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## Experimental and Numerical Study on the Effect of Dilution in Premixed CH<sub>4</sub>-Air Flame

M. Mahmoodi Arya<sup>1</sup>, A. Fahimirad<sup>2</sup>, P. Baziar<sup>3</sup>, H. M. Heravi<sup>4</sup> and A. Hajipour<sup>5\*</sup>

<sup>1</sup> Department of Mechanical Engineering, Faculty of Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran.

<sup>2</sup> Research and Development Center (R&D), Iran Heavy Diesel Mfg. Co. (Desa), Amol, Iran.

<sup>3</sup> FZA University of Applied Science and Technology, Amol, Iran.

<sup>4</sup> Department of Mechanical Engineering, Faculty of Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran.

<sup>5</sup> Young Researcher and Elite Club, Ayatollah Amoli Branch, Islamic Azad University, P.O. Box 46151-43358, Amol, Iran.

\*Corresponding Author E-mail: [alirezahajipour@gmail.com](mailto:alirezahajipour@gmail.com)

### Abstract

Dilution is considered as a method, which reduces the temperature of furnace and decreases the formation of thermal NO. All of the NO<sub>x</sub> controlling methods are based on the control of temperature or limiting the concentration of O<sub>2</sub>. In this study, the numerical and experimental effects of N<sub>2</sub> and CO<sub>2</sub> diluents on a premixed methane–air flame in a furnace are investigated. This experimental study is achieved by use of a cylindrical furnace for an equivalence ratio from 0.6 to 1.4 and different dilution ratios. The simulation is carried out by using a premix code of the CHEMKIN II software. The GRI-Mech 3.0 detailed reaction mechanism is employed for the combustion of methane. Numerical and experimental results show that the maximum temperature of a flame and the rate of NO<sub>x</sub> production are reduced by the increase of the dilution ratio. The results also demonstrate the fact that a CO<sub>2</sub> diluent is more effective than an N<sub>2</sub> due to its high thermal capacity that reduces the NO<sub>x</sub> production rate more than the N<sub>2</sub> can.

**Keywords:** Dilution, NO<sub>x</sub>, Experimental, Numerical, Premixed.

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## 1. Introduction

The combustion of fossil fuels leads to significant pollution and is probably the major contributing factor in global warming. Scientists and engineers are working to develop alternative energy sources in order to reduce society's reliance on oil and to minimize pollutants and greenhouse gas emissions. Fossil fuels are nonrenewable and a major source of pollutants, including CO<sub>2</sub>, NO<sub>x</sub>, UHC and soot (Briones *et al.* [2]). When fossil fuels (such as natural gas and oil) and their derivative compounds burn with air, oxidation products, like CO, CO<sub>2</sub> and H<sub>2</sub>O, are formed. In addition, nitrogen molecules in the air react with some oxygen molecules and form nitrogen oxides (Schefer *et al.* [29]). Nitrogen oxides include nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O), of which NO and NO<sub>2</sub> are known as NO<sub>x</sub> (Hill & Smoot [11]). NO is a toxic gas which is formed during combustion at high temperature zones in a combustion chamber (i.e. automobile engines, power plants and furnaces); while entering the atmosphere, NO changes into NO<sub>2</sub>. Generally, three mechanisms for the production of NO in combustion are considered: thermal NO, fuel NO and prompt NO. NO that is produced from nitrogen and oxygen molecules in the air are called thermal NO and that which is produced from nitrogen molecules in fuel is called fuel NO. The NO concentration near the flame zone of hydrocarbon fuels is less dependent on temperature and radicals, like O and OH, which help to form NO. Thus, in spite of the control by flame temperature and oxygen concentration, NO forms and is called immediate NO (prompt NO) (Fenimore). The thermal mechanism, which is also called the Zeldovich [33] mechanism, is the main route in the methane–hydrogen–air premixed flame since a suitable condition for the production of prompt NO and fuel NO is not available (Warnats *et al.* [31]). The thermal NO consists of the following reactions:



The first reaction has a high activation energy because of the strong triple bond of  $N_2$ . Therefore the reaction takes place at a high temperature; otherwise, it will limit the formation of thermal NO. Equation (2) is used for the concentration of NO (Warnats *et al.* [31]).

$$[NO] = K_1 \exp\left(\frac{-K_2}{T}\right) [N_2][O_2]^{\frac{1}{2}}.t \tag{2}$$

where  $K_1$  and  $K_2$  are the Reaction kinetics constants and  $t$  is time.  $T$  is temperature and  $[NO]$  is concentration. The thermal mechanism of NO is highly sensitive to temperature as an exponential function. At temperatures higher than 1700 K, the formation of NO will double per each 40 degrees increase so the techniques which reduce the flame temperature are effective for the reduction of NO (Lazic *et al.* [17]).

Dilution, as a way of reducing of  $NO_x$  is considered in many experiments since it shifts the combustion to the lean condition and reduces the formation of nitrogen oxides (Rortveit *et al.* [26] and Ghoniem *et al.* [9]). Adding a diluent with a high heat capacity increases the total heat capacity of the fuel–air–diluent mixture and, as a result, the mixture absorbs more heat during the combustion and reduces the temperature of the combustion chamber. This leads to the reduction of  $NO_x$  emission production which is related to the temperature decrease (Kim *et al.* [15]). Until now, there have been various types of diluents which have been studied in the field of combustion, such as  $CO_2$ ,  $N_2$ ,  $H_2$  and  $H_2O$ , along with their effects on the combustion parameters. Li & Williams [20] conducted an experimental and numerical study on the effects of air stream dilution using various agents ( $N_2$ ,  $H_2O$ ,  $CO_2$  and Ar) on  $NO_x$  emission from  $CH_4$ –air counter flow flames. On a mass basis, the effectiveness of

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various diluents in reducing  $\text{NO}_x$  emission was found to rank in this order:  $\text{H}_2\text{O} > \text{CO}_2 > \text{N}_2 > \text{Ar}$ . The greater effectiveness of  $\text{H}_2\text{O}$  was due to its higher heat capacity that lowers the flame temperature and thereby thermal  $\text{NO}$ , in addition to its ability to decrease the concentration of  $\text{CH}$  radicals that reduce prompt  $\text{NO}$ . Lee *et al.* [18] studied the effects of including  $\text{CO}_2$  in an oxidizer stream on the flame structure and on  $\text{NO}_x$  formation in a  $\text{CH}_4$ -air counter flow non-premixed flame. Liu *et al.* [21] studied the chemical effects of  $\text{CO}_2$  as an additive on soot and  $\text{NO}_x$  formations in an ethylene non-premixed flame. All of these studies focused on the molecular transport and chemical kinetic characteristics of  $\text{CO}_2$  dilution, which was thought to be mainly explained through chemical and thermal effects. In addition to these effects, however, the hydrodynamic effects due to  $\text{CO}_2$  dilution can change many fundamental phenomena, such as entrainment and mixing, local extinction due to flame stretching, diffusion and differential diffusion and vorticity distribution in a reacting flow field (Chen *et al.* [3]). Zhao *et al.* [34] numerically examined the effects of the steam addition on  $\text{NO}_x$  formation in methane-air diffusion flames. A 17% reduction in  $\text{NO}_x$  emission index with a 5% mass addition was observed, while the same flame temperature was maintained. Rortveit *et al.* [27] reported experimental and numerical results on the effects of various diluents in the fuel stream on  $\text{NO}_x$  emissions from  $\text{H}_2$ -air non-premixed and partially premixed flames. On a mole basis,  $\text{CO}_2$  was found to be a more effective diluent compared to  $\text{N}_2$  in reducing both the flame temperature and the  $\text{NO}_x$  concentration in these flames. Park *et al.* [23] also investigated the effect of steam addition on  $\text{NO}$  formation in  $\text{H}_2$ - $\text{O}_2$ - $\text{N}_2$  diffusion flames. Salvador *et al.* [28] studied the effect of dilution using  $\text{N}_2$  on  $\text{NO}_x$  emission in a furnace with natural gas as fuel. Their results showed  $\text{N}_2$  dilution reduces  $\text{NO}_x$  emission by more than 60%. Cho *et al.* [4] numerically investigated the effect of  $\text{N}_2$  and  $\text{CO}_2$  diluents on  $\text{NO}_x$  reduction. It was concluded that diluting with  $\text{CO}_2$  is more effective in  $\text{NO}$  reduction when compared to  $\text{N}_2$ , because of the large temperature drop due to the greater

specific heat of CO<sub>2</sub>. Prathap *et al.* [24] studied the effects of nitrogen dilution on the laminar burning velocity and flame stability of syngas fuel. Their results indicated that nitrogen dilution decreased the laminar burning velocity due to a reduction in heat release and increased the heat capacity of the unburned gas mixture and, hence, the flame temperature. Giles *et al.* [10] numerically investigated the effect of dilution on a non-premixed flame using H<sub>2</sub>O, CO<sub>2</sub> and N<sub>2</sub> as a diluent. It was reported that H<sub>2</sub>O and CO<sub>2</sub>, due to their higher heat capacities, are more effective than N<sub>2</sub> for reducing NO<sub>x</sub> emission and the temperature of the combustion chamber. Kobayashi *et al.* [16] explored the dilution effects of superheated water vapor on turbulent premixed flames at a high pressure and temperature. These studies revealed that water vapor plays an important role in reducing of NO<sub>x</sub> emission. Other findings reported that hydrogen enrichment alone leads to higher burning velocities (Coppens *et al.* [5]), while others indicated that dilution by nitrogen leads to a decrease in the burning velocity (Dyakov *et al.* [7]) and to a lower decrease in NO<sub>x</sub> emissions (Turns *et al.* [30], Dyakov *et al.* [8]).

## 2. Experimental

In order to investigate the effect of fuel dilution on the formation of pollutants NO<sub>x</sub>, a furnace was designed and constructed. The main body of the furnace is a hollow tube of steel AISI 316 with a diameter of 105 mm and a length of 1000 mm to withstand high temperatures. The air needed for combustion is supplied by a fan that is capable to change the mass flow rate of air. Fuel and diluents pass through a venturi in order to achieve a better mixture and after passing through a 35 mm wide tube, enter the furnace. This also prevents a possible flash back. The furnace is insulated by a layer of Indian cotton 1260 with a 15 mm thickness. In order to measure the temperature and observe the flame, 15 holes with a diameter of 20 mm and 70 mm apart from each other, were placed above the furnace body. For better

mixing of fuel and diluent, a collector is used. The flow rate of the fuel and diluents is measured before entrance to the collector and then they are allowed to enter the collector. After entrance to the collector, the rate is measured again. The collector was optimally designed to accommodate a short circuit input and an entrance by the fuel and diluents at an angle under 45 degrees. Figure 1 shows the schematic of the designed furnace and its accessories.

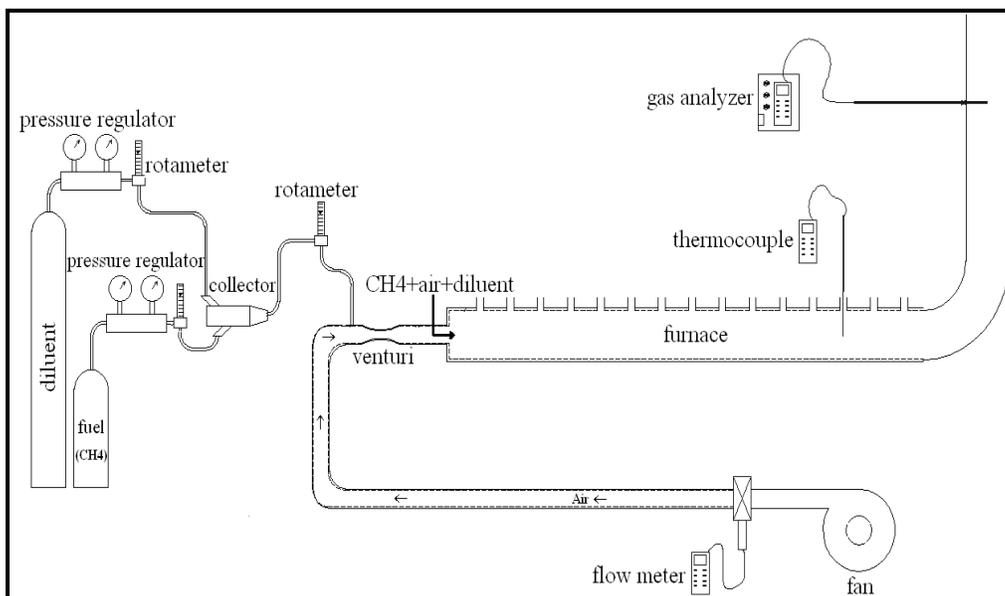


Figure 1. Schematic of experimental setup

To reduce pressure inside the CO<sub>2</sub> cylinder, (70 bar), a regulator is used which reduces the pressure to 2.5 bar (optimal pressure). Also, to reduce pressure inside the N<sub>2</sub> cylinder and adjust it from 140 bar to the desirable level, MORRIS barometers were used, there are capable of tolerating 200 bar of input pressure and can reduce pressure to 1 bar. A gas analyzer, the TESTO 350 XL model with an accuracy of 0.05 ppm, was chosen to measure

the NO<sub>x</sub> of the exhaust gases. A flow meter (Lutron YK-2005AM), with an accuracy of 0.01 to 0.05 m/s, was employed to measure the mass flow rates of the air and exhaust gas, in addition to the mass flow rate of the fuel and diluent. Two SWPF-06A rotameter, with an accuracy of 0.02 lit/min, were utilized. Because of their accuracy, type R thermocouples (platinum-rhodium alloy containing 13% rhodium for one conductor and pure platinum for the other conductor), measured the absolute temperature within a tolerance of ± 10°C and the relative temperatures within ± 1°C.

### 3. Experimental Errors

Regardless of the accuracy of experiments, errors may occur because of various reasons when collecting empirical data. Some errors types are random and some are due to pitfalls during the test. Obvious errors resulting from incorrect data are immediately identifiable and have been excluded. However, there are data that are suspicious and not easily identified. Therefore, to identify these errors, an uncertainty analysis of empirical data obtained via statistical method, was used. The amount of uncertainty or possible error, depending on test conditions, may change considerably. Fixed and random errors are the errors that may cause uncertainty in experimental measurements. Often, fixed errors can be corrected by the calibration of equipment, but random errors must be identified through statistical analysis. In this research, for each point, first four types of laboratory data are collected and then the arithmetic mean of data is calculated. The amount of potential error or uncertainty of data is calculated from the following formula:

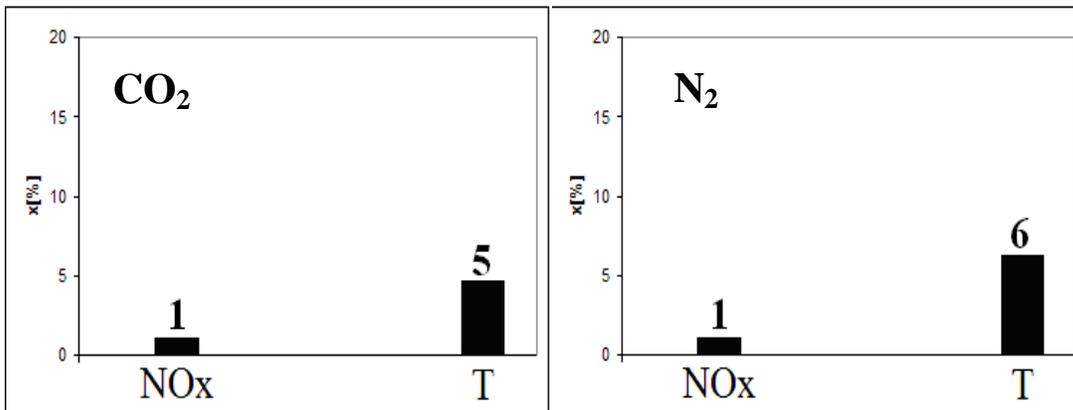
$$\sigma_m = \frac{\sigma}{n^{0.5}} \quad (3)$$

In this formula,  $\sigma_m$  is the standard deviation of the mean value,  $\sigma$  is the standard deviation measurement and  $n$  is the set of numbers of measurement at any point for

all the experimental results. The effect of dilution with CO<sub>2</sub> and N<sub>2</sub>, is 4. The amount of the experimental data uncertainty percentage, ( $X$ ), is calculated from the following equation:

$$X\% = \frac{\sigma_m}{\bar{x}} \times 100, \quad (4)$$

where  $\bar{x}$  is the arithmetic mean value of experimental data. Figure 2 shows the average uncertainty of experimental data in the furnace output.



**Figure 2.** Average uncertainty values for NO<sub>x</sub> output and the temperature of furnace methane-diluted air in the range of equivalence ratios and dilution ratios: CO<sub>2</sub>; N<sub>2</sub>

#### 4. Computational Method

The effect of dilution on a premixed methane–air flame is simulated using the commercially available CHEMKIN II package (Kee *et al.* [12]), more specifically, the Premix code (Kee *et al.* [13, 14]). The detailed reaction mechanism employed GRI-Mech 3.0 (Bowman *et al.* [1]) consisting of 325 elementary chemical reactions and 53 species describing methane oxidation chemistry. Multi component diffusion and thermal diffusion options were taken into account. The adaptive mesh parameters were GRAD=0.05 and CURV=0.5. The relative and absolute error criteria were RTOL=1×10<sup>-5</sup> and ATOL=1×10<sup>-</sup>

9, respectively; the total number of grid points was typically 350–400. The steady state mass, momentum, energy, and species conservation equations were solved along the stagnation streamline in a finite domain (Ren *et al.* [25]).

### 5. Results

The numerical and experimental study was conducted over a wide range of dilution and equivalence ratios. The dilution ratio ( $\beta$ ) is computed from:

$$\beta = \frac{n_{Diluent}}{n_{Fuel}}, \tag{5}$$

where  $n_{Diluent}$  and  $n_{Fuel}$  are the number of diluent moles and fuel moles. Figure 3 shows the effect of dilution with CO<sub>2</sub> and N<sub>2</sub> diluents at a maximum flame and furnace temperature in various equivalence ratios.

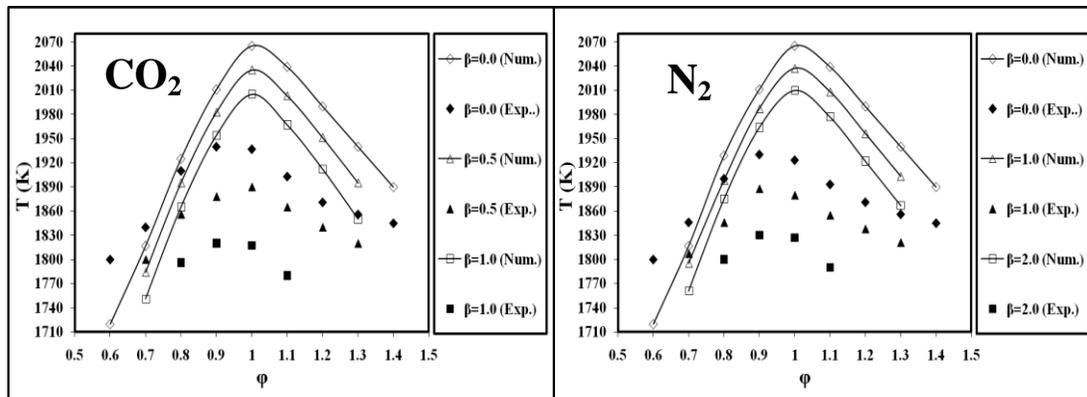


Figure 3. Effect of CO<sub>2</sub> and N<sub>2</sub> diluents on temperature; (experimental and numerical)

As it can be seen in Figure 3, the addition of diluents decreased the temperature of the furnace. Also, these figures indicate a decrease of the maximum temperature of the flame with the addition of diluents. The maximum flame temperature (numerical results (lines)) reached maximum values at  $\phi = 1.0$ , because of the presence of a sufficient amount of O<sub>2</sub>.

The temperature of the furnace's maximum values (experimental results (points)) occurs at about  $\varphi = 0.95$ , because of the presence of the diluent's and hydrodynamic effects leading to a shift in the combustion to the lean condition. Because of the diluents presence in the fuel-air mixture, the thermal capacity of the mixture increased and consequently the flame temperature and chamber temperature decreased. The breaking process of the  $N_2$  bond is endothermic, thus reducing the flame temperature and the formation of  $NO_x$ . Figure 4 shows the simulation results of the effect of  $CO_2$  and  $N_2$  diluents in the premixed methane-air flame at  $\varphi = 1.0$ .

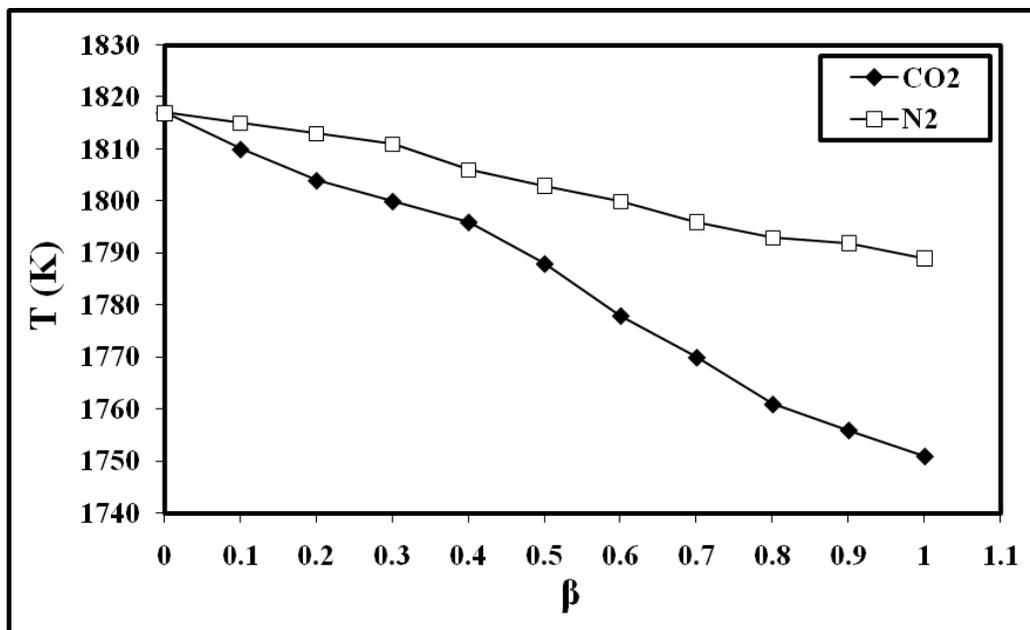
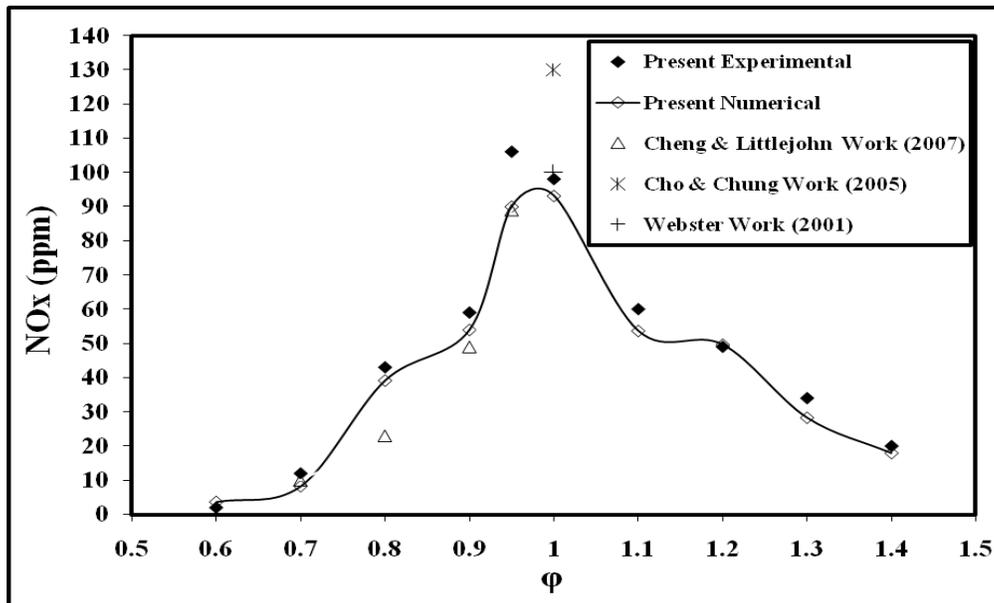


Figure 4. Effect of  $CO_2$  and  $N_2$  diluents on flame temperature at  $\varphi = 1.0$  (numerical)



**Figure 5.** Effect of  $\phi$  on  $\text{NO}_x$  emission and a comparison with the other researchers  
The decrease of the flame temperature with  $\text{CO}_2$  diluent is more remarkable than that of

$\text{N}_2$  because of  $\text{CO}_2$ 's higher thermal capacity. The thermal capacities of  $\text{CO}_2$  and  $\text{N}_2$  are 2.9 kJ/kg.K and 1.042 kJ/kg.K respectively. Figure 5 illustrates the numerical and experimental results of the effect of the equivalence ratio on  $\text{NO}_x$  formation in a premixed methane–air flame without dilution. The results also compared with other researchers.

From the figure it can be seen,  $\text{NO}_x$  formation increases with that of the equivalence ratios, from 0.6 to its peak at 0.95. After that,  $\text{NO}_x$  formation is reduced with the increase of the equivalence ratios in a rich mixture. This conforms to the temperature trend. Temperature is the main parameter in  $\text{NO}_x$  formation because of its exponential trend (Lazic *et al.* [17]). The concentration of  $\text{O}_2$  and  $\text{N}_2$  in a lean mixture may be reduced but the combustion moves toward a complete one in which the flame temperature reaches its peak.

The lack of  $O_2$  in a lean mixture diminishes the oxidization process of  $N_2$ . As a result, a rise in temperature will cause the  $NO_x$  to increase.

Figure 6 shows the experimental results of  $NO_x$  concentration over a wide range of equivalence ratios for various dilution ratios in a premixed methane–air flame. The presence of a diluent mixture increased the thermal capacity and reduced the oxygen mole fraction at the entrance, which will lower the flame temperature and  $NO_x$  emissions. All the factors that diminish the maximum flame temperature and eventually the temperature of furnace are considered effective in reducing  $NO_x$ . Also, with reduction of the oxygen mole fraction, the partial pressure will drop, which will cause the fundamental reaction kinetics and  $NO_x$  production rate to decrease.

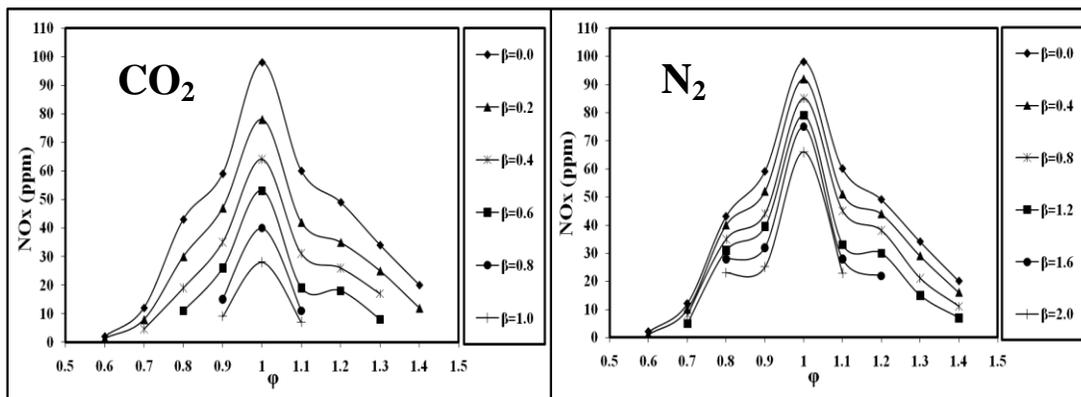


Figure 6. Effect of  $CO_2$  and  $N_2$  diluents on  $NO_x$  emission (experimental)

Experimental results show that in  $\varphi < 1.0$  (lean mixture),  $N_2$  and  $CO_2$  dilution lead to a decrease of the mass fraction of fuel in the mixture, which, in turn, causes flame extinction. This flame extinction also occurs in  $\varphi > 1.0$  (rich mixture) due to the reduction of air. Table 1 shows the extinction limitation of the flame in different equivalence ratios.

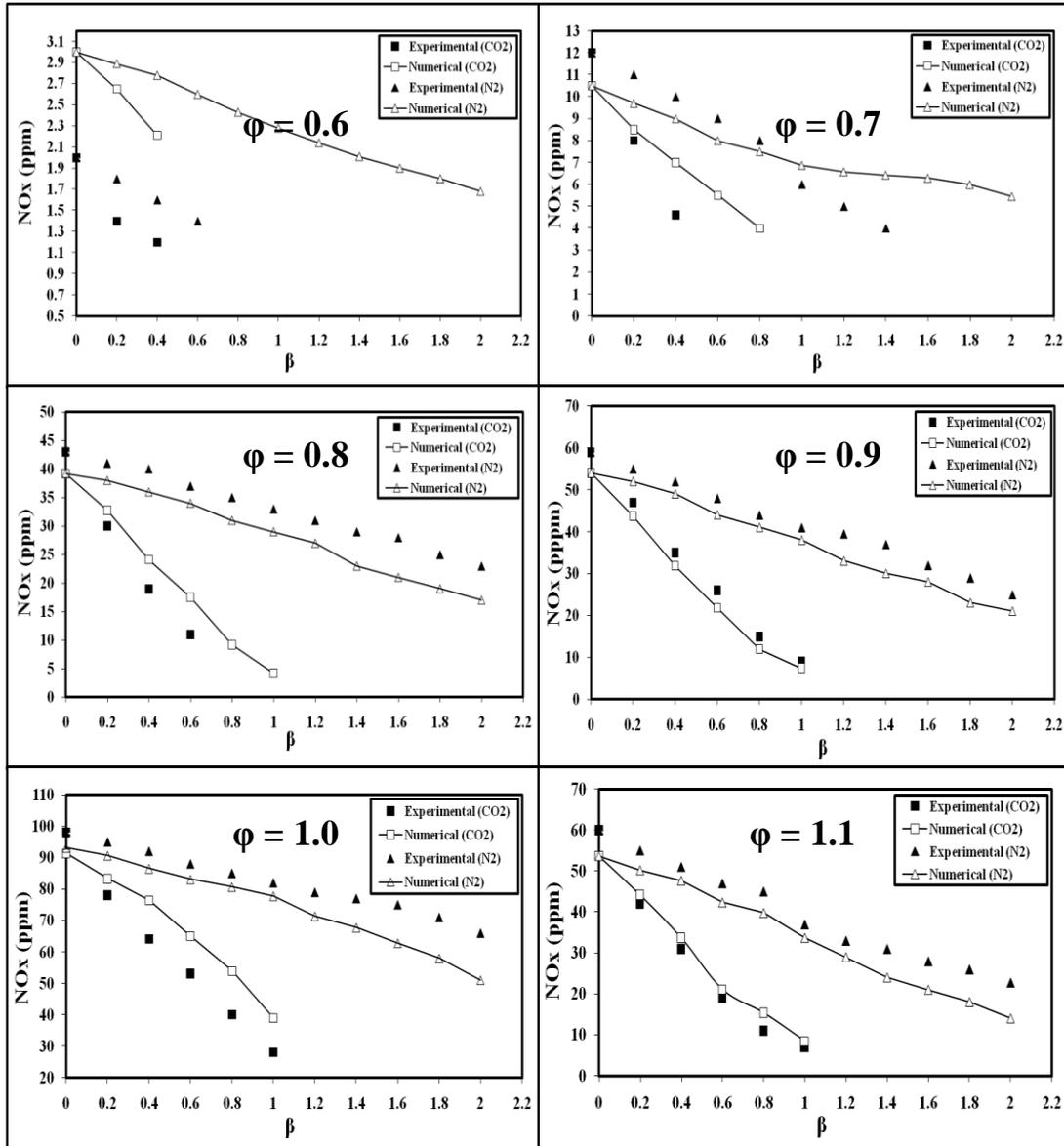


**Table 1.** Flame extinction limits in various equivalence ratios ( $0.0 < \beta_{CO_2} < 1.0$  and  $0.0 < \beta_{N_2} < 2.0$ )

equivalence ratio ( $\phi$ )	CO <sub>2</sub> ( $0.0 < \beta < 1.0$ )	N <sub>2</sub> ( $0.0 < \beta < 2.0$ )
0.6	0.4	0.8
0.7	0.6	1.6
0.8	0.75	-
0.9	-	-
1.0	-	-
1.1	-	-
1.2	0.75	1.7
1.3	0.7	1.55
1.4	0.4	1.3

Figure 7 shows the numerical and experimental results of the effects of CO<sub>2</sub> and N<sub>2</sub> diluents on NO<sub>x</sub> emissions for different equivalence ratios.

As it can be seen from these figures, with the increase of the dilution ratio, NO<sub>x</sub> emission decreases due to the increased heat capacity of fuel, air and the diluent mixture. In addition, the experimental results at the equivalence ratios of 0.6, 0.7, 0.8, 1.2, 1.3, in which extinction occurs, are not available. Table 2 shows the percentage of NO<sub>x</sub> reduction up to extinction (if it occurs) at different equivalence ratios.



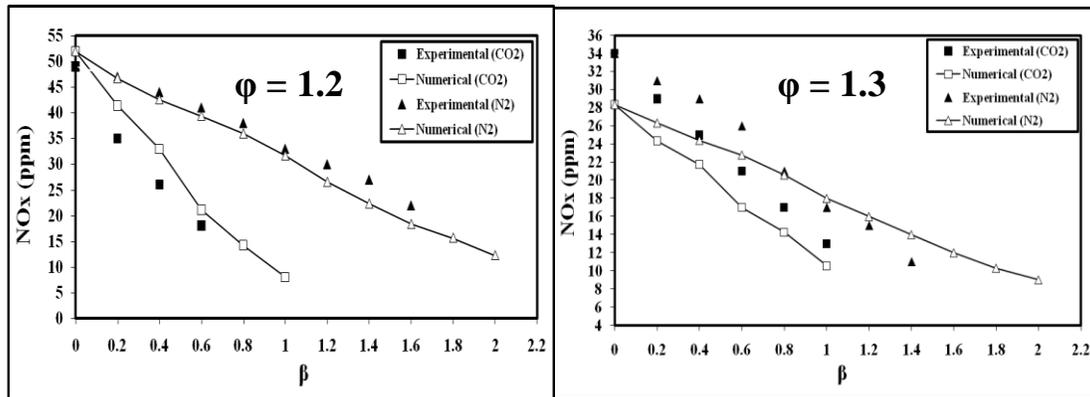


Figure 7. Effect of CO<sub>2</sub> and N<sub>2</sub> diluents on NO<sub>x</sub> emission (experimental & numerical)

Table 2. Percentage of NO<sub>x</sub> reduction for CO<sub>2</sub> and N<sub>2</sub> diluents

$\phi$	NO <sub>x</sub> reduction (%)			
	CO <sub>2</sub>		N <sub>2</sub>	
	Experimental	Numerical	Experimental	Numerical
0.6	40*	26	30*	44
0.7	61*	62	67*	48
0.8	74*	89	46	57
0.9	85	86	58	61
1.0	71	57	33	45
1.1	88	84	62	74
1.2	63*	84	55*	76
1.3	62*	63	68*	68

\*Extinction occurs

## Conclusion

In this study the effects of dilution on NO<sub>x</sub> formation are investigated numerically and experimentally. Results are as follows:



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- With fuel dilution, the temperature of a furnace decreases due to the increased thermal capacity of the mixture and the reduction of the oxygen concentration.
  - The maximum concentration of temperature and  $\text{NO}_x$  in the premixed flame without dilution occurs at the equivalence ratio of 0.95.
  - With an increase of the dilution ratio, the temperature of the furnace and, consequently,  $\text{NO}_x$  formation is reduced.

The decrease of the flame temperature and  $\text{NO}_x$  with the  $\text{CO}_2$  diluent is more remarkable than that of  $\text{N}_2$  because of  $\text{CO}_2$ 's higher thermal capacity.

## References

- [1] C. T. Bowman, D. F. Hanson Davidson, W. C. Gardiner, V. Jr. Lissianski, G. P. Smith, D. M. Golden, M. Frenklach, M. Goldenberg. <http://www.me.berkeley.edu/gri-mech>
- [2] A. M. Briones, K. Aggarwal, V. R. Katta. Effect of  $\text{H}_2$  enrichment on the propagation characteristics of  $\text{CH}_4$ -air triple flames. *Journal of Combustion and Flame*, 153 (2008), pp. 367-383.
- [3] S. J. Chen, W. J. A. Dahm, J. A. Silver, G. Tryggvason. Concentration fields of reactant and products species in a reacting vortex ring. 39<sup>th</sup> Aerospace Sciences Meeting and Exhibit, AIAA, Reston, VA., January 8, (2001), pp. 1-5.
- [4] E. S. Cho, S. H. Chung. Numerical study on  $\text{NO}$  emission with flue gas dilution in Air and Fuel Sides. *Mechanical Science and Technology*, 19 (2005), pp. 1358-1365.
- [5] F. H. V. Coppens, J. De Ruyck, A. A. Konnov. The effects of composition on burning velocity and nitric oxide formation in laminar premixed flames of  $\text{CH}_4 + \text{H}_2 + \text{O}_2 + \text{N}_2$ . *Experimental Thermal and Fluid Science*, 31(5) (2007), pp. 437-444.
- [6] P. Deuffhard. Newton methods for nonlinear Problems. Affine Invariance and Adaptive Algorithms. *Computational Mathematics*, 35 (2004), Springer.
- [7] I. V. Dyakov, A. A. Konnov, J. De Ruyck, K. J. Bosschaart, E. C. M. Brock, L. P. H. De Goey. Measurement of adiabatic burning velocity in methane-oxygen-nitrogen mixtures. *Combustion Science and Technology*, 172 (2001), pp. 81-96.
- [8] I. V. Dyakov, A. A. Konnov, J. De Ruyck. Nitric oxide formation in laminar flames of methane-oxygen-nitrogen mixtures. 6<sup>th</sup> International Conference on Technologies and Combustion for a Clean Environment, July 2001, vol. III, pp. 1441-1449.
- [9] A. F. Ghoniem, A. Annaswamy, S. Park, Z. C. Sobhani. Stability and emissions control using air injection and  $\text{H}_2$  addition in premixed combustion. *Proceedings of the Combustion Institute*, 30 (2005), pp.1765-1773.
- [10] E. D. Giles, S. Som, S. K. Aggarwal.  $\text{NO}_x$  emission characteristics of counter flow syngas diffusion flames with airstream dilution. *Fuel*, 85 (2006), pp. 1729-1742.
- [11] S. C. Hill, L. D. Smoot. Modelling of nitrogen oxides formation and destruction in combustion system. *Progress Energy combustion science*, 26(4) (2000), pp. 417-458.



- [12] R. J. Kee, F. M. Rupley, J. A. Miller. CHENKIN II: A FORTRAN chemical kinetics package for the analysis of gas phase chemical kinetics. Sandia National Laboratories report SAND, (1989), 89-8009. (a)
- [13] R. J. Kee, J. F. Grcar, M. D. Smooke, J. A. Miller. A FORTRAN program for modeling steady laminar one dimensional premixed flames, Sandia report, SAND, (1985), pp. 85-8240. (b)
- [14] R. J. Kee, F. M. Rupley, J. A. Miller. CHEMKIN II: A FORTRAN chemical kinetics package for the analysis of gas phase chemical kinetics, Sandia report, SAND, (1989), pp. 89-8009B. (c)
- [15] H. K. Kim, Y. Kim. NO reduction in 0.03-0.2 MW oxy-fuel combustor using flue gas recirculation technology. Proceedings of the Combustion Institute, 31 (2007), pp. 3377-3387.
- [16] H. Kobayashi, S. Yata, Y. Ichikawa, Y. Ogami. Dilution effects of superheated water vapor on turbulent premixed flames at high pressure and high temperature. Proceedings of the Combustion Institute, 32 (2009), pp.2607-2614.
- [17] L. Lazic, A. Varga, J. Kizek. An experimental study of the influence of FGR on NO<sub>x</sub> formation. ISSN 1580-2949. Material in Technology 38 (2004), pp. 269-274.
- [18] C. E. Lee, S. R. Lee, J. W. Han, J. Park. Numerical study on effect of CO<sub>2</sub> in flame structure and NO<sub>x</sub> formation of CH<sub>4</sub>-air counterflow diffusion flame. International Journal of Energy Research, 24 (2000), pp. 2-12.
- [19] S. C. Li, F. A. Williams. NO<sub>x</sub> formation in two-stage methane-air flames. Combustion and Flame, 118 (1999), pp.399-414.
- [20] D. Littlejohn, R. K. Cheng. Fuel effects on a low swirl injection for lean premixed gas turbines. Proceedings on the Combustion Institute, 31 (2007), pp. 3155-3162.
- [21] H. Liu, H. Guo, G. J. Smallwood, O. L. Gulder. The chemical effects of carbon dioxide as an additive in an ethylene diffusion flame: Implications for soot and NO<sub>x</sub> formation. Combustion and Flame, 125 (2001), pp. 778-787.
- [22] A. E. Lutz, R. J. Kee, J. A. Miller. SAND (1990), pp. 87-8248, Sandia National Laboratories Report.
- [23] J. Park, S. Kim, S. Keel, D. Noh, C. Oh, D. Chung. Effect of steam addition on flame structure and NO formation in H<sub>2</sub>-O<sub>2</sub>-N<sub>2</sub> diffusion flame. International Journal Energy Research, 28 (2004), pp. 1075-1088.
- [24] C. Prathap, A. Ray, M. R. Ravi, M.R. Investigation of nitrogen dilution effects on the laminar burning velocity and flame stability of syngas fuel at atmospheric condition. Combustion and Flame, 155 (2008), pp. 145-160.
- [25] J. Y. Ren, W. Qin, F. N. Egolfopoulos, H. Mak, T. T. Tsotsis. Methane reforming and its potential effect on the efficiency and pollutant emissions of lean methane-air combustion. Chemical Engineering Science, 56 (2001), pp. 1541-1549.
- [26] G. J. Rortveit, J. E. Hustad, S. C. Li, F. A. Williams. Effects of diluents on NO<sub>x</sub> formation in hydrogen counter flow flames. Combustion and Flame, 130 (2002), pp. 48-61.
- [27] G. J. Rortveit, K. Zepter, Ø. Skreiberg, M. Fossum, J. E. Hustad. A coparision of low-NO<sub>x</sub> burners for combustion of methane and hydrogen mixtures. Proceeding of the Combustion Institute, 29 (2002), pp. 1123-1129.
- [28] S. Salvador, Y. Kara, J. M. Commandre'. Reduction of NO Emissions from A VOC Recuperative Incinerator by Dilution of the Fuel Supply. Applied Thermal Engineering, 24 (2004), pp. 245-254.



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- [29] R. W. Schefer, D. M. Wicksall, K. Aggarwal. Combustion of hydrogen-enriched methane in a lean premixed swirl stabilized burner. Proceeding of the Combustion Institute, 29 (2002). pp. 843-851.
- [30] S. R. Turns, F. H. Myhr, R. V. Bandaru, E. R. Maud. Oxides of nitrogen emissions from turbulent jet flames: Part-II Fuel dilution and partial premixing effects. Combustion and Flame, 93 (1993), pp. 255-269.
- [31] J. Warnats, U. Mass, R. W. Dibble. COMBUSTION, 3<sup>th</sup> edition Springer-Verlag, Berlin, (2000).
- [32] T. Webster. Burner technology for single digit NO<sub>x</sub> emissions in boiler applications. CIBO NO<sub>x</sub> control XIV conference, by KOHN ZINK Company LLC, (2001).
- [33] Y. A. Zeldovich. Oxidation of Nitrogen in Combustion, Academy of Sciences of USSR, Institute of Chemical Physics, Moscow-Leningrad, (1947).
- [34] D. Zhao, H. Yamashita, K. Kitagawa, N. Arai, T. Furuhashi. Behavior and effect on NO<sub>x</sub> formation of OH radical in methane-air diffusion flame with steam addition. Combustion and Flame, 130 (2002), pp. 352-360.

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## Authors



**Mohammad Mahmoodi Arya (M. Mahmoodi Arya)** received his M.Sc. degree in Mechanical Engineering from Islamic Azad University of Mashhad. His current research interest includes Thermodynamics and Combustion. He published 3 journal papers and 18 conference papers. E-mail: [m.mahmoodi.arya@gmail.com](mailto:m.mahmoodi.arya@gmail.com)



**Afshin Fahimirad (A. Fahimirad)** is born in Amol, Iran in 1984. He received his B.Sc. degree in Mechanical Engineering from Islamic Azad University of Sari in 2006 and received his M.Sc. degree in Mechanical Engineering from Islamic Azad University of Mashhad in 2009. His current research interest includes Thermodynamics and Combustion. He published 2 journal papers and 30 conference papers. He is member of Iranian Society of Mechanical Engineering (ISME). He is currently Head of Research and Development Center (R&D) of Iran Heavy Diesel Mfg. Co. (Desa), Amol, Iran and as a lecturer at Islamic Azad University of Mahmoudabad, Iran. E-mail: [a.fahimirad@desa.ir](mailto:a.fahimirad@desa.ir)



**Peyman Baziar (P. Baziar)** is born in Amol, Iran in 1983. He received his B.Sc. in Mechanical Engineering from Islamic Azad University of Sari in 2006 and received his M.Sc. in Mechanical Engineering from Islamic Azad University of Mashhad in 2009. He published 13 conference papers. His current research interest includes Thermodynamics and Combustion.

He is a member of Iranian Society of Mechanical Engineering (ISME). He is currently works in Total Productive Maintenance (TPM) unit of Kalleh Dairy Co., Amol, Iran and as a lecturer at FZA University of Applied Science and Technology, Amol, Iran. E-mail: [peyman.baziar@yahoo.com](mailto:peyman.baziar@yahoo.com)



**Hamid Momahedi Heravi (H. M. Heravi)** received his PhD degree in Mechanical Engineering from Cardiff University. He is currently Assistance Professor at the Department of Mechanical Engineering, Islamic Azad University of Mashhad, Iran. His current research interest includes Combustion and Energy. He published 4 books, several journal (in Scopus) and conference papers. He is member of Association of Nanotechnology, Association of Combustion of Iran and Iranian Society of Mechanical Engineering (ISME). E-mail: [heravihm@mshdiau.ac.ir](mailto:heravihm@mshdiau.ac.ir)



**Alireza Hajipour (A. Hajipour)** is born in Amol, Iran in 1984. He received his B.Sc. degree in Mechanical Engineering from Islamic Azad University of Sari in 2007 and received M.Sc. degree in Mechanical Engineering from Science and Research Branch of Islamic Azad University in 2013. His current research interest includes Thermodynamics, Air-Standard Cycles, Internal Combustion Engines, Energy and Exergy. He is a member reviewer board of Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering (ISI) and International Journal of Engineering (Scopus). He was a member of Executive Committee of International Conference on Nonlinear Modeling & Optimization (ICMNO), Aug 2012, Amol and member of scientific committee of First Regional Conference on Municipalities and Electronic Citizen, Dec 2013, Amol. He published one book: An Introduction to Matlab (2014) (339 pages) (in Persian), 6 journal papers (2 of them are in Scopus) and 4 conference papers. He is a member of Iranian Society of Mechanical Engineering (ISME), Supreme Association of Iranian Elites – Mazandaran, Iran. He is currently as a lecturer at Islamic Azad University of Mahmoudabad, Iran. E-mail: [alirezahajipour@gmail.com](mailto:alirezahajipour@gmail.com)