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To cite this article: A. A. Saad *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **610** 012023

IOP Conf. Series: Materials Science and Engineering **610** (2019) 012023 doi:10.1088/1757-899X/610/1/012023

Hyperspectral imaging and analysis of swirling flames issued from two and four slots circumferential burners

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Abstract: A spectroscopy and visual investigation for turbulent swirling flames formed by four -circumferential swirling turbojet EV in comparison with a two-circumferential swirling air entries configuration burner using hyper spectral camera. The special design of the EV-burner guarantees flame stabilization at the burner exit by a recirculation of hot gases and entrained fresh reactance mixture. A recirculation zone (vortex breakdown) can be generated when a sufficient strong swirling flow exist. The main parameter of combustion diagnostics based on optical devices is the flame itself, whose spectrum is closely related to the process state, as a fingerprint of the instantaneous operational condition, in terms of energetic yield, fuel consumption and pollutants emissions. The hyperspectral imaging technique in the aspect of flame analysis to give a complete description for the flame zones behavior and distribution of reactions through the whole flame. The spectral peaks for issued flames have been studied to give complete vision for the effect of changing the equivalence ratio and different burner arrangement four and two circumferential swirling entries.

Keywords: Turbulent Swirling Flames, Hyperspectral Imaging, Spectroscopy, EV Burner.

Nomenclature

A	Amplitude	[m/s]
I	Intensity	[a.u.]
R	Burner radius	[mm]
r	Radial distance	[mm]
V_{air}	Air volume flowrate	[l/min]
V_F	Fuel volume flowrate	[l/min]
y	Axial distance	[mm]
Φ	Equivalence ratio	[-]
λ	Wavelength	[nm]

1. Introduction

Today's gas turbine technology is established in a wide range of applications, including the production of electrical power, thrust generation in turbojets and driving large size pumps and compressors. The greatest advantages of gas turbines versus other prime mover systems e.g. steam turbine and piston engine systems; lie in its higher specific power, compact design and low initial costs based on power output. Another advantage of today's gas turbines is its low emission characteristics, and thereby meeting the stringent environmental emission restrictions. In parallel to these advantages, the design optimization of gas turbine combustors, including burners, is currently dealing with many worldwide research institutes to realize lower specific fuel consumption that balances the ever increasing of the cost of fossil fuels.

The undesirable effects on the environment due to pollutant emissions, and the requirement of process operations for better economic profits have all urged the use of several methods for combustion diagnostics and monitoring. Recently, due to the decreasing cost of optical devices, several methods of combustion diagnostics using passive optical devices such as hyper spectral cameras have been proposed, [1, 2]. The main parameter of combustion diagnostics based on optical devices is the flame itself, whose spectrum is closely related to the process state, as a fingerprint of the instantaneous operational condition, in terms of energetic yield, fuel consumption and pollutants emissions, [3-6].

The special design of the EV-burner guarantees flame stabilization at the burner exit by a recirculation of hot gases and entrained fresh reactance mixture, a recirculation zone (vortex breakdown) can be generated when a sufficient strong swirling flow exist. The flames generated has two interacted zones, these zones namely (i) recirculation zone which is the zone formed at the burner exit due to the swirling movement of flue gases at the burner exit. (ii) Reaction zone which is the zone formed at the outer regime evolving the recirculation zone. A schematic drawing explains this zone is illustrated at figure 1. This burner design concept appears to offer many advantages, especially the replacement of the traditional fixed vane swirler by circumferential swirling air passages; and hence not only minimizes blockage and allows prior premixing of fuel and air within the conically shaped entry section to the combustor but also eliminates possible risk in case of swirler blade damage.

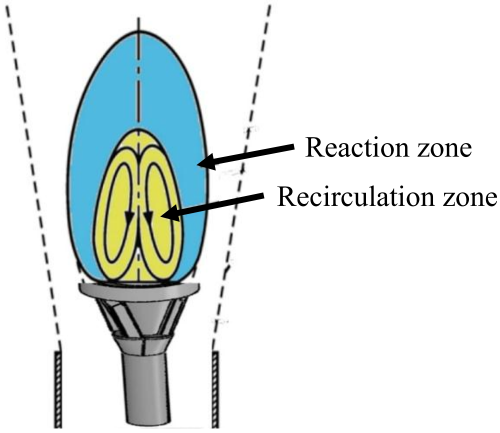

Figure 1. EV burner flame zones

Spectral analysis provides a detailed information of combustion processes analysis and investigations in both internal combustion engines and industrial burners, [7-8]. This method presents several advantages, compared to the conventional gas analysis techniques. This is because overcoming the change on flue gases characteristics due to the rapid flow of the exhaust gas from the combustion reaction zone to the chimney. Also, optical devices require low maintenance and low failure occurrence during measurement, compared to the gas analyzer. Moreover, the difficulty of measuring exhaust gas composition during combustion processes. So, the combustion diagnostics based on optical devices is recently used in combustion investigations, [9, 10].

2. The experimental facility

The schematic of the experimental test rig is illustrated in figure 2. This test rig essentially consists of:

1. Vertical water-cooled combustor with quartz glass combustion chamber to access the flame.
2. EV burner (2-slot or 4-slot).
3. Fuel and air supply and metering systems.
4. Hyperspectral camera with data acquisition and analysis software.

2.1. Two-Slot Burner

The two-slot burner shown in figure 3 consists of two shifted half cones with two slots between them, such that air is forced to enter the cone circumferentially. The resulting swirling airflow generates a recirculation zone along the centerline at the burner outlet. The main fuel is injected through 62 boreholes, 0.7 mm diameter each, that are distributed equidistantly along the two air slots. The main fuel is mixed with the swirling air resulting in a nearly premixed combustion.

2.2. Four-slot burner

The burner with Four circumferential air slots displaced (formed by quarter cones with four slots between them) shown in figure 4. Air is forced to enter the cone circumferentially. At each slot, main fuel is injected through equidistantly holes located along the entry of each air passage between the apex and the burner exit.

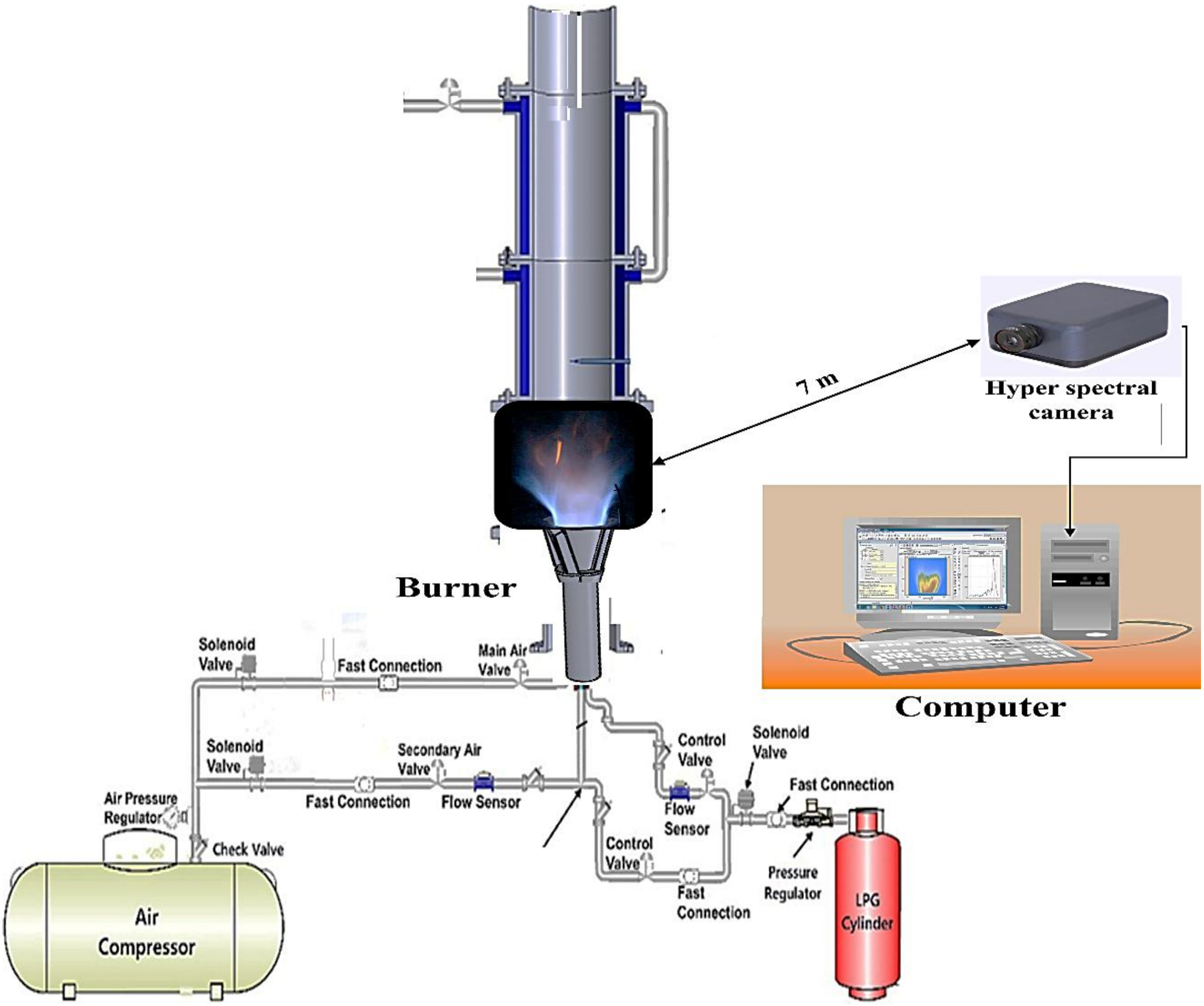

Figure 2. Schematic of the Experiment test rig.

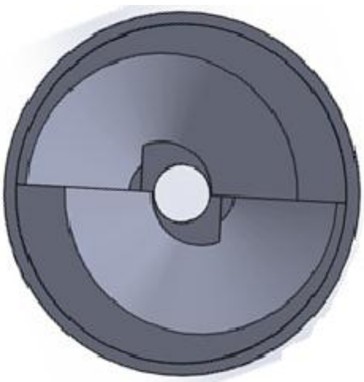

Figure 3. Two-Slot EV-Burner top view.

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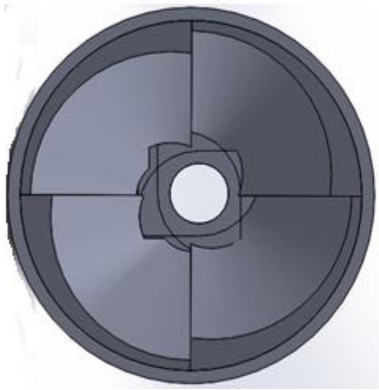

Figure 4. Four-Slot EV-Burner top view.

2.3. Fuel supply and metering systems
To achieve full control for the system and give an accurate reading, a control system consisting of an electronic card and software with an interface to the computer was utilized.

2.4. Hyperspectral camera system
Spectral images were taken by a hyperspectral camera model: SOC710V. This camera can capture images of flame from each available wavelength. The spectral range of the hyper-spectral camera is from 400 to 1000 nm separated by 4.6875 nm in a cube file. This camera was connected to a computer via USB cable for acquiring, saving, and analyzing the captured images as seen in figure 2.

3. Experimental program
Several spectral studies are focused on the radical's peaks, which represent a small part of the whole flame emissions. These peaks are detected to explain the combustion process. CH^* centered at 432 nm and C_2 centered at 554 nm, [18].

The explanation of the experimental data integrates between the results being obtained from the visual and spectroscopy analysis to form a full picture of the variations in the flame characteristics associated with the changes of the equivalence ration and the burner design.

Table 1 shows the experimental cases conducted on 2-slot and 4-slot EV-Burners. The main air flow rate was kept at 873 l/min for whole cases, with changing fuel flow rates from 24 to 32 l/min (4 l/min step) to achieve lean combustion conditions.

Table 1 The experimental program of the 2-slot and 4-slot EV burners.

Cases			1	2	3
2-slot EV-Burner	V_{air} = 873 l/min	Φ	0.39	0.45	0.52
		V_F [l/min]	24	28	32
4-slot EV-Burner		Φ	0.39	0.45	0.52
		V_F [l/min]	24	28	32

4. Results and Discussion

4.1. Visual flame structure investigation at different equivalence ratios

(a) For 2-slot burner

At Φ = 0.39; The flame was pale blue at the outer boundaries and little whitish yellow at the flame core where the reaction and recirculation zones are found respectively as seen in figure 5 panel (A). But when the equivalence ratio was increased to Φ = 0.45 as shown in figure 5 panel (B); the flame became bigger, longer and wider than that of Φ = 0.39, because the recirculation zone became visually larger. Finally, at figure 5 panel (C), at Φ = 0.52, the flame was the longest flame, because recirculation zone inside flame core became the largest size and reaction zone was minimized. The flame has more concentrated whitish yellow at flame core due to increase of fuel flow rate.

(b) For 4 slots burner:

At Φ = 0.39; the flame was only pale blue colored which is an indication that reaction rate is little weak. But by increasing fuel flow rate and reaching Φ = 0.45 the flame became longer and more concentrated blue at the flame core which indicates at high reaction rate which is in good agreement with spectral peaks intensity and emission contours in next sections. Finally, at Φ = 0.52, the flame will have little yellowish color due to improper mixing.

4.2. Hyper spectral visual analysis of the flame structure

Whereby spectral images of the different flame are taken for; (i) 2-slot EV burner, (ii) 4-slot EV-Burner at different volumetric fuel flow rates. For all cases, the variations in spectral flame images near UV range as well as the variations in spectral flame images at the visible range also spectral flame images near IR are compared and analyzed.

From figure 6, it is obvious that by increasing fuel volume flow rate the intensity of emissions became more concentrated at the core of flame in 2-slot burner; while at 4-slot burner, the intensity of emissions is distributed at the circumference of the flame due to high swirl of both fuel and air.

4.3. Analysis of the variations in the spectral peak emissions of the developed flames

The peak emissions at the different flame zones studied, whereby the red dote refer to reaction zone and yellow dote represent recirculation zone. From previous points, it is easily to measure activity and intensity of emission peaks.

(a) At wavelength λ= 401 (near ultraviolet)

At figure 7, Φ=0.39, it is obvious that the mixture is lean. So, the reaction rate of 2-slot burner is relatively low compared to 4-slot. Consequently, relative high emissions contour spectral are observed at 4-slot than 2-slot. This is because in 2-slot burner the centrifugal forces carrying the fuel for mixing with air are low. On the other hand, 4-slot burner has high centrifugal forces. Consequently, high mixing of fuel with air is producing low contour emission spectra.

At figure 9, Φ=0.45, the amount of fuel is increased from 24 l/min to 28 l/min. the highest peak of intensity is (890 a.u.) for recirculation zone of 4-slot burner while the highest peak of intensity of 2-slot is (850 a.u.) This is due to high centrifugal forces exerted using higher fuel flow rate. So, good mixing is happened resulting higher peak intensity of 4-slot than 2-slot.

At figure 11, by increasing fuel flow rate reaching to 32 l/min (Φ=0.52), the reaction rate will increase due to good mixing and turbulence. Higher peak of intensity at 4-slot burner. Low emission contour spectra for 4-slot burner. Table 2 shows the behavior of each 2-slots and 4-slot including, Φ, centrifugal forces, recirculation zone, reaction zone and emission intensity at wavelength λ= 401.

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(b) At wavelength λ= 716 (visible)

The emission contour intensity has different behavior compared to the previous one, where cases of equivalence ratios Φ = 0.38, 0.45 have the same trend. This trend is the reduction of the emission contour spectral. This is indication to good mixing, high reaction rate, and low emissions radicals. But at Φ = 0.52 the amount of fuel is relatively high to amount of air or centrifugal force is not enough to turbulence the flame well. So, the turbulence at Φ = 0.52 is weak in spite of high fuel flow rate.

(c) At wavelength λ= 913 (near infra-red)

In case of 4-slot burner, by increasing equivalence ratio, the rate of reaction will increase, and the emission contour spectra values will increase as seen from Φ = 0.39, 0.45 and 0.52 which are corresponding to 80, 800, 1500 a.u., respectively. But in case of 2-slot burner, the values of emission contour spectra are little lower than that of 4-slot except at Φ =0.39.

4.4. Emission contour intensity of both burners at different equivalence ratios

From figure 12, in the 2-slot burner, it is noticed that when the equivalence ratio was increased, the intensity of contour emissions at λ = 432 nm from 34 a.u. reaching to 170 a.u. this is due to:

- Increase of fuel flow rate.
- Increase of rate of reaction.
- Intensity of CH^* radicals emissions appeared clearly at Φ = 0.52 with value of 170 a.u. due to some of fuels not fully burned.
- Finally, this will affect the exhaust gas emissions.

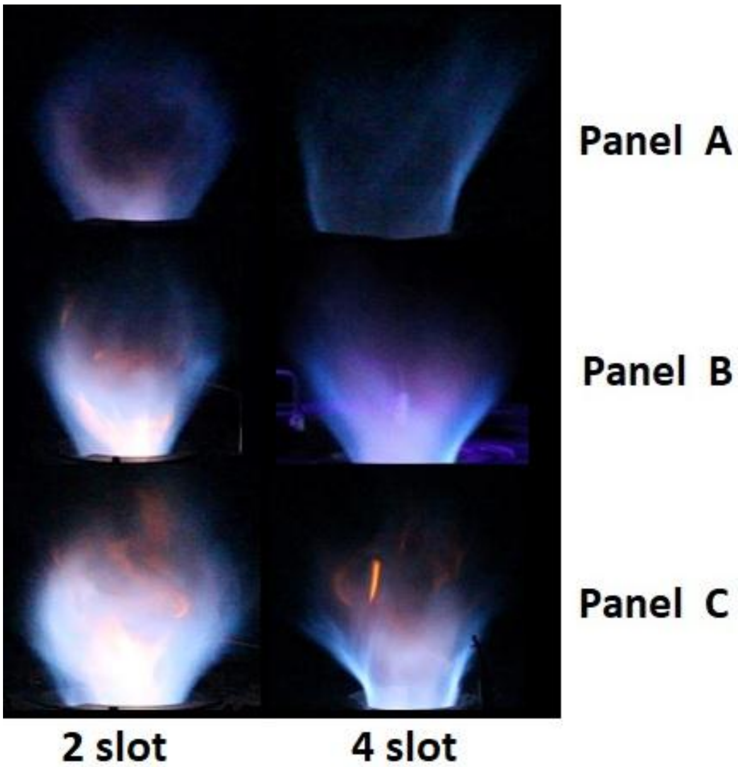

Figure 5. Visual flame observation of 2 and 4 slots burner at different equivalence ratios.

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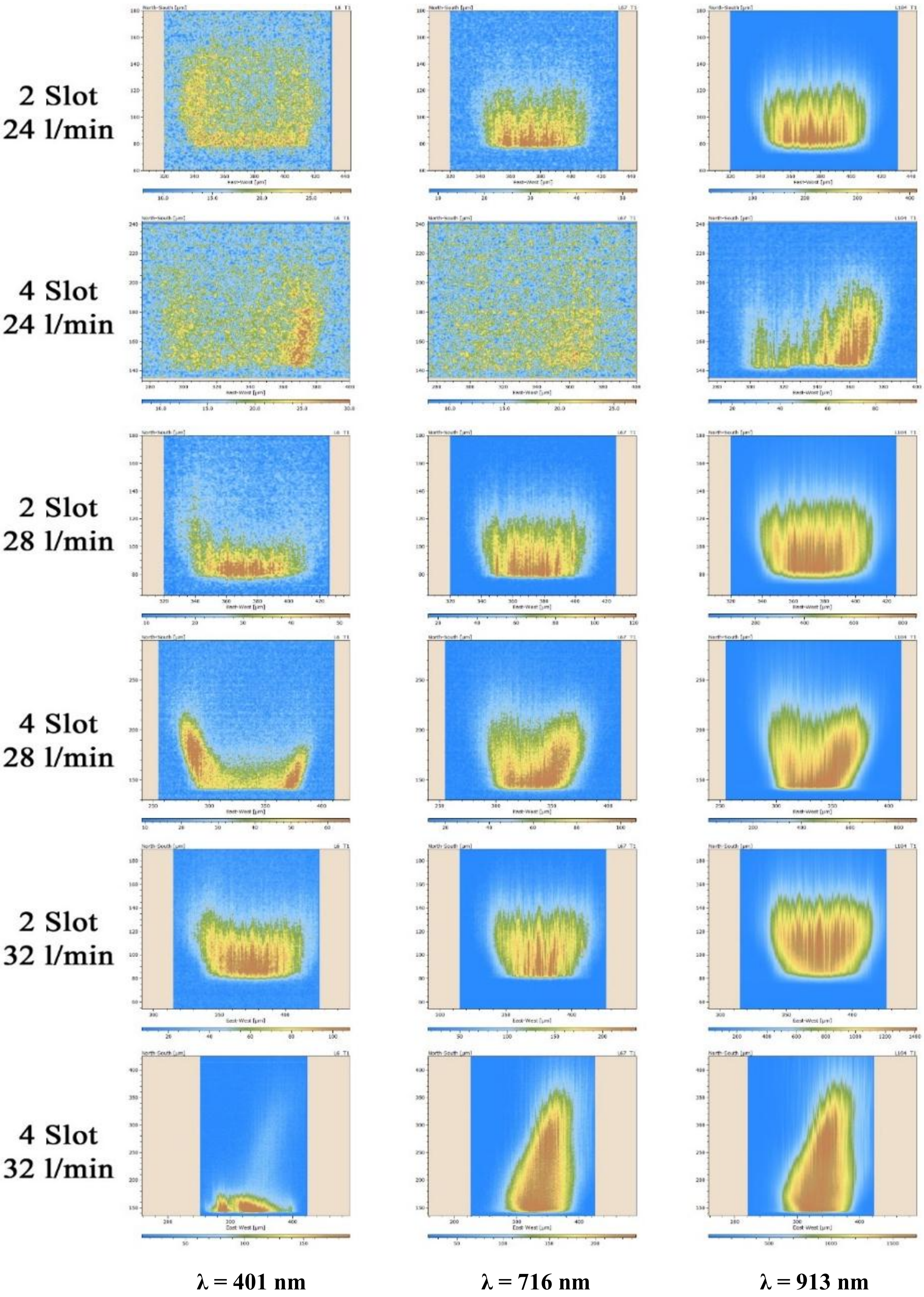

Figure 6. Intensity contours of flames structure at different wavelengths.

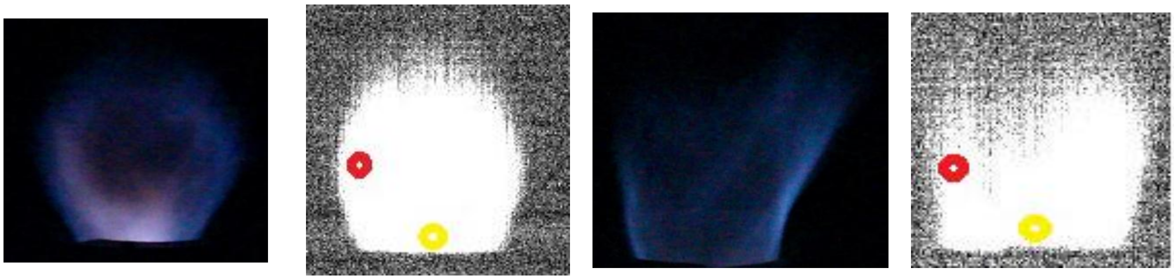

Figure 7. Images at (λ=913 nm) represent the selective points to compare spectral peak emissions at (Φ=0.39).

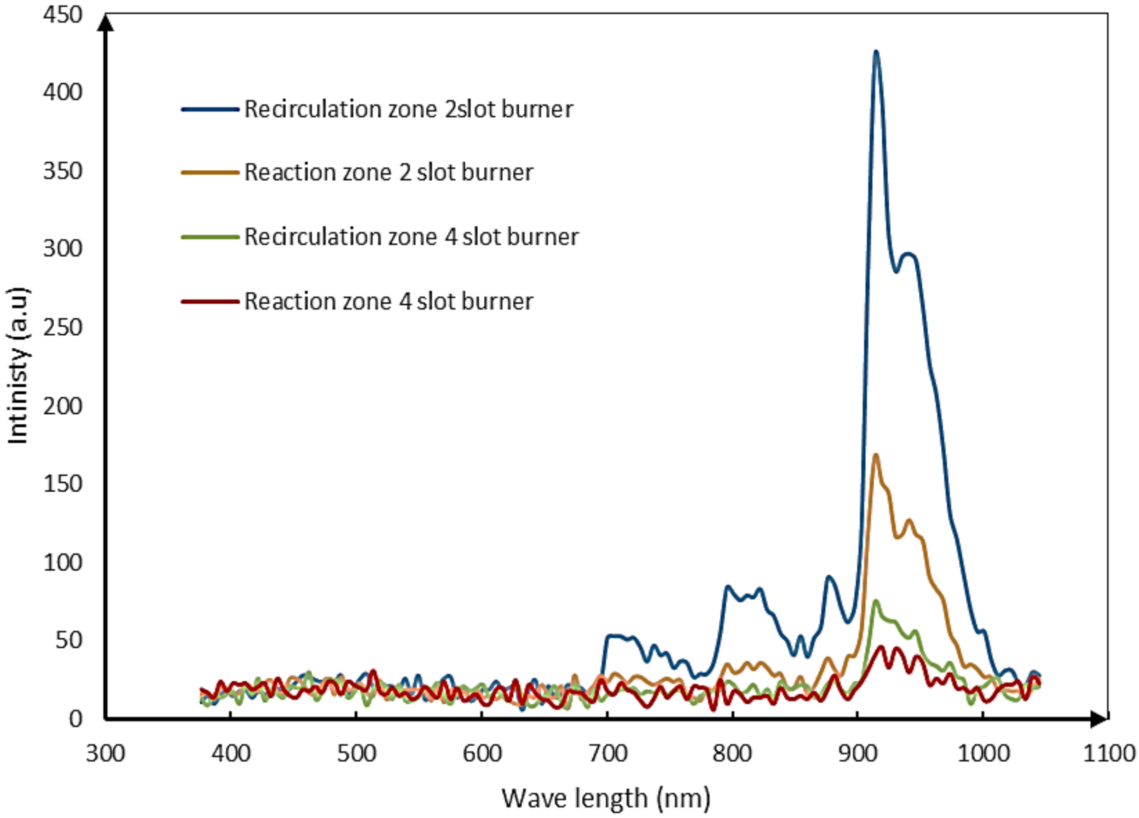

Figure 8. Wave length intensity at (Φ=0.39) for 2 slot and 4 slot burners

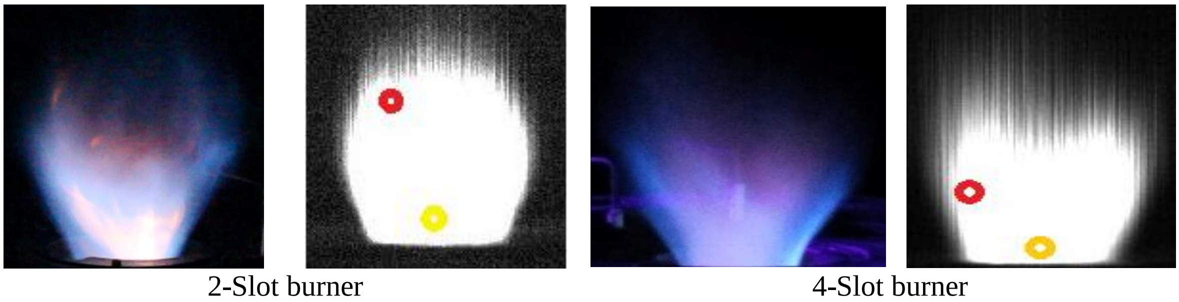

Figure 9. Images at (λ=913 nm) represent the selective points to compare spectral peak emissions at (Φ=0.45).

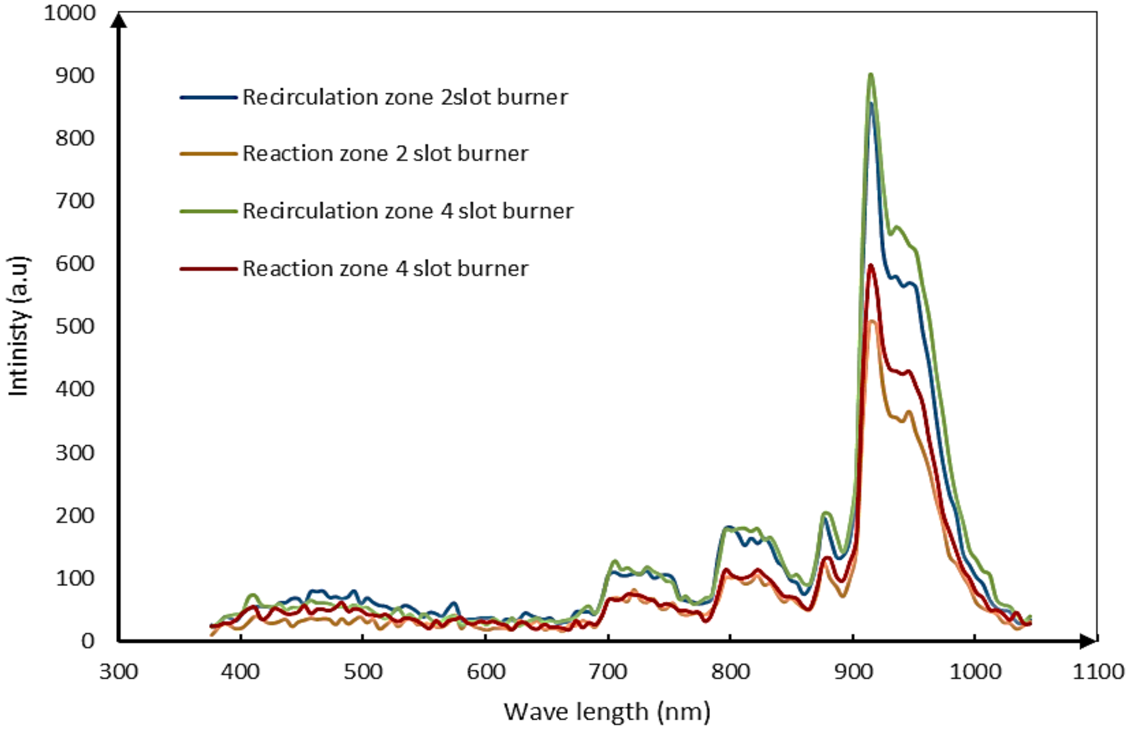

Figure 10. Wave length intensity at (Φ=0.45) for 2 slot and 4 slot burners

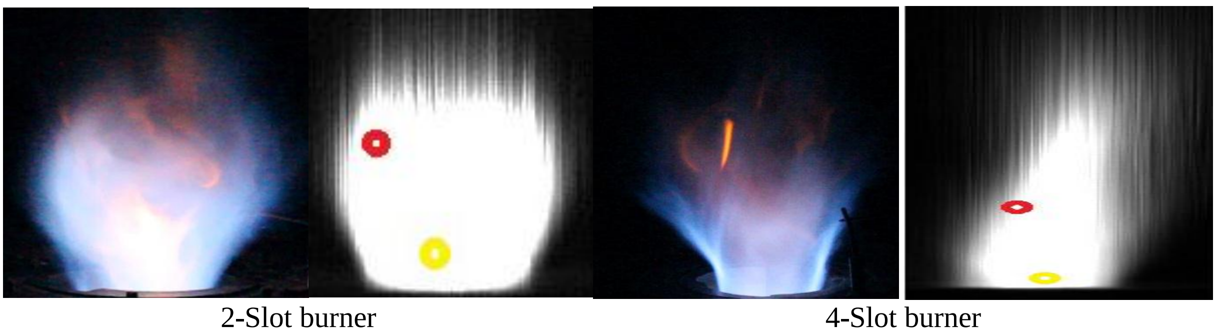

Figure 11. Images at (λ=913 nm) represent the selective points to compare spectral peak emissions at (Φ=0.52)

At 4-slot burner, also CH^* emissions radicals increase with the increase of fuel flow rate for the same reasons previously mentioned. But when equivalence ratio changed from $\Phi = 0.39$ to 0.45 the intensity of CH^* radicals changed from value of 42 a.u. to 90 a.u. this later value is little smaller than that of 2-slot burner at the same condition as shown in figure 13. This means that good mixing between air and fuel was achieved due to the high centrifugal force.
At $\Phi = 0.52$, 4-slot burner produces higher intensity of CH^* radicals of value 300 a.u.

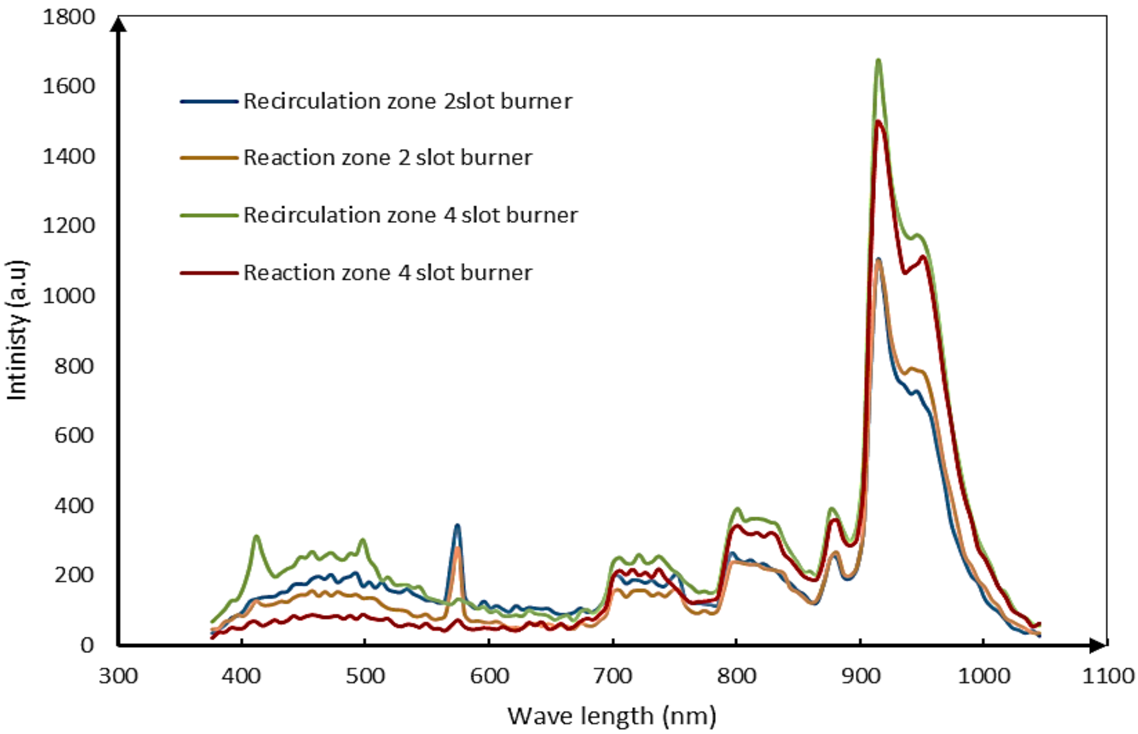

Figure 12. Wave length intensity at (Φ=0.52) for 2 slot and 4 slot burners.

Table 2 comparison between 2-slot and 4-slot behavior at wavelength λ= 401 in many points of views.

	Φ	Qualitative Description			
		Centrifugal Forces	Recirculation Zone	Reaction Zone	Emission Intensity
2 slots	0.39	Suitable for mixing	High intensity peak	High intensity peak	low intensity peak
	0.45	No good mixing	low intensity peak	low intensity peak	Little higher intensity peak
	0.52	Weak mixing, forces isn't enough	low intensity peak	low intensity peak	high intensity peak
4 slots	0.39	Easily carry fuel particles fast	low intensity peak	low intensity peak	High intensity peak
	0.45	Fuel particles mixed well with air due to centrifugal forces	Higher intensity peak	Higher intensity peak	High intensity peak
	0.52	Very suitable	Higher intensity peak	Higher intensity peak	Higher intensity peak

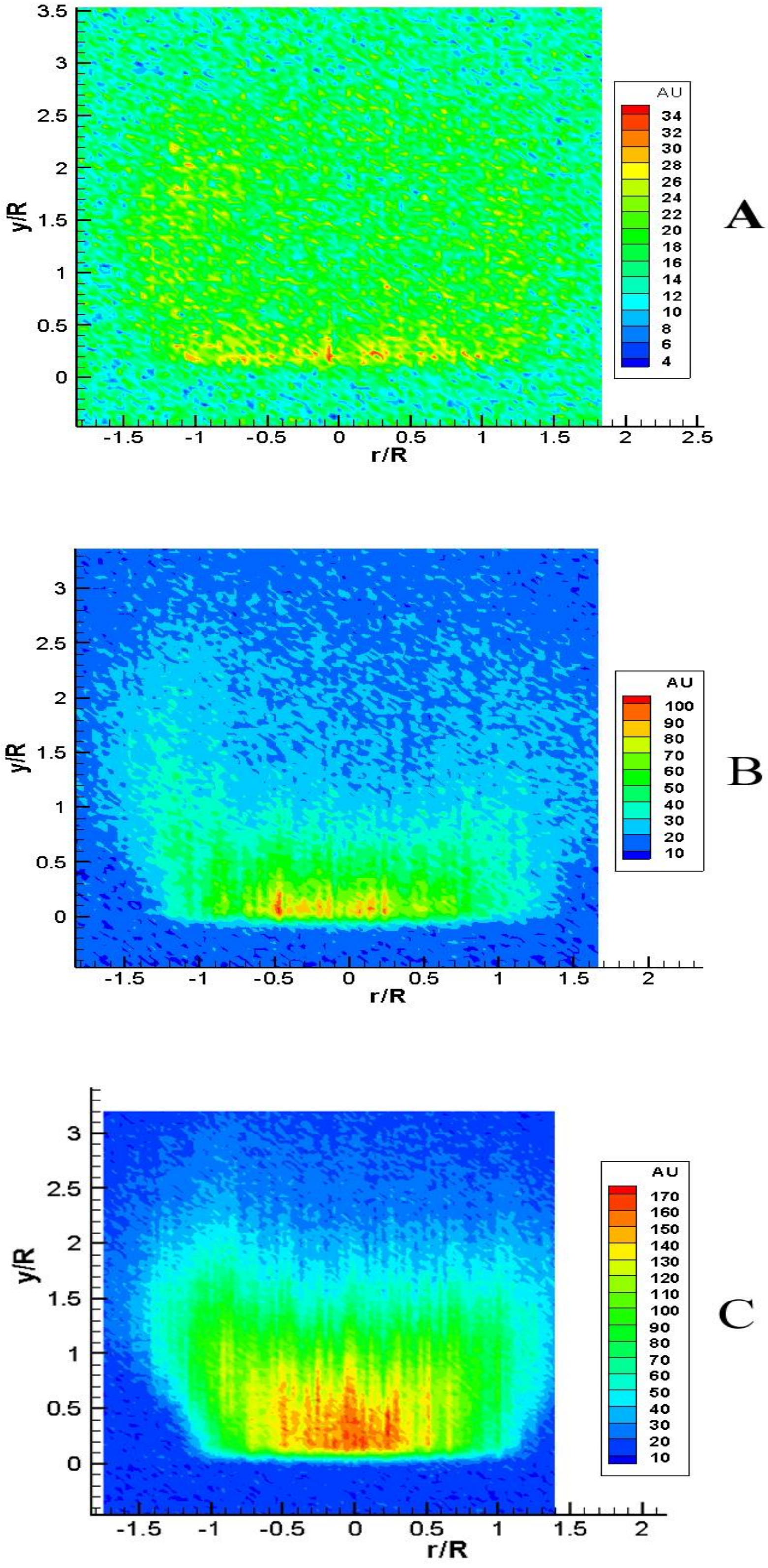

Figure 13. emission contour intensity of 2 slots burner at λ = 432 nm at various equivalence ratios

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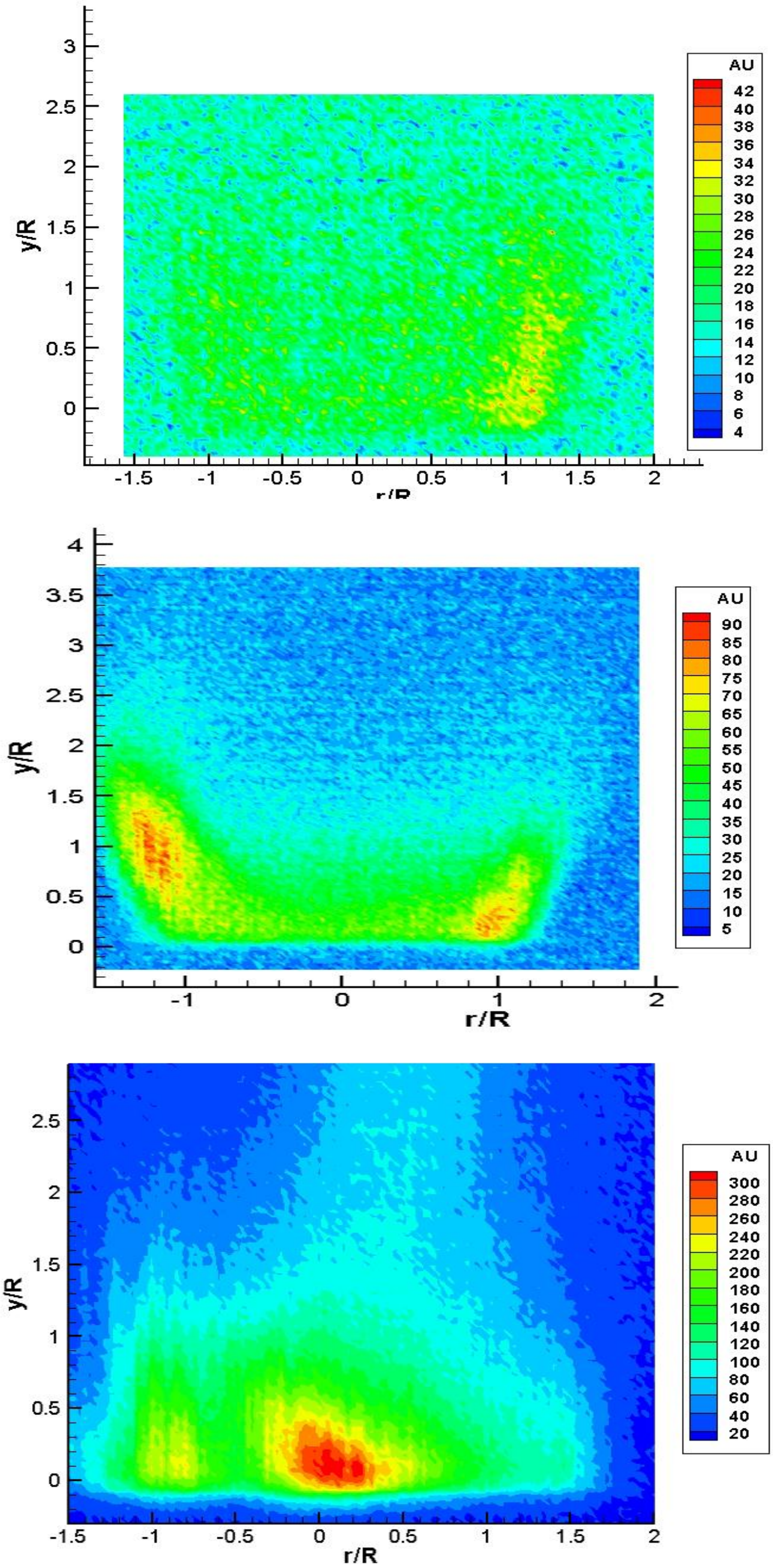

Figure 14. emission contour intensity of 4 slots burner at λ = 432 nm at various equivalence ratios

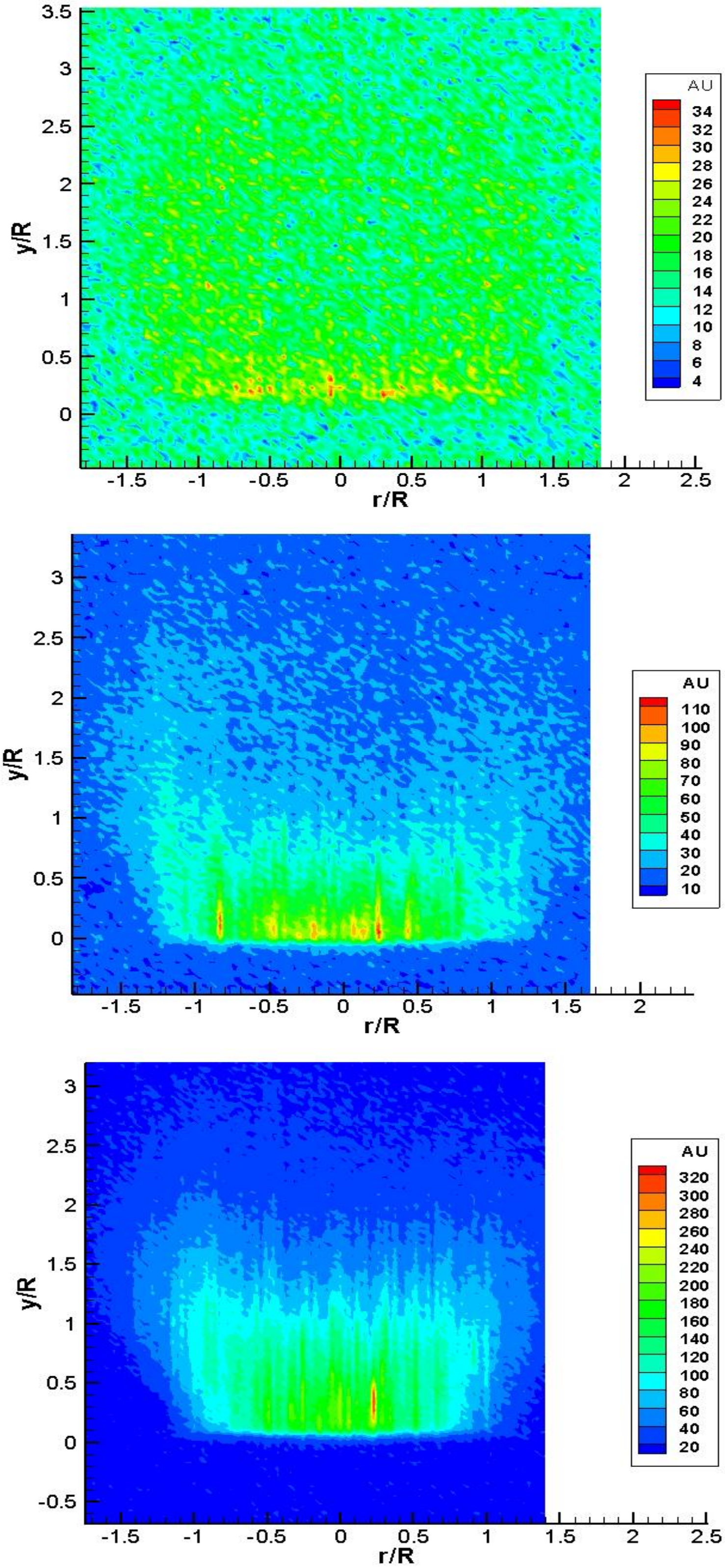

Figure 15. emission contour intensity of 2 slots burner at λ = 554 nm at various equivalence ratios

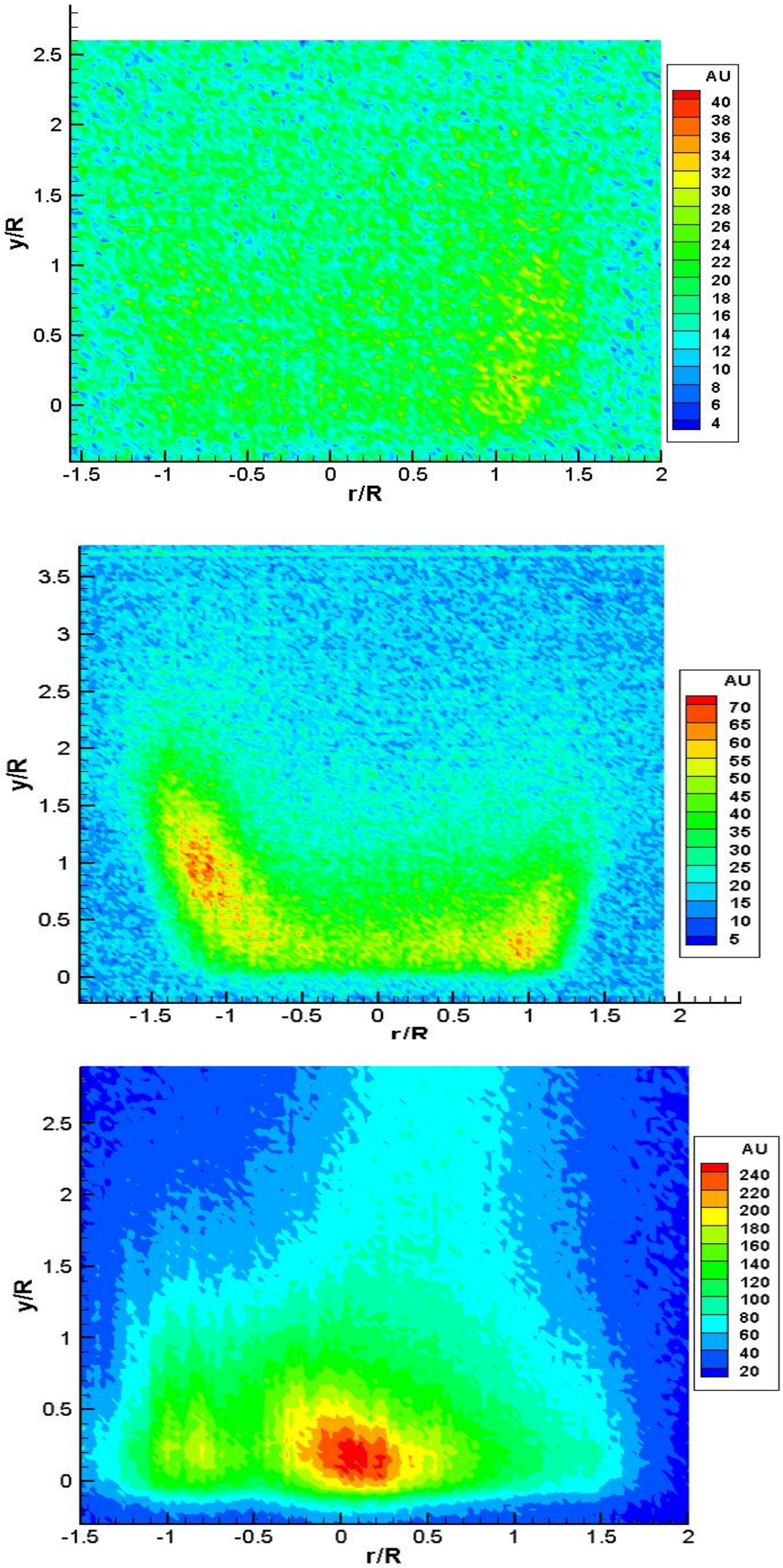

Figure 16. emission contour intensity of 4 slots burner at λ = 554 nm at various equivalence ratios

Finally, from figure 14 and figure 15, at λ = 554 nm, 2-slot burner produced C_2 emission radicals of intensity of 34, 110, 320 a.u. that corresponded to Φ = 0.39, 0.45 and 0.52 respectively. On the other side, the intensity of C_2 emission radicals of 4-slot burner had values of 40, 70, 180 a.u. linked with equivalence ratios Φ = 0.39, 0.45 and 0.52 respectively.

From intensity of both CH^* and C_2 emission radicals, it is highly recommended to use 4-slot burner at Φ = 0.45 where the expected exhaust gas emissions will be lower than that of 2-slot burner.

5. Conclusion

The demand of highly efficient, economically and environmentally gas turbine combustion is widely increasing. One of the most promising burner designs achieving these goals is EV-Burner. Visual and spectroscopy analysis were utilized to descripe the flame zones, reactions behavior and distribution of CH^* and C_2 radicals all over the whole flame. The results showed that the use of 4-slot burner at Φ = 0.45, gave lower intensity of contour emissions than that of 2-slots burner. So, this may reduce exhaust gas emissions. The deduction of the position of reaction and recirculation zone will create chance to control amount of heat released and control exhaust gas emissions through many methods like fuel/air staging or fuel pilot shift.

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