

Temperature and soot formation in a natural gas diffusion flame

J C Ofodu* and H I Hart

Department of Mechanical Engineering, University of Port Harcourt, Choba, Port Harcourt, Nigeria
Department of Mechanical Engineering, Rivers State University of Science and Technology, Nkpolu, Port Harcourt, Nigeria

Received 11 February 2005; revised 21 December 2006; accepted 24 April 2007

Study presents temperature and soot formation profile within a natural gas diffusion flame under the equivalence ratios of 0.35, 0.90, 1.70 and 2.56. An in-house combustion Test-Rig designed for diffusion flame studies was used for temperature distribution and gravimetric soot mass. The soot was samples with an isokinetic probe insert, from this; a fairly accurate value of the soot number density and volume fraction was computed. There was sharp increases in the line-of-sight flame temperature within the centerline with peak values occurring at some distances of 6, 12, 12 and 9 cm from the burner rim, corresponding to 0.35, 0.90, 1.70 and 2.56 equivalence ratios respectively, after which it decreases gradually. A clear marked reduction was observed in temperature values as the condition of fuel mixture changes from lean to heavy rich. This reduced temperature that was most evident of flame equivalence ratio of 2.56 has been traced to be as a result of high sooty condition imposed by this fuel rich mixture. This condition of soot laden, enhances high rate of heat losses through adverse radiative heat transfer, thereby decreases flame temperature and combustion efficiencies of the parent user device. It was also observed that the gravimetric soot mass profile is much regular in behaviour for the lean mixture flames as it increases with increase in measured temperature values. Contrarily, for a richer mixture of 2.56, it increases with decrease in temperature.

Keywords: Diffusion flame, Natural gas, Soot, Temperature

Introduction

Soot formation in fossil fuels is a very complex reaction involving several competing chemical reactions of several steps. Studies^{1,2} have stressed the negative effects of soot on the combustion efficiency. On the other hand, soot is an important industrial product mainly used for improving the structure of several materials. It has been used extensively for reinforcement of fillers in tire treads, also as black pigment due to its good pigmentation properties such as light stability and insolubility. Soot is also used as carbon black. In 1983, carbon black was produced on a large scale of 4748 megatons globally³. Choi *et al*^{4,5} undertook a measurement of soot volume fraction, etc. using both optical and gravimetric methods, which compared favourably. Musick *et al*⁶ studied structures of 5 low pressure CH₄/O₂/Ar flames at equivalence ratios of 0.92 - 1.92. Extensive^{7,8} research was done on the effects of O₂ on soot formation in some selected flames. Kennedy *et al*⁹ used a soot model in a laminar diffusion flame.

Present work aims at providing understanding of the role of individual parameters in the formation of

soot and their temperature dependency with respect to axial and radial distribution along the flame axis emanating from a natural gas (NG) fuel.

Experimental Details

An in-house experimental test rig was developed for NG combustion studies. For this, a NG-air diffusion flame was established on a co-annular burner, which consisted of a 16 mm diam steel fuel tube (where the natural gas is injected upwardly) and surrounded by a 109 mm diam air annulus (Fig. 1). The resulting flame was shielded by square shaped sheet (casing) to protect it from air. There exists probe insert holes on one side of this casing for isokinetic sampling and on the other side of the casing a window made of tough 4.5 mm thick glass material to provide optical access to the chamber for photographic shots and for personal visual inspection of the flame. Diffusion flame temperature was measured with a K - type thermocouple.

Operating conditions at different mixture fractions and equivalence ratio (Table 1) are as follows— m_a , 2.94×10^{-4} kg/sec; Q_a , 15 l/m; V_a , 2.68×10^{-2} m/sec; and Re_a , 186. At normal environmental condition at 25° (298 K) and pressure 1.013 bar, NG possessed following properties— ρ_{ng} , 0.874 kg/m³; μ_{ng} , 1.45×10^{-5} kg/ms;

*Author for correspondence
E-mail: ofodu_jc@yahoo.co.uk

Table 1 — Operating conditions

Sl. No	Z	Φ	m_{ng} kg/sec $\times 10^{-5}$	Q_{ng} m^3/sec $\times 10^{-5}$	Q_{ng} l/m	V_{ng} m/sec	Re_{ng}
1	0.02	0.35	0.73	0.83	0.50	0.042	41.0
2	0.05	0.90	1.46	1.67	1.00	0.084	81.0
3	0.09	1.70	2.91	3.33	2.00	0.167	161.0
4	0.13	2.56	4.37	5.00	3.00	0.250	241.0

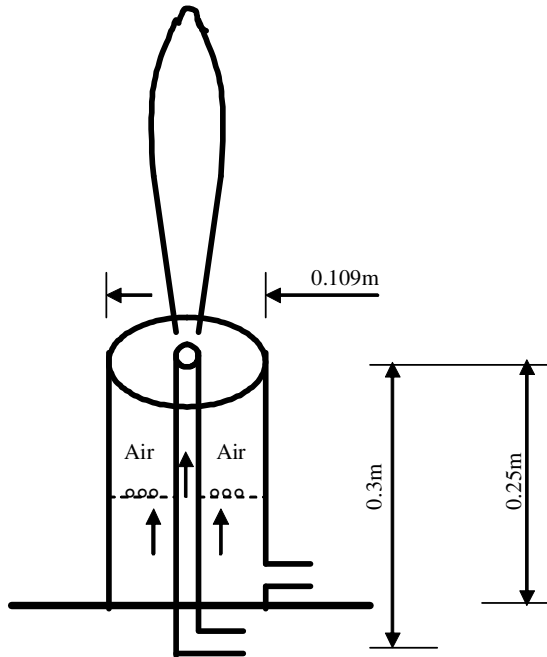


Fig. 1— Fuel nozzle and burner dimensions

D_{ngn} , 0.016m; A_{ngn} , $2.0 \times 10^{-4} m^2$; mol wt (M_{ng}), 18.48 g/mol. At the same conditions, oxidized gas (air) possessed following properties— density (ρ_a), 1.177 (kg/m^3); μ_a , $1.846 \times 10^{-5} kg/ms$; D_{an} , 0.109 m; A_{an} , $9.33 \times 10^{-3} m^2$; and Prandtl number (Pr), 0.707. Equivalence ratio indicates if the mixture is rich or lean and to what extent. The mixture fraction Z, is given as

$$Z = \frac{Q_{ng}}{Q_{ng} + Q_a} \quad \dots(1)$$

where Q_a and Q_{ng} represents volume flow rate of air and natural gas respectively (m^3/s), ρ_{ng} = density of natural gas, μ_{ng} = viscosity of natural gas, D_n , D_{ng} = Diameters of air and natural gas pipe respectively with areas A_a and A_{ng} .

Temperature Profile Measurement

A k – type (Chromel - Alumel) thermocouple, calibrated with Fluke 5502 multi-product, multi-function

calibrator, was used to measure axial and radial temperature profiles within the flame. Thermocouple with a well-designed attachment was inserted through the sample ports (15) made at right hand side of the chamber. Temperature profile was measured for 4 different diffusion flames of equivalence ratios, Φ s, (0.35, 0.90, 1.70 and 2.56). First two flames represents a lean condition while the last two are under rich condition.

Soot Mass Sampling

Isokinetic sampling technique, employed in this study, is a process of drawing a sample from a moving stream of gas (NG + air combustion flame) at the same velocity as that of the free stream. It can be water or air cooled¹⁰ depending on choice and condition of operation (Fig. 2).

To take a sample, probe is moved quickly to the desired axial positions (0, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30 cm) and / or radial distance positions (0, 4, 8, 12 mm). There exists two sets of bottle, sampling bottle A (which should exist at a reduced pressure than 1atm) and purge bottle B (containing either He or N_2 existing at over-pressure for purge flow). Once sample is to be taken, as the probe is being moved to the desired position, a small purge flow of He or N_2 should be allowed. At this point, sampling bottle is isolated. Once probe is at the appropriate location, purge flow valve is closed and bulb isolation valve (leading to the sample bottle A) is opened. The sampling ends at about 2 min or immediately when pressure in the sampling bottle reaches 1 atm. At this time, bulb isolation valve (for sampling bulb) is closed. It is evident that particulate matter (soot) would have been trapped by the funnel-shaped filter paper. By careful removal of filter paper from conical flask and cork after each run of the experiment and subsequently weighing content, soot mass (m_s) can be obtained. Soot concentration (M_s , g/m^3) can be computed as

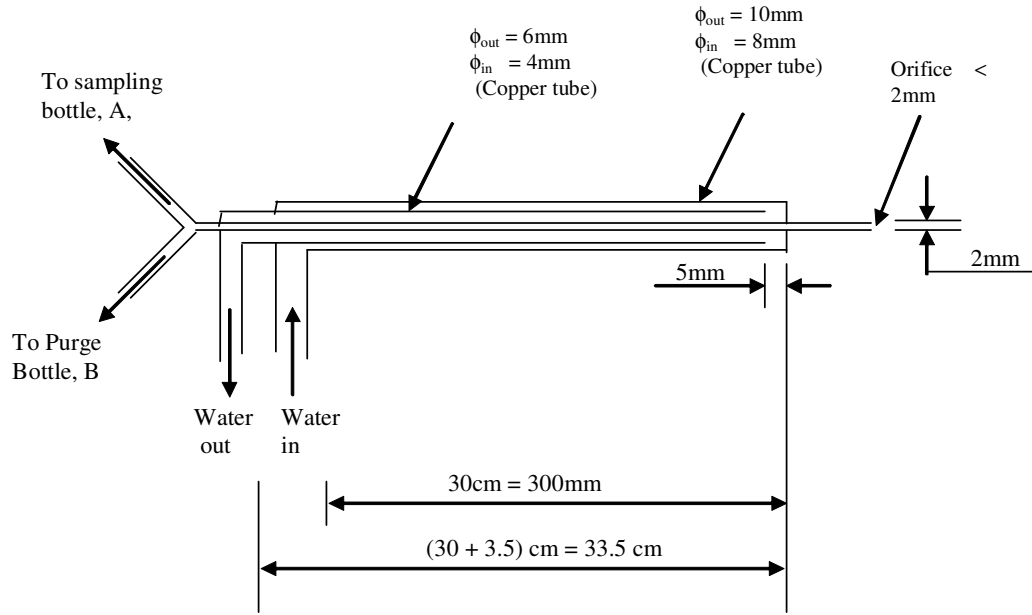


Fig. 2— Isokinetic probe insert

$$M_s = \frac{m_s}{V} \times \frac{T_\infty}{T_p} \quad \dots(1)$$

where, m_s = gravimetric mass of the soot collected from the filter paper, T_∞/T_p = ratio of ambient temperature to the temperature of the probe entrance, V = total volume of the gas sampled based on ambient temperature, $V = Qt = 120Q$ under sampling time t . Soot volume fraction based on gravimetric measurement can be obtained as

$$f_v = \frac{M_s}{\rho_s}, \quad \dots(2)$$

where $\rho_s = 1860 \text{ kg/m}^3 = 1.86 \text{ g/cm}^3$.

Alternatively, soot volume fraction f_v , can also be computed⁴ directly once the volumetric flow rate of the sample is known.

$$f_v = \frac{\frac{m_s}{\rho_s} \times \frac{T_\infty}{T_p}}{t \frac{dv}{dt}} \quad \dots(3)$$

where, dv/dt = volumetric flow rate.

Results and Discussion

Temperature Profile within the Flame

For equivalence ratio of 0.35, temperature of the flame rises from cooler unburned core (marked by blue zone) at the burner rim of about 600K to 1200K (Fig. 3). This corresponds to approx 6 cm distance from

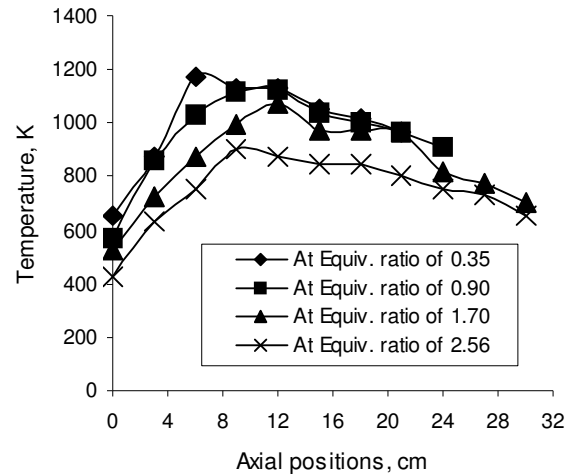


Fig. 3 — Axial flame temperature distribution with respect to equivalent ratios

the burner rim and plateaus till 12 cm. The rate of temperature increase within this region can be approximated to be 100 K per cm distance, from the burner exit. From this point, it falls gradually to 1000 K and fades away convectively. Flame temperature profile resulting from equivalence ratios of 0.90, 1.70 and 2.56 behaved in a similar manner except that their rate of temperature increase is of 62 K, 46 K and 32 K per unit cm axial distance, respectively. Highly reduced temperature at all positions recorded by the flame of

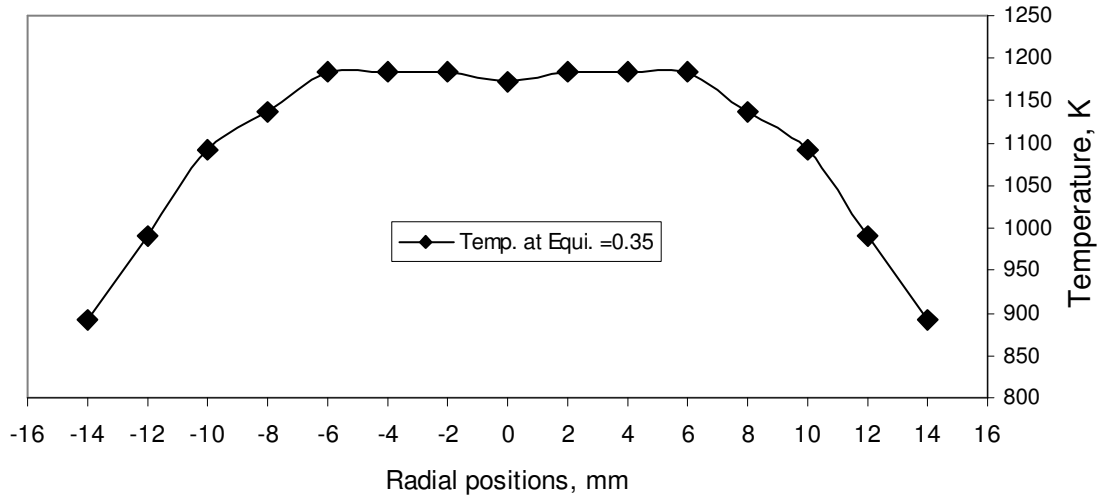


Fig. 4 — Radial flame temperature plot at $x = 6$ cm axial position, at equivalent ratio = 0.35 as obtained from the natural test rig

equivalence ratio 2.56 stems from heavy sooty condition imposed by the rich fuel mixture. This heavy soot production resulting from very rich flame leads to high radiative heat loss. That is why, it decreases flame temperature and efficiencies of the parent user device operating under this condition. There were also huge deposits of soot on the thermocouple wire joint tip.

For the same condition of flame of equivalence ratio 0.35, temperature radial profile, at axial position of $x = 6$ cm from the burner rim is shown in Fig. 4. As expected, the maximum temperature of 1200 K, which corresponds to that at axial distance of 6 cm maintains this value to the outer stoichiometric flame zone (which marks the contour of the flame, radially) at radial distance of 8 mm from the burner rim. After this point, because of high convective nature of the outer region, temperature decreases sharply. From the graphs (Figs 5, 6 and 7 respectively for radial plots at 6, 12 and 18 cm axial positions from the burner rim) of radial plots (except for equivalence ratio of 2.56), order of magnitude of temperature values are of 12 cm > 6 cm > 18 cm, while that of equivalence ratio of 2.56 is noted to be 18 cm > 12 cm > 6 cm.

To properly visualize the temperature variation at a particular position, x , as it relates to equivalence ratio, graphical combination of plots (Fig. 8) were made of temperatures against equivalence ratios at different axial locations of $x = 0, 6, 12$ and 18 cm. At all axial points with respect to equivalence ratio, there were clear marked reduction in temperature values as the condition of flame changes from lean to heavy rich.

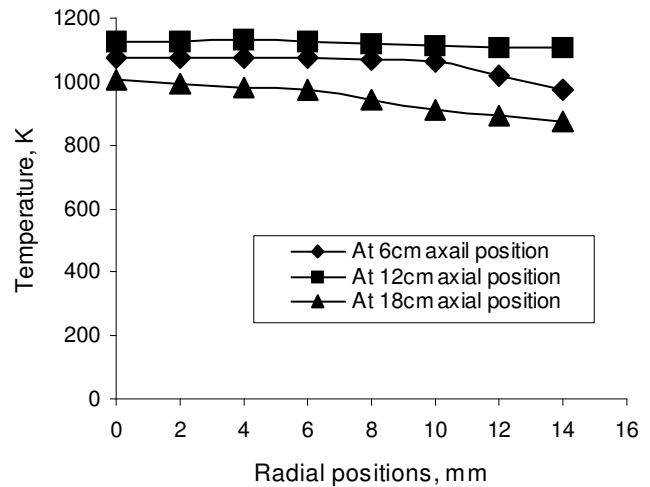


Fig. 5 — Radial temperature plots for equivalent ratio = 0.90

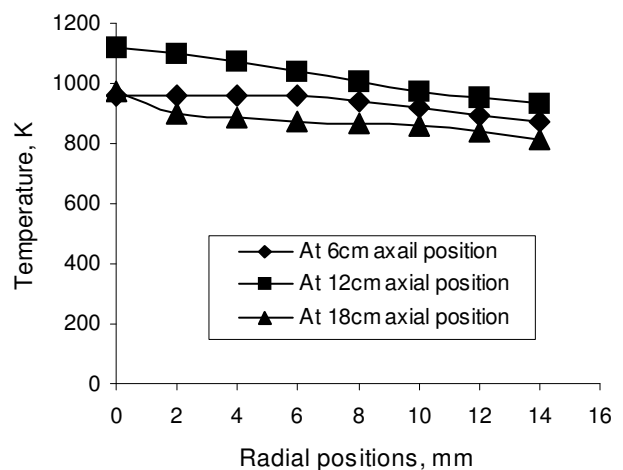


Fig. 6 — Radial temperature plots for equivalent ratio = 1.70