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EFFECT OF FLUE GAS RECIRCULATION ON BURNER PERFORMANCE AND EMISSIONS

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ملخص البحث

يتم استخدام تدوير العادم كوسيلة فعالة لتخفيض الانبعاثات. في هذه الدراسة يتم تدوير العادم خارجيا في عملية احتراق غير سابقة الخلط باستخدام الكيروسين كوقود سائل لدراسة تأثيره على ثبات اللهب وانبعاثاته. يمكن تحقيق استقرار اللهب في مدى مقبول من نسبة التدوير والتي تصل إلى 40%. مع زيادة نسبة التدوير يصبح اللهب أقصر نتيجة زيادة عملية الخلط المضطرب. تنخفض درجة حرارة اللهب تحت تأثير التخفيف وزيادة الحرارة النوعية للعادم المدار. كما ينخفض سطوع اللهب ويتحول للون الأزرق بزيادة نسبة التدوير. نتيجة انخفاض درجة حرارة اللهب تنخفض أكاسيد النيتروجين بشكل واضح من حوالي 90 جزء في المليون إلى رقم أحادي. تزيد انبعاثات أول أكسيد الكربون والكربوهيدرات الغير محترقة عند نسب التدوير العالية وعند ظروف الاحتراق الغنية بالهواء الزائد.

ABSTRACT

Flue gas recirculation (FGR) is an effective applicable way to reduce emissions. In the present study, external FGR was employed in non-premixed combustion using kerosene as liquid fuel to investigate its effect on flame stability, appearance and emissions. Flame stability can be attained through a reasonable range of recycling ratios up to 40%. Flame appearance exhibits shorter flame with increasing FGR% due to the increased turbulent mixing. Flame temperature was reduced because of dilution effect and increased specific heat of FGR. The flame luminosity decreased and bluish flame increased by increasing FGR%. As a result of the flame temperature decrease, an obvious reduction of NO emissions can be achieved. The NO can be dropped from about 90 ppm to a single digit number. Emissions of CO and UHC increased at high recycling ratios near to flame blow-off and more increase took place at leaner conditions i.e. lowest flame temperature.

Keywords: Flue Gas Recirculation; Liquid Fuel; Kerosene Combustion; Flame Stability; No_x Reduction

INTRODUCTION

Flue gases from fossil fuel-fired combustion facilities are major contributors to atmospheric pollution. Nitrogen oxides emissions are produced almost entirely by combustion processes. At common combustion temperatures, the NO_x in the product gas is almost completely composed of NO. As this gas leaves the combustion zone, it cools and some NO is oxidized to NO_2. However, the exhaust NO_x is still typically over 90 percent NO as it is emitted into the atmosphere. After entering the atmosphere, both NO and NO_2 participate in a series of chemical reactions to form other compounds such as ozone and particulate nitrate [1, 2].

There are three mechanisms for the formation of NO_x in combustion processes: thermal NO_x, prompt NO_x and fuel NO_x [3]. Prompt NO_x is usually negligible because industrial furnaces

mostly run under lean conditions. Fuel NO_x is formed from nitrogen atoms bound in the fuel. Accordingly, thermal NO_x is the main source in this study of liquid kerosene combustion.
In response to the air pollutant emission regulations, a variety of technologies for controlling pollution from combustion sources has been developed. These development technologies have drawn heavily on the understanding of the chemical pathways for the formation and removal of these pollutants.

Researches that focus on employing flue gas recirculation (FGR) in liquid fuel combustion are rather limited, which reflects on the number of publications available. Hence the present work, however, will focus on the use of FGR as an effective and easily applicable way to reduce emissions for non-premixed combustion using kerosene as fuel.
This technique has been developed to reduce temperature peaks in oxygen-rich parts of the flame. By recirculating part of the flue gases, NO_x emissions can be significantly reduced. The injection of the flue gases increases the ballast of the gases not involved in combustion, thereby lower the flame temperature. The recirculation can be performed either by recycling the flue gas from the exhaust of the combustor by mechanical means (external FGR) or by entraining the product gases from the combustion zone by high-velocity air or fuel jets (internal FGR).

With the external FGR technique, it is possible to obtain stable combustion and lower NO_x by 20% to 80%, and by adjusting the flue-gas recirculation rate 15% to 30%. The effect of high CO_2 and H_2O levels in the flue gas is to increase the specific heat capacity of the burned gases for a given quantity of heat release, thus lowering the operating temperatures [4–8].

The effect of flue gas recirculation on the stability and NO_x and CO emissions was investigated using a new alternative fuel, Dimethyl Ether (DME) [9]. The blow-off occurred at 50% of the FGR ratio for 300 K. By preheating the diluted air to 600 K, the blow-off was observed at 90% of FGR ratio. The NO_x concentration drastically reduced to 13 ppm at 0% O_2 (90% reduction) for 86% of the FGR ratio with 600K of the preheating diluted air [9].
The effect of FGR on staged air combustion was reported. The NO_x reduction level from staged air combustion was about 70%, while employing FGR can reduce the NO_x emissions by an additional 5% − 10% [10].

The FI-FGR (fuel-induced-FGR) method was determined to be more effective than the AI-FGR (air-induced-FGR) method in reducing NO_x emission because the high temperature region and the OH distribution region of the FI-FGR method were narrower. The reduction rates of NO_x emissions for the FI-FGR method and the AI-FGR were approximately 29% and 28% for an FGR ratio of 20% and 25%, respectively [11].

EXPERIMENTAL SETUP
The study was performed in a 20 kW laboratory furnace. The experimental system was designed so that air, liquid fuel and FGR could be introduced, controlled and metered. It comprises a horizontal furnace fired by laboratory designed burner equipped with facilities for flue gas recirculation.
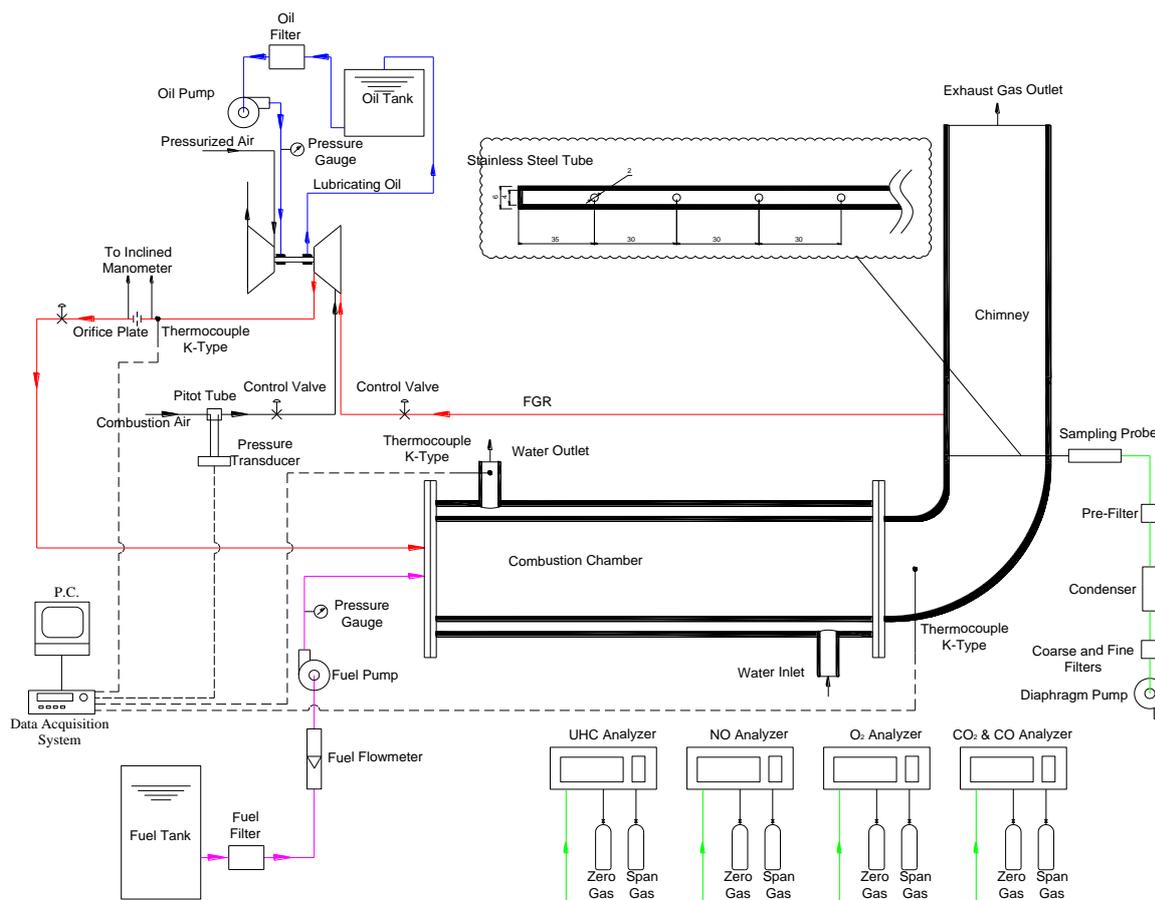
Fig. 1. Schematic diagram of the experimental apparatus.

The combustion chamber is cylindrical and consists of 150 mm inner diameter pipe with 800 mm length. The combustion chamber was surrounded by a cooling jacket of 200 mm inner diameter pipe. Cooling water was delivered from the water supply network. The flow rate of cooling water was measured and controlled with a calibrated rotameter and globe valve, and its temperature was measured with a type K thermocouple and indicator. The cooling water flow rate was kept constant in each case.

A schematic diagram of the experimental setup is shown in Fig. 1. The kerosene was used as a fuel and atomized into a fine spray by a fuel pump and a spray nozzle. This spray was ignited by an electric spark stimulated by two solid electrodes under high voltage (10000 V). The liquid fuel (kerosene) was measured by a calibrated rotameter. The fuel flow rate was controlled via a pressure bypass valve which is a part of the fuel pump. A turbocharger was used to withdraw both combustion air and recycled flue gases. The turbocharger is reversed in operation i.e. the turbine side is become the suction side while the compressor side is the prime mover by the use of pressurized air. The material of the turbine blades (Incoloy alloy) is high corrosion and heat resistance, therefore it is suitable to be used in flue gas applications. The speed of rotation was controlled by adjusting the flow rate of pressurized air, which was controlled by a control valve and a bypass. Both of combustion air and recycled flue gases paths were equipped with control valves to adjust flow rates. The combustion air flow rate was measured by a Pitot tube and the differential pressure was measured with a pressure transducer of range 25 mm H_2O. The transducer output signal was transferred to a data acquisition connected to a PC for storing and manipulating the data. The mixture of combustion air and recycled flue gases was measured by standard orifice plate manufactured according to British standard (BS1042). The differential pressure was measured by a variable angle inclined manometer of range 250 mm H_2O.

For flame appearance purposes, another specially designed combustor of a square cross section was used. One longitudinal side of the combustor was made of a heat-resistant clear glass (glass window). The flame photos were taken by the use of a professional digital camera (CANON). The shutter speed, the ISO and the aperture were adjusted according to the flame luminosity in each FGR%. The camera position with respect to the furnace glass window was kept constant to keep the flame scale constant for comparability.

The FGR, exhaust gas and cooling water temperatures were measured by type K thermocouples as indicated in Fig. 1.
The flue gas analysis was carried out for the measurement of the species O_2, CO, CO_2, UHC and NO concentrations. The sampling was achieved using multi-hole stainless steel probe, which can withdraw an average gas sample all over the whole chimney diameter. The sampling pump was 100% oil-free diaphragm pump and filtered with a sequence of filters of different sizes (coarse, fine and very fine). To get a dry gas analysis, a sample chiller was used to separate water vapor from the sample before entering instruments. The analytical instrumentation included a paramagnetic analyzer for O_2 measurements, non-dispersive infrared gas analyzers for CO, CO_2 and NO measurements and a flame ionization detector for UHC measurements. Zero and span standard gases were used periodically for the calibration of the instruments.

The accuracy of each measuring was as follows: fuel flow ±2.5%, air flow ±1%, oxidizer flow ± (0.6 − 1) %, temperature 1.5^{o}C, CO_2, CO, UHC ±1%, NO, O_2 ±0.1%.
The combustion tests with the flue gas recirculation were carried out based on the lean equivalence ratios from 0.95 down to 0.7 as a typical value considering industrial applications.
The recycling ratio R is defined as the ratio between the mass of flue gas being recycled and the total flue gas mass flow

R = recycled flue gas / total flue gas   (Equation 1)

For the purposes of a comparison, the emission concentrations measured in the flue gas were corrected to 3% oxygen by applying the sequence specified in [3] and the next equation [12]:

$$X_{i\,3\%} = [(21 − 3) /(21 − X_{O2})] \, X_i \qquad \text{(Equation 2)}$$

where: X_i is the pollutant concentration expressed on a dry volume basis, $X_{i\,3\%}$ is the concentration corrected to 3% O_2 and X_{O2} is the percent dry oxygen concentration in the actual conditions. The results are compared and the difference was negligible.
The experimental work was started by heating up the facility with the full power of 20 kW and taking flue gas recirculation gradually into use. When the chamber had reached a sufficient temperature level, the FGR was adjusted to the recirculation rate R and then was increased gradually.

Table 1 summarizes oxidizer conditions for experimental tests at different equivalence ratios. It should be noted that, for each equivalence ratio the fresh air flow rate was held constant and the flue gas flow rate gradually increased up to blow-off occurrence.

Table 1. Summary of combustion conditions and FGR

Φ	O_2 % (Vol.)	FGR % (mass)	Oxidizer $\dot{m}$ kg/h	Φ	O_2 % (Vol.)	FGR % (mass)	Oxidizer $\dot{m}$ kg/h
0.7	21	0.00	35.86	0.8	21	0.00	31.37
	20	4.21	37.51		20	4.32	32.87
	19	8.47	39.33		19	8.67	34.51
	18	12.78	41.35		18	13.07	36.34
	17	17.14	43.62		17	17.51	38.39
	16	21.55	46.17		16	21.99	40.69
	15	26.01	49.05		15	26.52	43.30
	14	30.53	52.35		14	31.09	46.28
	13	35.10	56.16		13	35.70	49.73
	12	39.73	60.60				
0.9	21	0.00	27.89	0.95	21	0.00	26.42
	20	4.29	29.21		20	4.42	27.72
	19	8.62	30.68		19	8.87	29.16
	18	13.00	32.31		18	13.35	30.75
	17	17.42	34.13		17	17.87	32.53
	16	21.88	36.17		16	22.42	34.54
	15	26.39	38.49		15	27.00	36.81
	14	30.95	41.14		14	31.62	39.41
					13	36.27	42.41

RESULTS AND DISCUSSION

The effect of FGR on NO emission (reduced to 3% O_2 in the combustion products) can be seen in Fig. 2 for different equivalent ratios. The tests were carried out from 0% FGR to the percentage of FGR at which the blow-off took-place. It can be observed that blow-off occurs at a recirculation ratio between 30% and 40%. For 0% FGR the NO emission reaches about 90 ppm, with increasing the recirculation of flue gases from 0% to greater than 30% the NO decreased to a single digit ppm for most cases. The thermal NO, which strongly depends on temperature due to its high activation energy, is the main source and the decreased temperature due to FGR dilution is the major factor affecting NO formation.
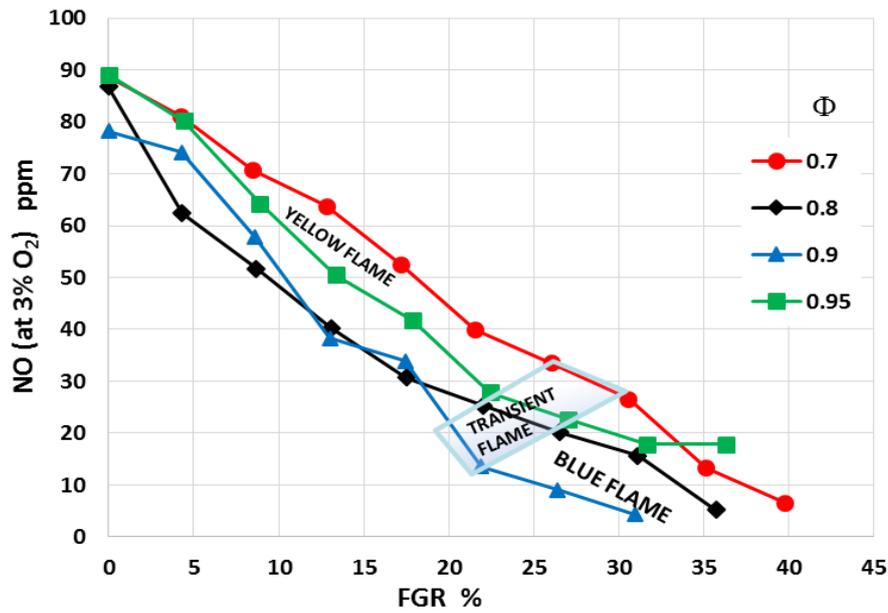
Figure 2. Effect of FGR on NO emission at different equivalence ratios.
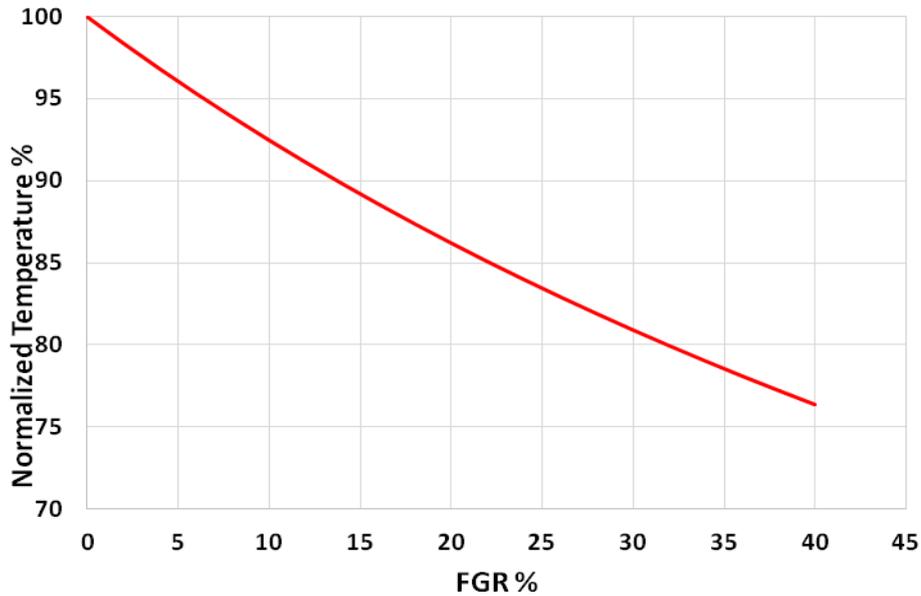
Figure 3. Dilution effect of FGR on flame temperature.

The flame color changes from yellow to blue through transient region with increasing FGR%. This conversion is due to more recirculated radicals and UHC which create a premixed mixture that enhance blue flame. The variable limits of FGR at which the flame changes from yellow flame to blue flame are shown in Fig. 2.

The decrease in temperature can be seen in Fig. 3 as a result of dilution effect of FGR. The temperature gradually decreases with recycling ratio and reaches about 77% of its value at 40% FGR when compared with conventional combustion without FGR.

Fig. 4 shows the overall trend of NO emission with recycling ratio where NO was presented as a percentage relative to the value of NO in conventional combustion. It can be seen that, for lean equivalence ratios, at maximum recycling ratios NO emission reduced to lower than

10% of its value at 0% FGR. It is apparent that the prompt NO mechanism dominates the total NO formation where thermal NO is suppressed due to temperature depression. D. Littlejohn *et al*. reported a similar conclusion based on their experimental and numerical study. For equivalence ratios 0.7 and 0.8 at 20% FGR cases, the results showed that lean flames produce primarily prompt NO_x [13].
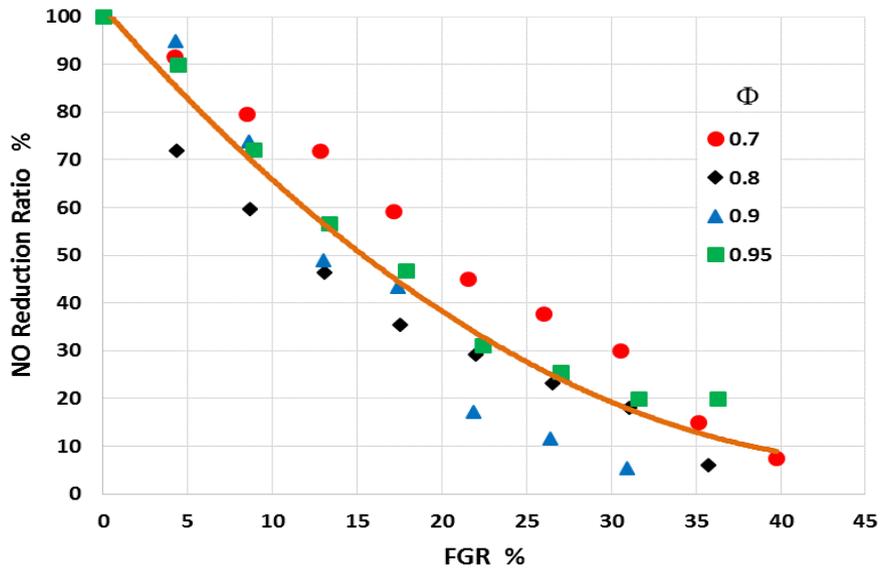

Figure 4. NO reduction as a function of recycling ratio.

Emissions of CO and UHC are presented in Fig. 5 and 6 (reduced to 3% O_2 in the combustion products) for different equivalent ratios and recycling ratios. CO and UHC emissions were, almost, unchanged with increasing recycling ratio to a value after which CO and UHC start to increase markedly. The increase of CO and UHC took-place at higher recycling ratios near to flame blow-off due to dilution effect and low flame temperature. For leaner equivalence ratios, the observed rise in the CO and UHC emissions is a result of increased dilution and decreased flame temperature.
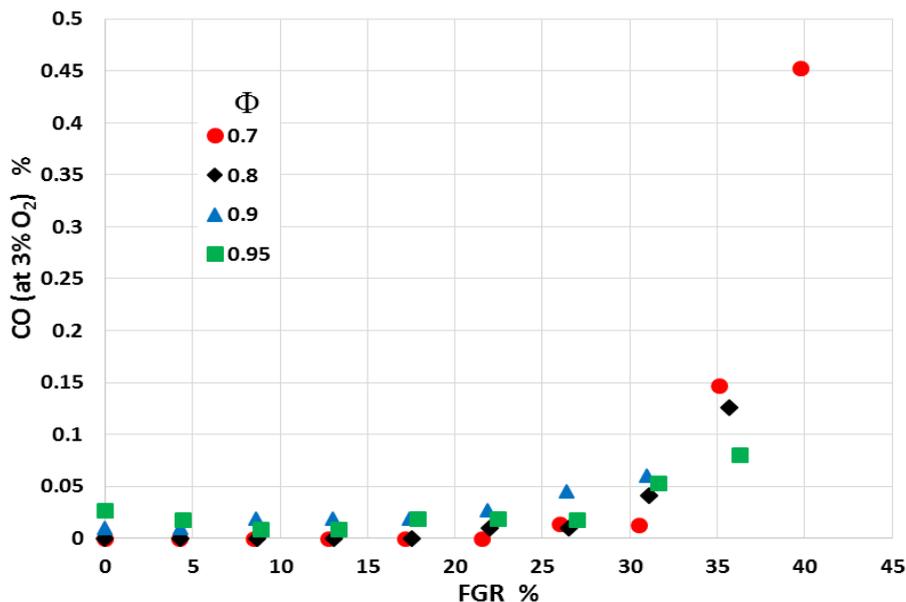

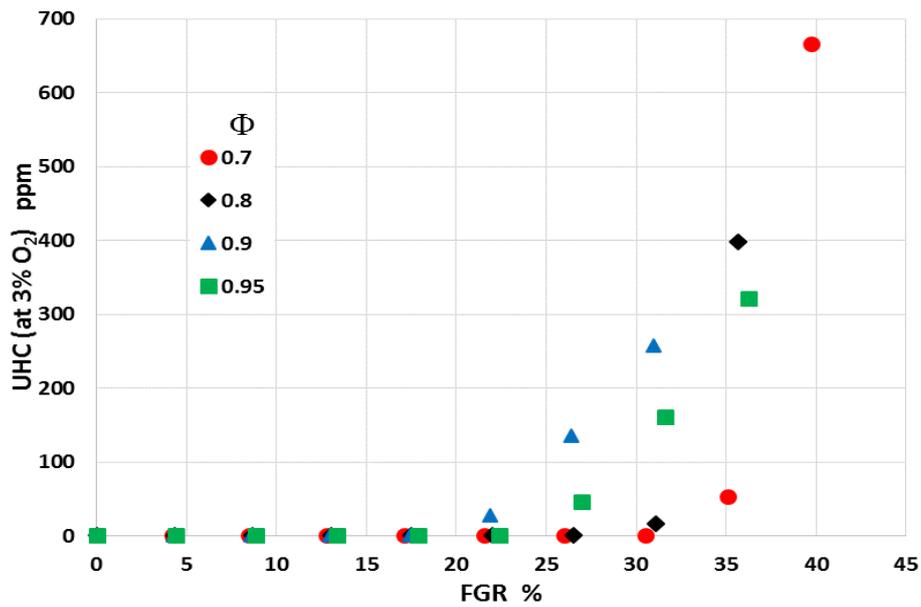**Figure 5. Effect of FGR on CO emission at different equivalence ratios.**

Figure 6. Effect of FGR on UHC emission at different equivalence ratios.

Despite the advantage of NO reduction, the whole system performance was dropped down as shown in Fig. 7. The cooling load is presented as a percentage of the fuel heating value which was transferred to the cooling water. More than 10% of the load was lost at maximum recycling ratios and for all equivalence ratios. Although the mass flow rate of combustion products was increased which enhancing convective heat transfer, the heat transfer between the combustion products and cooling water decreased due to the lower temperature difference between them and lower direct radiation from the flame of low luminosity. Also, the heat quality decreased, which is a function of temperature as deducted from the second law of thermodynamics.
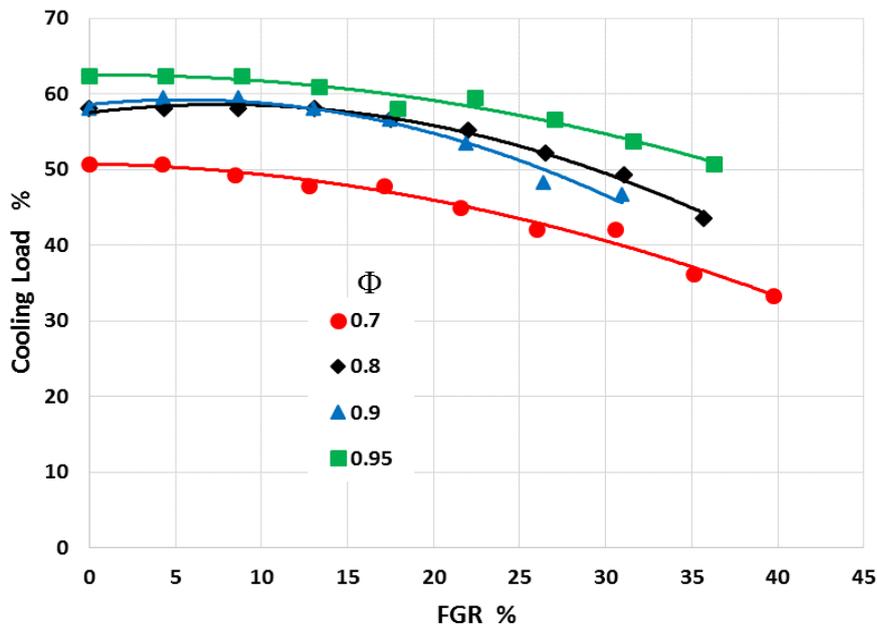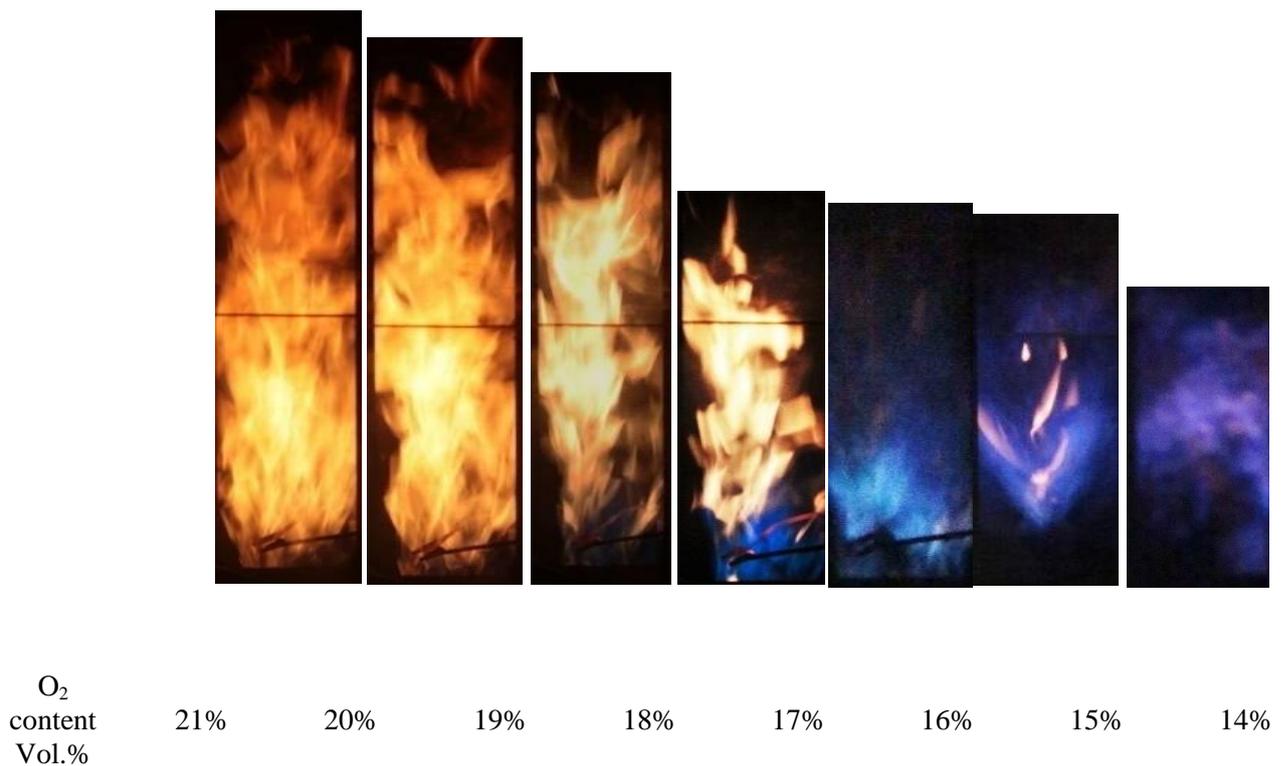

Figure 7. Cooling load at different recycling and equivalence ratios.

O$_2$ content Vol.%	21%	20%	19%	18%	17%	16%	15%	14%

Figure 8. Flame appearance at different oxygen ratios in oxidizer and 0.8 equivalence ratio.

Figure 8 shows the flame images of flame at equivalence ratio 0.8 for various oxygen ratios in the oxidizer. The oxygen ratios are indicated in table 1 with relevant values of FGR. It can be observed that the flame length decreased as the FGR ratio increased. The increased recycling ratio increases the total mass flow rate of the oxidizer consequently and leads to more turbulent intensity and mixing. The flame temperature behavior can be predicted from flame luminosity which decreased with increasing FGR ratios. The flame temperature reduction occurs due to dilution effect and increased specific heat capacity of the burned gases. The increased FGR ratio leads to much premixed zone in the upstream unburned zone, which yields the flame to change from yellow to blue.

This can be discussed as the following; the returned flue gas contains unburned vaporized fuel and hydrocarbons, if any, from the previous combustion process even if some traces. The mixing of unburned hydrocarbons in flue gas and the combustion air forms a premixed mixture of a kind of fuel and air. When the premixed mixture was introduced to the combustion chamber the blue color, which is main characteristic of premixed combustion, at the base of flame starts to appear with level proportional to the mixture strength and the flame behaves as partially aerated flame. The increase of the recycling ratio increases the UHCs, as illustrated in Fig. 6, therefore the premixed mixture strength increases. Thus, the blue color gradually dominates the flame appearance at higher mixture strengths and recycling ratios.

CONCLUSIONS

The effect of FGR on flame appearance and emissions was experimentally investigated using liquid fuel (kerosene) for different equivalence ratios. The main conclusions of this work are summarized as follows:

1. Recirculation of flue gas is a suitable method to reduce NO emissions with a stable flame using kerosene as a liquid fuel, with the drawback of high CO and UHC emissions.
2. Stable flame is achieved with recycling of flue gas up to 30 – 40%.
3. Flame length depends on recycling ratio and becomes shorter with increasing FGR and converted to bluish flame at higher recycling ratios. Also flame temperature and

    its luminosity decrease as a result of dilution effect and increased specific heat capacity of the burned gases.

4. Significant reduction of NO emissions more than 90% can be achieved with FGR due to lower temperature and better mixing (due to higher turbulence). Emissions of CO and UHC almost unchanged with increasing FGR to a value after which CO and UHC increased at higher recycling ratios near to flame blow-off, and more increase takes place at leaner conditions.
5. In spite of the advantage of NO reduction, the heat transfer efficiency decreased due to lower temperature. Also heat quality decreased, which is a function of temperature as indicated by the second law of thermodynamics.

ACKNOWLEDGMENTS

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