Korean J. Chem. Eng., **30**(8), 1588-1593 (2013)
DOI: 10.1007/s11814-013-0088-6

Experimental study of argon dilution effects on NO_x emission in a non-premixed flame in comparison with nitrogen

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(*Received 7 December 2012 • accepted 17 May 2013*)

Abstract−The effects of nitrogen and argon dilution on NO_X emission of turbulent propane-air non-premixed flame in a furnace are experimentally investigated. Dilution is an effective process in reducing NO_X emission, since diluents cause an increase in the mass flow of the fuel, and consequently the temperature in the combustion chamber and NO_X emission decreases. We measured NO_X emission and temperature for a wide range of dilution and equivalence ratios. The results show that nitrogen dilution is more effective than argon dilution in reducing NO_X emission. In addition, both dilutions caused the yellow color of the non-premixed flame to turn blue, which indicates more complete combustion and better mixing of fuel and oxidant.

Key words: NO_X, Dilution, Nitrogen, Argon, Propane, Non-premixed

INTRODUCTION

Currently, the main source of world energy is provided by the combustion of fossil fuels. The increasing demand of fossil fuels and the environmental problems caused by pollutants from the combustion of these fuels have motivated researchers to find strategies for reducing pollution from the combustion of fossil fuels. NO_X emission, as one of the main pollutants resulting from the fossil fuels combustion, has always been studied by researchers in the field of combustion. This pollutant has harmful effects on humans, animals, and plants such as respiratory diseases, photochemical smog, acid rain, and ground level ozone. Two most important oxides of nitrogen are NO and NO_2, generally called NO_X emissions. NO is formed during combustion at high temperature zones in the combustion chamber and changes into NO_2 as it enters into the atmosphere.

Successful control of NO_X production depends on understanding the mechanism and chemical kinetics of NO formation. There are three primary mechanisms for the formation of NO during the combustion process: thermal NO, prompt NO, and fuel NO. Thermal NO forms in high temperature through the oxidation of diatomic nitrogen found in combustion air. This mechanism is the major source in the non-nitrogenous fuel and determined by a group of highly temperature-dependent chemical reactions known as the Zeldovich mechanism. The principal reactions governing the formation of thermal NO from molecular nitrogen are as follows:

$$O+N_2 \leftrightarrow N+NO \quad (1)$$

$$N+O_2 \leftrightarrow O+NO \quad (2)$$

$$N+OH \leftrightarrow H+NO \quad (3)$$

The basis of the prompt NO mechanism is the reaction between the molecules of nitrogen and hydrocarbon radicals (CH) which consequently depends on the concentration of hydrocarbon radicals in the flame front. Also, the prompt NO is frequently produced in rich flames. Fuel NO is produced by the conversion of fuel nitrogen to NO. The major source of NO_X production in nitrogen-bearing fuels such as coals and oil is the oxidation of the fuel bound nitrogen during combustion process [1].

There are several general strategies for reducing NO_X emission such as fuel dilution, staged combustion and, EGR (exhaust gas recovery) [2,3]. In fuel dilution, with respect to the important role of highly temperature-dependent reaction (1) in the formation of thermal NO, mixing fuel with another substance causes an increase in the mass flow of the fuel, since more heat is required for its heating up which in turn reduce temperature in the combustion chamber and consequently NO_X emission decreases [4]. Diluents such as carbon dioxide, nitrogen and argon have been examined by researchers so far. In 2004, Salvador et al. [5] investigated reduction of NO emissions from a VOC (volatile organic compounds) recuperative incinerator by dilution of the fuel supply. Their results showed that addition of N_2 to the fuel (natural gas) can reduce NO emission by approximately 30%.

In 2004, Cho et al. [6] studied numerically the effect of fuel gas dilution in air and fuel sides on NO emission. Dilution with CO_2 as compared to N_2 was found to be more effective in NO reduction because of greater temperature drops due to the larger specific heat of CO_2. In 2006 Giles et al. [7] studied the effect of dilution on non-premixed flames numerically using H_2O, CO_2 and N_2 as diluents. Their results also indicated that H_2O and CO_2 are more effective than N_2 in reducing NO_X emission and temperature of the combustion chamber due to their higher heat capacities.

In 2008 Kumar et al. [8] studied the effects of N_2 on bluff-body stabilized LPG (liquefied petroleum gas) jet diffusion flame. It was shown that N_2 dilution reduces NO_X emission and increases the flame length. In 2009, Kobayashi et al. [9] investigated experimentally a methane/air turbulent premixed ame diluted with superheated water vapor. They also compared their findings with the results of their

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previous study [10] on effects of CO_2 dilution on turbulent premixed ame at high pressure and temperature. Dilution with superheated water vapor was more effective in reducing NO_X emission than CO_2. In 2009, Moneib et al. [11] considered NO_X emission control in SI engines by adding argon inert gas to the intake mixture. They observed that argon dilution had a significant effect on NO_X emission reduction.

In 2011, Chun et al. [12] performed a numerical study on the effect of dilution on NO_X characteristics of syngas fuel. They observed that the NO_X production for the CO_2 dilution is lower than the NO_X production of N_2 dilution. In 2012, Lee et al. [13] investigated experimentally the effect of N_2, CO_2 and steam dilution on the combustion performance of syngas. It was found that 40% dilution of N_2, CO_2 and steam reduces NO_X by 79%, 88% and 95%, respectively.

The above literature survey indicates that effects of argon dilution on NO_X emission in a non-premixed flame have not received proper attention in previous studies. Our aim was is to investigate experimentally the effect of argon dilution on the NO_X emission in a turbulent propane-air non-premixed flame. Furthermore, argon dilution effects are compared with nitrogen which has a significant effect on NO_X reduction and has been examined extensively.

A non-premixed flame was used in the cylindrical furnace in this experiment due to its safety and wide range of applications [14]. In this type of flame, fuel and oxidant are mixed after entering the combustion chamber. Propane, which has many applications in industrial burners, power plants, cooking stoves, heating systems has been used as a fuel [15]. LPG, which is a mixture of propane and butane, is mostly used as fuel in vehicles.

EXPERIMENTAL SETUP

As it can be seen in Figs. 1 and 2, the furnace for the present study has a cylindrical combustion chamber with 1 m length and inner radius of 0.105 m. The combustion chamber is made of steel AISI316 and completely isolated during the experiments. For flame observation and temperature measurement, fifteen holes with 0.02 m in diameter and equal spacing were arranged on the top of the combustion chamber.

Fig. 1. Experimental setup of the furnace.

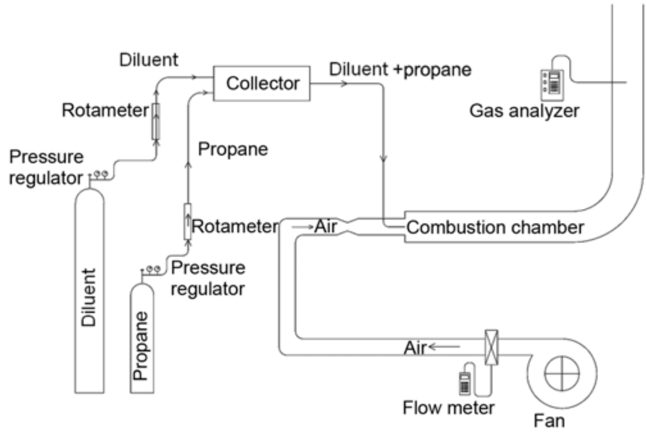

Fig. 2. Schematic of experimental setup.

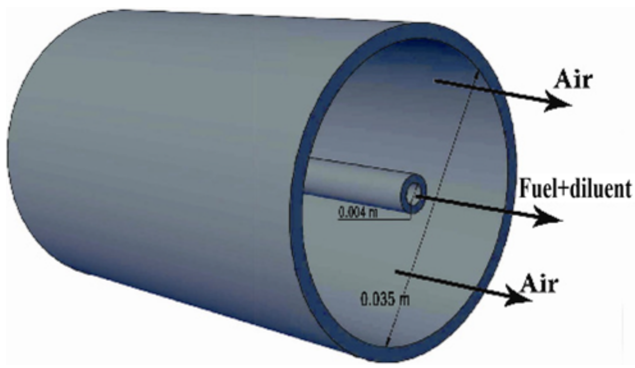

Fig. 3. A cutaway of the burner setup.

As can be seen in Fig. 3, to create a non-premixed flame, propane enters into the combustion chamber through a 0.004 m diameter pipe which is surrounded by a 0.035 m diameter air tube. The amount of NO_X emission in exhaust gases is measured by a gas analyzer (TESTO350XL) with the accuracy of 0.05 ppm.

Two rotameters with the accuracy of 0.02 L/min were used to measure the flow rate of diluent and fuel. To measure the air flow rate, a flow meter (Lutron YK-2005AM) with the accuracy of 0.1 to 0.05 m/s was used. The axial temperature of the furnace was measured by a K-type thermocouple.

EXPERIMENTAL RESULTS

Experiments were performed for various equivalence ratios in the range of 0.7-1.3. The air velocity was kept constant at 3 m/s and the fuel flow rate could be adjusted according to the desired equivalence ratio. In the present study dilution ratio, β, is defined as the fraction of diluents moles to the fuel moles.

$$\beta = \frac{n_{Diluent}}{n_{Fuel}} \tag{4}$$

where $n_{Diluent}$ is the number of diluents moles and n_{Fuel} is the number of fuel moles. In some studies, dilution ratio is defined as the fraction of the diluents moles to the total sum of the number of oxidant and diluents moles. In this experiment, dilution was performed from β=0 to the flame extinction limit.

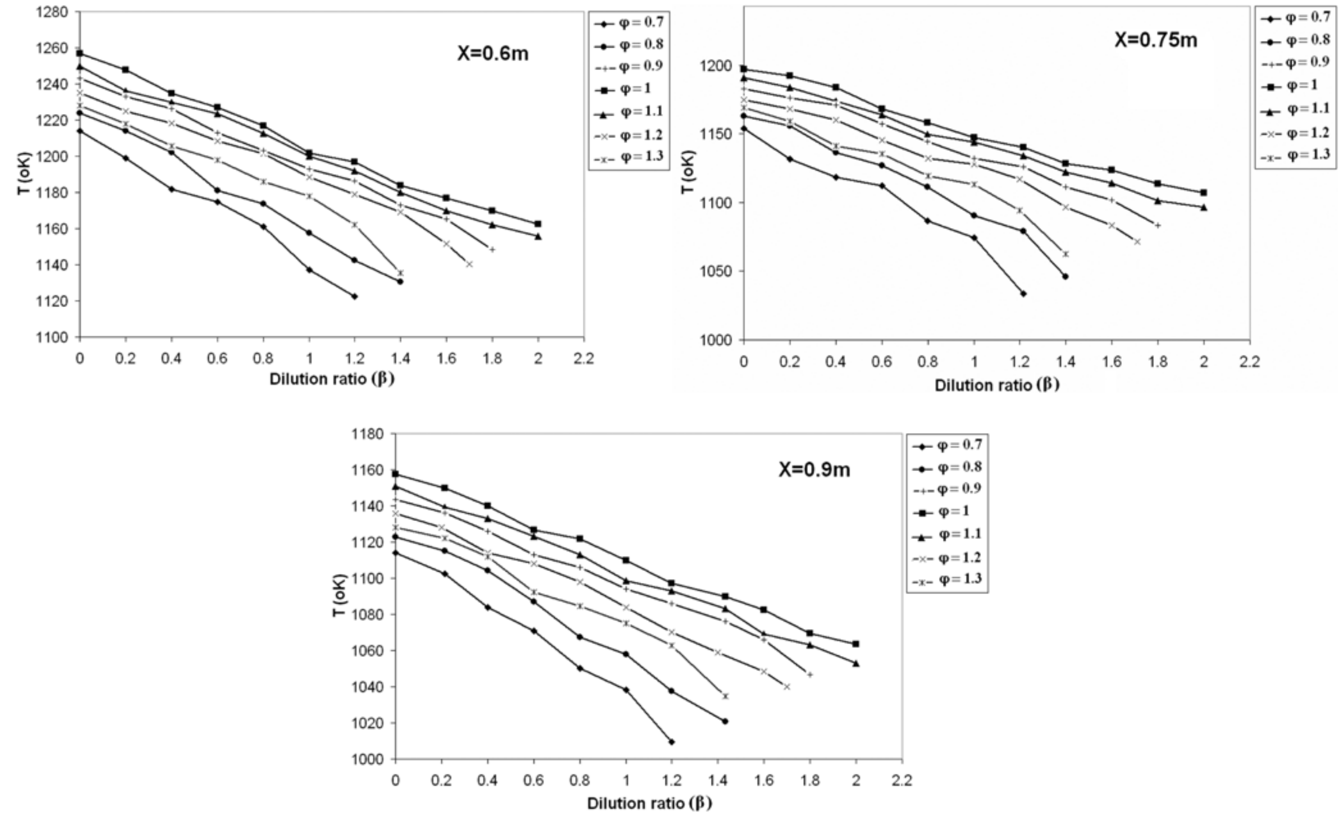

Fig. 4. Effect of nitrogen dilution on combustion temperature at 0.6 m, 0.75 m and 0.9 m from the entrance of the combustion chamber.

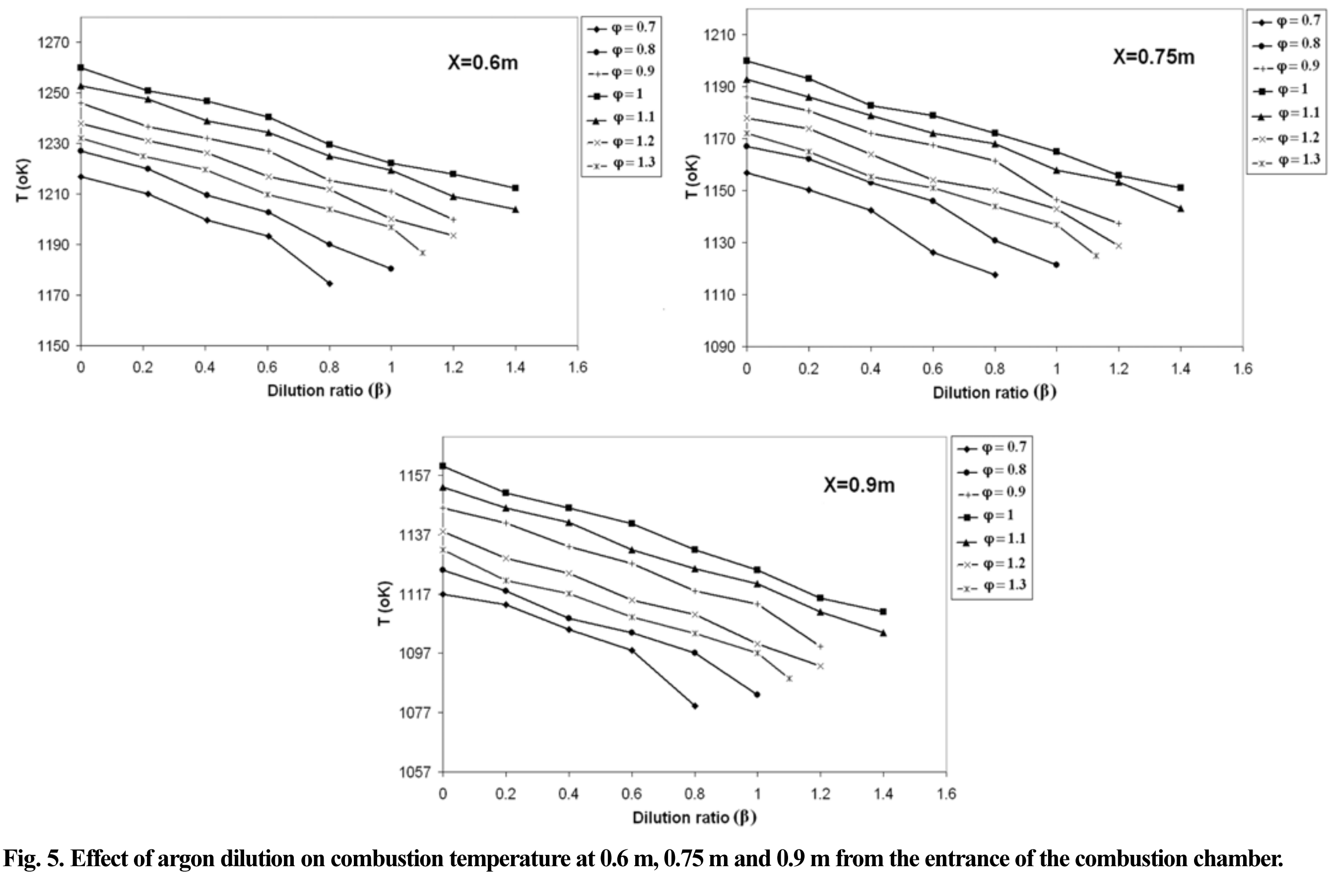

Fig. 5. Effect of argon dilution on combustion temperature at 0.6 m, 0.75 m and 0.9 m from the entrance of the combustion chamber.

1. Effect of Dilution on Temperature

Temperature is considered an important factor in thermal NO_X formation. In this experiment, temperature was measured at three locations of 0.6 m, 0.75 m and 0.9 m from the chamber inlet along the combustion chamber axial line. In Figs. 4 and 5 the effects of nitrogen and argon dilution on combustion temperature for different equivalence and dilution ratios are presented. As it can be observed, increasing dilution ratio causes the temperature to drop due to the increase in mass flow of the mixture. However, higher temperature drop is observed for the case of nitrogen dilution due to its larger heat capacity. Furthermore, the temperature at φ=1 is higher than other equivalence ratios, as expected.

2. Effect of Dilution on NO_X Emission

Fig. 6 reveals the variation of the NO_X emission for different equivalence ratios. As can be seen, by increasing the equivalence ratio

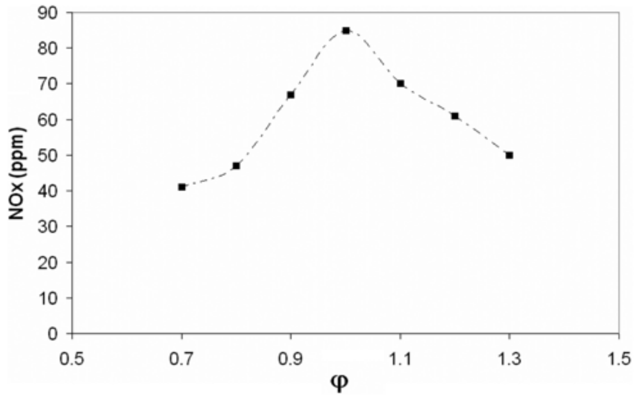

Fig. 6. Variation of the NO_X emission for different equivalence ratios without dilution.

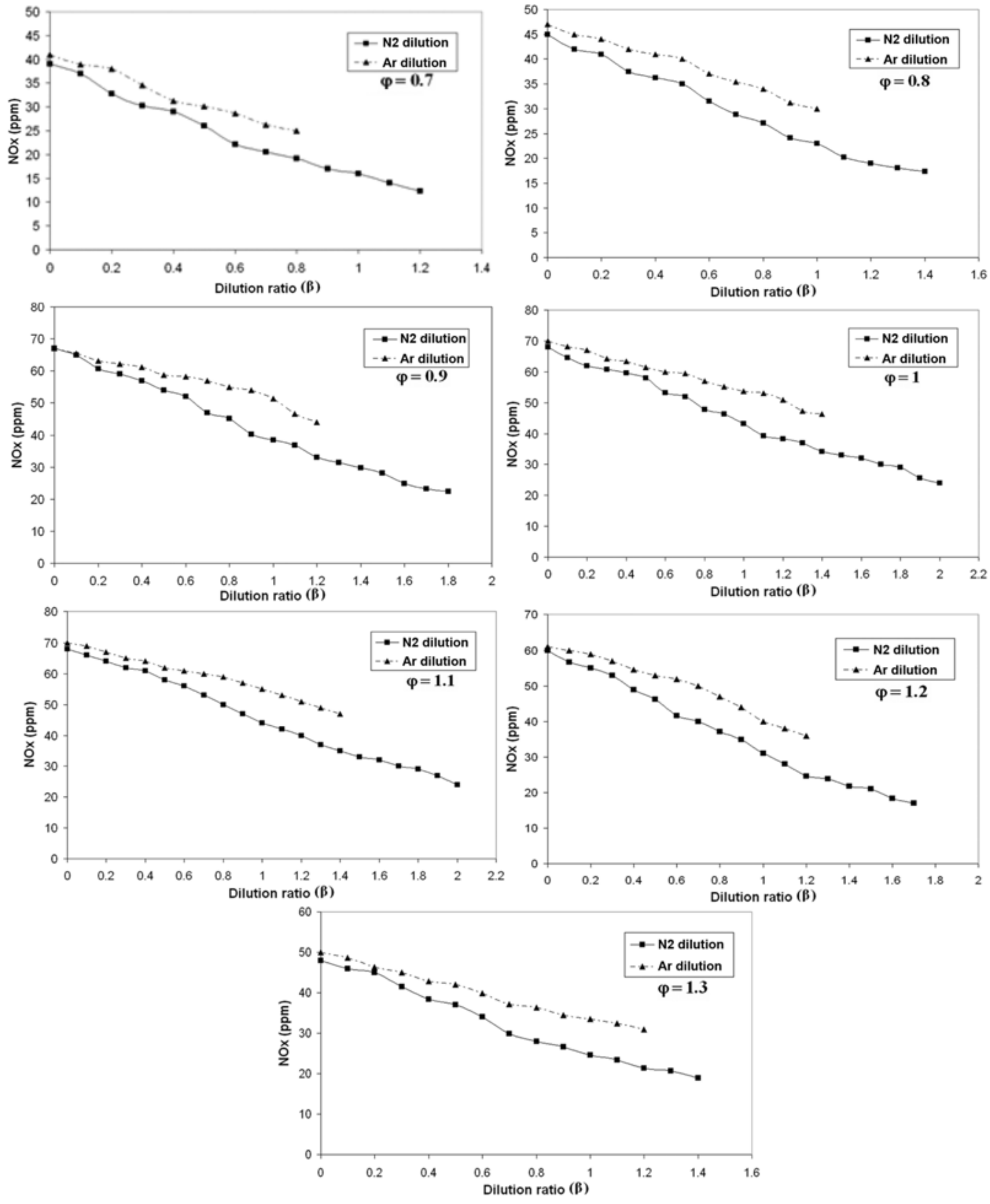

Fig. 7. Effect of nitrogen and argon dilution on NO_X emission for various equivalence ratios.

from 0.7 to 1, NO_X emission increases. However, for the equivalence ratios in the range of 1 to 1.3, NO_X emission decreases. This trend is observed because going from lean to stoichiometric combustion increases the temperature, which subsequently leads to an increase in the production of thermal NO. The opposite trend is encountered for $\varphi>1$ due the increase in fuel-to-air ratio, which causes a temperature reduction and the related NO_X formation.

Fig. 7 shows the effect of nitrogen and argon dilutions on NO_X emission for different equivalence and dilution ratios. Clearly, increasing dilution ratio decreases the NO_X emission. It also indicates 37% reduction in NO_X emission for argon dilution, while 63% NO_X reduction is obtained for nitrogen dilution. This can be explained by the higher heat capacity of nitrogen, which in turn further reduces the combustion chamber temperature as compared to argon. Moreover, dilution increases the momentum flux of the combustion products at high temperature, which reduces the residence time and the NO_X level.

3. Effect of Dilution on Flame Extinction

Flame extinction occurs at a certain dilution ratio for a given equivalence ratio. Since, fuel dilution reduces mass fraction of fuel in the mixture and flame temperature, at the extinction limit the chemical reaction time is much longer than the diffusion time, and the chemical reaction is slow because the reactants do not release the energy stored in their chemical bonds [16]. With respect to higher molar mass of argon as compared to nitrogen, the extinction limitation of the flame in argon dilution is lower than nitrogen dilution. Moreover, reducing the flame temperature plays an important role in the flame extinction. Table 1 shows the flame extinction limits at different equivalence ratios for nitrogen and argon dilution.

4. Effect of Dilution on Flame Color

Figs. 8 and 9 show dilution effects on flame color. Clearly, dilution causes the yellow color of turbulent non-premixed flame to turn to blue, which indicates more complete combustion and better mixing of fuel and oxidant. Dilution increases the momentum flux and the flame length, and thus the fuel and oxidant have a higher chance to be in contact with each other to complete the combustion process.

Table 1. Flame extinction limit in nitrogen and argon dilution for various equivalence ratios

φ	β	
	Nitrogen dilution	Argon dilution
0.7	1.2	0.8
0.8	1.4	1
0.9	1.8	1.2
1	2	1.4
1.1	2	1.4
1.2	1.7	1.2
1.3	1.4	1.1

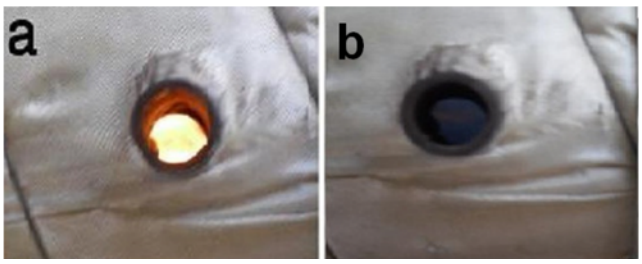

Fig. 8. Effect of nitrogen dilution on flame color, the hole is a distance of 30 cm from the inlet of the combustion chamber in, (a) before dilution, (b) after dilution.

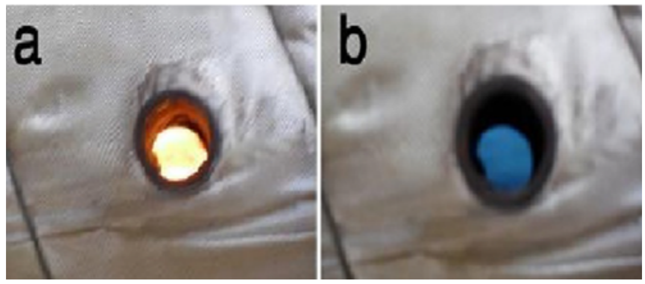

Fig. 9. Effect of argon dilution on flame color, the hole is a distance of 30 cm from the inlet of the combustion chamber in, (a) before dilution, (b) after dilution.

Hwang et al. [17] have also investigated the hydrodynamic effects of dilution on changing the color of non-premixed flame. They concluded that the dilution increases the vortex radius and causes better mixing of fuel and air and also changes the flame color from yellow to blue.

CONCLUSION

The effects of nitrogen and argon dilution on NO_X emission in turbulent propane-air non-premixed flame have been studied experimentally. Results show that nitrogen and argon dilution reduce the combustion chamber temperature because of the enhancement in mass flow of mixture and the heat required for its heating up. In nitrogen dilution, due to the higher heat capacity of nitrogen than argon, the temperature is further reduced. Therefore NO_X emission reduction in nitrogen dilution is higher than argon dilution. It was found that 37% reduction in NO_X emission can be obtained for argon dilution, while NO_X reduction can reach up to 63% for nitrogen dilution. As a result of nitrogen and argon dilution, the yellow color of turbulent non-premixed flame turned to blue, which indicates more complete combustion and better mixing of fuel and oxidant due to the increases in momentum flux and flame length.

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