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Investigation of Cylindrical Porous Burner Behavior under Various Equivalence Ratios

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ABSTRACT

The current study is aimed to investigate the behavior of cylinder porous burner in various equivalence ratios for two various stabilization locations. Regarding to this target, one-dimensional modeling of premixed combustion radial flow and thermal non-equilibrium between the gas phase and porous matrix were applied. The results have shown that the range of firing rate in radial flow burner is wider than axial flow burner for all mixture ratios. By transferring the flame location to the upstream of the flow, the temperature of the porous matrix and gas get closer and the maximum gas temperature is increased and it is fixed after a definite distance of the radius. Radiation efficiency is reduced by transferring the flame to downstream and Carbon monoxide (CO) pollutant rate is also increased Nitrogen monoxide (NO) concentration is decreased almost in all the mixture ratios by transferring the flame location to downstream.

KEYWORDS: Porous burner, combustion stability, premixed flame, pollutants emission.

1. INTRODUCTION

Premixed porous burner is one of the issues taken into attention by many researchers in two recent decades and various indices of its behavior are evaluated experimentally or numerically [1, 2]. One of the issues is the stability of the flame inside the burner or in the porous bed level. One of the drawbacks of the porous burner is providing the high thermal power density compared to other industrial burners [3]. To eliminate this problem, various methods are proposed with the aim of increasing the burner stability.

In the laboratory sample of Bakry et al. [4], a porous burner with conical geometry was proposed for the stability of the flame when the combustible mixture pressure was high. The study showed that dilute premixed flame region was independent from the pressure but it was mostly dependent upon the preheat temperature. They reported that there was an acceptable stability in mixture ratios 0.6 to 1 and preheat temperature $400^{\circ}C$.

One of the possible configurations for porous burners is cylindrical configuration in which the flow moves in the burner radially. The radial movement of the fluid in the burner reduces the speed in radial direction and this causes natural stability of the flame in the burner. Dobrego et al., [5, 6] performed various studies to present the stability criterion of the flame inside the cylinder porous burner. They showed that the flame location not only was dependent upon inlet fuel flow rate and the parameters of the system but also was dependent upon firing coordinate.

In the study performed by Mohamad and Kamal [7], various aspects of porous burner with radial flow were investigated. They reported the maximum radiation efficiency of 37% with Nitrogen oxides (NOx) less than 29ppm and stability combustion with ratio of 0.74. They showed that swirl of flow in combustion mixture helped the performance of porous burner. In another study performed by Mohamad [8], it was shown that at equal conditions, the maximum temperature of porous burner flame with radial flow was less than porous burner with axial flow. The improvement of the porous burner performance with radial flow compared to axial flow was presented in details in the study performed by Maerefat et al. [9].

In porous burner with radial flow, the speed is inversely related to the radius and it can create a natural stability in premixed flame or flame front location. In free flame, the stability location of the flame doesn't affect its parameters and properties while in embedded flame inside the porous media is very effective based on three parameters of energy internal flow, the change of contact duration between the sold and fluid matrix and the change of heat transfer rate. In some of the previous studies regarding the porous burner, its stability was presented in axial flow [10-13]. However, there was no study about radial flow.

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The current study is aimed to investigate the premixed flame of porous burner with radial flow in various equivalence ratios. One of the interesting aspects of this study is the comparison of the radial flow burner and axial flow. The properties of the flame such as the flame speed; thickness and residence time was compared between the radial flow burner and axial flow. The effect of flame stability location is investigated in radial flow burner and finally the emission of the pollutants is studied with consideration of effective parameters such as the residence time, equivalence ratio and temperature profile. Regarding to these targets, a one-dimensional model is applied. A cylinder porous burner with limited diameter and bigger height is considered to ignore the lateral boundary effects in burner radial behavior.

2. The governing equations and solution method

The governing equations generally include gas and solid energy equations, continuity, radiation transfer equation (RTE), gas species conservation and gas state equation.

Continuity

$$\frac{d}{dr}(\rho u A\varphi) = 0 \tag{1}$$

Gas energy

$$\rho u A\varphi \frac{dT_g}{dr} - \frac{1}{c_{pg}}\frac{d}{dx}\lambda_s A\varphi \frac{dT_g}{dr} + \frac{A}{c_{pg}}\varphi\sum_{k=1}^{K}\rho Y_k V_k c_{pk}\frac{dT_g}{dr} + \frac{A}{c_{pg}}\varphi\sum_{k=1}^{K}\dot{\omega}_k h_k W_k - \frac{A\varphi H_V}{c_{pg}}(T_s - T_g) = 0 \tag{2}$$

Solid energy

$$\begin{gathered}\frac{1}{c_{ps}}\frac{d}{dr}\lambda_s A_s \frac{dT_s}{dr} - \frac{A_s H_V}{c_{ps}}(T_s - T_g) - \frac{A_s(\nabla\cdot q_{rad})}{c_{ps}} = 0 \\ \nabla\cdot q_{rad} = \frac{1}{r}\frac{\partial}{\partial r}(r q_{rad}) = (\beta - \sigma_s)\left(4\sigma T^4 - G\right)\ ;\ G = \int_{4\pi} I d\,\Omega\end{gathered} \tag{3}$$

Radiation transfer equation

$$\begin{gathered}Sin(\theta)\left(Cos\phi\frac{dI}{dr} - \frac{Sin\phi}{r}\frac{dI}{d\phi}\right) = S - \beta I \quad (\theta : Polar\ angle;\ \phi : Azimuthal\ angle) \\ S = (\beta - \sigma_s) I_b + \frac{\sigma_s}{4\pi} G\end{gathered} \tag{4}$$

Species conservation

$$\rho u A\varphi \frac{dY_k}{dr} + \frac{d}{dr}(\rho A\varphi Y_k V_k) - A\varphi\,\dot{\omega}_k W_k = 0, \quad (k = 1, \ldots\ldots, K) \tag{5}$$

State equation

$$\rho = \frac{p\overline{W}}{RT} \tag{6}$$

In order to solve the equations above, the famous PREMIX code from CHEMKIN group which was originally used for simulating one-dimensional free and laminar flame was applied [6].

For this purpose solid energy and radiation transfer equations were added to the code. Also some changes were made in gas energy equations. Solving the equations is done in three stages:

First, a chemical species distribution is found by using a temperature preliminary guess. In the second stage, by using distribution obtained from the first stage as preliminary guess, energy, species conservation, and continuity equations are solved without taking into account the radiation. In the last stage, all equations are solved implicitly by using the previous stage results as preliminary guess. In order to solve radiation transfer equation, the Discrete Ordinates Method (DOM) (S_8) was used. In this method, radiation heat transfer equation is transformed into partial differential equations set, in which each equation is written for one special ordinate. The total of these ordinates

should cover a sphere with 4π solid angle [14]. The chemical kinetic applied in modeling kinetic combustion process of air-methane is based on GR13.0 [15]. Boundary conditions of equations 1-6 are shown as following.

Continuity boundary condition

$$\dot{m} = \dot{m}_{in} \tag{7}$$

gas energy boundary condition

$$\dot{m} c_{pg} (T_{gi} - T_g) = -k_g \frac{dT_g}{dx} \tag{8a}$$

$$\frac{dT_g}{dx} = 0 \tag{8b}$$

Solid energy boundary condition

$$H_V (T_{gi} - T_s) + \sigma\varepsilon (T_{suruond}^4 - T_g^4) = -k_s \frac{dT_s}{dx} \tag{9a}$$

$$H_V (T_{go} - T_s) + \sigma\varepsilon (T_{suruond}^4 - T_g^4) = -k_s \frac{dT_s}{dx} \tag{9b}$$

Radiation transfer equation boundary condition

$$I(\vec{r},\hat{s}) = \varepsilon_i I_b + \frac{1-\varepsilon_i}{4\pi} \times \int_{4\pi} I(\vec{r},\hat{s}).|\hat{s}'.\hat{n}| d\Omega' \tag{10a}$$

$$I(\vec{r},\hat{s}) = \varepsilon_o I_b + \frac{1-\varepsilon_o}{4\pi} \times \int_{4\pi} I(\vec{r},\hat{s}).|\hat{s}'.\hat{n}| d\Omega' \tag{10b}$$

Species conservation boundary condition

$$Y = Y_{in} \tag{11a}$$

$$\frac{dY}{dx} = 0 \tag{11b}$$

In the study performed by Hanamura and Echigo, the role of radiation in flame stability was emphasized [16]. In boundary conditions, to increase the share of radiation, it is assumed that the porous burner surrounding environment temperature is 300K. A good comparison of two samples of temperature conditions at downstream of porous burner was presented in the study performed by Hayashi et al., [17]. The boundary conditions were applied in accordance with the study performed by Mendes et al [18] without the increase of calculation length to the geometry length.

A schematic figure of cylinder porous burner with radial flow is shown in Figure 1 and its properties are shown in Table 1.

Table 1: The properties of the applied porous material

parameter	Value	unit
β	270	m^{-1}
H_V	10^7	W/m^3K
ρ_s	5.56×10^3	kg/m^3
σ_s	216	m^{-1}
λ_s	0.2	W/mK
ϕ	0.835	$for\ 25.6PPC\ PSZ$

The thickness of porous matrix is 10 cm. It is assumed to have a porous burner with inlet cross section 1cm^2 in axial flow and the area is equal to the inlet cross section in cylinder burner, it can be said that the radius in the inlet section is $r_i = \frac{1}{2\pi}$. Based on the thickness, the radius in outlet section is r_0=10.159cm.

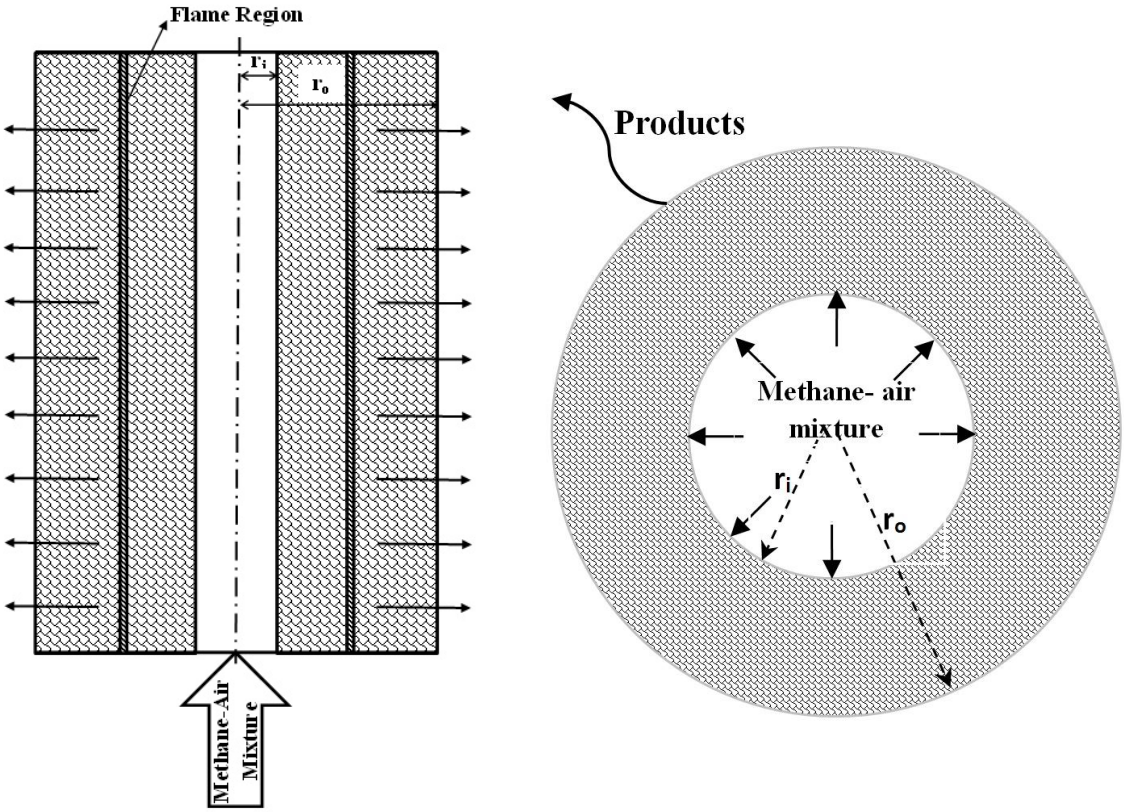

Figure1. Porous burner with radial flow

3. CONCLUSION AND DISCUSSION

In the previous study, the validation methods of the results of numerical solution were presented [9] and they are not presented here. As it was mentioned in the introduction, because of the increase of cross section in radial burner, it is expected to apply this geometry for the stability of higher speed. This was issued was investigated by a comparison made between porous burner of axial flow and then its behavior was presented for the flame being stabilized in various sections.

The comparison of the radial flow burner and axial flow

The flame speed, its thickness and residence time are the properties of the flame and their comparison in these two flows is interesting. Equivalence ratio 0.9 was applied in the comparison. The inlet sections are considered equal in two burner examples for comparison and the thickness of both of them is equal. It is attempted to create the stable flame at the middle of two flame samples to make the mentioned comparison. The flame speed depends upon preheat of the initial mixture. By the increase of the area in radial flow, it is predicted to increase preheat. It is expected that the flame moves to the downstream of the flow. In order to stabilize the flame at the middle of the burner, the inlet flow rate (or inlet speed) is increased. It is expected that the flame speed is in radial flow higher than axial flow.

Flame thickness is another property of the flame various equations are recommended for its description. The following equation is applied:

As CO, NO_x pollutants depend upon the flow residence time in the burner, a comparison is made. The exact determination of preheat from the flame front is very difficult. Because of some chemical reactions can be started at low temperature. However, the aim is the comparison of residence time in both burners; a reference temperature (1000 K) is considered for flame front location.

The results are presented in Table 2.It is observed that there is no difference between the maximum gas and solid temperature in both burners. The flame thickness is fixed but residence time, mass flow rate and firing rate of both burners are different. As it was mentioned, the preheat region in radial flow is most effective than axial flow burner because of its bigger section and to make the flame location fixed, the inlet flow rate or initial mixture speed

should be increased. As we get approached to the end of radial flame, the flow speed is reduced and the residence time is increased. As it is observed, the residence time in axial flow is less than that of radial flow but the gas temperature of axial flow is about 55 degree more than gas temperature in radial flow. These issues caused that at the outlet of two burners, NO_x is reported similar. However, CO is reported considerably less in radial flow.

Table 2: The comparison of radial and axial flow porous burner in equal inlet section area and stabilized flame at the middle of burner with the length 10 cm in equivalence ratio 0.9

	Max Solid Temperature (k)	Max Gas Temperature (k)	Flame Thickness (mm)	Residence Time (ms)	Radiative efficiency (%)	NO (ppm)	CO (ppm)	Firing rate (MW/m^2)	Mass flow (gr/s)
Axial	2141.9	2202.7	0.332	9.06	14.66	153	951	2.24	0.089
Radial	2146.2	2206.5	0.332	14.28	19.58	154	291	70.68	2.831

Another case with different condition was investigated. The burner length is reduced from 10 cm to 7cm and the flame is stabilized at the end three quadrants. The results are shown in Table 3 and as it is shown, the behavior is as shown in Table 3.

Table 3: The comparison of radial and axial flow porous burner in equal inlet section area and stabilized flame at three final quadrant burners with the length 7 cm in equivalence ratio 0.9

	Max Solid Temperature (k)	Max Gas Temperature (k)	Residence Time (ms)	NO (ppm)	CO (ppm)	Mass flow (gr/s)
Axial	2085.0	2162.1	4.21	96	951	0.083
Radial	2080.1	2157.4	5.32	93	291	2.603

The comparison of two tables showed that the applied change on the flame location and porous burner length is different in terms of mass flow change rate and the change of firing rate for both burners. It can be said that the flow change rate region or firing rate in axial flow porous burner is wide. It is observed that in radial flow burner firing rate is changed 11 times more compared to axial burner.

The above conclusion is true in all the equivalence ratios. To prove this fact, a comparison is made between the maximum to minimum ratio of firing rate of two examples of axial and radial flow porous burner [19], [20] and it is shown in Fig. 2. As is shown, the flame stability range in radial flow burner is wider (3 times more) than axial flow burner.

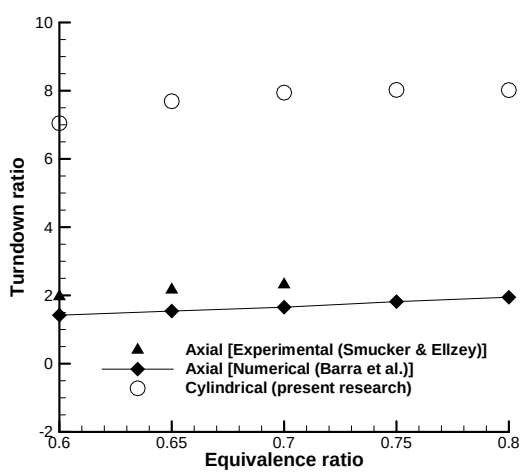

Figure 2. The change trend of maximum to minimum ratio of firing rate in radial flow porous burner compared to axial flow

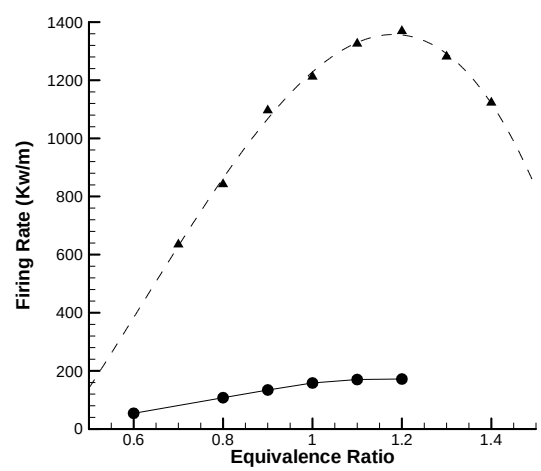

Figure 3. The maximum and minimum change trend of firing rate in various equivalence ratios of radial flow porous burner

It can be said that in radial burner, the distance between the minimum and maximum firing rate is different in various equivalence ratios. The minimum firing rate is fixed in all equivalence ratios while the maximum firing rate in equivalence ratios has parabolic behavior. In other words, the distance between the maximum and minimum firing rate is different in various equivalence ratios. This behavior is presented in Figure 3.

The effect of flame stability location in radial flow burner

To investigate the effect of flame stability location, stoichiometric equivalence ratio was applied. It was attempted to stabilize the flame in locations with the distance of 1cm. The temperature changes are shown in Figure 4. As it is shown, because of the thermal transfer to downstream of the flow, if the flame is inclined to the bigger radiuses, its peak temperature is reduced. This is effective on burner thermal efficiency and the length of preheat region. For the stabilized flame at the beginning of the preheat region, the length 1.57 cm is considered and the length for the stabilized flame is calculated as 1.19cm. The comparison of the maximum temperature of solid and gas phases for each of 8 phases is shown in Figure 5.

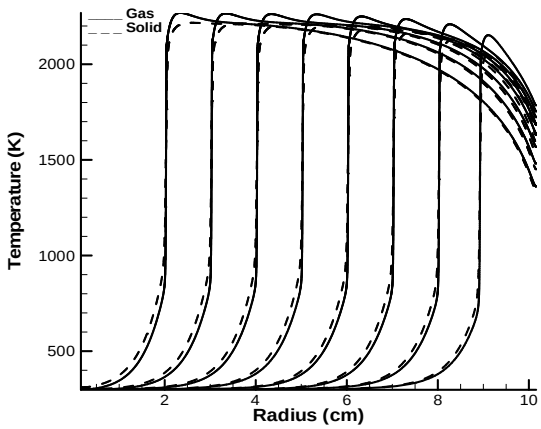

Figure 4. The temperature change in various location of flame stability in stoichiometric equivalence ratio

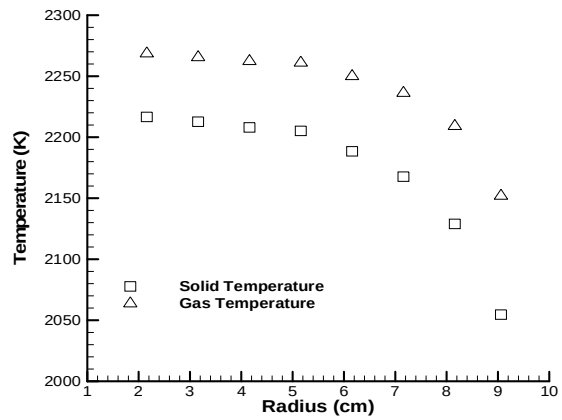

Figure 5. The maximum temperature of gas and solid for the stabilized flame in various radii and stoichiometric equivalence ratio

According to the calculations, there was no considerable change in the size of flame thickness and it was estimated as 0.32 mm. Based on the comparisons with axial flow porous burner, they have same flame thickness size. It can be said that the flame thickness of porous burner is bigger than the premixed free flame burner. Another parameter defined as the properties of porous burner is output radiation heat transfer efficiency. The changes are shown in Figure 6. As is shown, by the increase of the radius of flame stability location, radiation efficiency is reduced considerably. The reason is the inlet fuel flow rate. In other words, by the increase of the radius, the mass flow rate is increased and in accordance with Figure 7, the solid temperature is reduced in outlet section but this reduction is not as considerable and the reduction of radiation efficiency is observed by the increase of flame stability radius. It can be said that the more the flame is inclined to the upstream of the flow, the more the radiation efficiency. The reported trend for stoichiometric equivalence ratio is observed in other air and fuel mixture ratios. This issue is presented for two locations of flame stability in Figure 8 for dilute and strong mixture ratios.

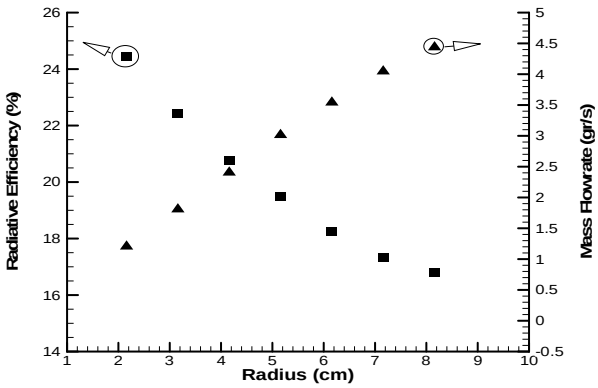

Figure 6. The radiation efficiency and mass flow rate changes of combustion mixture for various locations of the flame in stoichiometric equivalence ratio

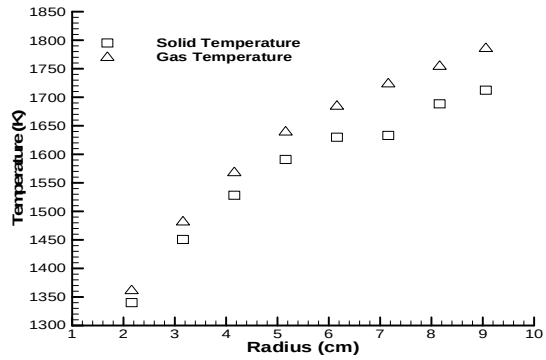

Figure 7. The gas and solid temperature in outlet section for stabilized flame in various radii and stoichiometric mixture ratio

The emission of the pollutants is one of the challenging issues in the burners and NO and CO pollutants are selected as indicators. Both of the pollutants depend upon the residence time, equivalence ratio and temperature profile with some parameters as turbulence rate. As is shown in Figure 4, the maximum temperature is not significantly different in the flame situated at the middle of porous media with the flames stabilized in its upstream. For two stabilized flames at radius 6, 7 cm in which their maximum temperature is relatively less than 2%, the maximum temperature change of the flame is ignored but in two other flames located in the proximity of the external level of the burner, the maximum temperature change of the flame is considerable. The study of the residence time in various states of flame stability location showed that as we approach the end of the burner, its value is reduced as exponential function (Fig. 9). It is expected that the effect of the mentioned temperature change is neutralized. Figure 10 shows the production rate of CO, NO pollutants in stoichiometric mixture ratio. As is shown, the increase of residence time increases the production of NO and reduction of CO by converting it to CO2. As we study the pollutants emission in other mixture ratios, we know this conclusion in dilute mixtures ratio a valid. For strong mixture ratios, the change of CO pollutant emission concentration is lower for the same reason of the increase of residence time for the stabilized flame in the proximity of the upstream and this difference is reduced by the increase of equivalence ratio to rich condition. The trend of the changes is shown in Figure 11.

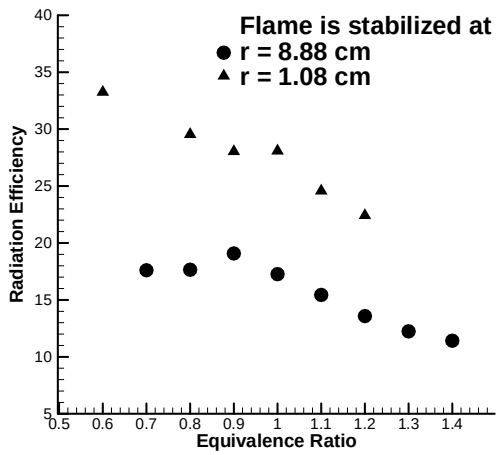

Figure 8. The change of radiation efficiency in various equivalence ratios for two locations of flame stability at the beginning and the end of radial flow burner

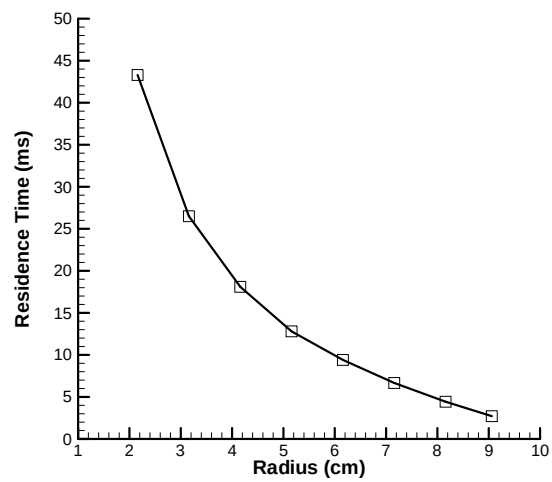

Figure 9. The residence time for the stabilized stoichiometric in various radii

Based on Figure 11 and the kinetic study of CO reactions, it is defined that the concentration difference is due to the different residence time and in combustion dilute ratios by the change of geometry dimensions of the burner, the concentration of CO is changed but in rich combustion ratios, the stability location of the flame is independent from the pollutant CO production rate.

The investigation of the NO production in various mixture ratios showed that based on residence time and flame temperature maximum effects, considerable changes are made. As is shown in Figure 12, in dilute region, the stabilized flame temperature at the beginning of the burner and residence time is more compared to the stabilized flame at the final end. Thus, it is expected that NO pollutant production rate is similar to the trend shown in stoichiometric mixture ratio (Fig. 10).

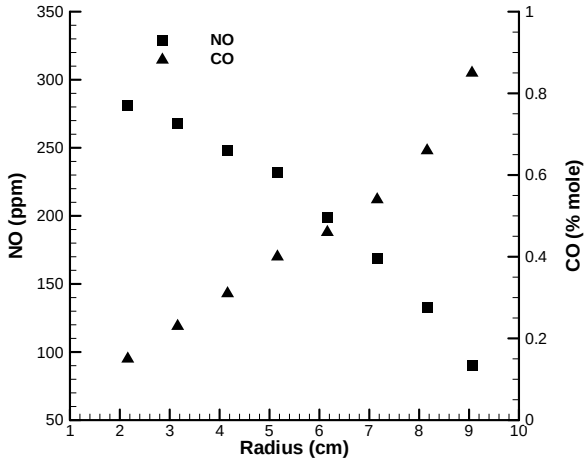

Figure 10. CO, NO rates in outlet section of burner for the stabilized stoichiometric flame in radius

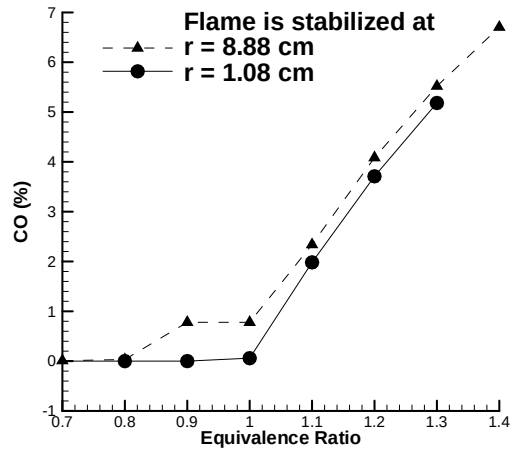

Figure 11. CO rate for various equivalence ratios in two different stability locations of flame

In rich combustion region in accordance with Figure 13, NO in stabilized flame at the proximity of the beginning of the burner is reduced compared to the stabilized flame at the end of the burner. In other words, at first by Fenimore mechanism, NO is produced then by the movement of the flow along the radius, it is degraded and is converted to other ingredients including N2O. If equivalence ratio is bigger again, the degradation is such that it is lower than the produced NO at lower temperature formed in stabilized flame at the end of the burner (Fig. 12). This trend is consistent with the previous studies [21] regarding the production of NO in rich mixture (Bell chart 12).

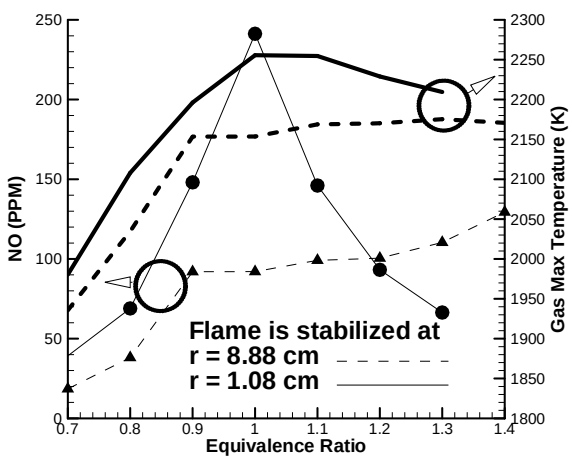

Figure 12. NO rate and maximum flame temperature for various equivalence ratios in two different locations of flame stability

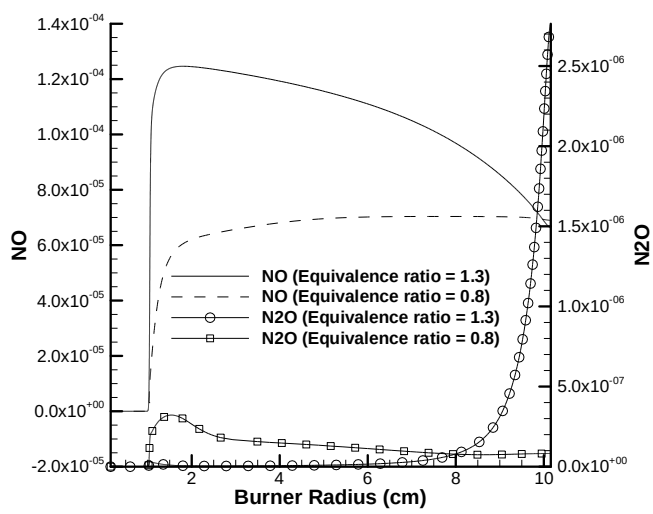

Figure 13. The molar concentration of NO, N2O for the stabilized flame at the beginning of radial burner

According to Figure 13 in rich combustion region, NO degradation affects its concentration in burner outlet and the degradation in the formed flame at the beginning of the burner is more. Also, for the flame being stabilized at the end of the burner, there is no adequate opportunity for degradation of NO chemical species and the major influence is due to the gas temperature defining the formation rate. In other words, it can be said that NO formed at flame temperature based on residence time or inlet flow speed didn't find degradation opportunity in burner outlet.

4. DISCUSSION AND CONCLUSION

According to the results, it can be said that firing rate control in cylinder porous burner compared to axial porous burner is wider (3 times more). Although due to the increase of residence time in radial flow model compared to axial flow, it is expected that more NO pollutant is produced. However, due to the higher radiation efficiency, the maximum temperature of the flame is lower and the effect of residence time effect is neutralized. In sum, it can be said that radial flow model is better than axial flow model. The study of the stability location of the flame in cylinder porous burner showed that the flame thickness is without the change and residence time by the increase of the radius of flame stability location is reduced as exponential function. The mass flow rate and the density of firing rate are increased linearly by the increase of radius and radiation efficiency is reduced. CO pollutant concentration by the reduction of residence time or transfer to flame location to the flow upstream is increased in all mixture ratios. NO pollutant concentration by transfer of the flame to the downstream of the flow is reduced in all mixture ratios and if the mixture is considerably enriched, it is possible that due to NO degradation, its concentration rate in stabilized flame in upstream is lower compared to the stabilized flame at the end of the burner.

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The authors declare that they have no conflicts of interest in the research.

REFERENCES

1. Mujeebu, M.A., et al., 2009. A review of investigations on liquid fuel combustion in porous inert media. Progress in Energy and Combustion Science, 35(2): 216-230.
2. Mujeebu, M.A., et al., 2009. Applications of porous media combustion technology – A review. Applied Energy, 86(9): 1365-1375.
3. Durst, F. and D. Trimis, 2002. Combustion by free flames versus combustion reactors. Clean Air, 3(1): 1-20.
4. Bakry, A., et al., 2011. Adiabatic premixed combustion in a gaseous fuel porous inert media under high pressure and temperature: Novel flame stabilization technique. Fuel, 90(2): 647-658.
5.Dobrego, K.V., S.A. Zhdanok, and A.I. Zaruba, 2001. Experimental and analytical investigation of the gas filtration combustion inclination instability. International Journal of Heat and Mass Transfer, 44(11): 2127-2136.
6. Zhdanok, S.A., K.V. Dobrego, and S.I. Futko, 1998. Flame localization inside axis-symmetric cylindrical and spherical porous media burners. International Journal of Heat and Mass Transfer, 41(22): 3647-3655.
7. Kamal, M.M. and A.A. Mohamad, 2006. Development of a cylindrical porous-medium burner. Journal of Porous Media, 9(5): 469-481.
8. Mohamad A.A. , 2002. Numerical simulation of combustion in a cylindrical porous medium. Houston, TX, United States: American Society of Mechanical Engineers.
9. Maerefat, M., M. Astaraki, and M. Khosravy-el-Hosseini, 1390. Investigation on improvement of radial flow porous burner compared with axial flow porous burner. Journal of Applied and Computational Sciences in Mechanics, 23(1): 15-28 (in persian).
10. Mendes, M.A.A., J.M.C. Pereira, and J.C.F. Pereira, 2008. On the stability of ultra-lean H2/CO combustion in inert porous burners. International Journal of Hydrogen Energy, 33(13): 3416-3425.
11. Xu, K., M. Liu, and P. Zhao, 2011. Stability of lean combustion in mini-scale porous media combustor with heat recuperation. Chemical Engineering and Processing: Process Intensification, 50(7): 608-613.
12. Djordjevic, N., P. Habisreuther, and N. Zarzalis, 2011. A numerical investigation of the flame stability in porous burners employing various ceramic sponge-like structures. Chemical Engineering Science, 66(4): 682-688.
13. Du, L. and M. Xie, 2011. Numerical prediction of radiative heat transfer in reciprocating superadiabatic combustion in porous media. Journal of Environmental Sciences, 23, Supplement(0): S26-S31.
14. Modest, M.F, 2003. Radiative Heat Transfer.: Academic Press.
15. Smith, G.P., et al. 1999. GRI-Mech 3.0.; Available from: http://www.me.berkeley.edu/gri_mech/.
16. Hanamura, K. and R. Echigo, 1991. Analysis of flame stabilization mechanism in radiation burners. Waerme- und Stoffuebertragung/Thermo- and Fluid Dynamics, 26(6): 377-383.
17. Hayashi, T.C., I. Malico, and J.C.F. Pereira, 2010. Effect of different downstream temperatures on the performance of a two-layer porous burner. Combustion Theory and Modelling, 14(3): 405-423.
18. Mendes, M.A.A., J.M.C. Pereira, and J.C.F. Pereira, 2008. A numerical study of the stability of one-dimensional laminar premixed flames in inert porous media. Combustion and Flame, 153(4): 525-539.
19. Barra, A.J., et al., 2003. Numerical study of the effects of material properties on flame stabilization in a porous burner. Combustion and Flame, 134(4): 369-379.
20. Smucker, M.T. and J.L. Ellzey, 2004. Computational and experimental study of a two-section porous burner. Combustion Science and Technology, 176(8): 1171-1189.
21. Glarborg, P., J.A. Miller, and R.J. Kee, 1986. Kinetic modeling and sensitivity analysis of nitrogen oxide formation in well-stirred reactors. Combustion and Flame, 65: 177-202.