ENGINEERING *for* SUSTAINABILITY

# iNESCO

2011

**EDITOR:**

**Nor Azam Ramli | Farzad Ismail | Ishak Hj.Abdul Aziz | Badorul Hisham Abu Bakar**
**Mariati Jaafar @ Mustafa | Widad Ismail | Zuhairi Abdullah | Ridzuan Zakaria**
**Azhar Abu Bakar | Rosmiwati Mohd Mokhtar**

# ENGINEERING *for* SUSTAINABILITY

**E D I T O R :**

**Nor Azam Ramli | Farzad Ismail | Ishak Hj.Abdul Aziz | Badorul Hisham Abu Bakar**
**Mariati Jaafar @ Mustafa | Widad Ismail | Zuhairi Abdullah | Ridzuan Zakaria**
**Azhar Abu Bakar |Rosmiwati Mohd Mokhtar**

# ENGINEERING for SUSTAINABILITY

DISTRIBUTOR
Pusat Pengajian Kejuruteraan Awam
Kampus Kejuruteraan, Universiti Sains Malaysia
Nibong Tebal, Pulau Pinang, Malaysia

Publisher Pusat Pengajian Kejuruteraan Awam, Universiti Sains Malaysia, 2011

.

*Perpustakaan Negara Malaysia* *Data Pengkatalogan – dalam - Penerbitan*

Engineering for Sustainability/ editor Nor Azam Ramli … [et al.].

ISBN 978-967-0167-05-3

PUBLISHER
Pusat Pengajian Kejuruteraan Awam
Kampus Kejuruteraan, Universiti Sains Malaysia
Nibong Tebal, Pulau Pinang, Malaysia

Front page designed by Mohamad Shahrul Affendi Baharom dan Mohd Saidina Dandan Satia

Printed in Malaysia by Alternatif Maju Enterprise

# SIMULATION OF THERMAL EFFICIENCY AND ENVIRONMENTAL POLLUTANT IN COMBUSTION CHAMBERS

**[1]Ahmad Amani,[2]HadisAmani, [2]Manase Auta, [2]Ayodele OlumideBolarinwa, [2]Zahra Gholami**

[1]Department of Aerospace Engineering, Amirkabir University of Technology, Tehran, Iran
[2]School of Chemical Engineering, Engineering Campus, UniversitiSains Malaysia, Malaysia

## Abstract

A simulation study was carried out to salvage global environmental pollution challenge posed by NOx in the atmosphere which is often released from incomplete combustion reactions of methane and air. This was done using computational fluid dynamics software package to model three 3-dimensional combustion chambers. The chambers were categorized into symmetric baffled, asymmetric baffled and non-baffled combustion chamber. Methane gas (fuel) and air were the combustion reactants charged into the chambers. The model focused on evaluation of some significant combustion properties at the outlet such as mass fraction of methane, temperature, velocity, turbulence, and mass of NOx released into the atmosphere. Thermal efficiency, percentage combustion, pattern factor and pollution caused by the combustion were among other parameters determined in the model. The baffled symmetric and asymmetric chambers yielded thermal efficiency of 71.1 and 68.05%, respectively while the non-baffled yielded a thermal efficiency of 63.3%. The combustion percentage for the baffled chambers was 8.6 % while the non-baffled chamber was 5.37 %. Pattern factor for the non-baffled, asymmetric and symmetric chambers were 0.91, 0.70 and 0.66, respectively. The evaluation of pollution caused by combustion results revealed that baffled combustion chambers can give 97 % decrease of NOx pollutant released to the environment from combustion of methane and air. The model results showed that baffled combustion chambers can be used as an economically viable chamber with high thermal efficiency and high reduction of NOx pollutant released to the environment with symmetric system as the best method.

**Keywords**: Baffle, Combustion chamber, Computational fluid dynamics, Pollutant, Thermal efficiency.

## INTRODUCTION

Simulation is an invaluable integral part of modern technological operations.Chemicalprocessesmust operate consistentlywithmaximum speedandminimumcost; therefore, the increased scaleof operationsandprocesschangeorimprovementisneeded. Thesecasesusuallyrequirealot oflaboratory work which is in conflict with the need for quick decisions.Modelingiskey toresolvingthese issues [1].

Ifmodelsareavailableforalloperatingunitsthe number oftestsnecessaryto increase thescaleandgeometrychangesinaproductionunitcan besignificantlyreduced, and this translates to time and cost reduction [2].

Nitrogenoxidecompounds in air from combustion reactions are toxic [3].Their toxicity to the environment has prompted the enactment of environmental laws in order to maintain clean and safe environment [4].

This studyhas tried touse the computationalfluid dynamicssoftware toanalyzethe effect ofturbulenceon improvingcombustion of gasesandcompoundsthat causeenvironmentalpollution by NOx pollutants. It is aimed at providing better understanding ofturbulenceanditsimpactonimportantcombustionparameters [5].

## MATERIALS AND METHODS

Methane gas and air (79% of $N_2$; 21 % of $O_2$) were used for the combustion reaction. High pressure and temperature resistant combustion chambers made of steel materials were used for the reactions.

### Method

Methane gas at a constant temperature of 300 K was injected at a velocity of 60 m/s into the three dimensional combustion chambers where air at temperature of 650K was concurrently injected at a velocity of 18 m/s. The three chambers used had different internal arrangements: the first chamber was completely hollowed without baffles, the second chamber used had six baffles symmetric format and lastly, the third chamber used had same number of asymmetric baffles position. The schematic diagram of the three chambers is shown in Figure 1 and summary of combustion chambers profile is illustrated in Table 1.
The results from the three 3-dimensional combustion chambers were modeled using computational fluid dynamics software (Fluent 6.3.26). The viscosity model from the software used was K-epsilon (RNG) and the solver was pressure based [6]. The meshing information of the computational fluid dynamics software for modeling is summarized in Table 2.

Table 1: Profileofcombustionchamber

| | **No of baffle** | **Baffle width (cm)** | **Air inlet diameter (cm)** | **Fuel inlet diameter (cm)** | **Combustion chamber height (cm)** | **Combustion chamber width (cm)** | **Combustion chamber length (cm)** |
|---|---|---|---|---|---|---|---|
| Non-baffled chamber | - | - | 24 | 2.3 | 30 | 30 | 120 |
| Symmetric baffled chamber | 6 | 2.5 | 24 | 2.3 | 30 | 30 | 120 |
| Asymmetric baffled chamber | 6 | 2.5 | 24 | 2.3 | 30 | 30 | 120 |

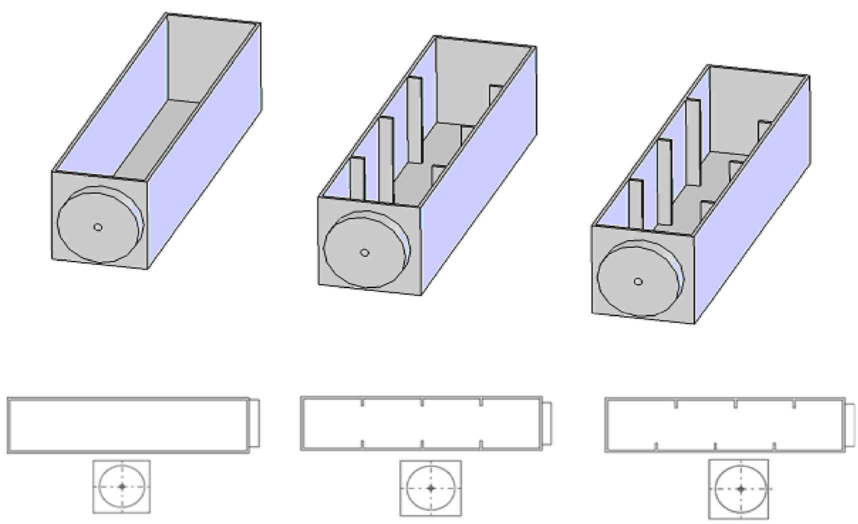

Fig. 1: Non-baffled, symmetric and asymmetric baffled combustion chambers

Table 2: profile of mesh used

| **Element** | **Type** | **Cells (1)** | **Cells (2)** | **Cells (3)** |
|---|---|---|---|---|
| hexahedron | Map | 128011 | 104305 | 104305 |

## RESULTS AND DISCUSSION

### Effect Of Baffle On Combustion Output

The three 3-dimensional combustion chambers used with different internal features were investigated in relation to their suitability for combustion. The summary of the combustion results of the significant output properties are shown in Table 3

Table 3: Output properties of the combustion chambers

| **Property** | **Chamber with asymmetric baffle** | **Chamber with symmetric baffle** | **Chamber without baffle** |
|---|---|---|---|
| Output mass fraction of methane | 0.0826 | 0.0851 | 0.0897 |
| Output average temperature (K) | 1600 | 1641 | 1758 |
| Output average velocity (m/s) | 23.58 | 24.35 | 25.68 |
| Pressure drop (Pa) | 32 | 38 | 27 |
| Turbulence ($m^2/s^2$) | 125.44 | 124.72 | 116.39 |
| Output mass of NOx | $4.46x10^{-5}$ | $4.22x10^{-5}$ | $1.66x10^{-3}$ |

*Temperature*

This is an important property of combustion reactions whose effect was observed in this study. The combustion chamber without baffles had the highest average output temperature of 1758 K as compared with the baffled chambers at same inlet conditions. The higher discharge of temperature signifies non-usage, wastage and incomplete combustion in the inner chambers [6]. The baffled chambers reduced outlet temperatures implied that there is adequate utilization of temperature as can be seen in Fig. 2. The red portion of the cross-sectional area of the chamber as relayed in the adjacent legend showed higher temperatures as compared with the blue colored cross-sectional portion of the non-baffled chambers. The inadequate utilization of temperature in the inner portion of the non-baffled combustion chambers and its subsequent release through the vents or pipes may promote corrosion activities; it can also negatively affect turbine blades faster in systems where combustion gases are used to power the blades [7]. Temperaturereductioninoutputdue to baffle features will increase area of heat transfer thereby reducing temperature wastages at the outlet. Temperature against length of combustion chamber is represented diagrammatically in Fig. 3.

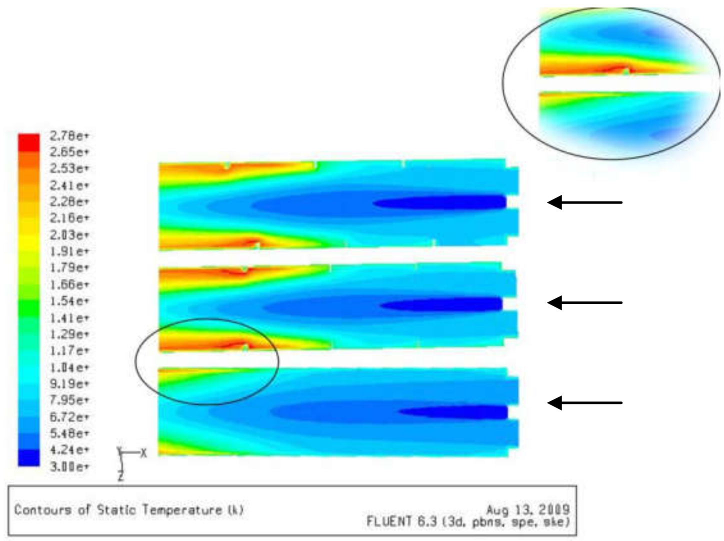


Fig. 2: Profiles of temperature in baffle and non-baffle chambers

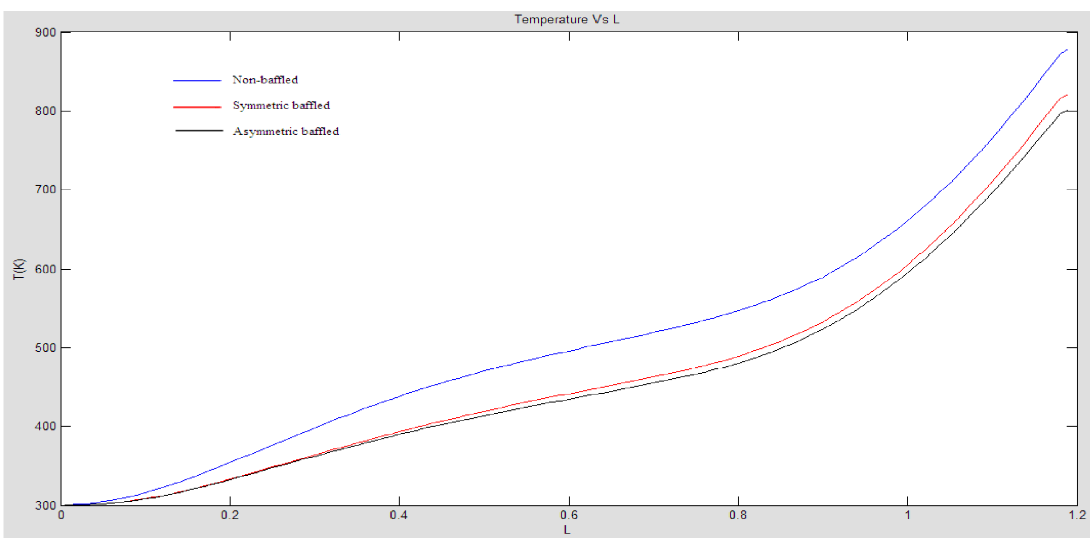


Fig. 3: Temperaturechangesinalongitudinalincisionat the centre of baffled and non-baffled chambers

*Velocity*

The presence of baffles in the chambers served as impediment to free flow of the gases as compared with the non-baffled chambers velocity. The symmetric and asymmetric baffled combustion chambers had outlet velocities of 24.35 and 23.58 m/s, respectively as compared with the velocity of 25.68 m/s for the non-baffled chamber; this can be seen in Table 3. The cross-sectional velocity profiles of the baffled and non-baffled chambers are shown in Fig. 4 while the diagrammatic representation of the velocity against length of the combustion chamber is shown in Fig.5.

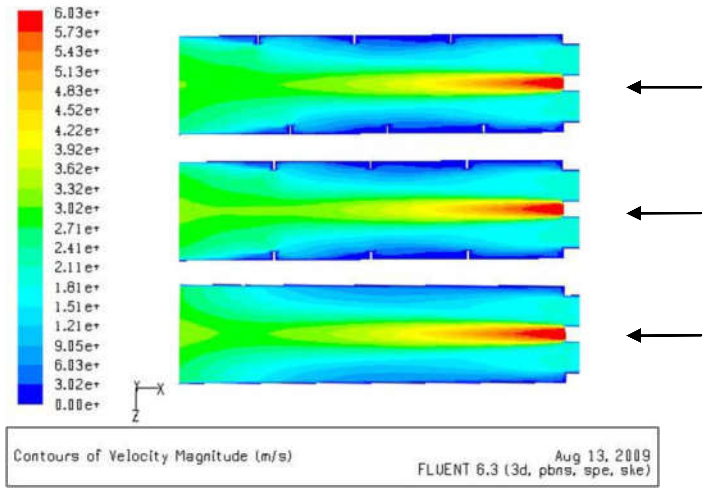


Fig. 4: Profiles of velocity in baffle and non-baffle chambers

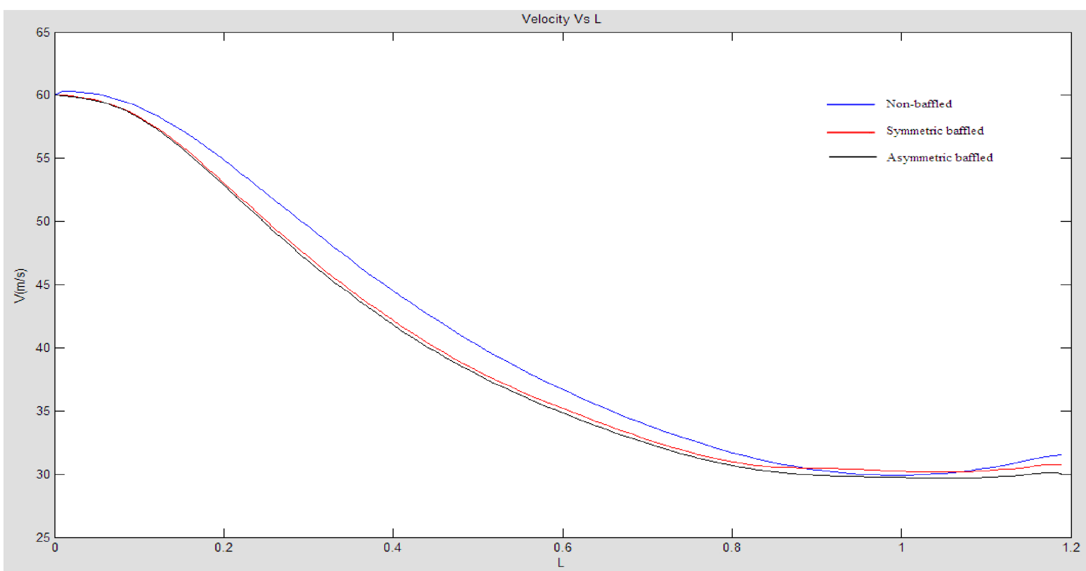


Fig. 5: Changes in the velocity of a longitudinal incision at the centre of baffled and non-baffled chambers

*Turbulence*

The high turbulence experienced in the baffled combustion chambers promoted homogeneous contact between the fuel and the air thereby enhancing good combustion activities. It was observed that asymmetric baffled chambers enhanced better combustion than the symmetric baffled chambers. This was due to higher degree of dispersion of the gas molecules in the asymmetric baffled chambers. This can be seen from the results presented in Table 3. The cross-sectional profile for the turbulence activities is shown in Fig. 6.

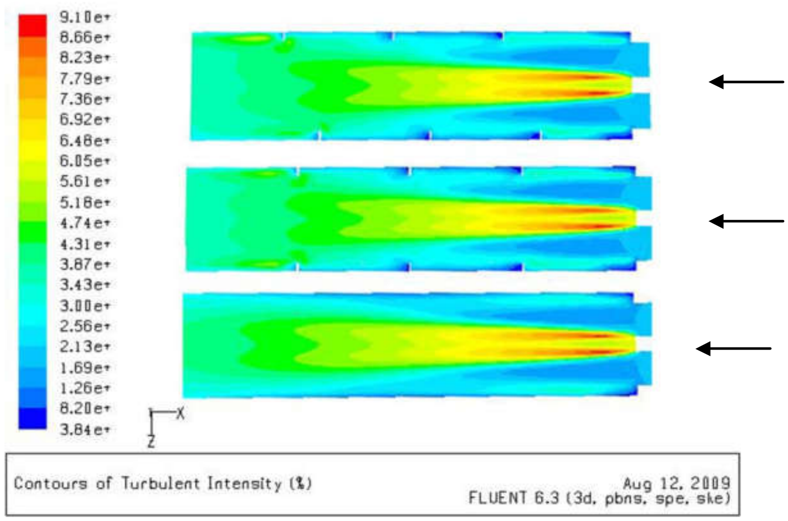


Fig. 6: Profiles of turbulence in baffle and non-baffle chambers

*Mass fraction of methane*

The high output of methane after combustion activities signifies incomplete combustion activities and is tantamount of wastage which in economic terms will result to financial loss. The baffled combustion chambers promoted adequate utilization of the methane charged to the system as can be seen by the low output values shown in Table 3. Asymmetric baffled chamber made the maximum utilization of the methane gas and the non-baffled combustion chamber gave the highest wastage with their output values of 8.26% and 8.97%, respectively. The mass fraction of methane profile is shown in Fig. 7.

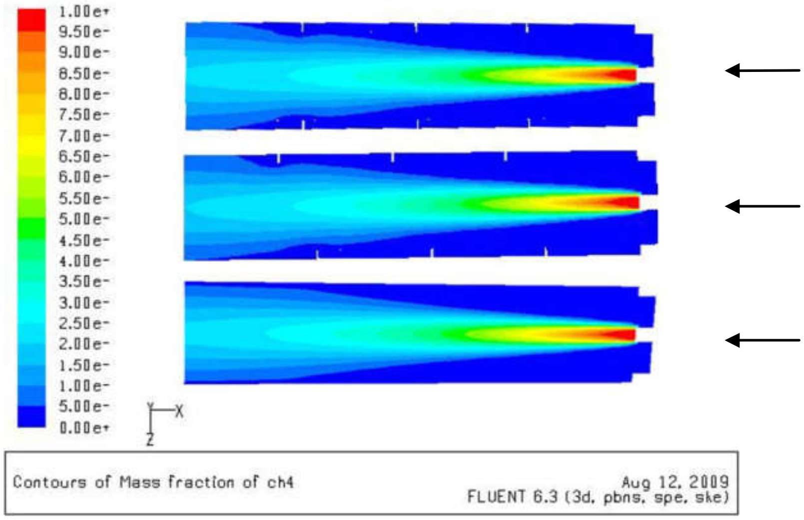


Fig.7: Profiles of methane combustion in baffle and non-baffle chambers

The diagrammatic expression of mass fraction of methane with respect of the length of the chambers is shown in Fig. 8. At initial or inlet position of the chambers, the mass fraction of methane was the same, but as the reaction moved along the longitudinal direction, the non-baffled chamber had the highest mass fraction to the end. The baffled combustion chambers maintained the lower mass fraction of methane even at the output point of the chamber with least fraction from the asymmetric (unparallel) chamber. Although the difference in mass of methane at the outlet of the three chambers studied is small as seen in Fig. 8, but the mass becomes increasingly large as the reactants are continuously charged into the system.

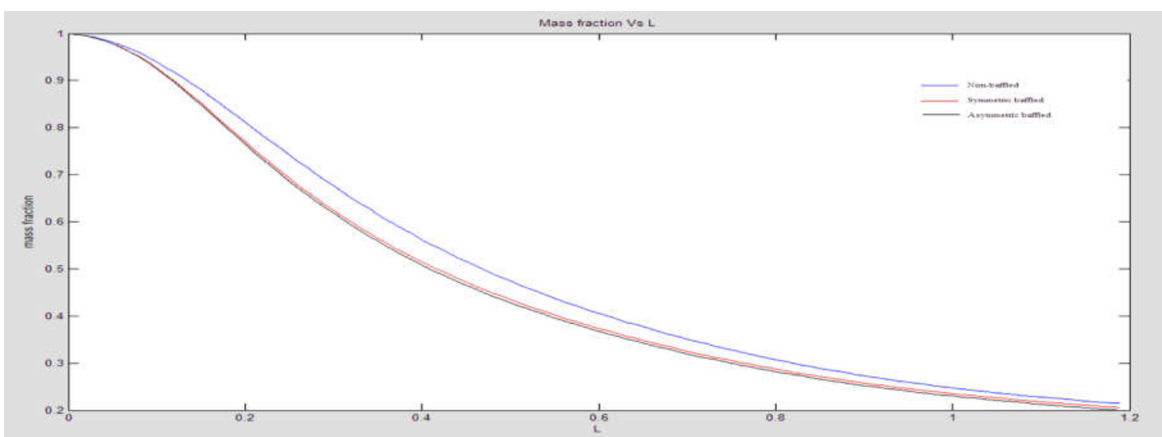


Fig. 8: The concentration ofmethaneat the centre of baffled and non-baffled chambers

## Parameters Comparison Of Combustion Chambers

The major parameters investigated were the thermal efficiency, percentage of combustion, pattern factor and evaluation of pollution caused by pollution.

## Thermal Efficiency

Thermalefficiencyisan important factorin thedesign ofthe combustion chamber [7]. It is a criterionformeasuring theefficiency of thecombustion chamberandis can be evaluated as follows:

$$\eta = 1 - \frac{T_{\max} - T_{av}}{T_{\max}} \quad (1)$$

The results of the thermal efficiency of the three chambers revealed that symmetric baffled combustion chamber gave the best efficiency of 71.1 %, the asymmetric baffled chamber was 68.05 % while the non-baffled combustion chamber gave the poorest efficiency of 63. 3%.

## Percentage Of Combustion

Combustion Percentage ismeasured by amount of methane gases output of the combustion reaction; the lower the methane gases in the output the higher the percentage and vice versa. The lower concentration of methane gases in the output denoted better combustion activities in the inner chambers which was economically viable for the process and environmentally friendly for its reduced release to the atmosphere. The study revealed that baffled chambers had percentage combustion of 8.6 % while the non-baffled chamber had 5.37 %.

## Pollution Caused By Combustion

The most important cases in combustion is evaluation of environmental pollution caused by combustion gases. Evaluation of the output NOx results showed that introduction of baffles caused its significant reduction in output. The reduction further confirmed that there was adequate combustion activity which leads to reduction of NOx which is toxic and has adverse effect to the environment [7]. The introduction of baffles enabled methane to adequately react with the oxygen from air; the less oxygen in the process did not promote formation of NOx in the chamber that would have gone out at the outlet. On the whole, the introduction of baffles to the chambers gave 97 % decrease of NOx in the output gases released.

## Pattern factor

The pattern factor (PF) which is a non-dimensional form of temperature in output is expressed as follows:

$$P.F = \frac{T_{\max} - T_{av}}{T_{av} - T_{in}} \quad (2)$$

where is maximum temperature at outlet surface; is average temperature at outlet surface; and, is average temperature at inlet surfaces. When the PF value is much lower in the outgoing chamber, it shows that the averagetemperature iscloserto themaximumtemperature signifying even distribution of temperature at the output. In PF studies, the ideal situation is that the PF value should be as small as possible [7,8]. From the studies undertaken, the symmetric, asymmetric and non-baffled chambers had PF values of 0.658, 0.70 and 0.91, respectively.

**Effect of baffle width on combustion**

The baffle widths introduced in the chambers were varied to determine their effect on the combustion reaction. The two different baffles used had widths of 15 mm and 25 mm which are shown in Fig. 9. The results of the baffle width variation showed that the 25 mm width baffle gave a better result as summarized in Table4.

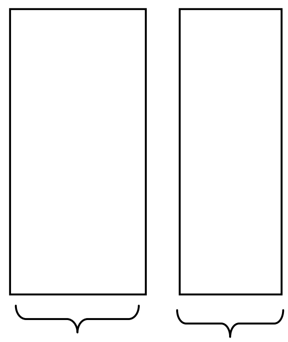


Fig.9: Baffle width evaluation

Table 4: Baffle width variation

| Property | 15 mm baffle width | 25 mm baffle width |
|---|---|---|
| Mass fraction of methane | 0.077 | 0.061 |
| Turbulence ($m^2/s^2$) | 94.9 | 98.3 |
| Mass fraction of NOx | $3.7x10^{-3}$ | $3.8x10^{-4}$ |

The result of the width variation revealed that about 23.18 % improvement on combustion was recorded as the baffle length increased from 15 to 25 mm. The increase baffle length of 25 mm prevented excessive inflow of methane and air which would have promoted incomplete combustion activities in the system. This change in length also decreased a significant amount of NOx pollutant to 89.7 % to the atmosphere. But excessive increase in width may lead to blockage of the chamber which may hinder free passage of fuel and air for proper combustion activities.

## CONCLUSIONS

The baffled and non-baffled combustion chambers for combustion of methane gases and air were successfully modeled using computational flow dynamics soft ware package. The introduction of baffles in the combustion chambers allowed adequate residence time for the gases and air to combust thereby limiting the amount of oxygen available for formation of NOx pollutant which is usually released to the environment as a product on incomplete combustion reaction. Baffled chambers yielded fewer amounts of methane and temperature in the output; this was because the presence of baffles promoted turbulence activities which allowed even distribution of temperature in the chamber. The result of the research revealed that baffled combustion chambers application in combustion reaction of methane gases and air can effectively and efficiently alleviate negative pollutant products (NOx) released to the environment.

## REFERENCES

[1] W. Herodotus, S.Yoshikazu, M. Yohsuke, Spray combustion simulation including soot and NOformation , *Journal of Energy Chemical Engineering*, 250, pp. 2077-2089, 2007

[2] S. Behbehani, "*Fuel Combustion*", second edition, published bythe Oil Industry, Tehran, 2005.

[3]F.Tamanini, *Numerical model for the prediction of buoyancy controlled turbulent diffusion flames* , Factory Mutual Research, Norwood, MA, Report No. FMRC22360-1, 2001.

[4]*Fluent Manual*, Fluent Inc., September 2006.

[5]R. Rahimi, M.R. Rahimi, A review on computational fluid dynamic in chemical engineering , *The 4th IranianChemical Engineering Congress*, pp. 23-25, 2004.

[6] M. Woolley, M.S.J. Fairweather, Conditional moment closure modeling of soot formation in turbulent, on-premixed methane and propane flames , *Journal of Fuel Chem* 220, pp. 1-15, 2008.

[7]R. Rahimi, M. Soltani, "*Computational fluid dynamics software Fluent*", Fifth edition, publishing designer, Tehran, 2007.

[8] B. William, J. Zimmerman, *Process molding and simulation with finite element methods* , Word Scientific, pp.10-15, 2004.