separation wall, 60% of the heat can be extracted at 1300 K.

1. Introduction

The constant decline in the global fossil fuel reserves have sent a ripple through humanity to invent methods of harnessing energy at higher efficiencies. There has been an immense push to identify environmentally friendly technologies to generate electricity economically. The concept of using a porous micro burner for burning lean fuel/air mixtures and extract the high temperature heat to generate electricity, leads to an environment friendly path for compact power generation systems.

Using a porous combustor over non-porous combustor has certain advantages other than stabilizing the flame within a shorter length of burner. The presence of porous medium in a micro burner results in efficient heat transfer between the solid and the gas phase and helps in intense mixing of the products and reactants. This intermixing enhances the effective heat transfer in the gas phase. Weinberg [1] provided the idea of heat recirculation inside a burner in 1971. He found that recirculating some of the heat from the hot flame zone to cold reactant zone (without diluting reactants with combustion products) results in flame temperatures higher than the adiabatic flame temperature. This phenomenon leads to higher thermodynamic efficiency for converting heat to power. Babkin [2] concluded that for low velocity regimes of gaseous filtration combustion, strong interfacial heat transfer reduces thermal non-equilibrium between the gas and the solid phase. Some of the recent studies on the porous media combustion can also be seen in [3–5].

The ability of porous medium to recuperate heat from the reaction zone to the incoming reactants differentiates the filtration combustion from homogenous oxidation [6,7]. Downstream the flame zone the hot gases transfers the heat to the solid porous matrix through convection, the solid porous medium conducts and radiates the heat upstream the combustor. This increases the flammability limits [8]. In the past few years, researchers have been able to build systems to recirculate heat based on convection [1,9], conduction using porous plug [10] and radiation heat transfer in a porous medium [10,11]. Porous burners have already found their ways in the market. Some of the applications of the porous burners include water and space heating, chemical processing, coating and paint drying, metal heat treating, wood drying and food processing [11,12].

Filtration combustion deals with stationary [13–16] and transient flames [17,18]. The upstream displacement of combustion front results in underadiabatic flame [19] whereas the downstream displacement creates superadiabatic flame temperatures [15]. Superadiabatic combustion is known to significantly extend the flammability limits to the regimes of fuel/air mixtures with very low heat content. Since the last two decades, researchers have mainly worked with two types of porous burners namely counterflow burner and reciprocal flow burners. There are considerable amount of articles related to flame stabilization in porous burners [20,21]. Different designs of porous burner are studied to reach to the conclusion that heat recirculation results in better performance

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Nomenclature

c	specific heat at constant pressure
C	coefficient of inertial resistance
D_{ax}	thermal dispersion in porous media
D_m	diffusion coefficient of species
D_P	pellet diameter
F	radiative heat exchange factor
h_i	molar enthalpy of species i
h_v	volumetric convective heat transfer coefficient
k	thermal conductivity
LHV	lower heating value
$\dot{m}$	mass flow rate
T	temperature
q_e	rate of heat extraction by heat exchanger
v	velocity
p	pressure
W	molar mass
x	distance along the burner axis
Y	mass fraction

Greek symbols

α	coefficient for viscous resistance
ε	porosity
ϕ	equivalence ratio
ρ	density
σ	Stephan-Boltzmann constant
μ	mass averaged viscosity
$\dot{\omega}$	molar rate of production of species

Subscripts

CH_4	methane
eff	effective
f	fluid
g	gas
i	species
in	interstitial
o	ambient
rad	radiation
s	solid
su	superficial

and enhancement of the flammability limits [22–28]. Bubnovich et al. studied electric power generation from combustion in porous media [29]. Some of the studies are aimed towards radiant burners [15–17,30,31] and surface combustor heaters, where tubes of coolant are embedded in the porous matrix [14,32]. Few researchers reported the effect of thermal conductivity of the burner casing wall on the heat recirculation and flame stabilization of the porous burner [33,34]. High temperature heat extracted from the excess enthalpy porous burners can be applied for portable power generation using thermoelectric converters and Stirling engines.

Present article studies the heat extraction from an excess enthalpy porous burner arranged in a conterflow configuration. The heat extraction efficiency is analyzed for six different heat exchanger positions inside the burner and heat extraction temperatures from 300 K to 1300 K. The heat recirculation in the burner is studied for two materials of the burner wall. The influence of superficial velocity of fuel-air stream on the heat extraction efficiency is evaluated.

2. Numerical model

The schematic diagram of the computational model is shown in Fig. 1. A premixed mixture of methane/air enters the burner of dimension 20 × 2.5 cm. The inlet and outlet of the porous burner is separated by a 0.5 cm thick ceramic wall. The heat exchangers are modelled as 2-D cylinders with a diameter of 0.6 cm. Constant temperature is imposed on the walls of the cylindrical heat exchangers and their location is varied at every 5 cm, with initial location being 6 cm from the inlet. Ceramic spheres of alumina having 0.3 cm diameter is used to generate 40% porosity. The assumptions used to simulate the phenomenon are: (i) thermodynamic properties of the fuel-air mixture and combustion products are functions of temperature and concentration, (ii) thermal equilibrium exists between the gas and the solid phase, (iii) pressure drop across the flame is negligible, (iv) the solid spheres comprising the porous medium are homogeneously distributed, (v) the flow is one dimensional and incompressible, (vi) the gaseous radiation is neglected compared to the solid radiation, (vi) the solid spheres forming the porous medium are non-catalytic. Lean mixture of fuel/air is fed into the burner at a specific superficial velocity ranging from 0.16 m/s to 0.76 m/s. Heat exchangers P_i and P_o are placed near the inlet and outlet of the system to stabilize the flame inside the burner. These heat exchangers are maintained at 300 K. Fuel/air mixture burns in the inlet channel and the hot exhaust gases leaves the system through the exhaust channel. The ceramic wall separates the exhaust mixture from fresh charge of fuel entering the burner, transfers heat from the firing channel to the exhaust channel and also from the exhaust channel to the incoming reactants, thus preheating the reactants.

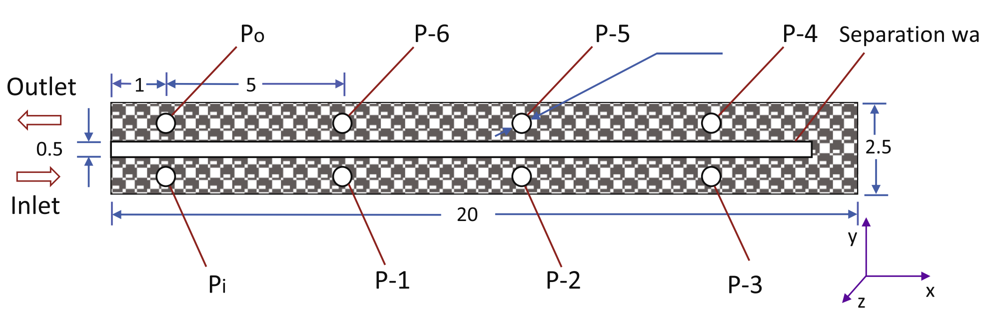

Fig. 1. Schematic of the porous burner showing the positions of the heat exchangers. The dimensions are expressed in cm.