

OPTICAL DIAGNOSTICS OF A TURBULENT SWIRLING FLAME

A. Rahman, G. G. M. Stoffels and Th. H. van der Meer

Division of Thermal Engineering, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
Tel: +31 53 489 2530; Fax: +31 53 489 3663

[Email: a.rahman@utwente.nl](mailto:a.rahman@utwente.nl)

ABSTRACT

The interaction between experiments and calculations is necessary if the objective of providing a numerical tool for combustor design is to be achieved. This interaction is most fruitful when simple, well-defined laboratory burners are adopted as model problems. In order to have better insight into the processes present in the combustion zone of a swirling flame, an academic, natural gas fired swirl burner is investigated. In this burner the swirl is generated by the rotation of the outer pipe of the annular air passage, therefore providing well defined inflow conditions which can be easily reproduced in computational and modeling studies. A number of different flames produced with different operating conditions are investigated by both optical (chemiluminescence) and laser (Raman scattering) spectroscopy methods. Chemiluminescence from a reactive species gives insight in its presence in the combustion process. Raman scattering is a laser based method which provides information about the concentration of major species of combustion in the combustion environment.

Keywords: Chemiluminescence; Swirl flames; Raman spectroscopy.

1. INTRODUCTION

Non-premixed swirling flows are widely used in industrial combustion systems, notably, gas turbines, boilers and furnaces, because of safety and stability reasons. When of sufficient strength, swirl will produce a large adverse pressure gradient in the direction of the flow, which leads to vortex breakdown and flow reversal. The recirculation zone, which then forms, carries back to the burner's exit plane hot combustion products which act as a constant source of energy for combustion and stabilizing the flame [1, 2].

The recirculating vortex may be associated with an unsteady precessing motion which remains incompletely understood in both reacting and nonreacting flows [3]. Despite these possible instabilities, swirl combustors have the added advantage of improved combustion efficiency, better ignition stability and reduced emissions of pollutants. These positive effects are believed to result from improved mixing rates due to enhanced turbulence levels. Due to the permanent increase in the development of these devices, experimental and numerical investigations of swirl turbulent flow are very important. Swirl can be imposed in various ways. The most common and simplest ways are the tangential inflows and use of guide vanes [4]. While these methods are most convenient in industrial applications, each has some shortcomings that make them sub-optimal choice for experimental investigation of the physics of swirling flames. For example, in order to produce uniform tangential velocity over the circumference, the tangential inlets need to be placed sufficiently upstream, but the

swirl will decay on the way along the burner and may not have a sufficient strength at the exit. However, the major common deficiency of tangential inlets and guide vanes is in difficulties to define precisely the inflow conditions, i.e. the velocity, turbulence intensity and scales, the reproduction of which is crucial for computational studies. The uncertainties in the inflow conditions are the reasons why many excellent measurements are only of limited use for the validation of computational models.

Hence, the proper understanding of swirling flames and of the effect of swirl on turbulent transport, mixing and chemical reaction calls for new experiments that will provide detailed information about fluid velocity, temperature, species concentrations and their turbulent fluctuations in various regimes and at well-defined inflow and boundary conditions [5].

For the reasons outlined above, a novel gas-fired academic burner was designed in which the swirl is generated by rotating the outer pipe of the annular air supply. The sufficiently long annular passage ensures fully developed rotating flow at its exit which can be easily reproduced computationally by simulating this simple one-dimensional problem.

This paper reports the work continuation of the research of Werner Huebner [6] which aims at developing an improved quantitative understanding of the structure of swirling nonpremixed flames and providing a comprehensive data bank which may be used as a benchmark for model validation. Here non-intrusive diagnostics methods both optical namely chemiluminescence and laser spectroscopic i.e. Raman

scattering technique are used for characterization of the flame [7]. The results of chemiluminescence measurements of OH* and CH* radicals which are markers of the flame front show the main combustion zone. The results of the Raman scattering technique show the variation of concentrations of different combustion products along the axial position of the flames.

2. EXPERIMENTAL SETUP

A schematic view of the experimental setup is shown in the Figure 1. The laser beam crosses the flame over the symmetry line of the middle of the burner head. The detail of the burner and flame have been described in [4, 5]. Hence a short description of the burner head and the optical scheme is given below.

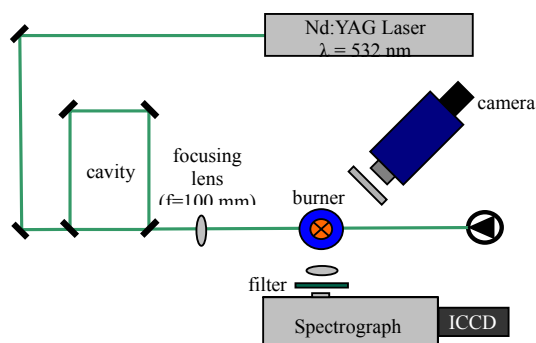


Fig 1: Schematic view of the experimental setup

2.1 Burner and Flame

A non premixed natural gas fired, academic, swirl burner is investigated in this research work. A schematic diagram of the burner nozzle is shown in Figure 2.

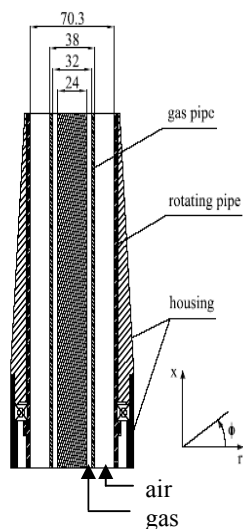


Fig 2: Downstream part of the swirl burner

The fuel and air are not premixed and fed to the burner through two concentric annular passages. Therefore the burner consists of two concentric pipes with inner diameters of 70.3 mm and 32 mm and a length of 1.23 m.

To form the inner annular passage for the fuel, a solid rod with a diameter of 24 mm is placed in the center of the inner pipe. The wall thickness of the inner pipe is 3 mm, resulting in an inner diameter of 38 mm for the outer annulus, through which air is supplied. Both air and fuel are provided at the base of the burner through radial inlets.

Dutch natural gas is used as the fuel. The fuel is taken from the gas supply line and the flow is controlled by a tap. The gas feed is continually monitored by means of a mass flow meter which is calibrated for natural gas. The air flow is controlled with a pressure regulator in combination with a critical plate orifice meter.

Swirl is introduced into the air by rotating the 1 m long downstream segment of the outer pipe, while a mantle around the rotating pipe prevents swirling of the ambient air. The intensity of the swirl plays an essential role for the occurrence of vortex break down, this prediction is often done by the non-dimensional swirl number. Swirl number describes the ratio between the transport of tangential momentum in axial direction and the transport of axial momentum of axial direction. But a simplified expression of swirl number is used by Huebner in [4-6] which is,

$$S = \frac{W_{\max}}{2\bar{U}} \quad (1)$$

with $W_{\max} = W_w$

In this expression, \bar{U} is the mean axial velocity and W_{\max} is the maximum tangential velocity, which corresponds here to the tangential velocity of the wall W_w . The intensity of the swirl can be varied continuously by adjusting the rotation rate of the pipe from zero rpm (no swirl) up to a maximum of 5000 rpm. This corresponds to a maximum wall velocity of $W_w = 14.7$ m/s.

The burner is placed on a translation stage. Measurements are obtained at different axial and radial positions in the flame by moving the burner with a positioner relative to the laser beam in steps of 1 cm.

2.2 Optical Scheme

Chemiluminescence is the emission of photons from species in a chemically or thermally excited state (denoted by *). The emission from different species is collected through an optical filter by an intensified CCD camera. The chemiluminescence and fluorescence signals of OH* while falling to the ground state around 308 nm is filtered by a Schott glass UG11 colored glass filter which has 80% transmission around 300 nm. A band pass filter centered 430 nm with a full width half-maximum of 10 nm is used for the detection of CH* chemiluminescence.

A monochromatic CCD camera (Redlake MotionScope 1000S with enhanced memory) is coupled to a high speed intensifier (La Vision HS IRO) which is used for the detection of the signal. The dynamic range of the camera is 8 bit. It has 480 x 420 pixels up to 250 Hz, which is reduced to 320 x 156 at 1000 Hz. The opening

time of the system is controlled by the intensifier. For the chemiluminescence measurement a gate of 100 μ s is used.

The optical scheme for spontaneous Raman measurements is shown in Figure 1. For the Raman measurements system the green frequency-doubled radiation of $\lambda = 532$ nm of a Nd:YAG laser (Spectron Laser, Model SL856G) is used. The laser has a repetition rate of 10Hz with the pulse duration of 6 ns. The beam diameter is approximately 1cm and the effective pulse energy is approximately 300 mJ per pulse.

The laser beam passes an own build pulse stretcher. The pulse stretcher is a cavity formed by three 45° high reflectivity mirrors and a beamsplitter (70% transmission and 30% reflection). The pulse stretcher stretches the pulse of the laser so that the power of the laser beam is distributed for longer time which prevents the dielectric breakdown. Then the laser beam is focused by a lens of focal length of 1000 mm to the measuring volume of the flame. After passing through the flame it is directed to a conical beam dump which absorbs the laser beam. The scattered radiation (Raman signal) is focused by a lens of focal length 100 mm to the entrance slit of the spectrograph (Acton Research Spectra Pro 500i) coupled to an intensified CCD camera. The spectrograph is oriented in such a way that its entrance slit is parallel to the exciting laser beam. The slit width of the spectrograph is kept very small (250 μ m) for getting better resolution. At the exit plane of the spectrograph, an intensified 1024 \times 256 pixels CCD camera (Princeton Instruments, PI max) with 16 bits digital conversion is mounted. A notch filter is placed just before the entrance slit of the spectrograph to reject the Rayleigh signal of the laser at 532 nm.

The camera spectrometer combination gives an image with place resolution in vertical direction and spectral resolution in horizontal direction. By adding all signal in the vertical direction a Raman Spectrum is obtained.

3. RESULTS

A number of different flames can be produced with different operating conditions varying rotation speed of the burner tube, air-fuel ratios and flow rate of air and fuel. This paper will show the diagnostic results of two different flames. Table 1 gives an overview of the operating conditions of different flames. Both flames have the same rotation value and equivalence ratios. But the flow rate of air and fuel are different which give different swirl number (Equation 1). Flame L1 has a higher flow rate of air and fuel which caused a low swirl number compared to flame L2 which has lower air and fuel flow rates. The equivalence ratios of the flames are kept constant which is, $\lambda = 1.2$.

Table 1: Operating conditions of different flames investigated

Flame	\dot{V}_{air} [m ³ /h]	\dot{V}_{fuel} [m ³ /h]	\dot{U}_{air} [m/s]	\dot{U}_{fuel} [m/s]	Re_{air}	Re_{fuel}
L1	52.0	5.25	5.3	4.1	11250	2250
L2	41.6	4.2	4.2	3.3	10125	2025

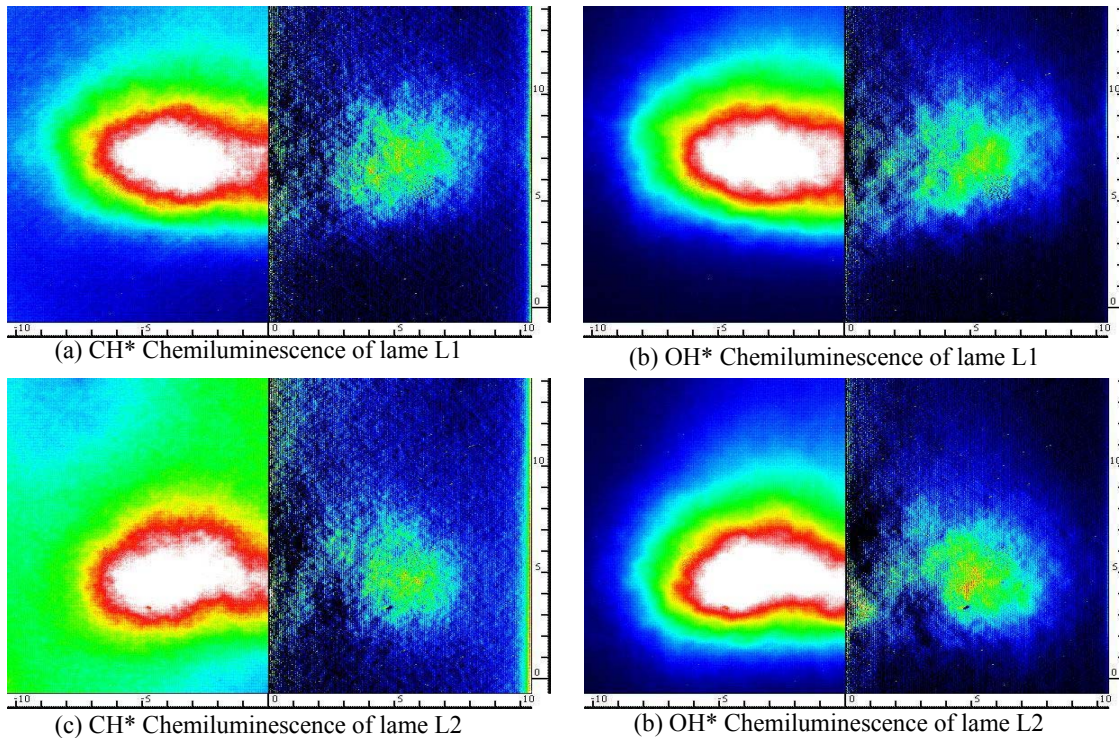


Fig 3: Chemiluminescence emission from different flames; left CH* chemiluminescence of flame L1 and L2; right OH* chemiluminescence of flame L1 and L2

3.1 Results of Chemiluminescence

The data obtained by Chemiluminescence experiments are composed of a series of 1024 frames, together forming a movie. A Matlab program is used to average the data. All the measurements were taken having approximately 21.5 cm wide and 19 cm high from the burner head. Figure 3 shows filtered CH* and filtered OH* emission for both of the flames investigated here. Each individual figure shows on the left side the averaged original data (average of 1024 frames) and on the right the data after inverse Abel transformation has been applied to it, which transforms the integrated signal into a two dimensional distribution of cross section.

Both sets of measurements, from flame L1 and flame L2 show that the main formation zone of CH* and OH* are inside the main blue combustion zone. Though OH* may exist above this zone, the lack of radiation indicates that it is not formed here. The formation zone of CH* and OH* gives a good deal of information about the shape of the main combustion zone. It is clearly seen that the main combustion takes place several centimeters (between 4 and 10 cm) above the air outlet. Clearly, the main mixing and combustion takes place on the contact surface of the air and fuel flows, fanning outward due to the rotational motion. Higher outflow velocities push the main combustion zone up, when the rotation is kept the same. Since the main combustion area will stabilize on the area where mixing has taken place, and this point gets “blown” upward with higher velocities.

Abel transformation images give an indication that the combustion zone is dough nut shaped, with a zone of little reaction in the middle. For higher outflow velocities (higher Reynolds number) the dough nut moves higher above the burner, and more butterfly shaped (with wings upward). When the size of the zone that has little combustion in the middle of the dough nut is compared to the geometry of the burner head, it is found that this zone, or the edge of the combustion zone, does not coincide with where the gas and air feed meet. The dough nut, and also the “hole” in the middle are somewhat larger the inner diameter of the air feed being 38mm, and the hole in the dough nut being about 55 mm. This enlargement is most likely caused by the outward motion effect of the swirl, when it is no longer contained. In fact, the size of the hole in the dough nut is slightly bigger for higher flow rates.

3.2 Results of Raman Spectroscopy

Raman spectroscopy technique is applied to both flames. Our Raman system allows point measurement. By traversing the burner up and down a series of measurements have been performed along a line parallel to the axis of the burner. The line of the measurements is 3.5 cm off-centre from the burner axis which is in the outer ring of the dough nut. The measurements start from 1 cm up to 14 cm above the burner head. Along the line 14 measurements were performed at the step of 1 cm. During the measurements 300 mJ laser power was used. The laser pulse is 6 ns which was stretched by the pulse stretcher. The gate width of the CCD camera was 500 ns to capture the Raman signal. In order to have a better resolution of the signal the slit width of the spectrometer

was kept very small to 100 μm . The systematic noise, dark current as well as natural emission of flame was corrected by background subtraction. Each Raman measurement was followed by a background measurement. The background measurement used exactly the same settings as the original measurement, with the sole difference that the laser radiation is temporarily blocked, thus only random and systematic noises were caught.

All of the measurements were performed with time averaging of 500 laser shots which increase the precision of measurements and detection limits. Commercial software WinSpec 32 was used to acquire the data. A special program was written in Matlab to analyze the data and find the concentration values.

Figure 4 shows 3 spectra from both flames at different axial positions (14 spectra were taken but 3 of them are shown here). The top two spectra were taken from 1 cm above the burner head. At this position there was no flame only the fuel and air were mixed here and was referred to mixing zone. In these spectra three significant peaks are found. The small peak at around 580 nm is for O₂, the one around 607 nm is for N₂ and the greatest one around 630 nm is for CH₄. If the both spectra are compared it is noticed that the amount of CH₄ is higher in flame L1 then to flame L2. This gives an indication of better mixing of flame L2. Flame L2 having lower flow rate so higher swirl number giving better mixing compared to flame L1 which has higher flow rate i.e. lower swirl number.

The middle spectra of Figure 4 were taken at the position of 8 cm above the burner head for both flames ((a) for flame L1 and (b) for flame L2). This position was inside the main combustion zone. In these spectra a number of peaks are found. The main difference between these two spectra is the peak (also the concentration) of CH₄. Flame L1 gives a high peak of CH₄ at around 630 nm where as flame L2 doesn't. This gives a clear indication that at this position all CH₄ is burned and almost no CH₄ is present in flame L2. But in case of flame L1 there is still some CH₄ at this position and combustion is still taking place. This is in good agreement with chemiluminescence result which also shows that the higher outflow velocities push the main combustion zone up of flame L1.

The bottom spectra of Figure 4 were taken from 14 cm above the burner head. If this spectrum is compared to middle spectrum (at h = 9 cm) for flame L2, they look quite similar which means there were not many reactions between these two positions and all the combustion was ended at 9 cm above the burner head (in the middle spectra). But if those spectra of flame L1 are compared there is some difference. Specially, the middle spectra has a high CH₄ peak which is vanished at the bottom spectra. This means in flame L1 at position 9 cm above the burner head there are still some combustion taking place but at position 14 cm above the burner all the combustion is finished. So flame L1 is larger than flame L2.

Figure 5 gives a profile of major species of combustion along the line of measurement for flame L1 (left) and flame L2 (right). These plots show that at the

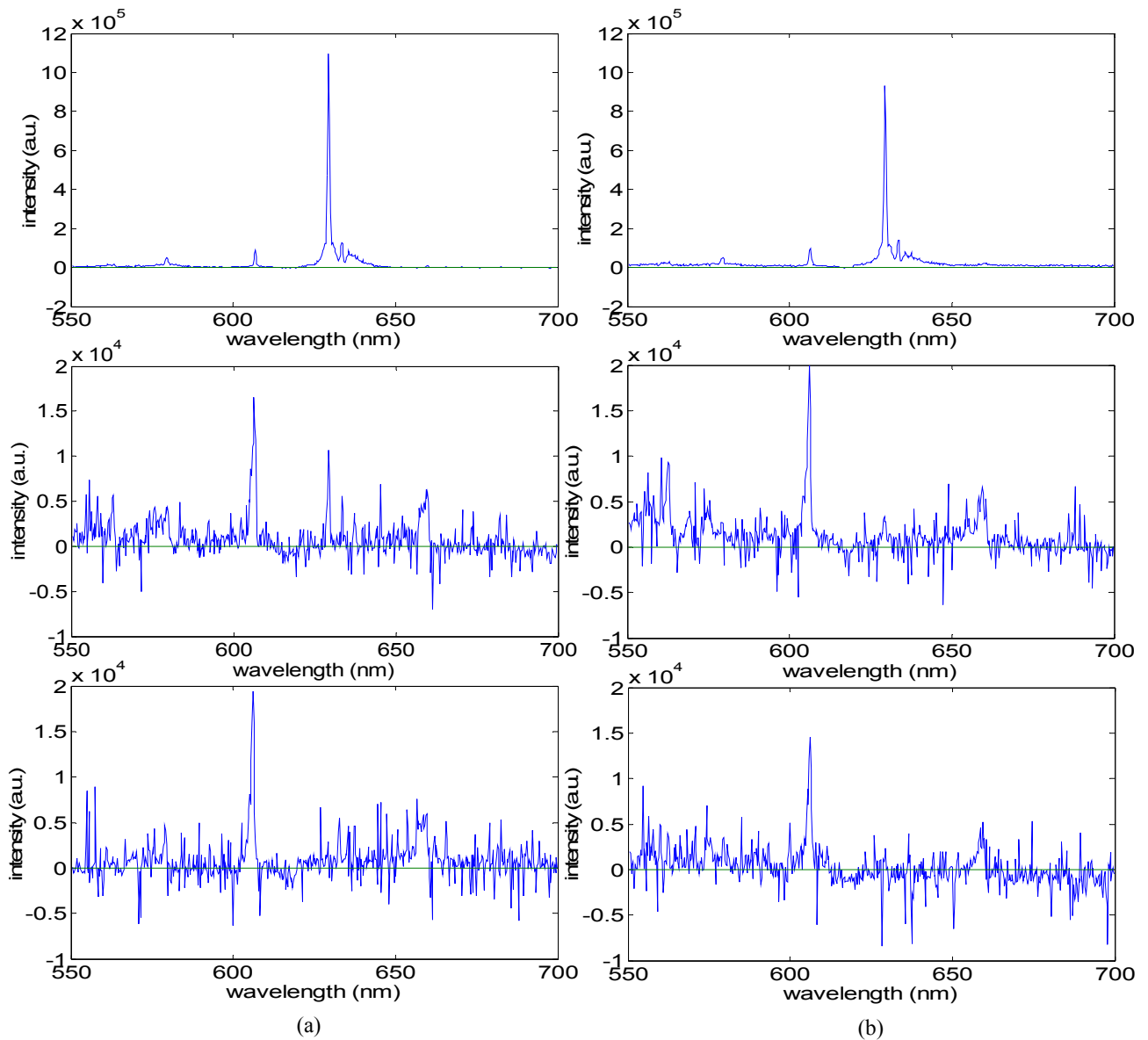


Fig 4: Raman spectra at different axial positions ($h = 1$ cm, $h = 9$ cm and $h = 14$ cm from the burner head) of (a) flame L1 and (b) flame L2

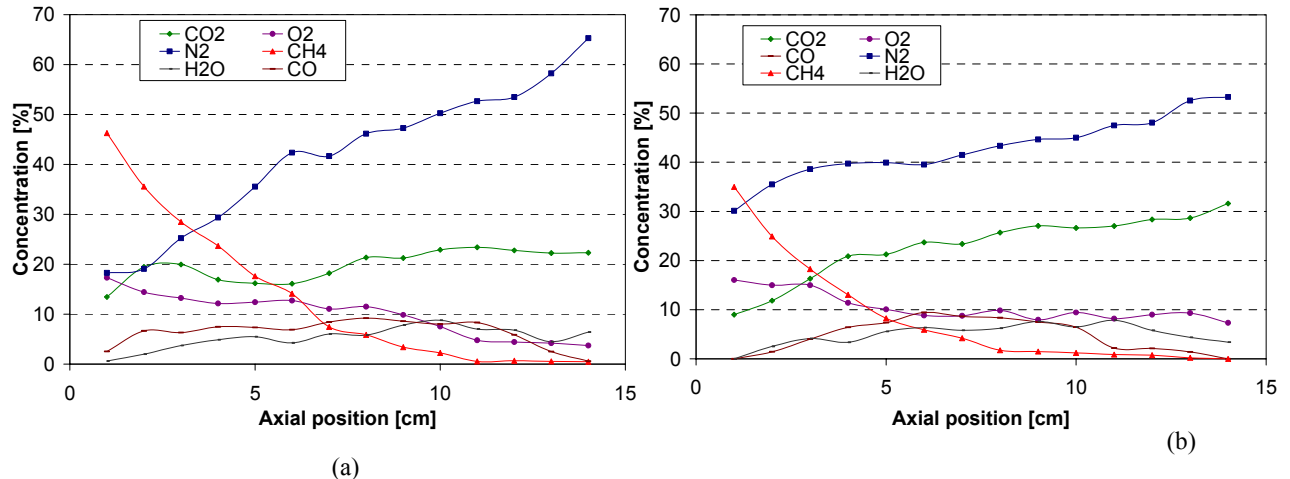


Fig 5: Concentration of different combustion species along the axial position of the flames; (a) for flame L1 and (b) for flame L2

first point (1 cm from the burner head) flame L1 has more CH₄ and less N₂ than that of flame L2. This indicates better mixing in flame L2 than flame L1. CH₄ profile also shows combustion ended at 11 cm above the burner head in flame L1 but in case of flame L2 it is 8 cm. Concentration of CO₂ increases gradually along the height while concentration of O₂ is decreasing. In the mixing zone (before the combustion started) still some CO₂ is found which may come from the outer recirculation motion of combustion product.

4. CONCLUSIONS

Both optical (chemiluminescence) and laser spectroscopy (Raman scattering) techniques are applied to two different flames on our academic burner. Chemiluminescence gives qualitative information while Raman scattering technique gives quantitative information. Chemiluminescence results of CH* and OH* show a main combustion zone which is dough nut shaped. In the middle of the dough nut there is less combustion due to lack of oxidant present here. The main combustion zone (also the dough nut) shifts upward with the increase of outflow velocities even having the same rotation speed of the burner tube. Results of Raman spectroscopy give the concentration profile of major combustion species along the line of measurement. The concentration plots also give information about the mixing of air and fuel. The mixing is better in case of high swirl flame than that of low swirl flame.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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7. NOMENCLATURE

Symbol	Meaning	Unit
S	Swirl number	(-)
W_{max}	Max tangential velocity	(m/s)
W_w	Wall velocity	(m/s)
\bar{U}	Mean axial velocity	(m/s)
\dot{V}_{air}	Volume flow rate of air	(m ³ /h)
\dot{V}_{fuel}	Volume flow rate of fuel	(m ³ /h)
\bar{U}_{air}	Velocity of air flow	(m/s)
\bar{U}_{fuel}	Velocity of fuel flow	(m/s)
Re_{air}	Reynolds number of air	(-)
Re_{fuel}	Reynolds number of fuel	(-)