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The Effects of Added Hydrogen to Premixed Methane and Air in an MEMS Channel

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ABSTRACT

In this paper, the effects of adding hydrogen to the composition of methane and air in a micro combustor were investigated by a three-dimensional numerical method. Firstly, the results of the current study in determining the wall temperature of the micro combustion chamber were compared with those obtained from the experimental and numerical results of previous research. Secondly, by confirming the numerical solution of this study, the effect of adding hydrogen to the mixture of methane and air on the distribution of temperature, pressure and outlet velocity of the gases was calculated numerically. The numerical results showed that adding a percentage of hydrogen to the mixture of methane and air led to nonlinear changes in the outlet velocity, pressure, and temperature. In addition, the results showed that by increasing the percentage of hydrogen to 2.5% and 5%, the maximum outlet velocity of the gases and minimum temperature were obtained in the micro combustor, respectively.

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1. Introduction

Although there have been a limited number of studies conducted on combustion in micro-electro-mechanical systems (MEMS), but the issue of combustion in micro-channels is constantly expanding. The reason is that, MEMS channels are developing because of their low weight, long life and high efficiency in energy production. Examples of the use of MEMS, in reality are micro rockets and micro turbines that are used to produce thrust and power, respectively.

Recently, some new investigations [1-6] have been carried out on the behavior of gases injected in to the MEMS combustor. As an example, Yan et al. [1] conducted a numerical investigation on the combustion of methane and air in MEMS. In their study, they carried out two-dimensional calculations on the effect of increasing of the inlet velocity on temperature and outlet velocity. In another study, Yan et al. [2] also conducted numerical investigations on the MEMS combustor with a mixture of hydrogen and air. In their investigation, by using a two-dimensional solution, the fluid dynamic simulation was done on the triangle body in the micro combustor. Using two-dimensional numerical simulation in fluent software, Yan et al. [3] also studied the effect of the geometry of the MEMS combustion chamber, as well as the influence of inlet velocity of the mixture of gases on the outlet velocity of the exhaust gases after combustion. Furthermore, Yan et al. [4] performed a numerical investigation to determine the characteristic properties of MEMS combustors. Nadimi and Jafarmadar [5] used the numerical simulation to determine the temperature in a micro fin. In their paper, the results were determined in order to compare the fluid flow temperature with the results of previous numerical and experimental studies which showed a very good agreement between the results. As can be seen in Ref [6], Yang et al., used a two-dimensional simulation method to determine the temperature in the MEMS combustor. The numerical results which determined the temperature were compared to those obtained by experimental tests. The results of the two numerical and experimental methods had a good agreement.

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Other investigations have been carried out on the matter of heat transfer of combustion in the MEMS channel. Akhtar et al. [7] studied the effect of wall temperature on heat transfer in the MEMS combustor. Jiaqiang et al. [8] investigated the effects of combustion temperature of a mixture of hydrogen and air on the heat transfer components of the MEMS combustion chamber. Using numerical solutions in fluent software, Huh et al. [9] studied the effect of temperature changes, as well as pressure on the thrust force of combustion in micro cooling channels. The numerical results that determined the thrust force were compared to those obtained by experimental tests. The results of the two numerical and experimental methods also had a good agreement. In another publication by, Ning et al. [10], they investigated the diffusion model of the mixture of methane and air after combustion in the Y shape MEMS channel with the three-dimensional numerical method. In their paper, the effect of increasing the velocity of the input gases on ignition positions in the Y shape MEMS channel was studied numerically and experimentally. Pan et al. [11] also conducted an experimental study on the mixture of methane and air in the MEMS channel. They showed the effect of increasing the volume percentage of methane in air on the position and shape of the combustion. In a further study, Seo et al. [12] investigated the effect of increasing the mass flow on static pressure in the micro gas turbine experimentally. Zha et al. [13] also studied the effect of the combustion characteristics of the mixture of methane and air on flame stability in the MEMS channel experimentally. Their results showed that the stability of the flame decreased with increasing the velocity of the input gases.

Moreover, Zhang et al. [14] investigated the effect of the MEMS channel geometry, as well as the number of channels on air and methane combustion components. In another paper by Zuo et al. [15], they studied the combustion characteristics of the mixture of hydrogen and air in the elliptical MEMS channel. In their paper, by using a two-dimensional numerical solution, the temperature, pressure, and velocity in the MEMS channel were calculated. Tang et al. [16] studied the effect of combustion characteristics of the mixture of methane and air on the combustion performance of the MEMS channel numerically and experimentally. They found that, the experimental and numerical results had good agreement in determining the temperature of the MEMS channel wall. Additionally, Valipour et al. [17] studied optimization of the shell and tube heat exchanger by using a new multi-objective method. They introduced a new algorithm and its application to determine heat transfer coefficients as well as pressure drop. Rahbar et al. [18] conducted a two-dimensional numerical analysis of micro tubes. They investigated the fluid flow and energy separation in a micro-scale Ranque-Hilsch vortex tube. Bahoosh et al. [19] studied energy and exergy analysis of a diesel engine. In their publication, the effect of crank angle on the pressure and temperature of the engine was investigated.

According to the literature mentioned above, it is observed that the problem of combustion in micro-channels is complicated and very few numerical and experimental studies have been done on this issue. Furthermore, with regard to the history of numerical and experimental studies, particularly, the effect of adding hydrogen to the combustion chamber of a mixture of methane and air in the MEMS channel regarding the effects on velocity changes of the exhaust gases, temperature, and pressure of the combustion chamber have not been investigated.

The main topic of this paper is the influence of adding hydrogen to the mixture of methane and air on the velocity of outlet gases, temperature, and pressure in the MEMS channel, during combustion. The innovation of the current paper is the study of the effect of the addition of hydrogen to the combustion of air and methane on the velocity of exhaust gases and the pressure, and temperature of the combustion chamber in the MEMS channel. In this regard by using numerical calculations of the fluent commercial CFD code, the computational fluid dynamic calculation was performed to calculate fluid simulation of adding hydrogen to the combustion of the mixture of methane and air. First, in order to assure the accuracy of the method of analysis of the current paper, the numerical results of this study in determining the temperature of the combustion chamber wall of a sample of the MEMS channel were compared with the numerical results and experimental tests of previous research. In the next step, by assuring the correctness of the method of solving the present problem, the effect of adding hydrogen to the combustion of air and methane on the velocity of exhaust gases and the pressure, and temperature of the combustion chamber in the MEMS channel was investigated.

2. Numerical Calculations

2.1 Geometrical model

The geometrical model of the MEMS channel as well as the entry of the mixture of methane and air, and the exhaust gases are shown in Fig. 1. The length, width, and height of the channel are 18, 9 and 3 millimeters, respectively. There are two combustor walls with dimensions of 18, 9 and 0.5 millimeters in the upper and lower surfaces of the combustion chamber. The mixture of methane and air with an initial velocity of 0.4 *m/s*, were entered into the MEMS channel combustion chamber.

2.2 Mathematical model

To simulate the combustion in the MEMS channel, the equations for conservation of continuity, momentum, and energy in the Cartesian coordinates system were used in three-dimensional control volume, which are classified as Eqs. (1) to (3). Furthermore, Eqs. (4) to (6) are the composition, closure, and state of ideal gas equations, respectively. The parameters used in Eqs. (1) to (6) are introduced in the nomenclature.

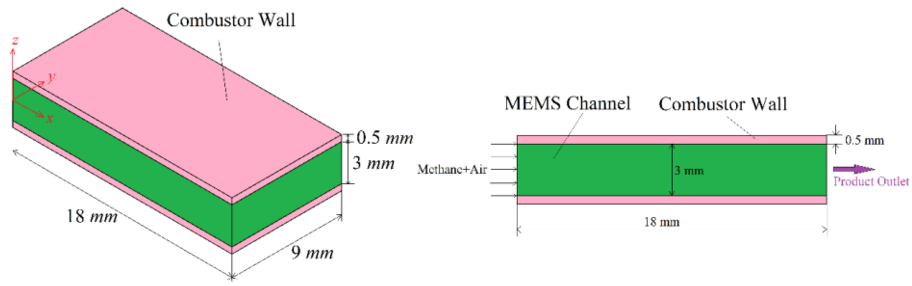

Figure 1. Structural diagram of MEMS channel.

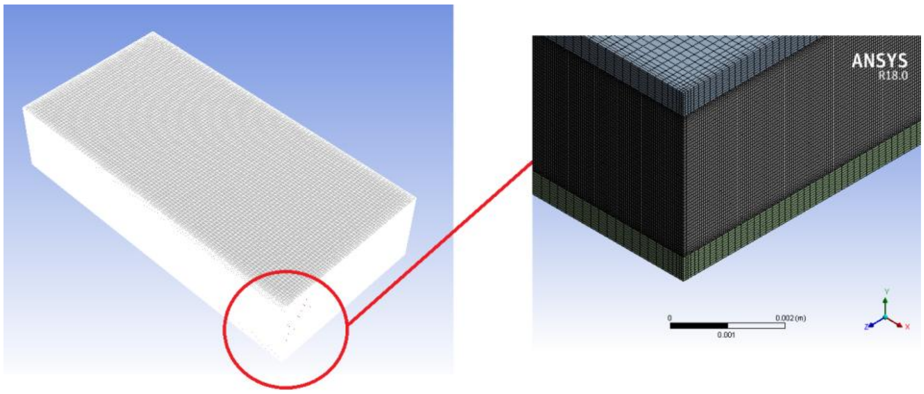

Figure 2. Meshing diagram of the MEMS channel.

Continuity equation:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_i}=-\frac{\partial P}{\partial x_i}+\frac{\partial\tau_{ij}}{\partial x_j} \tag{2}$$

Energy equation:

$$\frac{\partial(\rho u_i h)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\lambda\frac{\partial T}{\partial x_i}\right)+\frac{\partial}{\partial x_i}\sum_{s=1}^{N_g}\left[h_s\rho D_j\frac{\partial Y_j}{\partial x_j}\right] + q \tag{3}$$

Composition equation:

$$u_i\frac{\partial(\rho Y_j)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\rho D_j\frac{\partial Y_j}{\partial x_i}\right]+R_j \tag{4}$$

Closure equation:

$$\sum_{j=1}^{N_g} Y_j=1 \tag{5}$$

State of ideal gas:

$$P=\rho RT\sum_{j=1}^{N_g}\frac{Y_j}{M_j} \tag{6}$$

2.3 Numerical simulation

Fig. 2 presents the three-dimensional meshing model of the MEMS channel in fluent. In order to achieve the exact solution, the mesh dimensions in the fluid and the wall of the channel were assumed to be 30 and 100 micrometers, respectively. In addition, in order to consider the fluid boundary layer and the interaction effect of solid and fluid, the mesh dimensions of the fluid edge zone as well as, the edge zone of the wall were assumed to be 10 and 30 micrometers, respectively. The combustion model for the mixture of methane and air was based on a reaction mechanism, including 16 species and 25 for methane and air, respectively, and the mixture entered the MEMS channel at an initial velocity of 0.4 *m/s*. In order to determine the numerical solution of the combustion in the MEMS channel, three-dimensional analysis was performed with assumptions of the k-ε turbulent model and boundary conditions including the velocity inlet condition as well as pressure outlet values which were specifically defined. In order to analyze, the heat transfer between the combustion chamber and the MEMS channel wall, the interaction of heat transfer between the fluid and solid was defined.

3. Numerical results and discussion

3.1 Comparison between the numerical and experimental results

In order to confirm the numerical results of this study, the numerical results obtained by fluent in determining the temperature of the MEMS channel wall were compared with the numerical and experimental results of Ref. [16]. The geometrical dimensions of the MEMS channel model considered in Ref. [16] are the dimensions assumed in the present paper in Fig. 1. The combustion model for the mixture of methane and air was based on a reaction mechanism, including 16 species and 25 for methane and

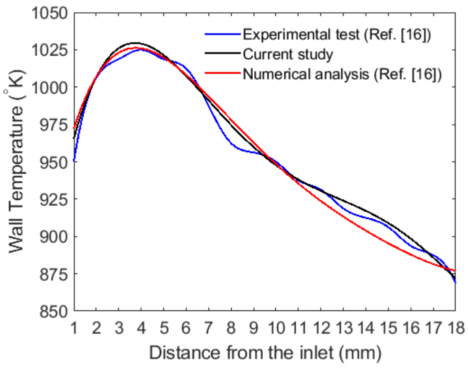

Figure 3. Comparison the wall temperature changes in terms of the MEMS channel length for the current study, numerical and experimental results of Ref. [16] on the plane parallel to *xz* at *y*=4.5 *mm*.

air, respectively, and the mixture entered the MEMS channel at an initial velocity of 0.4 *m/s*. Fig. 3 shows the temperature changes in accordance with the length of the MEMS channel on the plane (parallel with the *xy* plane and the position *y*=4.5 *mm*) obtained from the present study, compared to the results of an experimental and numerical study of Ref. [16].

According to Fig. 3, it is observed that the results of the present study have very good agreement with the numerical and experimental results of Ref. [16], in determining the wall temperature of the MEMS channel. According to the numerical solution of the mixture of methane and air, the results of Figs. 4 and 5, respectively, are obtained for the temperature and pressure contours on the plane parallel to the *xz* plane at *y*=4.5 *mm*.

In addition, Fig. 6 shows the three-dimensional stream lines due to the combustion of methane and air in the MEMS channel. According to Fig. 6, it is observed that the fluid velocity was increased from the initial value of 0.4 *m/s* to 2.418 *m/s* at the outlet position.

3.2 The effect of adding hydrogen

In our study, the effect of adding hydrogen to the combustion of the mixture of methane and air was investigated on the maximum velocity of exhaust gases as well as, temperature and pressure variations in the combustion chamber of the MEMS channel. Hydrogen was added to the mixture of methane and air in the inlet part of the MEMS channel and the amount of the addition was calculated as a percentage of the ratio of hydrogen to the partial composition of three methane, air, and hydrogen compounds.

Fig. 7 shows the maximum combustion temperature variations in terms of the percentage of hydrogen addition inside the combustion chamber. According to Fig. 7, the maximum combustion temperature increased to 1561°K, by increasing the hydrogen to the mixture of methane and air by 3%. On the other hand, by increasing the amount of hydrogen to the mixture of methane and air to 5%, the maximum combustion temperature decreased to 1288°K. Increasing the amount of hydrogen to the mixture of

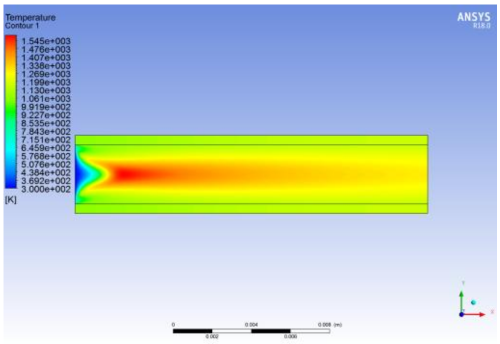

Figure 4. Temperature contour on the plane parallel to *xz* at *y*=4.5 *mm*.

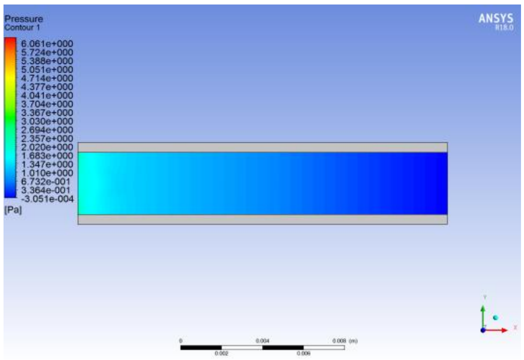

Figure 5. Pressure contour on the plane parallel to *xz* at *y*=4.5 *mm*.

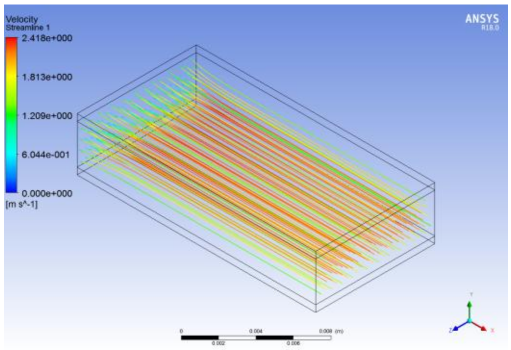

Figure 6. Three-dimensional stream lines in the MEMS channel.

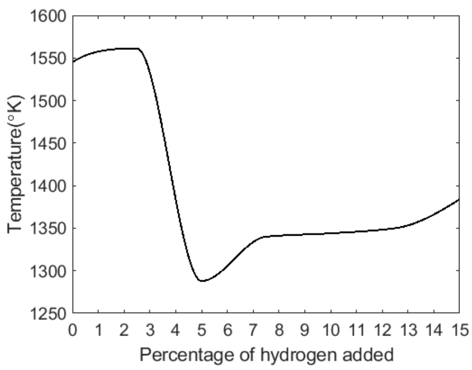

Figure 7. The variation of the maximum combustion temperature in the MEMS channel in terms of the percentage of the hydrogen added.

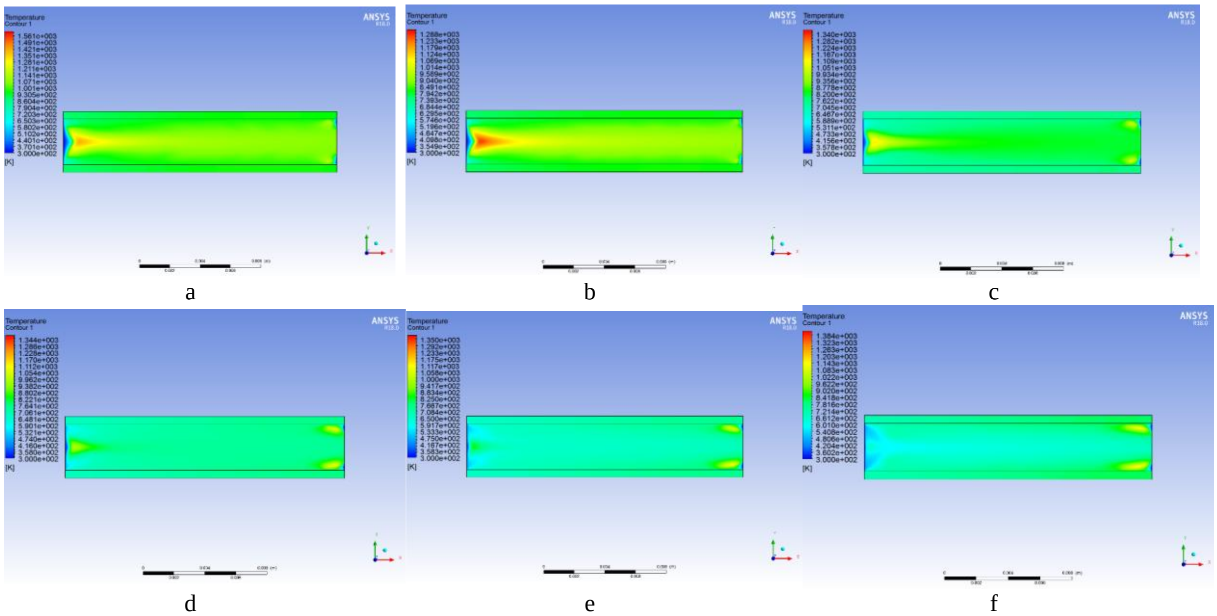

Figure 8. Temperature contours on the plane parallel to *xz* at y=4.5 *mm* for a) 2.5%, b) 5%, c) 7.5%, d) 10%, e) 12.5% and f) 15% of the hydrogen added.

methane and air to more than 5% led to an increase in the maximum combustion temperature. Fig. 8 shows the temperature contours for 6 different percentages of adding hydrogen to the mixture of methane and air in the MEMS channel. According to Figs. 8(a), 8(b) and 8(c), it can be observed that the maximum temperature occurred at the center line of the MEMS channel. This means that for variable amounts of hydrogen added that were less than 7.5 %, the location of maximum temperature was in the middle surface of the MEMS channel. For variable amounts of hydrogen added to more than 10%, it is observed that, the location of the maximum temperature was nearest to the outlet plane of MEMS.

Fig. 9 shows the variations in the maximum combustion pressure gauge in terms of the percentage of hydrogen addition inside the combustion chamber. According to Fig. 9, the maximum combustion pressure gauge decreased to 3.811 *Pa*, by increasing the hydrogen to the mixture of methane and air up to 2.5%. In addition, by increasing the amount of hydrogen to the mixture of methane and air to 5%, the maximum combustion pressure gauge increased to 3.975 *Pa*. Moreover, increasing the amount of hydrogen to the mixture of methane and air to more than 5% led to a decrease in the maximum combustion pressure gauge. Fig. 10 shows the pressure gauge contours for 6 different percentages of added hydrogen to the mixture of methane and air in the MEMS channel.

Additionally, Fig. 11 shows the variations of the maximum outlet velocity of exhaust gases in terms of the percentage of hydrogen addition inside the combustion chamber. According to Fig. 11, the maximum outlet velocity increased to 5.237 *m/s*, by increasing the hydrogen to the mixture of methane and air up to 2.5%. In addition, by increasing the amount of hydrogen to the

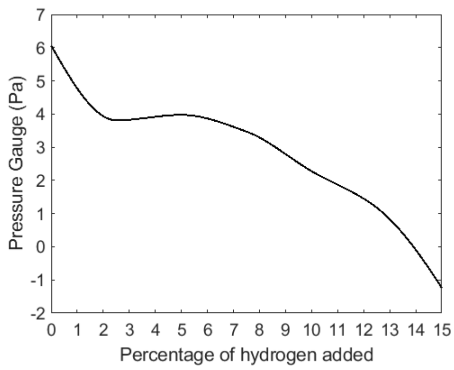

Figure 9. The variation of the maximum pressure in the MEMS channel in terms of the percentage of the hydrogen added.

mixture of methane and air to 10%, the maximum outlet velocity decreased to 3.791 *m/s*. It can be seen that, increasing the amount of hydrogen to the mixture of methane and air to more than 10% caused the maximum combustion pressure gauge to increase.

Fig. 12 shows the three-dimensional stream lines due to adding hydrogen to the combustion of methane and air in the MEMS channel for 6 different percentage values of hydrogen added.

Conclusions

In the current paper, the numerical study was carried out in order to determine the maximum outlet velocity of the exhaust gases as well as, the maximum temperature and pressure of the combustion chamber in relation to the percentage of hydrogen added to the mixture of methane

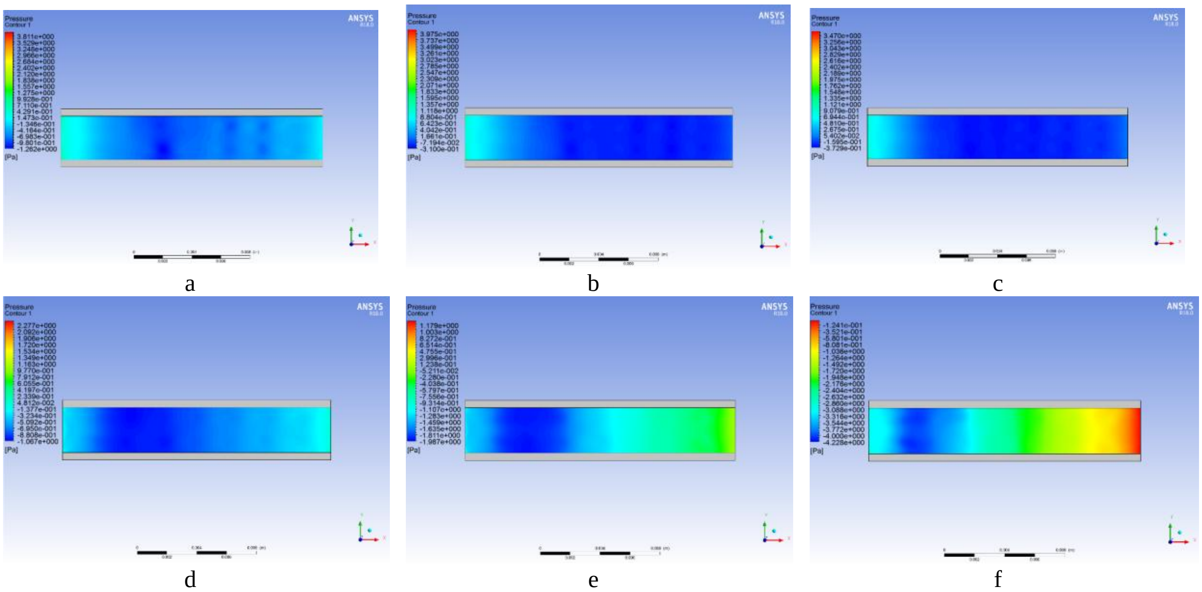

Figure 10. Pressure gauge contours on the plane parallel to *xz* at *y*=4.5 *mm* for a) 2.5%, b) 5%, c) 7.5%, d) 10%, e) 12.5% and f) 15% of the hydrogen added.

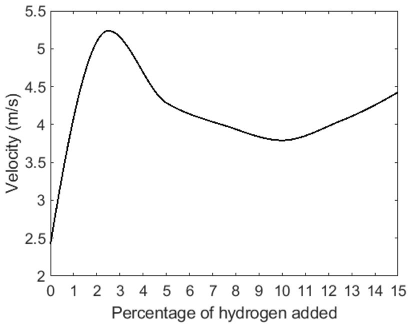

Figure 11. The variation of the outlet velocity of exhaust gases in the MEMS channel in terms of percentage of the hydrogen added.

and air. It was observed that a minimal variation in the percentage of hydrogen in the range of zero to five percent resulted in drastic changes in the maximum combustion temperature, pressure and even the outlet velocity of the exhaust gases. However, the issue of the heat release changes after adding hydrogen to the premixed methane and air were not investigated in the current study. Therefore, this can be presented as a new topic in the continuation of this study in the future. Moreover, as a suggestion for further research, the effect of adding nitrogen instead of hydrogen can be studied to determine those effects on the pressure, temperature and exhaust velocity.

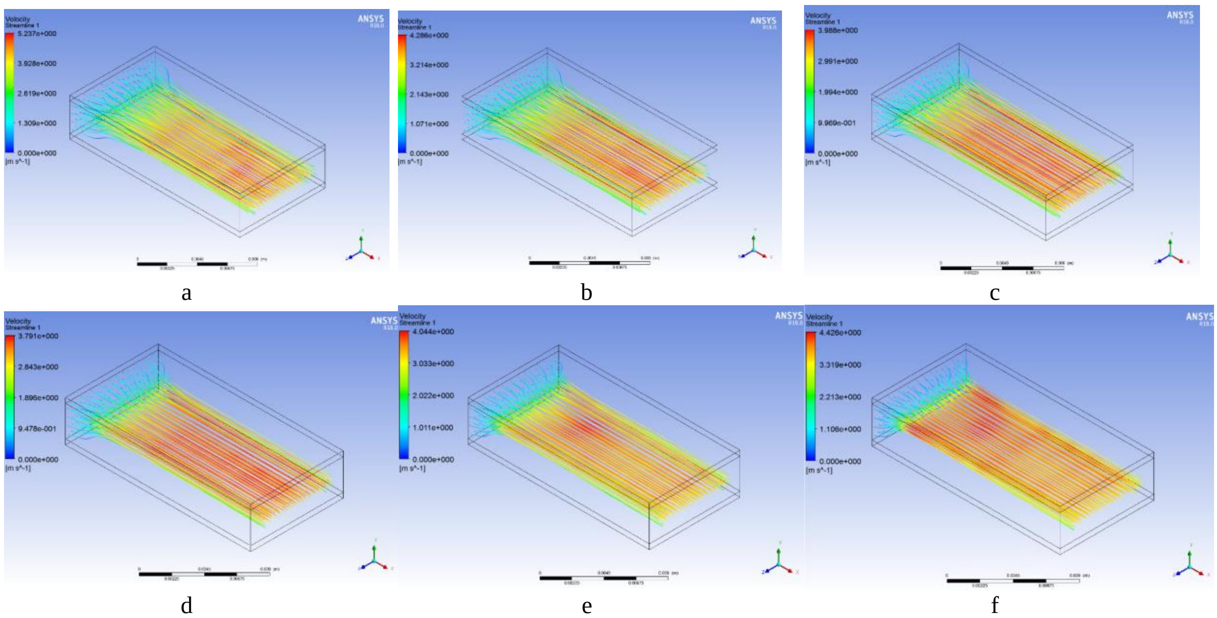

Figure 12. Three-dimensional stream lines for a) 2.5%, b) 5%, c) 7.5%, d) 10%, e) 12.5% and f) 15% of the hydrogen added.

Nomenclature

D_j	The diffusion coefficient of component *j* (*cm²/s*);
h	The total enthalpy of premixed methane/ (and adding hydrogen) (*KJ/Kg*);
h_j	The enthalpy of component *j* (*KJ/Kg*);
M_j	The molar mass of component *j* (*mol*);
Ng	The number of gas phase components;
P	The pressure of premixed methane/air (and adding hydrogen) (*Pa*);
q	The heat of reaction (*J*);
R	The universal gas constant $J/(mol.K^0)$;
R_j	The production rate of component *j* by chemical reaction (*1/s*);
u_i	The velocity components of x_i (*x*, *y* and *z*) direction (see Fig. 1);
Y_j	The mass fraction of component *j* (*wt%*);
λ	The thermal conductivity of the fluid ($W/m.K^0$);
ρ	The premixed methane/air (and adding hydrogen) (Kg/m^3);
τ_{ij}	The stress tensor (*Pa*);

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