Optimization of Fluid Flow Pattern in a Perforated Porous Burner

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ABSTRACT

In this study the premixed flame stability conditions on perforated porous plate has been investigated. To examine this issue; the geometry of two-dimensional channel with axial symmetry is used to simulate the flow on a perforated porous plate. Since the objective of this study is conditions of velocity distribution on the plate which has the potential to form the stable premixed flame‹flow is modeled as a cold, regardless of the energy equation. Since the objective of this study is determination of velocity distribution on the plate which has the potential to form the stable premixed flame‹cold flow model is mentioned, regardless of the energy equation. Different parameters such as Block geometry, inlet flow velocity (Reynolds number) and the porosity of perforated plate were studied in order to achieve the appropriate velocity on the porous perforated plate. It has been found that increasing Reynolds number will lead to increasing flame stability and decrease in the porous block width will lead to flame blow-off.

KEYWORDS: Porous burner, perforated plate, combustion stability, premixed flame.

Nomenclature

x	x direction, [m]		p_{in}	Inlet pressure, [Pa]
y	y direction, [m]		p_{out}	Outlet pressure, [Pa]
X	Dimensionless x direction, [-]		p_∞	Reference pressure, [Pa]
Y	Dimensionless y direction, [-]		ppc	Pore per centimeter, [1/cm]
u	x velocity, [ms^{-1}]		Eu	Euler number, [-]
U	Dimensionless x velocity, [-]		Re	Reynolds number, [-]
v	y velocity, [ms^{-1}]		K	Permeability, [m^2]
V	Dimensionless y velocity, [-]		d_p	Effective Pore diameter, [m]
v_{in}	Inlet Velocity, [m/sec]		K	permeability of porous medium, [m^2]
a	Block length, [m]		Da	Darcy number, [-]
b	Block width, [m]		F	Shape factor, [-]
t	Thickness between blocks, [m]		*Greek symbols*	
L	Channel length, [m]		ρ	Density, [kg/m^3]
H	Channel Width, [m]		φ	porosity, [-]
p	Fluid pressure, [Pa]		Φ	Mixing ratio, [-]
P	Dimensionless fluid pressure, [-]		μ	Viscosity, [kg/(m.sec)]

1. INTRODUCTION

One of the conventional methods for flame stability is using barriers on the flow passage. The key role of the barriers is to produce a low-velocity and turbulent zone to optimize combustion reactions. The shape and geometry of the barriers effect on flow stability conditions and flame stability zone. Therefore various geometries such as triangle, sphere and so on has been suggested [1]. The main mechanism of flame stabilization in this geometry is vortices in the downstream which has been studied by several researchers [2-4]. It should be noted that the main reason of premixed flame stabilization is mixing the air-fuel mixture with high temperature combustion products, because of turbulent flow and vortices. The general characteristics of the flame holder are presented by the investigation of Zukofsky, Marble, William and Long [5]. In these researches flame extinction criterions have been studied for a homogeneous mixture of premixed flame holder with different geometries. Some other researches have been reported the effect of temperature and pressure [6, 7].

Since barrier object causes flame stability, another type of pre-mix burner with perforated plate's structures, which recently have been considered in many household and industrial applications are used. Stability of the flame in the burners is based on the mechanism of heat transfer between plate and combustion products.

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The relationship between the stand of and the temperature was investigated by McIntosh and Clarke [8]. De Goey and De Lange analytically studied premixed laminar flames which were cooled by walls of the burner and they showed the impact of flame thickness on the flame stability [9]. Lee and Tsai [10], Daou and Matalon [11], Kim and Maruta [12] and Song et al [13] conducted a numerical study of flame propagation in tubes with different temperature conditions at different inlet mixture velocity using the single-step kinetic. They have completely reported the structure, multi-branch and extinction conditions of transient premixed flame. The one-dimensional model has been used in the investigation while the recent investigations have benefited of two-dimensional modeling and multi-step kinetics [14, 15].

In a recent study which has been done by Kedia and Ghonien, perforated plate with different holes diameters are used to investigate the parameters of flame stability [16]. This study has shown that the rate of heat dissipation have effective role on the flame behavior. In a recent laboratory study which was conducted by Konnov and Dyakov for study of cellular flames, shown that flame speed systematically are greater than laminar flames and their difference will increase with increasing temperature of flame stabilizer plate [17].

Based on the knowledge of the authors instead of laboratory experience of Alzeta Company [18-20] there is not any research which shows that the flame stabilization mechanism using a perforated porous plate. Regarding to effective role of perforated plate temperature in the flame stability and because of the importance of radiation heat transfer mechanism in addition to the thermal conductivity, so it can be acknowledged that the use of perforated porous has advantage than conventional perforated plate.

In other words it can be said that flame stabilization mechanism in this structure is affected by the amount of radiation.In the present study, numerical modeling of the perforated porous plate has been conducted in various geometrical properties of holes so that stable surface flame is formed on perforated porous plate. Cold flow modeling has been used for this purpose [21-22] and by solving the governing equations, the conditions has been reported for the formation and stability of the flame on the perforated porous plate.

2. PHYSICAL MODEL AND GOVERNING EQUATION

In the present study two dimensional geometry was used for modeling fluid flow in the perforated porous plate. Schematic of the geometry and the simulation domain are chosen as
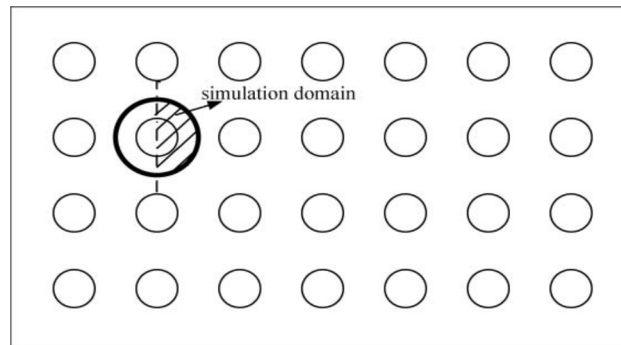Figure1.

Figure1 Schematic of the perforated porous plate and simulation domain

Assumptions used in the present problem include:
- Fluid flow in the porous medium follows Darcy's law.
- The properties of fluid and porous medium are isotropic and homogeneous.
- The porous medium is gray and the walls are diffuse.
- All thermophysical properties of the fluid are constant.
- The flow is assumed laminar, two-dimensional, incompressible and steady state.
- Cold flow modeling has been used for determination of flame stability conditions.

Given the above assumptions, the governing equations are summarized as follows:
The continuity equation:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

The momentum equation:

$$U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re}(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}) - \frac{1}{Re\,Da}U - \frac{F\varphi}{\sqrt{Da}}|\bar{U}|U \tag{2}$$

$$U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re}(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}) - \frac{1}{Re\,Da}V \quad 167 \quad \bar{I}|V \tag{3}$$

Where:

$$U = \frac{u}{U_{in}}, \quad V = \frac{v}{U_{in}}, \quad P = \frac{p - p_{in}}{\rho U_{in}{}^2}, \quad Da = \frac{K}{b^2} \tag{4}$$

In the equation (2) and (3), φ is the porosity. Permeability (K) and F are calculated as below:

$$K = \frac{\varphi^3 d_p{}^2}{150(1-\varphi)^2} \tag{5}$$

$$F = \frac{1.75}{\sqrt{150\varphi^3}}, \tag{6}$$

where d_p is the effective pore diameter. In the present study two dimensional geometry is used for modeling the flow pattern as showed in figure 2. In this problem the inlet flow velocity to the porous blocks is v_{in}, the blocks dimension is $a \times b$ and blocks spacing is t. In fact the number of the blocks determines the number of holes in the burner. Since there is symmetry in the vertical direction, instead of modeling the whole geometry, the consideration of one block with the periodic boundary condition is sufficient for modeling the flow pattern. By this assumption the new geometry is defined as figure 3. As seen in the figure 3, there is a duct in the width of the H and length of the l. The outlet boundary condition of the duct is chosen as outlet pressure (p_{out}). In the above and below of duck we have the periodic condition for modeling the symmetry between the blocks and expectation of the same condition in the two geometry (Fig 1 and 2). For omitting the effect of the outlet boundary condition on the flow field the duct length is chosen long enough.
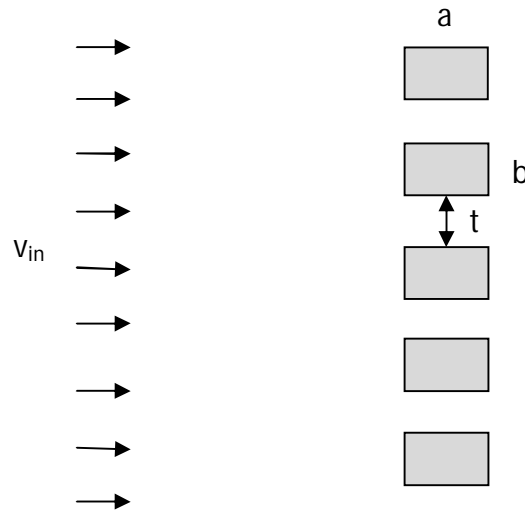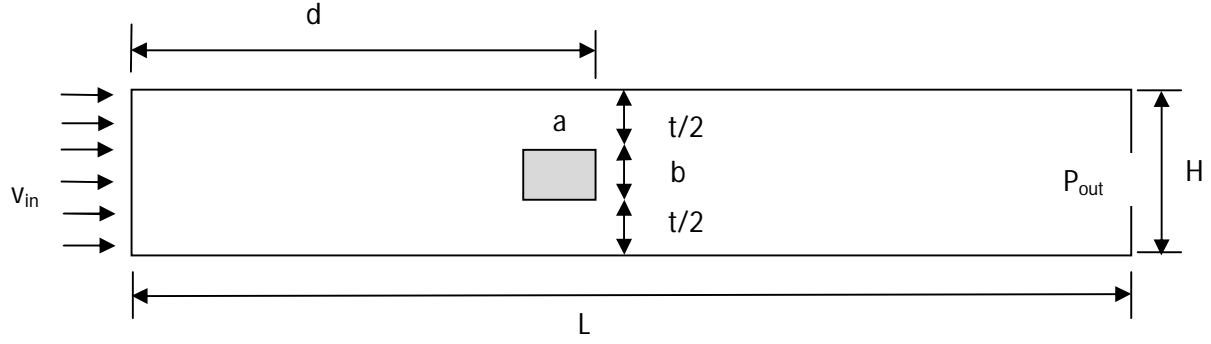
Figure2 Schematic of the physical model

Based on the mentioned assumptions and flow characteristic the boundary condition for the present problem is formulated as below:

$$\text{at } X = -\frac{L-a}{2a} \rightarrow U = 1, V = 0$$

$$\text{at } X = \frac{L+a}{2a} \rightarrow P = 0 \tag{7}$$

$$\text{at } Y = -\frac{t}{2b}, \frac{t+2b}{2b} \rightarrow \frac{\partial U}{\partial X}, \frac{\partial V}{\partial Y}$$

Porous media can be modeled by two parameters; 1-porosity φ , 2- number of pores per centimeter (ppc). The pressure difference between duct inlet and outlet base on the equations (2) and (3) can be demonstrate as below:

$$\Delta p = p_{in} - p_{out} = f\left(v_{in}, \rho, \mu, L, d, a, b, t, \varphi, ppc\right) \tag{8}$$

As regards that the upper and lower wall of the duct have the periodic boundary condition, indeed there is a no shear tension flow near the walls and the viscose effect is only because of porous block. Also it is not important where the block situates from the duct inlet because the flow before the block is uniform and frictionless. Therefore in the equation (8) L and d doesn't have any effect on the duct pressure difference, so it can be written:

$$\Delta p = p_{in} - p_{out} = f\left(v_{in}, \rho, \mu, a, b, t, \varphi, ppc\right) \tag{9}$$

By using the dimensional analysis the number of dimensionless quantities can be produced as below:

$$\frac{2\Delta p}{\rho v_{in}^{2}} = f\left(\text{Re}, \frac{a}{b}, \frac{t}{b}, \varphi, ppc \times b\right) \tag{10}$$

The left term of the equation (10) is defined as Euler number. For validation of the equation (10) which depends on just $\text{Re}, \frac{a}{b}, \frac{t}{b}, \varphi$ and $ppc \times b$ parameters, two cases with different geometry but the same dimensionless quantities were developed and solved as given in table (1). If the Euler number remain constant for two cases we can expect the formulation is valid. As seen in the table (1) despite of the different geometry the result is the same therefore the only effective parameters for the present problem are $\text{Re}, \frac{a}{b}, \frac{t}{b}, \varphi$ and $ppc \times b$.

Table 1 validation of the chosen number of dimensionless quantities for the present problem

Items	Case 1	Case 2
$a \ (cm)$	2	4
$b \ (cm)$	1.43	2.86
$t \ (cm)$	0.57	1.14
$v_{in} \ (m/\sec)$	1.65	0.825
$\rho \ (kg/m^3)$	1.225	1.225
φ	0.9	0.9

$\mu \ (kg \ / \ m.\sec)$	1.79e-5	1.79e-5
$a \ / \ b$	1.4	1.4
$t \ / \ b$	0.4	0.4
$ppc \times b$	69.57	69.57
Re	1.61e3	1.61e3
Eu	14.05	13.91

In order to choose the appropriate grid distribution for the present geometry, grid independency analysis is applied here. As seen in the Table 2 the optimum number of the grid is 630×30. A specified sample of the grid distribution is shown in Figure3.

Table 2 Grid independency analysis

Gird number	Eu	Err
315×15	14.91	6.6%
630×30	14.05	0.5%
900×60	13.98	-
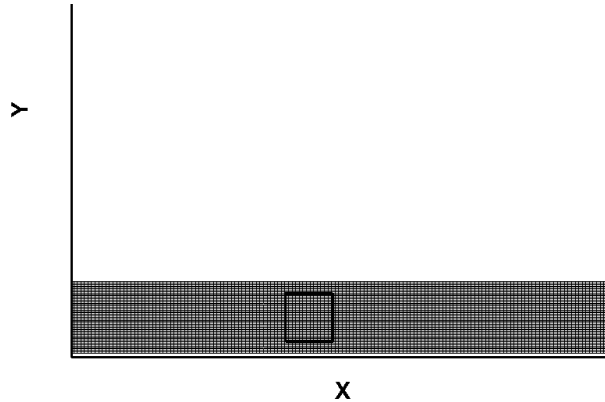
Figure3Grid distribution around the porous block

3. REAULTS AND DISCUSSION

The effect of Porous Blocks Arrangement

Here, the aim of study porous block arrangement determine proper geometry to achieve the appropriate velocity on the outlet surface of porous blocks according to reference [23] for having stable flame. In current study for determining suitable geometry, the geometric parameters a/b a/b and t/b t/b changed, while other parameters including Re, φ and $ppc \times b$ ppc × b were selected to be constant and respectively equal to 2260, 0.9 and 97.4. In Figure4 the minimum velocity ratio on the outlet surface of porous blocks for various values of geometric parameters is shown. It can be seen, with increasing t/b t/bthe minimum velocity on the outlet surface of porous blocks is decreasing. That is due to distribution of fluid velocity. In Figure5, distribution of fluid velocity is shown for $a/b = 1$ a/b = 1and various values of t/b t/b. As it's seen, decreasing thickness of porous blocks and consequently increasing space between blocks, fluids would like to pass the spaces between blocks more than porous spaces and so the velocity on the outlet surface of porous blocks decreases.

As seen in the Figure6, by reducing a/b a/b, the velocity ratio increases. Those are because of decrease of block's thickness and hence decrease of flow pressure loss. Supposing inlet velocity equal to 1.65 according to ref. [23] where is seen in Table 3, the stable flame geometry condition range can be seen in Fig. 7 According to this figure, the stable flame for different mixing ratio values and different geometries can be achieved at $t/b < 0.7$.

Pressure drop is one of the important parameter which should be considered to design a porous burner. For this reason the effect of porous blocks arrangement on the pressure drop also is reported in this investigation. As seen in the

Fig. 8, reduce in *t/b* and increase in *a/b*, causes increase in Euler number. Indeed by reducing *t/b* and increasing *a/b*, flow resistance is increased and consequently pressure drop is increased. Since Euler number indicates portion of the pressure drop to the inertia, then it was obvious that Euler number also increases.

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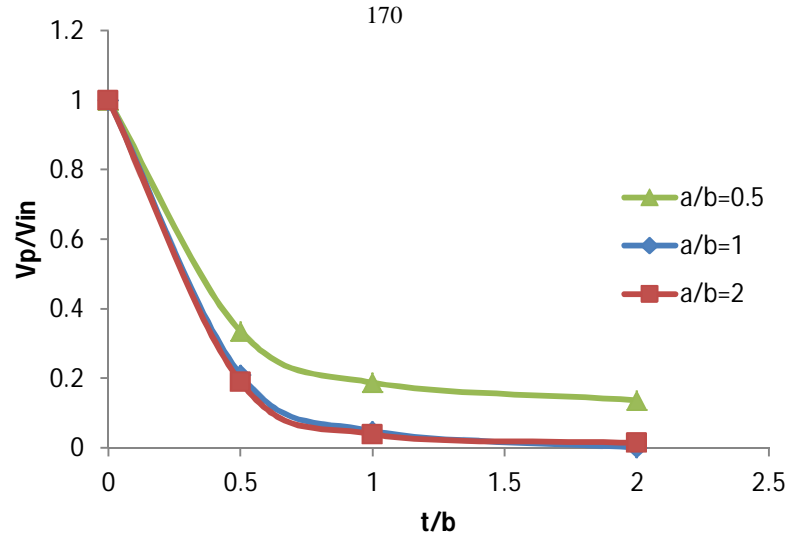
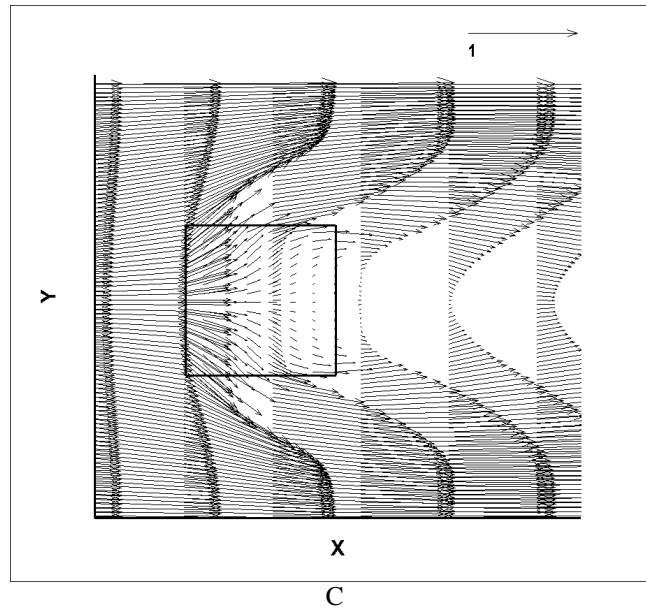Figure4 The effect of geometry on porous surface minimum velocity at $Re = 2260, ppc \times b = 97.4 \; and \; \varphi = 0.9$

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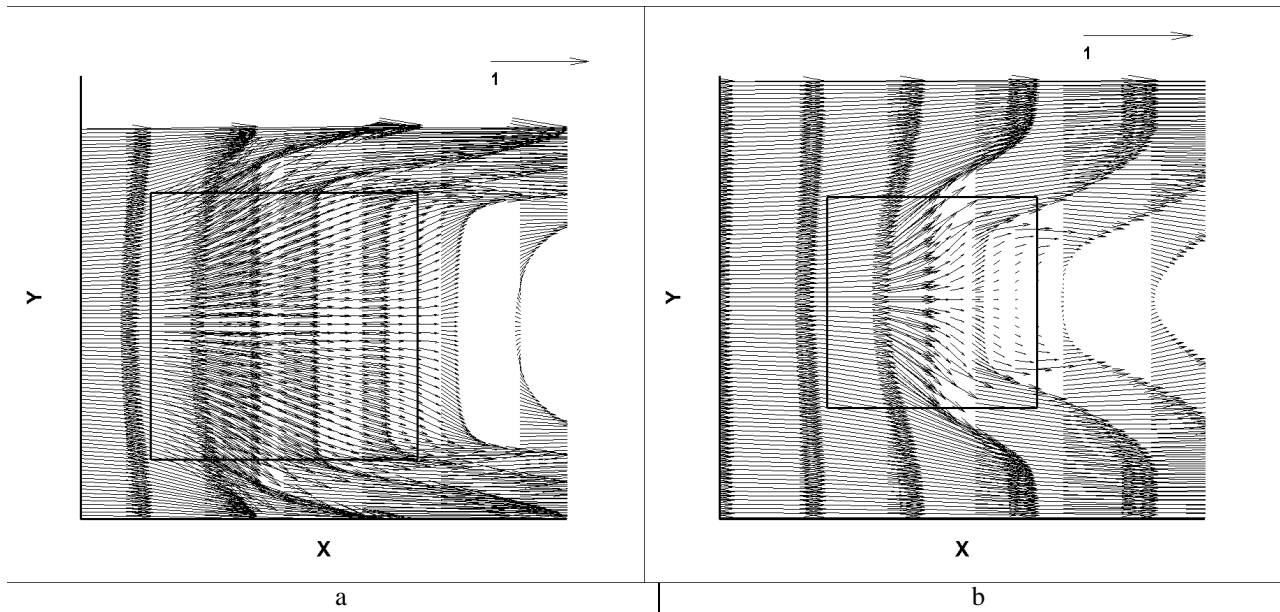
Figure5 The velocity vector at $\mathrm{Re}=2260, ppc \times b=97.4, \dfrac{a}{b}=1\, and\, \varphi=0.9$ a) $\dfrac{t}{b}=0.5$ b) $\dfrac{t}{b}=1$ c) $\dfrac{t}{b}=2$
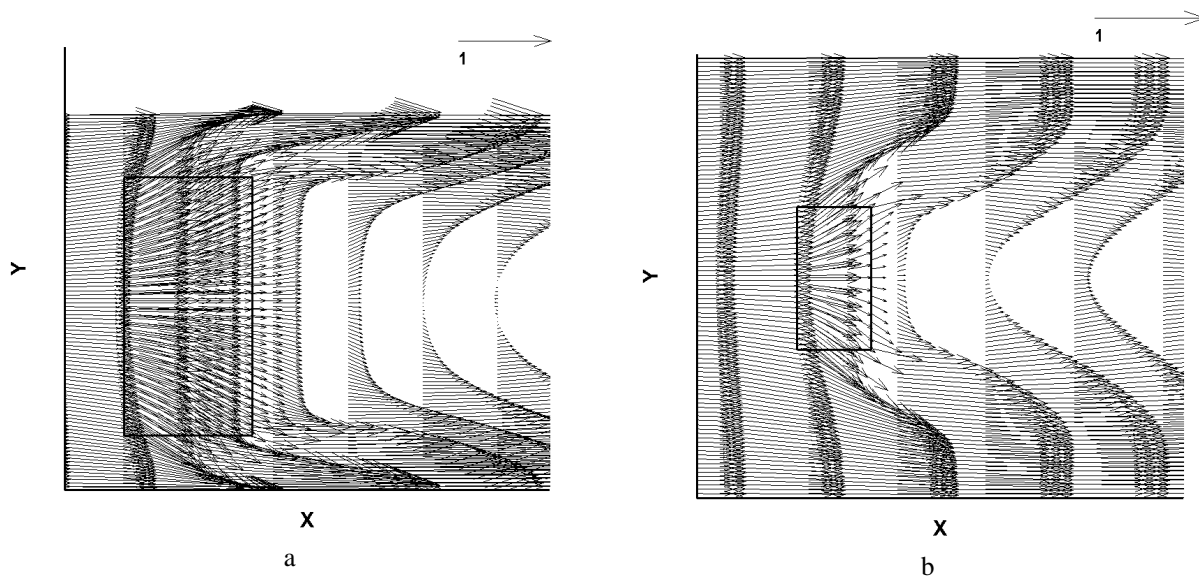

a

b

Figure6 The velocity vector at $\mathrm{Re}=2260, ppc \times b=97.4, \dfrac{a}{b}=0.5\, and\, \varphi=0.9$ $\mathrm{Re}=2260, \mathrm{ppc} \times \mathrm{b}=97.4, \dfrac{a}{b}=$

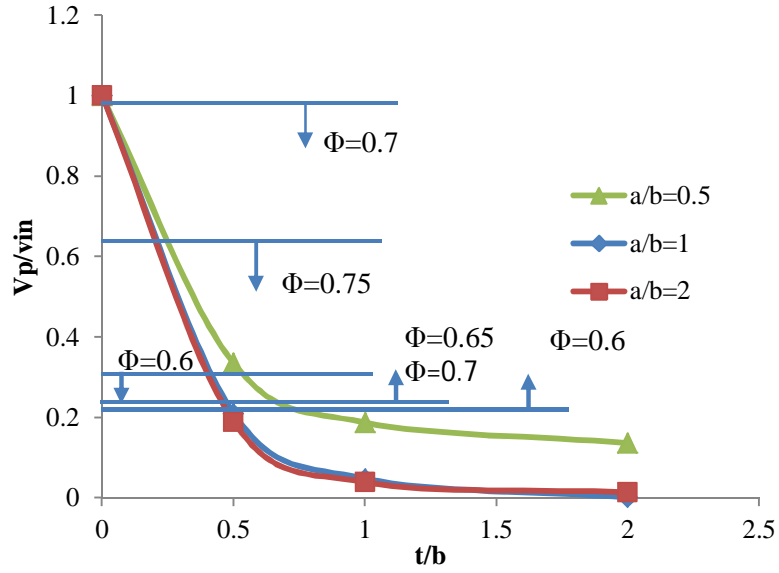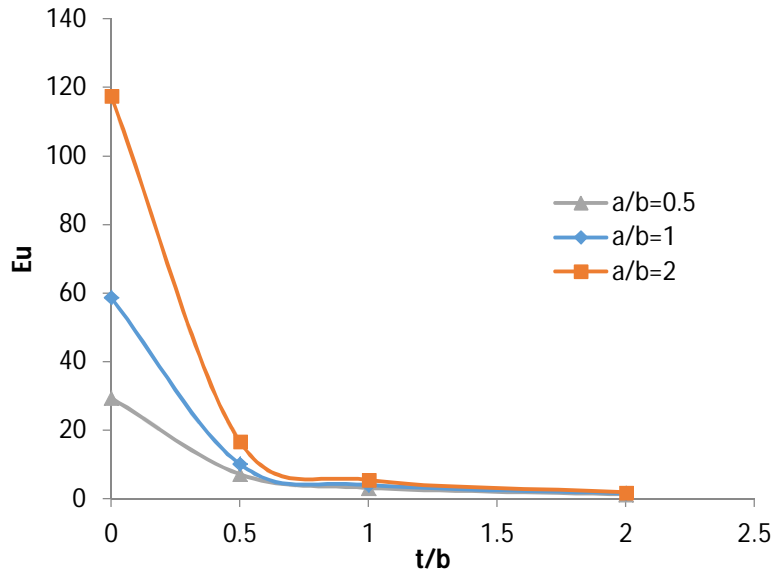$0.5\, and\, \varphi=0.9$ a) $\dfrac{t}{b}=0.5$ b) $\dfrac{t}{b}=2$

Fig. 7 The suitable range of flame stability

Table 3 the proper velocity range of flame stability for various mixing ratio values

	Stable Range(cm/s)	
Φ=0.6	**Flashback**	**35**
	Blow-off	**45**
Φ=0.65	**Flashback**	**40**
	Blow-off	**190**
Φ=0.7	**Flashback**	**40**
	Blow-off	**150**
Φ=0.75	**Flashback**	**35**
	Blow-off	**100**

Fig. 8 The effect of geometry on Euler number at $\text{Re} = 2260, ppc \times b = 97.4 \ and \ \varphi = 0.9$

The effect of Reynolds number

One of the important parameters in determining burner capacity is the burner flow rate. Since the fluid flow rate is function of fluid velocity and cross section area of burner, so knowing the effect of Reynolds number on stream behavior can be useful to determine the capacity of burner and proper condition for creating stable flame. Figure9 shows the effect of Reynolds number on the ratio of minimum velocity on the outlet surface of porous burner to inlet velocity. As it is seen, increasing Reynolds number will lead to increasing velocity ratio and consequently smooth velocity profile. The main reason of this phenomenon is increase of ratio of inertial force to viscos force with increasing Reynolds number. Figure10 shows the effect of Reynolds number on velocity distribution profile. For this geometry, the inlet velocity for stable flame is selected equal to $1.65\ m/\sec$ m/sec from Table 3.Figure11 shows the Re number effect on *Eu* number. As seen in the figure increase in Re lead to decrease in *Eu*. The main reason of this phenomena is increasing inertia force.
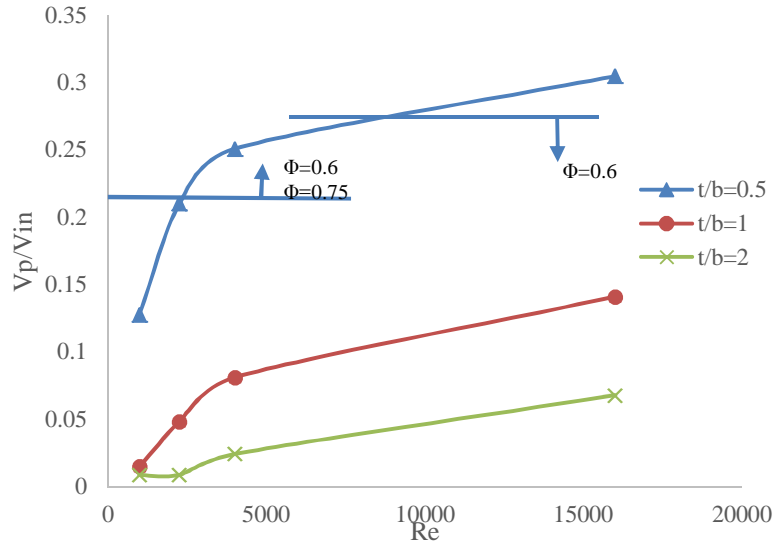

Figure9 The effect of Reynolds number on porous surface minimum velocity ratio at $\varphi = 0.9$, $ppc \times b = 97.4$ and $\dfrac{a}{b} = 1$
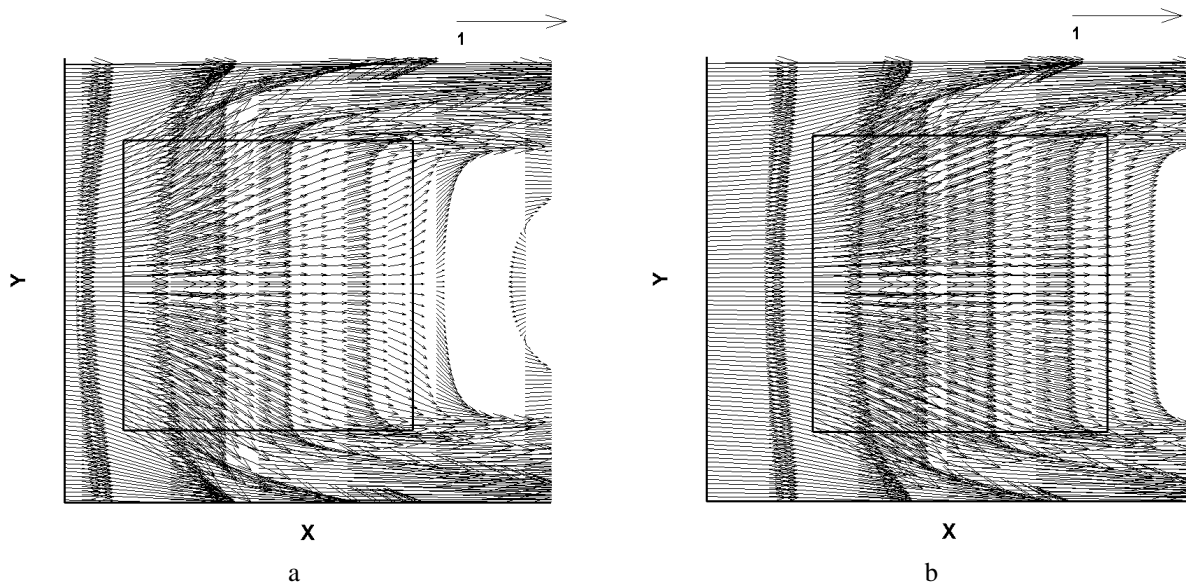

Figure10. The effect of Reynolds number on velocity vector in porous block for
$ppc \times b = 97.4,\ \varphi = 0.9\ and\ a/b = 1\ A.\text{Re} = 1000\ B.\text{Re} = 16000$
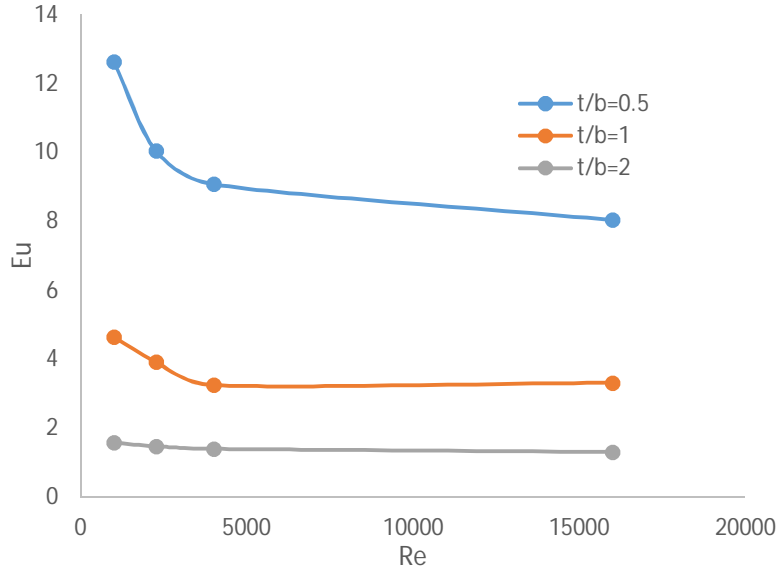
Figure11 The effect of Reynolds number on Euler number at $\varphi = 0.9$, $ppc \times b = 97.4$ and $\dfrac{a}{b} = 1$

Effect of porosity

The porosity of blocks effects on fluid flow behavior in porous burner and consequently effects on the stable flame conditions.

Figure 12 shows the effect of porosity on the velocity ratio for various geometric parameter t/b t/b. As it can be seen decreasing porosity values will lead to decreasing velocity ratio because in less porosity values blocks act like barrier against fluid flow and then fluids pass between spaces near the blocks. The effect of porosity on Euler number has been indicated in the Figure 13. As seen, increase in porosity lead to decrease in *Eu*. This is because of reducing flow resistance of porous media by increasing porosity. Since the less flow resistance the less pressure drop, so *Eu* is reduced subsequently.
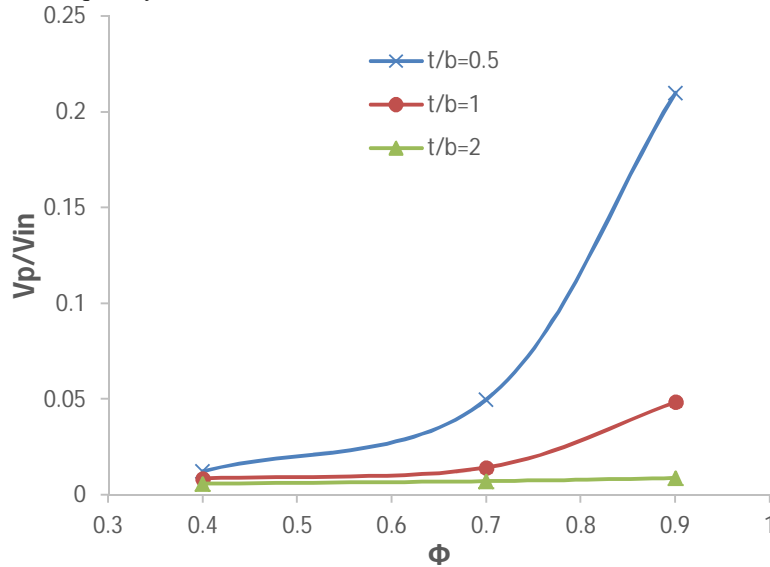

Figure 12. The effect of porosity versus velocity ratio at $Re = 2260, ppc \times b = 97.4$ *and* $a/b = 1$
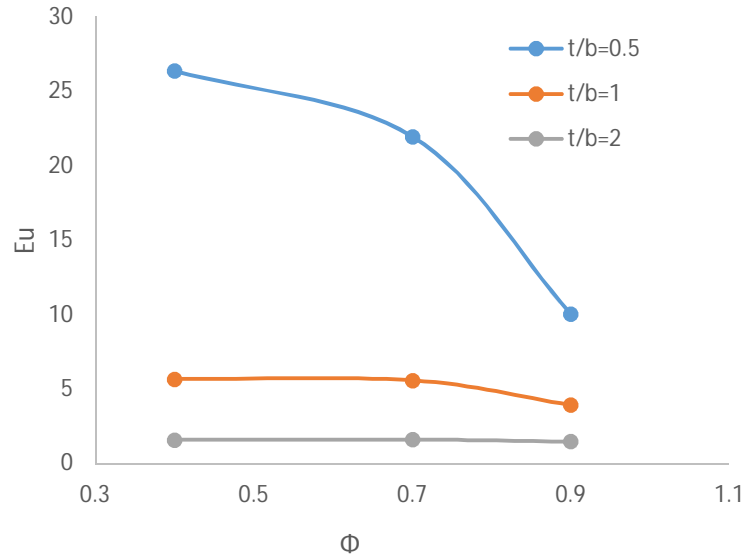
Figure 13. The effect of porosity on Euler number at $Re = 2260, ppc \times b = 97.4 \ and \ a/b = 1$

Conclusion

The most important parameters on the perforated porous plate premixed flame stability have been investigated in the present study. The parameters include porous blocks arrangement, Reynolds number and porosity. Appropriated range of these parameters to achieve the proper velocity range on the outlet side of porous block for creating stable flame was reported. It was shown that:

- Increase in *t/b* causes flame instability. Indeed in the higher *t/b* blow-off is happened.
- The stable conditions are mostly achieved for $t/b < 0.7$ t/b < 0.7 in different geometries and mixing ratio values.
- Increase in *t/b* will lead to decrease in Euler number
- Increasing Reynolds number will lead to increasing flame stability.
- Reynolds number can effect on Euler number so that in the higher Reynolds number Euler number is reduced
- Decreasing porosity will lead to decrease the velocity on the outlet surface of porous blocks
- The higher porosity the less Euler number

Acknowledgment

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