

EXPERIMENTAL STUDY OF OPERATING RANGE AND RADIATION EFFICIENCY OF A METAL POROUS BURNER

by

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In this paper, a radiant metal porous burner which is formed from wire mesh layers is studied. Surface temperature of the burner is measured in different equivalence ratios and firing rates and radiation efficiency is calculated for each case. The experiments are performed for different thicknesses of the porous medium. The results show that the surface temperature increases with increasing firing rate and maximum surface temperature occurs in a lean mixture. Comparing the results for different thicknesses shows that maximum surface temperature is obtained in a medium with three-layer of wire mesh. The radiation efficiency of the burner decreases with increasing firing rate. The maximum radiation efficiency is about 30 percent which is obtained in three-layer of wire mesh in the minimum firing rate. Comparison of the results with the other works shows a good agreement between them.

Key words: porous medium, radiant burner, wire mesh, radiation efficiency, surface temperature

Introduction

In the past few years radiant porous burners are developed due to their potential advantages such as high radiation efficiency, low emission of NO_x, high flame speed, lower burner dimension, and ability to operate in low equivalence ratio [1, 2]. However, in order to use these advantages, flame should be stabilized in the porous bed. Flame stabilization is an important issue in the porous radiant burners.

Sathe *et al.* [3] experimentally studied the stability and heat transfer characteristics of lean premixed methane-air flames in a porous burner. They obtained flame speed and radiant output for different equivalence ratio of the input mixture. The results indicate that a stable combustion can be maintained either in the upstream half of the porous region or near the exit plane. The heat release and radiant output increase as the flame is shifted towards the middle of the porous layer.

Howell *et al.* [4] described the structural properties of non-catalytic porous media and their heat transfer properties experimentally. They presented the effects of the properties of po-

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rous matrix on reaction rates, flammability limits, flame stabilization, exhaust emissions, and radiant output from the burner. Mital *et al.* [5] studied flame stabilization in a radiant burner made of reticulated ceramic matrices in terms of stability limits, radiation efficiencies, and global pollutant emission indices. They obtained temperature profiles and species data and were observed quenching at the ceramic matrix and very broad reaction zone. Also they reported tendency of the burner to flash back with increasing firing rate. Khandelwal and Kumar [6] carried out an experimental investigation on the effect of mixture equivalence ratio and flow rate on the shape, position, and stability of flame and emissions in a diverging channel. Flames obtained for rich mixtures are more stable than that of lean mixtures. Bubnovich *et al.* [7] studied conditions for flame stabilization and provided some temperature profiles in the porous medium and product composition. Qiu and Hayden [8] focused on thermophotovoltaic (TPV) power generation using natural gas-fired radiant burners. These burners were used as radiation sources. It was found that for a non-surface combustion radiant burner; the radiation output can be enhanced using a thermal radiator with a porous structure. At another research, they studied oxygen-enriched combustion of natural gas in ceramic porous radiant burners [9]. They showed that heat recuperation affects combustion behavior and leads to a significant increase in the radiant efficiency even under modest air preheating. Also they showed that the effect of heat recuperation on radiant efficiency appears to become somewhat smaller when the oxygen concentration is increased in combustion air.

Various porous media are typically used with different structures [10, 11]. Wire mesh network is one of these structures. Thermal shock resistance of metal alloys is high. Emissivity coefficient for metal alloys is changed according to the alloy surface. Variation range of emissivity coefficient for the metallic alloys at 300 K is between of 0.045 to 0.5 [1]. Obviously, this values increases when these alloys are used as a porous medium. The reason is that the porous medium closes to a black body due to multiple holes and absorption of radiation in the holes [12].

Less research on metal porous burners has been done in comparison with the ceramic media [13-20]. Some experiments were carried out by Christo *et al.* [21] on a metal fiber burner. Surface temperature, exit gas temperature and rate of radiation were measured. They showed that with increasing firing rate surface temperature increases and radiation efficiency decreases. Also, the maximum temperature occurs in a lean mixture.

Leonardi *et al.* [22] experimentally studied a combined metal porous burner made from woven metal alloy fiber pads. They measured the burner surface temperature, exit gas temperatures and total radiation and convection efficiencies. They showed that the burner surface temperatures increase with firing rate and total efficiencies and surface temperatures for a single-layer pad are lower than that of a double layer pad.

Vogel and Ellzey [23] investigated a two-section burner made of metal foam. At equivalence ratios of 0.65 and below, stable combustion both above and below the laminar flame speed was observed; at higher equivalence ratios the burner could operate in below the laminar flame speed only.

The effect of thickness of porous medium on performance of a radiant burner has not been considered mainly at the previous works. In the present work, the effect of thickness in a wide operating range via firing rate (FR) and equivalence ratio (ϕ) on the performance of a metal porous burner is experimentally studied.

Test device

Test device is shown in fig. 1. For air and gas flow measurement, two rotameters are used with ranges proportional to the flows, as shown in fig. 1. According to the information ob-

tained from the local gas company, the natural gas density is considered at 0.744 kg/m^3 and net heating value is about 35170 kJ/m^3 . The porous medium consists of several mesh layers with square cross-section has an effective area (A) of 0.012 m^2 . A single mesh layer has approximately 6 pores in centimeter (6 ppc) and its thickness is 0.5 mm. INCONEL alloy has a high temperature resistance that suitable for this type of radiation burner. Figure 2 shows the used

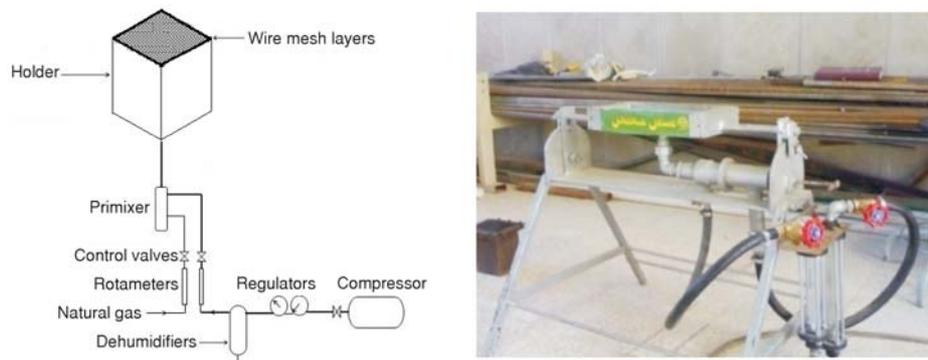


Figure 1. The porous burner test set

mesh.

Surface temperature of the burner is measured using an infrared radiation thermometer (pyrometer). This method is recommended by many researches *e. g.* [21, 24]. The used infrared pyrometer in this work is made by SMART SENSOR Corporation with model RS232. Measurable temperature range of this pyrometer is set between 18 and $1650 \text{ }^\circ\text{C}$.

This type of thermometer compute an effective surface temperature based on the radiation output from the surface. Surface temperature measurement using pyrometer requires the emissivity factor of the surface. The value of emissivity coefficient is assumed to be 0.8 [21].

Two parameters used in the experiments are; equivalence ratio and firing rate. Firing rate is obtained from the relation:

$$FR = \frac{LHV\dot{m}_f}{A} \quad (1)$$

where LHV , \dot{m}_f , and A are heating value, mass flow rate of the fuel, and burner section area, respectively. Firing rate is changed with changing \dot{m}_f and equivalence ratio is change with changing air flow rate (in a fixed \dot{m}_f).

Test results

The results are demonstrated in five firing rates include 98 kW/m^2 , 196 kW/m^2 , 294 kW/m^2 , 392 kW/m^2 , and 490 kW/m^2 . It should be noted that the flow rate of inlet air is so adopted that the flame becomes stable in the medium. So in less and more air flow rate than that is shown, a stable flame is not obtained. This means that the flame may blow out or flash back.



Figure 2. A photograph of used wire-mesh

Surface temperature of the burner with 2 to 7 layers of wire mesh are measured for different firing rates and equivalence ratios. Radiation efficiency for each case is calculated using the obtained surface temperature. Some tests were repeated several times and no significant change was observed.

It is necessary to conduct a special procedure in order to produce a stable flame in the medium. In fig. 3 the procedure of flame formation is shown in 3 layers mesh medium. At the first stage, the fuel valve opens so that the desired fuel flow rate (and so the firing rate) are obtained. A flame is formed upon the surface of the burner with applying a spark. In this case a yellow diffusion flame is observed on top of the burner, fig. 3(a). Then, the inlet air valve opens. With increasing air flow rate, the flame height decreases and color of the flame changes from yellow to blue, fig. 3(b) and (c). With further increase in air flow rate, surface color becomes red gradually and free flame is disappeared, fig. 3(d). With increasing excess air, the surface creates a uniform combustion surface, fig. 3(e) and (f). More increase in inlet air flow rate over a specified limit causes flame extinction.

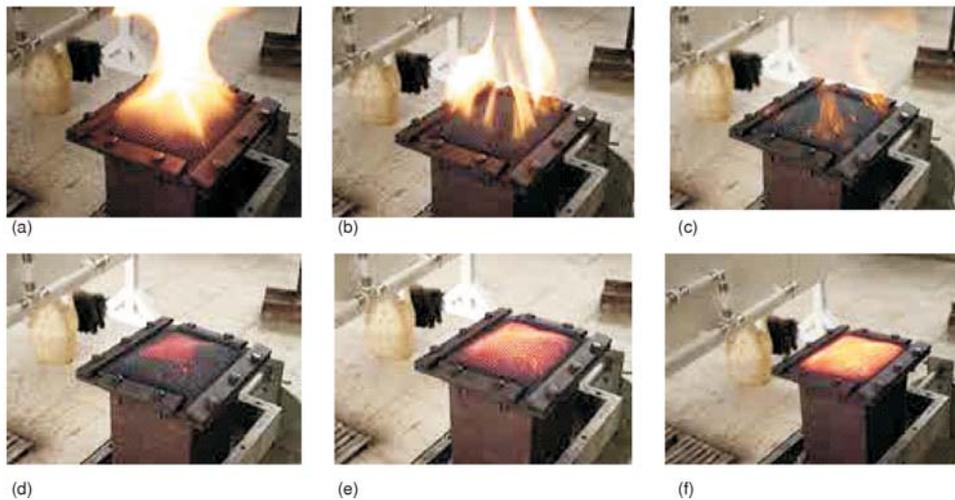


Figure 3. Photographs of the proceeding of flame formed at a burner with 3 layer of mesh

Figure 4 shows the profile of surface temperature vs. equivalence ratio in different firing rates for different number of mesh layers.

The flame does not form in the seven mesh layers porous medium in $FR = 98 \text{ kW/m}^2$, so the results are presented for remaining 4 firing rates. Figure 4 shows that flammability limit which states versus equivalence ratio is different at each firing rate. The maximum flammability limit is in $FR = 98 \text{ kW/m}^2$ where equivalence ratio is extended from 0.5 to 1.3. In general, the flammability limit becomes smaller with increasing firing rate.

Some parameters which affects surface temperature of the burner are; input energy (which is a function of FR), heat losses (to the holder), hot gases velocity (which is a function of ϕ and FR), hot gases temperature (or flame temperature which is a function of ϕ and flame position).

Surface temperature is determined by the heat transferred from hot gases to the wire mesh (Q_1) and heat loss from the wire mesh to the holder (Q_{loss}) and radiative heat transfer from the wire mesh (Q_{rad}) and returned heat (Q_{re}) to preheating region (region before flame zone):

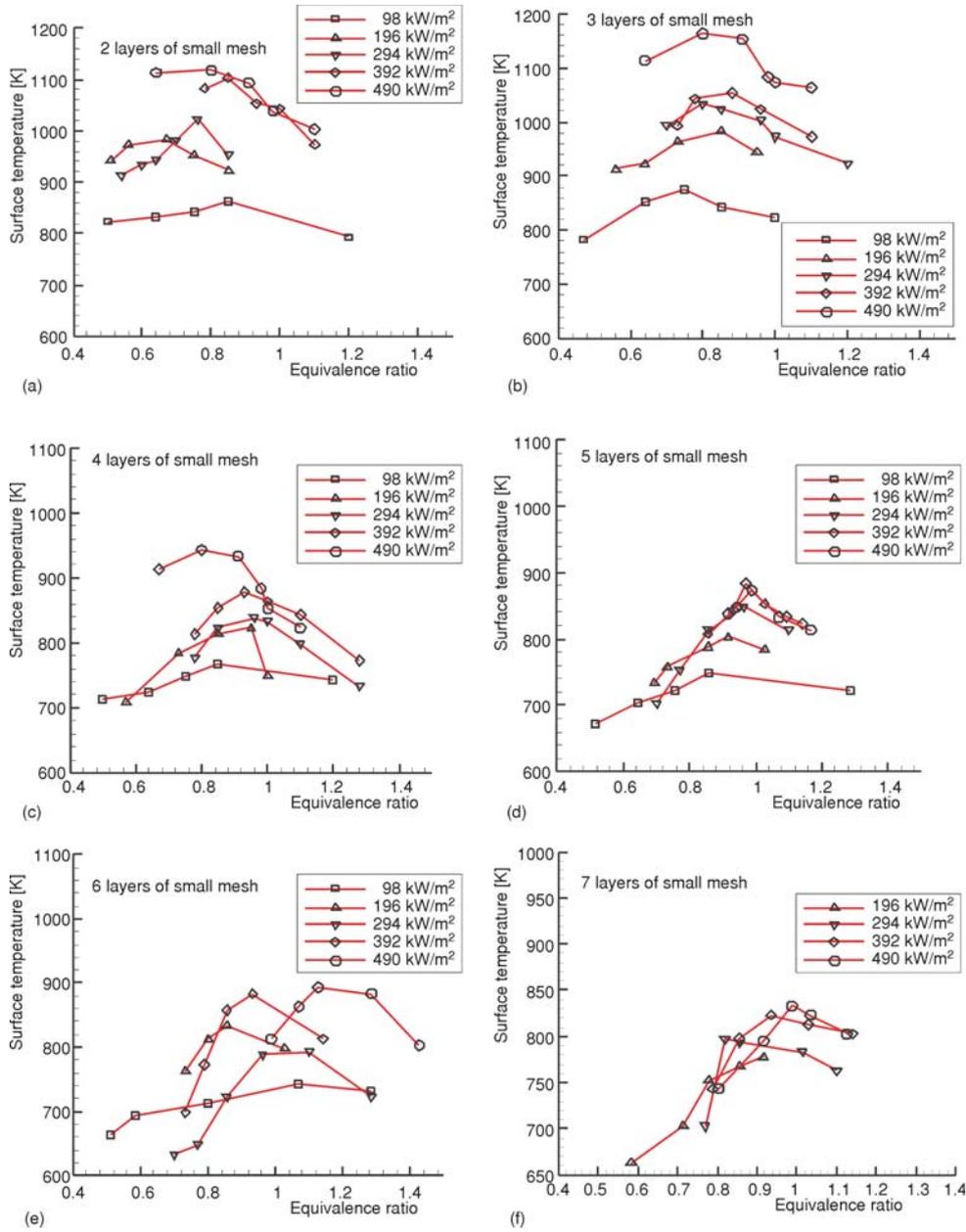


Figure 4. Surface temperature for burner with (a) 2 layer mesh, (b) 3 layer mesh, (c) 4 layer mesh, (d) 5 layer mesh, (e) 6 layer mesh, and (f) 7 layer mesh

$$T_s \propto (Q_t - Q_{\text{loss}} - Q_{\text{rad}}), \quad Q_{\text{re}}, \quad \delta \quad (2)$$

where δ is the flame position from bottom and Q_t , Q_{re} , and Q_{loss} are:

$$Q_t \propto h(V) \cdot T_g(\varphi), \quad V \propto FR, \varphi, \quad Q_{\text{loss}} \propto k, T_s, \quad Q_{\text{re}} \propto d, \delta, k, \alpha, T \quad (3)$$

where, h , V , φ , T_g , d , k , α , and T_s are convection heat transfer coefficient, gas velocity, equivalence ratio, gas temperature, thickness of porous medium, conductivity heat transfer coefficient, absorption coefficient, and wire mesh temperature. The relation can explain the results. It can be observed that increasing FR causes Q_t to be increased and hence T_s increases. In a conventional free flame T_{max} occurs in a slightly rich mixture ($\varphi > 1$) [24] but in this porous burner it occurs in $\varphi < 1$. Its reason is that in a FR , decreasing φ causes V and subsequently h to increase. So according to relation (2) and (3) it would be expected that T_{max} to have a maximum value in $\varphi < 1$ region as can be seen in fig. 4.

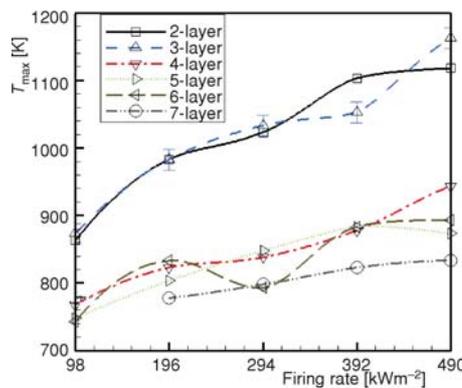


Figure 5. Maximum surface temperature for different layers

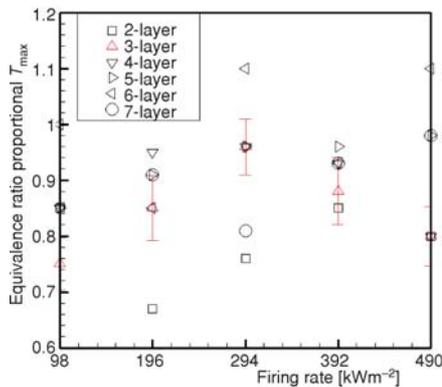


Figure 6. Equivalences ratio corresponds to maximum surface temperature for different layers

obtained from the relation [22]:

$$\eta_{rad} = \frac{Q_{rad}}{FR} \quad (4)$$

The amount of radiation energy derived from Stefan-Boltzmann relations:

The maximum surface temperature (T_{max}) is obtained at different cases and presented in fig. 5. It is observed that T_{max} increases with increasing FR and T_{max} . The increasing rate is higher for 2-layer and 3-layer wire mesh.

The thickness of the porous medium in these experiments is changed with changing the number of wire mesh layers. Based on the observations, in four to seven-layer the flame is formed on top of surface of the burner and the measured surface temperature is lower than that of two and three-layer burners. In fact, when the flame formed inside the wire mesh layers, the measured surface temperature increases. Also it is observed in three to seven-layer burners, when the thickness increases T_{max} almost decreases.

Figure 6 shows the equivalence ratio which yields T_{max} in the burner surface. With considering this figure, it is concluded that the maximum surface temperature is almost obtained at a lean mixture (equivalence ratio less than 1). Also it can be observed that the equivalence ratio at two and three layers mesh are generally less than the others.

Radiation efficiency

Thermal efficiency is an important parameter in radiant burners. In this section, the radiation efficiency is calculated for different numbers of mesh layers in different firing rates and equivalence ratios. Radiation efficiency is defined as the ratio between energy content of the fuel and the radiation energy emitted from the burner surface* and can be

* Since a porous media is considered for heat radiation the actual area is so hard to calculate and instead of it an apparent effective area is used

$$Q_{\text{rad}} = \varepsilon\sigma(T_{\text{surf}}^4 - T_{\text{surr}}^4) \quad \sigma = 5.6697 \cdot 10^{-8} \text{ W/m}^2\text{K}^4 \quad (5)$$

where ε is the emissivity coefficient for gray body, σ – the Stefan-Boltzmann constant, and T_{surr} and T_{surf} are environment temperature and surface temperature of the burner, respectively [25]. The value of T_{surf} is measured by pyrometer and T_{surr} is 300 K. The value of emissivity coefficient is assumed to be 0.8 [21].

Figure 7 shows the radiation efficiency in terms of equivalence ratios for different number of wire mesh layers in different firing rates. According to figs. 7(a) to (f), it can be observed that with increasing firing rate the radiation efficiency decreases, so the highest radiation efficiency occurs in the lowest firing rate 98 kW/m². The maximum efficiency for a fixed firing rate is obtained at the equivalence ratio which yields maximum surface temperature.

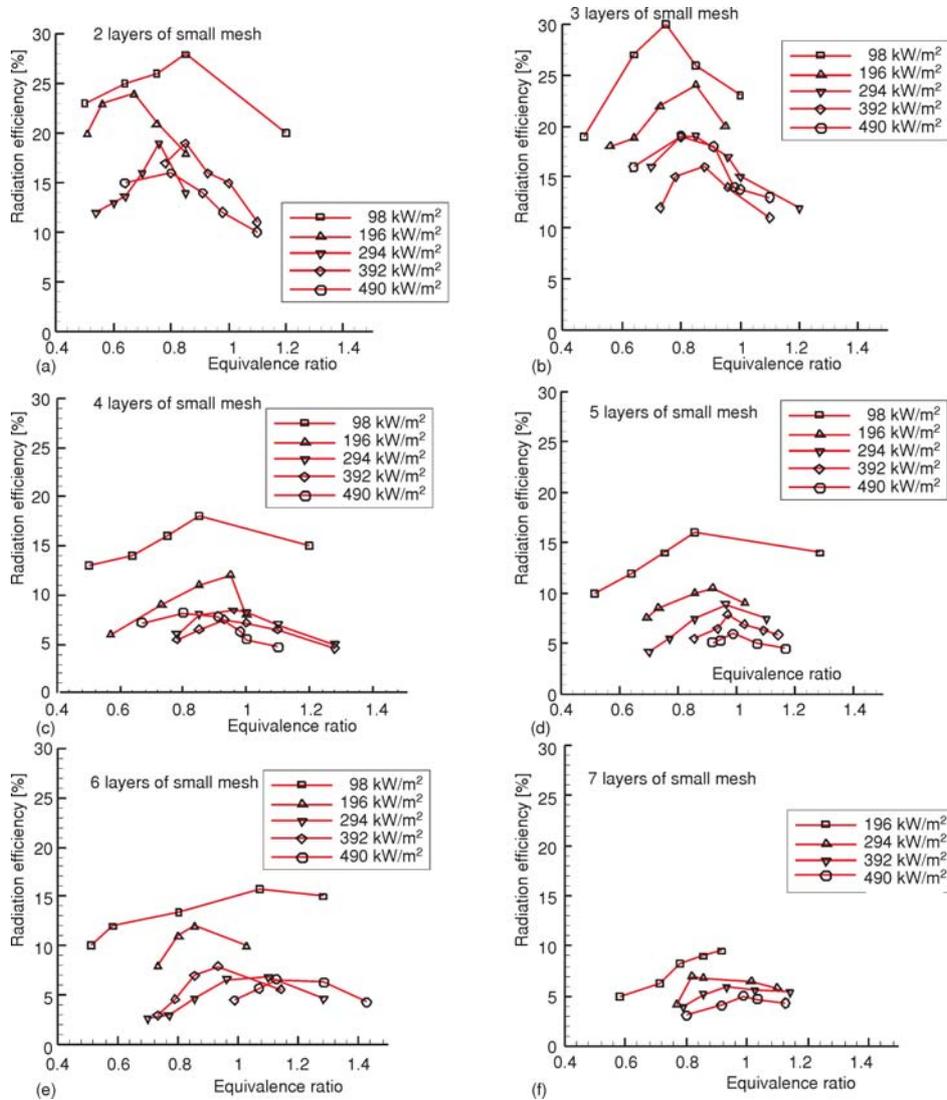


Figure 7. Radiation efficiency for burner with (a) 2 layer mesh (b) 3 layer mesh (c) 4 layer mesh (d) 5 layer mesh (e) 6 layer mesh (f) 7 layer mesh

Figure 7(b) shows that the radiation efficiency of three-layer burner is the highest at all cases. The highest radiation efficiency for this case is 30% at $FR = 98 \text{ kW/m}^2$ and equivalence ratio 0.75. The radiation efficiency is reduced for burners with more mesh layers.

Comparison with the other studies

The results obtained are compared with those obtained in refs. [9, 21, and 22]. Compared with mentioned studies our result are obtained in more wider range of different operation parameters – equivalence ratios, firing rates, and porous medium thicknesses.

The maximum surface temperature and maximum radiation efficiency of [9] and [21] as well as the present study occurs in a lean mixture, while it is obtained at a rich fuel mixture in [22]. As indicated by [22], the surface temperature and radiation efficiency increases with increasing number of mesh layers, but it is shown in this study that there is an optimum thickness of the medium (three mesh layers) which results in maximum surface temperature and radiation efficiency. With an increase in firing rate, the radiation efficiency decreases in [21] and [22] as well as in the present study. Values of radiation efficiency in the four studies are close together (about 30% at the maximum).

Figure 8 shows a comparison between current study (in $FR = 490 \text{ kW/m}^2$ and 3-layers) and the work of Christo *et al.* [21] (in $FR = 417 \text{ kW/m}^2$). The maximum surface temperature is near in two studies and obtained in a lean mixture ($\phi < 1$).

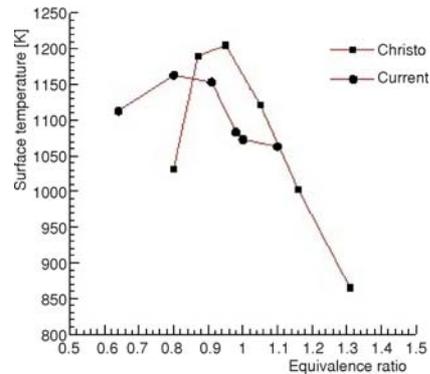


Figure 8. A comparison between surface temperature of current study and the study of Christo *et al.* [21]

Uncertainty analysis

A precise method of estimating uncertainty in experimental results has been presented by Kline and McClintock [26]. The method is based on a careful specification of the uncertainties in the various primary experimental measurements:

$$W_R = \left[\sum \left(\frac{\partial R}{\partial X_i} w_i \right)^2 \right]^{0.5} \quad (6)$$

where, R is a given function of the independent variables x_1, x_2, \dots, x_n . W_R is the uncertainty in the result and w_i is the uncertainty in the independent variables [27].

According specifications given by manufacturers, measurement accuracy is: for rotameters $\pm 2\%$ full scale, for pyrometer 1% of reading, for accuracy of the entered emissivity coefficient 10%.

Uncertainties of maximum surface temperatures for $FR = 98, 196, 294, 392,$ and 490 kW/m^2 , respectively, are about 15, 17, 18, 19, and 20 and uncertainties of equivalence ratio proportional T_{\max} for the same FR are about 0.5, 0.064, 0.053, 0.06, and 0.023, as it is shown on figs. 5 and 6.

Conclusions

In the present study, the effect of various parameters (firing rate, equivalence ratio, and the thickness of the porous medium) on the performance of a radiant metal porous burner is studied. The results are as follows.

- Increasing firing rate generally increases the surface temperature.
- The maximum surface temperature occurs in a lean mixture (equivalence ratio between 0.8 to 1). The maximum radiation of the burner is obtained at the maximum firing rate and in this range of equivalence ratio.
- Between different thicknesses of porous medium, the burner with three layers mesh has maximum surface temperature and maximum radiation efficiency.
- The highest radiation efficiency is obtained at three layers mesh burner and in the lowest firing rate is 30%. It is obtained at the equivalence ratio of 0.75. It would be the optimum case with respect to fuel consumption.
- Radiation efficiency of the investigated burner is less sensitive to changes in equivalence ratio than that of the other studies.
- Flammability limits are different at each firing rate. The firing rate of 98 kW/m² has the widest flammability limit includes equivalence ratio from 0.5 to 1.3. In general, with increasing of the firing rate the flammability limit decreases.
- The maximum surface temperature increases with a different rate when *FR* increases. The rate for 2-layer and 3-layer is more than that of the others.
- The results are in a good agreement with other studies.

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Nomenclature

A	– burner section area, [m ³]
d	– thickness of porous medium, [m]
FR	– firing rate, [kWm ⁻²]
h	– convection heat transfer coefficient, [kWm ⁻² K ⁻¹]
k	– conductivity coefficient, [kWm ⁻¹ K ⁻¹]
LHV	– heating value, [kJm ⁻³]
\dot{m}_f	– mass flow rate of the fuel, [m ³ s ⁻¹]
ppc	– pores in centimeter (number per cm)
Q_t	– heat transferred from hot gases to the wire mesh, [kW]
Q_{loss}	– heat loss from the wire mesh to the holder, [kW]
Q_{rad}	– radiative heat transfer from the wire mesh, [kW]
Q_{re}	– returned heat to preheating region, [kW]
R	– function of the independent variables x_1, x_2, \dots, x_n
T_g	– gas temperature, [K]
T_s	– wire mesh temperature, [K]
T_{max}	– maximum surface temperature, [K]

T_{surr}	– environment temperature, [K]
T_{surf}	– surface temperature of burner, [K]
V	– gas velocity, [ms ⁻¹]
W_i	– uncertainty in the independent variables
W_R	– uncertainty

Greek symbols

α	– absorption coefficient
δ	– fame position from botom, [m]
ε	– emissivity coefficient for gray body
η_{rad}	– radiation efficiency
σ	– Stefan-Boltzmann constant, [Wm ⁻² K ⁻¹]
φ	– equivalence ratio

Subscripts

f	– fuel
g	– gas
rad	– radiation
surr	– environment
surf	– surface

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