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On the influence of flue-gas recirculation on pollutant emissions from a small-scale laboratory furnace

M. COSTA, M. RUÃO, M.G. CARVALHO

Instituto Superior Técnico, Mechanical Engineering Department, Avenida Rovisco Pais,
1096 Lisbona Codex, PORTUGAL

This paper describes an experimental study undertaken to investigate the effect of flue-gas recirculation (FGR) on pollutant emissions. The trials have been performed in a small-scale laboratory furnace fired by an industry-type gas swirl burner. Two fuels were used: propane and ethylene. Baseline flames of the two fuels without FGR have been established at three excess air levels and then various degrees of FGR were applied to each of them. To this end, dry flue-gases were injected directly into the secondary air stream before the burner. The data reported includes simultaneous flue-gas concentrations of O_2, CO, CO_2, unburnt hydrocarbons (UHC) and NO_x and of the Bacharach Index for several furnace operating conditions. Overall, the results show, for both fuels, a decrease in NO_x emissions with FGR without negative effects on CO, UHC and soot emissions, combustion efficiency and flame stability. For both fuels, it is concluded that there is an optimum value of FGR rate for simultaneously reducing NO_x, CO, UHC and soot emissions.

Introduction

One of the most widely used methods of NO_x emission reduction from combustion is the use of flue-gas recirculation (FGR). The use of FGR seems to have, however, a potential disadvantage regarding flame stability, combustion efficiency and CO, unburnt hydrocarbons (UHC) and solids emissions, see, e.g. [3]. The present work was undertaken to investigate more thoroughly the effects of FGR on flame stability, combustor performance and pollutant emissions. The combustion tests have been performed in a relatively small-scale laboratory furnace which allowed for the collection of reliable data while representing to some extent the combustion behaviour in full-scale equipment.

Previous related studies include those of [2, 3, 4, 5, 6] among others. These investigations have concentrated primarily on the influence of FGR on flame stability and NO_x emissions from which it was possible to draw a number of useful conclusions. The literature reveals, however, that most studies on FGR paid little or no attention to its consequences on CO, UHC and solids emissions. The results reported herein are intended to help redress this problem.

In the present paper, data is reported for two fuels, propane and ethylene, and includes flue-gas concentrations of O_2, CO, CO_2, UHC and NO_x and of the Bacharach Index for forty six experimental flames. Together they allow for an assessment of the effect of FGR on flame stability and flue-gas emissions at three excess air levels for the two fuels.

The remainder of this paper has been prepared in five sections, which describe the test furnace and the instrumentation, present the experimental conditions, the results and related discussion and summarise the more important conclusions.

The test furnace

A schematic of the experimental facility is shown in Figure 1. It comprises a small-scale laboratory furnace up-fired by an industry-type swirl burner equipped with facilities for flue-gas recycling. The combustion chamber is cylindrical in shape and consists of five interchangeable steel segments each 0.2 m in height and 0.3 m in internal diameter. One of the segments has four rectangular ports for probing and viewing which are closed with quartz or steel inserts. The burner geometry, shown in Figure 2, is typically of that used in power stations for wall-fired boilers and consists of a burner gun (i.d. 8 mm, o.d. 12 mm) and a secondary air supply in a conventional double-concentric configuration terminating in a quarl of half angle 24° and a length to diameter ratio of one.

Both propane and ethylene (99.8% purity), stored in standard bottles, were used in the present trials. The fuel flow rate was controlled with a pressure regulator and a valve, and measured using a calibrated rotameter. The secondary air was supplied by an air compressor. The air flow rate was measured using a calibrated rotameter. Before entering the burner the air flowed through an ejector in order to suck flue-gas directly from the exhaust duct of the furnace as illustrated in Figure 1. The remainder of the flue-gas was exhausted from the test furnace. The flue-gas withdrawn for recirculation purposes was cooled by a water coil placed in the recycling duct after which the condensate was removed. The flow rate of the recirculated flue-gas was controlled by a valve. The oxidant mixture (fresh air + flue-gas) was then directed to the burner. An aerodynamically quenched quartz probe was permanently placed just before the burner to measure the oxidant composition so that recirculation rates could be calculated.

Measuring techniques and experimental uncertainties

The sampling of flue-gas for the measurement of O_2, CO, CO_2, UHC and NO_x concentrations was achieved using an aerodynamically quenched quartz probe. The probe design and dimensions were similar to those used by [1]. The probe was mounted on a traverse mechanism which enabled radial movement across the entire furnace at the exit sampling location ($x/D=25.7$).

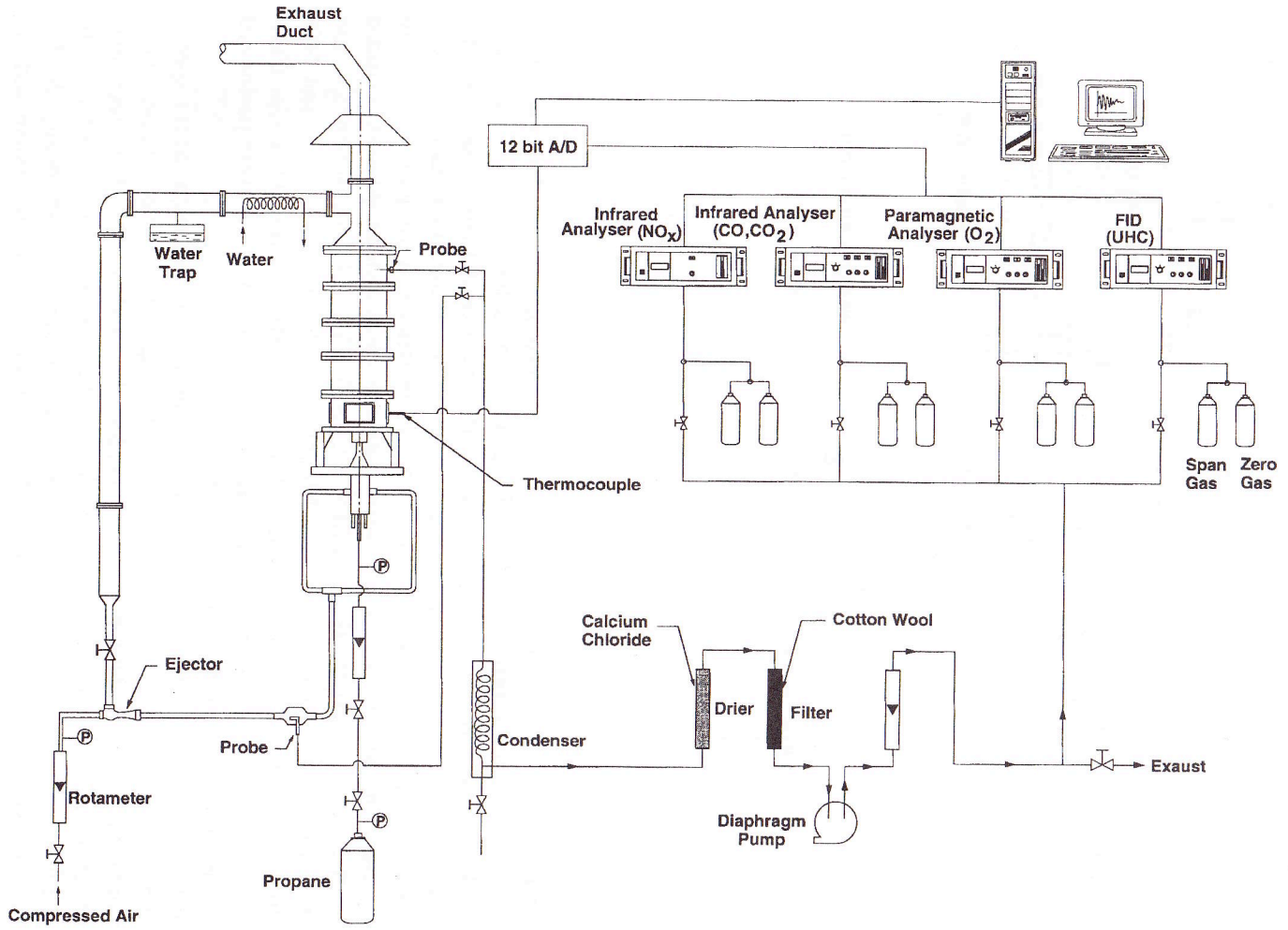

Fig. 1. Schematic of the furnace and measurement equipment

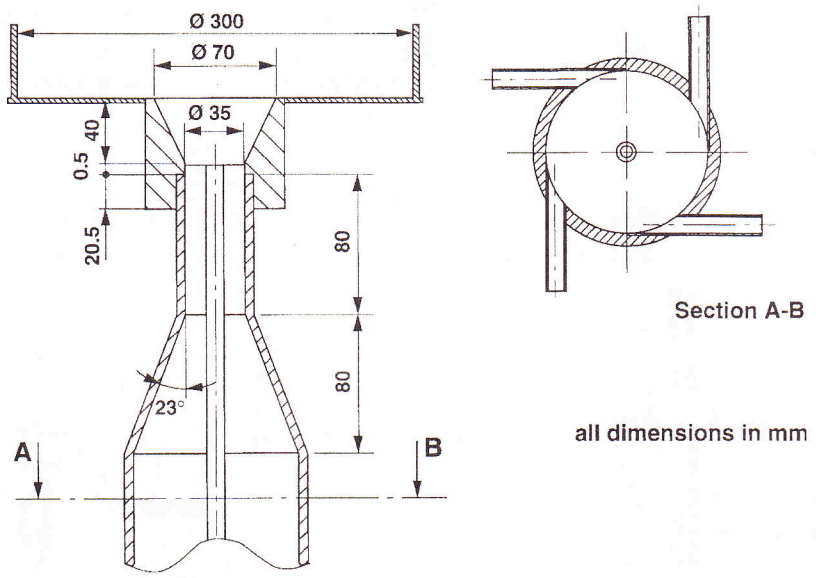

Fig. 2. Schematic of the burner arrangement

A schematic of the gas analysis system is also shown in Figure 1. The gas sample was drawn through the probe and part of the system by a 100% oil-free diaphragm pump. A condenser removed the main particulate burden and condensate. A filter and a drier removed any residual moisture and particles so that a constant supply of clean dry combustion gases was delivered to each instrument through a manifold to give species concentrations on a dry basis. The analytical instrumentation included a magnetic pressure analyser (Horiba Model CFA-321A) for O_2 measurements, non disperse infrared gas analysers (Horiba Model CFA-311A) for CO, CO_2 and NO_x measurements and a flame ionization detector (Amluk Model FID 2020 E) for UHC measurements. Zero and span calibrations with standard mixtures were performed before and after each measurement session.

At the furnace exit, radial traverses showed that the concentrations of the species were uniform so that probe effects were likely to be negligible and errors arose mainly from quenching of chemical reactions, sample handling and analysis. Fast quenching of the chemical reactions was achieved and our best estimates indicated that the uncertainty due to the solubility of CO_2, UHC and NO_2 in water was negligible. The error due to the dissolution was estimated by operating the sampling system with the probe supplied with samples of standard mixtures with compositions similar to those in the flames studied. Reproducibility of the data was, on average, within 5%.

Finally, a measure of the smoke intensity was obtained by using the Bacharach method.

Experimental conditions

The furnace operating conditions are summarised in Tables 1 (propane) and 2 (ethylene) and encompass forty five experimental flames. Flames PA1, PB1, PC1, EA1, EB1 and EC1 serve as the baseline cases for studying the influence of the FGR on flame stability, overall combustion efficiency and flue-gas emissions at thrree excess air levels for the two fuels. Note that the fuel flow rates of propane and ethylene were chosen to establish an equivalent heat input which has resulted in different inlet primary and secondary jet velocities. It should also be noted that, for each group of experimental flames, the fresh air flow rate was held constant being the flue-gas flow rate gradually increased. In this work the FGR rate is defined as [3]:

$$R=\frac{\dot{m}_{rec}}{\dot{m}_a+\dot{m}_f}\times 100 \qquad (1)$$

where $\dot{m}_{rec}$ is the mass flow of recycled flue-gas products per unit time.

Table 1

Furnace operating conditions for the propane trials and flue-gas data

Flame	λ	R (wt%)	Pollutant Emissions	
			CO (dry vol. %)	UHC (dry vol. ppm)
PA1	1.01	0	1.14	4370
PA2		5.0	0.53	1474
PA3		9.0	0.89	3867
PA4		12.8	0.93	2093
PA5		19.7	0.93	1425
PA6		31.9	1.09	1611
PB1	1.07	0	0.21	340
PB2		7.4	0.22	330
PB3		13.3	0.02	27
PB4		16.7	0.03	36
PB5		20.5	0	29
PB6		23.6	0	18
PB7		27.7	0	37
PB8		41.8	0.1	59
PC1	1.14	0	0	78
PC2		6.6	0	57
PC3		11.5	0	25
PC4		16.1	0	11
PC5		22.0	0	13
PC6		26.0	0	4
PC7		28.6	0	18
PC8		42.6	0	71

$\dot{m}_a = 3.9\times10^{-3}$ kg/s for $\lambda=1.01$; for all flames: $\dot{m}_f = 2.5\times10^{-4}$ kg/s; $T_f = 20°C$, $T_{ox} = 20°C$; $S_{ox} = 0.5$

Table 2

Furnace operating conditions for the ethylene trials and flue-gas data

Flame	λ	R (wt%)	Pollutant Emissions	
			CO (dry vol. %)	UHC (dry vol. ppm)
EA1	1.01	0	0.62	1441
EA2		16.7	0.14	140
EA3		26.5	0.15	201
EA4		33.3	0.12	102
EA5		42.6	0.13	74
EA6		47.7	0.13	78
EA7		50.0	0.60	614
EA8		55.8	0.83	1282
EB1	1.07	0	0.43	857
EB2		6.8	0.26	374
EB3		15.5	0.21	203
EB4		24.8	0.22	253
EB5		34.5	0.16	162
EB6		43.7	0.07	56
EB7		51.9	0.11	81
EB8		57.3	0.12	87
EC1	1.14	0	0.12	192
EC2		6.4	0.06	75
EC3		14.8	0.05	25
EC4		26.0	0.05	43
EC5		40.6	0.04	35
EC6		46.5	0.03	27
EC7		53.6	0.05	84

$\dot{m}_a = 3.5 \times 10^{-3}$ kg/s for $\lambda = 1.01$; for all flames: $\dot{m}_f = 2.5 \times 10^{-4}$ kg/s; $T_f = 20°C$, $T_{ox} = 20°C$; $S_{ox} = 0.5$

Results and discussion

Tables 1 and 2 and Figures 3 to 6 summarise the results of the experiments on the effect of FGR on flue-gas emissions for the propane and ethylene trials. Figures 3 and 4 show the effect of FGR on NO_x emissions (reduced to 0% O_2 in the combustion products) at the three excess air levels studied for propane and ethylene, respectively. Both figures reveal a decrease in NO_x emissions with increase in R throughout the entire range studied, regardless of the fuel and of the excess air considered. The decline in NO_x emissions is, however, less accentuated in the case of the ethylene, particularly in the region $0 \leqslant R \leqslant 26\%$. This suggests that a higher value of R may be required for significant NO_x reduction in the case of the ethylene.

Figures 5 and 6 show the effect of FGR on the Bacharach Index at the three excess air levels studied for propane and ethylene, respectively. Both figures reveal that the

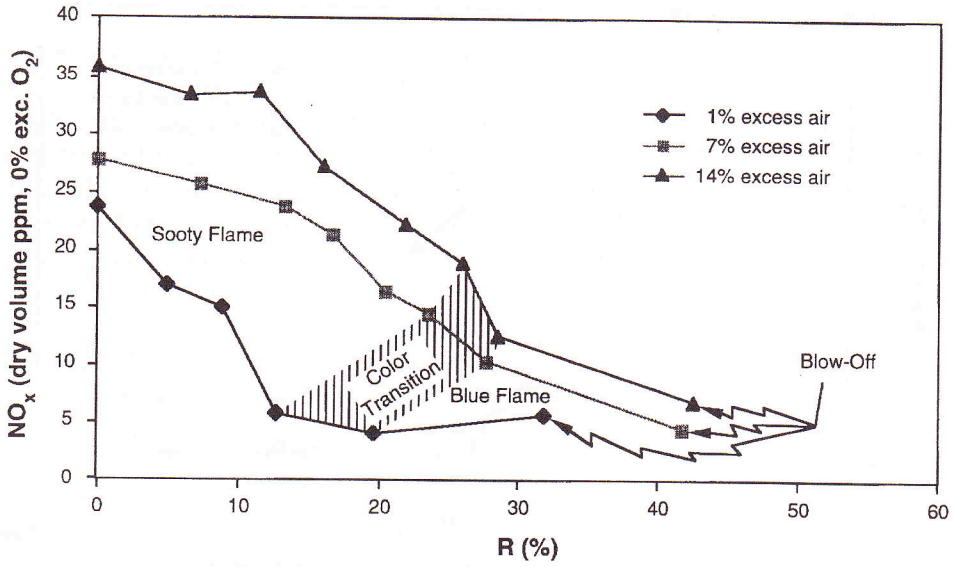

Fig. 3. Effect of FGR on NO_x emission at three excess air levels, with propane

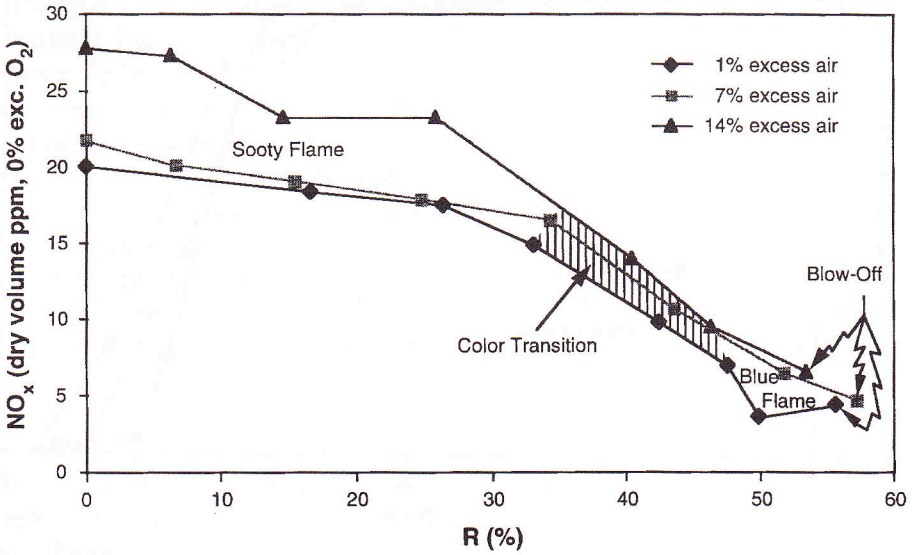

Fig. 4. Effect of FGR on NO_x emission at three excess air levels, with ethylene

Bacharach Index remains relatively unchanged for both fuels up to a value of R beyond which a further increase in R causes a significant decrease in the Bacharach Index. It can be observed that the region of constant Bacharach Index is larger in the case of the ethylene. This is simply because of the higher sooting tendency of the ethylene.

The CO and UHC emissions for both fuels do not vary directly with R as does NO_x, as can be seen in Tables 1 and 2. In other words, there is not a tradeoff between

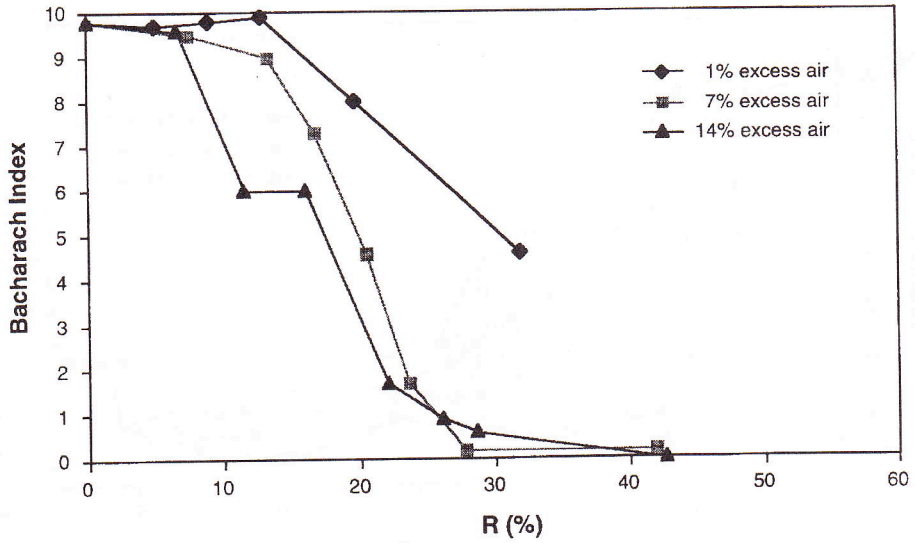

Fig. 5. Effect of FGR on Bacharach Index at three excess air levels, with propane

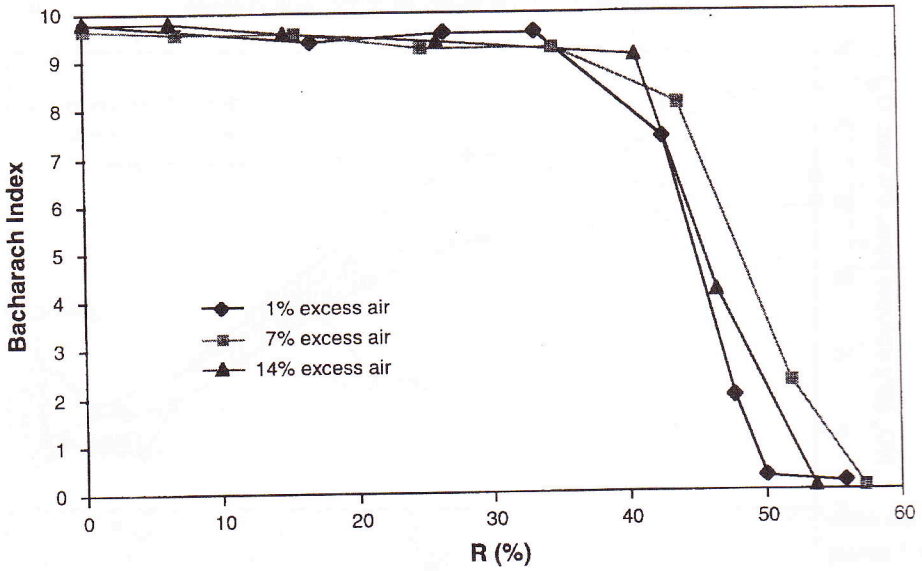

Fig. 6. Effect of FGR on Bacharach Index at three excess air levels, with ethylene

reduced NO_x emissions and increased CO and UHC emissions even at very low excess air operation. Instead, both CO and UHC emissions generally decrease on increasing the flue-gas recirculation rate up to a value beyond which a further increase in R causes an increase in CO and UHC emissions. This increase in both CO and UHC emissions is probably due to unstable combustion noticeable as R approaches blow-off. It should be stressed that during furnace operation with recirculating flue-gas, flame attachment oscillations were observed only close to blow-off:

specifically, for R values greater than about 30% in the case of the propane and 50% in the case of the ethylene, regardless of the excess air level considered. For the present flow configuration and fuels it is concluded that there is an optimum value of R for simultaneously reducing NO_x, CO, UHC and soot emissions. This is achieved through careful attention to the furnace operating conditions. Note that the overall combustion efficiency, at a given λ value, varies only marginally with R as indicated by the CO_2 concentration measured values.

Figures 3 and 4 also indicate the various combustion regimes observed for both fuels. It can be observed that the blow-off in the ethylene trials occurs at higher values of R than those in the propane trials. This is a consequence of the higher primary jet velocity and lower secondary jet velocities used in the ethylene trials. It can also be seen in Figures 3 and 4 that the transition between the yellow flame and the blue flame occurs at higher values of R in the case of the ethylene. This is due to the higher sooting tendency of the ethylene.

Concluding remarks

Measurements have been obtained in a small-scale laboratory furnace fired by an industry-type gas swirl burner. Data is reported for two fuels, propane and ethylene, and includes flue-gas concentrations of O_2, CO, CO_2, UHC and NO_x and of the Bacharach Index for several furnace operating conditions. The main conclusions drawn from the present results are the following:

1. For both fuels studied NO_x emissions decrease on increasing the flue-gas recirculation rate. At low values of recirculation rates the decline in NO_x emissions is, however, less accentuated in the case of the ethylene.

2. The benefits of flue-gas recirculation in reducing NO_x were obtained without degrading the performance in other respects, namely, flame stability, overall combustion efficiency and CO emissions.

3. For the present test furnace and fuels it is concluded that there is an optimum value of the recirculation rate for simultaneously reducing NO_x, CO and UHC emissions.

4. Stable combustion is achieved when flue-gas is recycled up to a FGR rate of about 30% in the case of the propane and of about 50% in the case of ethylene, regardless of the excess air level studied. The transition between the yellow flame and the blue flame occurs at higher values of R in the case of the ethylene due to its higher sooting tendency.

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Nomenclature

D diameter of secondary air tube (mm)
$\dot{m}$ mass flow rate (kg/s)
R flue-gas recirculation rate (%)
S swirl number
T temperature (°C)
x axial distance from quarl exit plane (mm)
λ excess air factor = (actual air-fuel ratio)/(stoichiometric air-fuel ratio).

Subscripts

a air
f fuel
ox oxidant
rec recycled flue-gas products

References

[1] DRAKE M.C., CORREA S.M., PITZ R.W., SHYY W., FENIMORE C.P., *Superequilibrium and Thermal Nitric Oxide Formation in Turbulent Diffusion Flames*. Combustion and Flame, **69**, 347–365 (1987).

[2] DREHER H., GASS J., SCHULER O., SUTER P., *Optimization of Recirculating Low NO_x Combustion Systems by Numerical Simulation*. Proceedings of the 2nd Conference on Combustion Technologies for a Clean Environment, Lisbon, Portugal (1993).

[3] GODRIDGE A.M., *Flue Gas Recirculation on Oil-Fired Plant*. Journal of the Institute of Energy, **61**, 38–54 (1988).

[4] MOORMAN R.J., LONG C.H., *Design, Development and Testing of a Swirl Type Gas Burner with Flue Gas Recirculation for NO_x Control*. The American Society of Mechanical Engineering, Paper No 73-Pwr-21 (1973).

[5] PLETNEV G.P., PARCHEVSKII V.M., KOLPAKOV M.D., *Control of Emissions of Nitrogen Oxides from Gas- and Oil-Fired Stream Boilers by Recirculation of Flue Gases*. Thermal Engineering, **32**, 152–155 (1985),

[6] SIGAL I.Ya., KOSINOV O.I., DUBOSHII A.N., NIZHNIK S.S., *Increasing the Effectiveness of Methods of Reducing the Formation of Nitrogen Oxides in Boiler Furnaces*. Thermal Engineering, **33**, 353–357 (1986).