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# Parametric study of triple coaxial ports inverse diffusion flame

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**Abstract:-**The effects of swirling, flow divergence and porous media, of triple coaxial ports inverse diffusion flame (TCP-IDF) on the flame shape, temperature, and gas emissions arestudied.A comparison between non swirlingTCP-IDF burner and a swirling TCP-IDF burner, using a5$^o$ air swirleris conducted. On the other hand 2mm and 1 mmPorous screensand65$^o$, 45$^o$ and 15$^o$ flow divergence diffuser are investigated.The effect of these parametric on the flame radial and centerline temperatures, CO, NOxand unburned hydrocarbons have been performed. In all experiments the air to fuel ratio was the same., the study showed the highest temperature on average have been recorded in the subsequent order, the 15$^o$ diffuse, then the 45$^o$ diffuser, the swirling TCP-IDF, the non-swirlingTCP-IDF, the 1mm wide mesh porous screen , 2mm wide mesh porous screen and finally the 65$^o$ diffuser flame was unstable and could not be recorded, as far as the NOx emissions the highest recorded emissions have been for the 15$^o$ diffuser, then the 45$^o$ diffuser, the swirling TCP-IDF, the 2mm wide mesh porous screen, the non-swirling TCP-IDF and finally the least NOx emissions have been recorded for the 1mm wide mesh porous screen, while for the CO emissions the highest recorded emissions have been recorded for the 1mm wide mesh porous screen, then the 2mm wide mesh porous screen, the non-swirling TCP-IDF, the 45$^o$ diffuser, thenthe swirling TCP-IDF, and at last the lowest CO emissions have been recorded for the 15$^o$ diffuser, on the other hand for the unburned hydrocarbons the highest percentages was respectively for the for the 1mm wide mesh porous screen, then the 2mm wide mesh porous screen, the non-swirling TCP-IDF, the 45$^o$ diffuser then the 15$^o$ diffuser, while the lowest percentages of the unburned hydrocarbons was recorded for the swirling TCP-IDF,

## I. INTRODUCTION

The continuous requirement of increasing combustion efficiency is becoming increasingly covetable [21],[22] IDF is characterized by its high efficiency in comparison to conventional diffusion flames, as a result of the shear between the inner and outer air jet velocities and the supply of air into the interior of the fuel flow, causes the fuel to be entrained inwards at high velocities forming a partially premixed flame in addition to the diffusion flame, gaining a better flammability range than premixed flame [23], but with lower soot and NOx emissions than NDF, [24], [25]the introduction of other parameters, such as Swirling, Flow divergence& porous media interaction, is expected to increase the combustion efficiency & reduce soot and CO emissions, this, in theory, could be achieved because of several factors, Changing axial momentum into tangential momentum, also the vortex from the swirl causes recirculation from the outer radii to the inner radii which causes a negative velocity axially to achieve balance between flame speed and flow velocity, as well as the generated turbulence assists in maintaining higher flame speeds, in addition to enhance mixing, which is reflected upon better combustion efficiency [13].

Triple co-axial port inverse diffusion flames (TCP-IDF) have higher overall temperature distribution, lower soot and PAH this could be attributed to the fact that due to the center air injection, the fuel consumption occurs in both inner and outer flames, which also increases turbulence. On the other hand, for the double port burner (IDF), the oxygen is supplied from one side air, and as a result, providing more mixing and turbulence, the fuel consumption rate is relatively lower. Hence, by the center air injection, the fuel consumption is largely accelerated, resulting in the reduction of PAH and soot, this could be identified by the shorter and wider flame length of triple flame when compared to IDF under the same conditions [8].

Several studies have been reported on the performance and emission characteristics of Inverse diffusion flame compared to normal diffusion flame and with the introduction of swirl on inverse diffusion flame,
These include studies dealing with the comparison of normal diffusion flame to inverse diffusion flame, Christopher R. Shaddix, Flame structure of steady and pulsed sooting inverse jet diffusion flames [1], indicated that inverse diffusion flame and soot concentrations are somewhat smaller than for the normal flames, Makel and Kennedy [2] have reported peak soot concentrations an order of magnitude lower in an IDF in comparison to an NDF.Stansel et al. [3,4] found reduced NOx emissions from a controlled-air burner that incorporates an inverse diffusion flame concept, Takagi et al. [5] reported that the maximum temperature of IDF was higher than the usual diffusion flame at different flame heights. Sidebotham and Glassman [6] investigated the soot formation characteristic of IDF under the effect of temperature, fuel structure and fuel concentration, and found that soot formation was lower in the IDF, other studies have been conducted to test the effect of implementing

swirl & turbulence to improve the properties of inverse diffusion flame even further, Vandsburger and Ding [7], found that triangular cross sections were have superior emission performance due to the small scale turbulence enhancement, , H.S. Zhen [9] studies reveled CO and NOx concentrations for the impinging swirling IDF are greatly lowered in comparison to non-swirling inverse diffusion flame , while other studies by V. Piffaut and S. Bonnafous [10,11];, were carried out on co-axial sharp corners' ports whose enhanced mixing features were reportedfor co-axial square jets where they had an experimental evidence of axis-switching for both the inner and outer jets. In this regard, straining the flow that concentrically surrounds the sharp corners' jet becomes a favorable feature to enrich researches on both premixed and non-premixed flames.

Yamamoto.et.al [8], compared the result of double port burner (IDF) to triple port burner (TCP-IDF), in terms of PAH and soot, the results were obtained using PAH–LIF (laser-induced fluorescence) and soot LII (laser-induced incandescence). The system of GC/MS was also used to obtain quantitative PAH concentration, benzene and naphthalene were used as fuel while fuel and air velocities have been modified.

It was reported through PAH measurements that are two peaks in the radial profiles. One corresponds to the PAH region of internal air and fuel, and the other corresponds to that of fuel and external air. Since two diffusion flames are formed in thetriple port burner, one at the inner air tube and one at the external air tube, two separate PAH and soot regions are observed. But, further away from the burner these two regions are merged. When radial distributions of PAH and soot are compared, there are two peaks in soot regions, with maximum PAH concentration existing between them. This has been explained by the fact that PAH is associated with soot formation predeceasing it, with PAH forming at an earlier stage than soot particle growth. Indeed, only PAH is detected near the fuel port.

When compared to IDF, TCP-IDF showed generally lower soot and PAH emissions, as a result of the enhanced, mixing between fuel and air of the triple flame, which is further augmented by the increase of air flow rate, this is evident form the shorter and wider flame appearance of the triple flame burner.

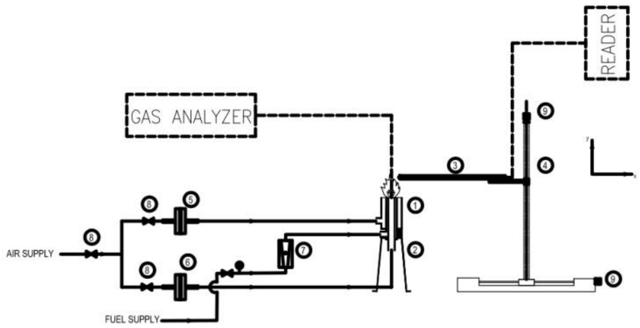
Accordingly, we have focused on a TCP-IDF burner, it has three concentric tubes, where air flows in both inner (central) and outer tubes and fuel flows in the annulus between air tubes (see Fig. (2)). Then, and the temperature and gas emissions on an fixed air to fuel ration of 27and a Reynolds's number of 8069for inner air tube and8045 for outer air tube respectively.

the same measurements have been conducted on the same air to fuel ratio of 27 with the introduction of a Swirler, 2mm Porous screens, 1mm porous screen, 45$^o$ flow divergence diffuser, 15$^o$ flow divergence diffuser & 65$^o$ flow divergence diffuser, Since the axis of symmetry lies in the oxidizer stream, rather than the fuel stream, the temperature decays more quickly in the fuel rich regions, which is confirmed in this study , It is expected that higher temperatureshall be recorded, in addition NOx emissions and soot formations shall be largely reduced as a result of introduction of swirl & turbulence.

## II. EXPERIMENTAL SETUP AND METHOD

Fig. (1) Shows the experimental setup for the triple co-axial ports inverse diffusion flametest rig, while the TCP-IDFburner is shown on Fig. (2). The burner is consisting of three concentric tubes, where air flows in both the inner (central) and the outer tubeswhile the fuel flows in the annulus between the air tubes, i.e. the intermediate tube.The inner diameter of the inner air tube is 10mm, while the outer diameter of the fuel tube is 16.5mm as shown in Fig. (2), as a result the LPC fuel flow in the annulus distance of 2.5mm. The inner diameter of the outer air tube is 34 mm. The combustion air is supplied to the TCP-IDF burner by using a dual stage reciprocating air compressor rotating at 2800 rpm to produce a maximum air pressure of 7 bar. The air compressor is driven by 3 phase electric motor (7.5 Hp, 2800 rpm, 50 HZ). Air is forced to the TCP-IDF burner from a 1000 liter size compressor tank. The supplied air from the compressor air tank is passing through a pressure regulator supplying a constant pressure of 3 bar to the TCP-IDF. The air is supplied to the test rig by a hose 3 m long and 8 mm inner diameter hose, which connects the laboratory main air line and the test rig via 0.5 inch gate valve was fitted in the air line and connected with the hose as a shut-off valve, then the outlet of this valve is connected to flexible hose of 0.5m long & 8 mm internal diameter, supplying a Tee-connection, this connection is then fitted to feed two mass flow rate control valves with a size of 0.5 inch. each, each is later on connected to two orifice meters which are connected to two water type manometers, in order to measure the air flow rate for each air jet, which then are connected to two hoses, one with an internal dimension of 12mm providing air to the internal air jet and the other is supplying a hose with an internal diameter of 8mm providing air for the outer air jet of the burner.,

Gaseous fuel LPG, (analysis carried out by Misr Petroleum 60% $C_4H_{10}$ and 40% $C_3H_8$ by volume) was fed into the gas burner from a bottle at a gauge pressure of (5000 ±100) Pa, after passing through a pressure regulator valve fitted in the LPG bottle outlet. This regulator is used to keep the outlet fuel pressure at 30x10$^{-3}$ bar. The feeding fuel line is equipped with a calibrated pressure gauge, 60x10$^{-3}$ bar maximum pressure and placed after the pressure regulator valve which used to control the fuel flow rate. The fuel delivery line is connected to a calibrated fuel rotameter used to measure the fuel flow rate.

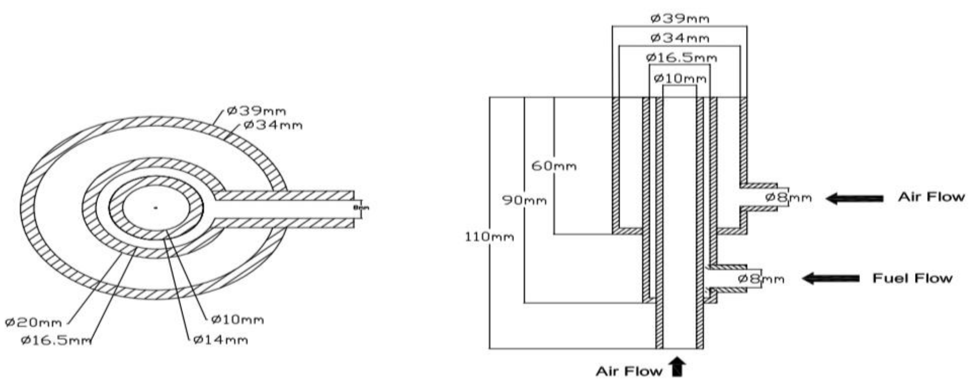



| | | | | | |
|---|---|---|---|---|---|
| 1 | BURNER | 4 | 2D POSITIONER | 7 | FUEL ROTAMETER |
| 2 | BURNER HOLDER | 5 | OUTER AIR ORIFICE METER | 8 | CONTROL VALVE |
| 3 | THERMOCOUPLE TYPE S | 6 | INNER AIR ORIFICE METER | 9 | STEPPER DIRECTIONERS |

Fig.(1). Parametric study of TCP-IDF test rig setup

The flow rates of the inner & outside air are adjusted, by the means of manually operated ball valves, in order to adjusting air to fuel ratio of at 27, for a fuel rate of 2 L/min. The flame temperature is measured by Type S (Pt-Pt Rh 10%) thermocouple,The thermocouple wires have a diameter of 0.25 mm and their joint is smaller than 0.5 mm in diameter, this size is small enough to reduce the error caused by thermal conduction but big enough to keep the thermocouple rigid, the thermocouple is connected to a reader with a digital display to record the flame temperatures as aided by corrections for convective and radiative heat transfer from the thermocouple bead, accordingly five vertical locations (two for the flow divergence diffusers) are selected measured from the center of the flame, at z= 0, 0.6 cm, 1.6 cm, 4.2 cm and 5.1cm, (at z= 4.2 cm and 5.1 cm for flow divergence nozzles) at each these five locations the point at which each temperature measured is varied axially giving 8 sets of reading at each vertical position, this is done for the non-swirling triple coaxial port inverse diffusion flame (TCP-IDF) as shown on fig (2), then the same burner was provided withaswirler as shown on fig (3), the swirler vanes are machined at an angle of $5^o$, where the distance between each vane is 5mm (center to center), then two porous screens were used respectively, one porous screen with mesh dimension of 3mm and the other with a mesh dimension of 1.5mm, finally three flow divergence diffusers were installed on the conventional inverse diffusion flame burner sequentially, $45^o$ flow divergence nozzle, $15^o$ divergence nozzles (fig (4)), then finally a $65^o$ flow divergence nozzle.

The appearance of the TCP-IDF under different operating conditions was obtained using a digital camera with 16 Mega pixels, 50 frames per second imaging rate. The position of the used camera relative to the flame position was the same during all shots in order to keep the height and size scales the same for all shots. To address the combustion efficiency and performance under different parametric effects, an electrochemical gas analyzer (Lancom III) is utilized to quantify CO, NOx and HC concentrations using a water-cooled steel probe with a tapered end, the gas emissions have been measured centrally at three vertical distances from the tip of the flame, y= 3cm, y= 5cm & y =9cm, this process has been repeated for each of the parameters listed and described above.



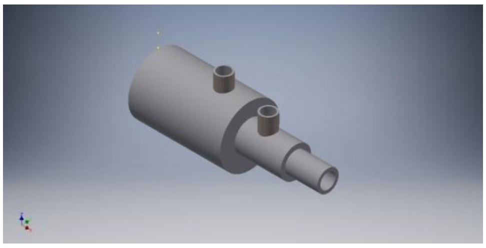


Fig. (2).TCP-IDF burner.

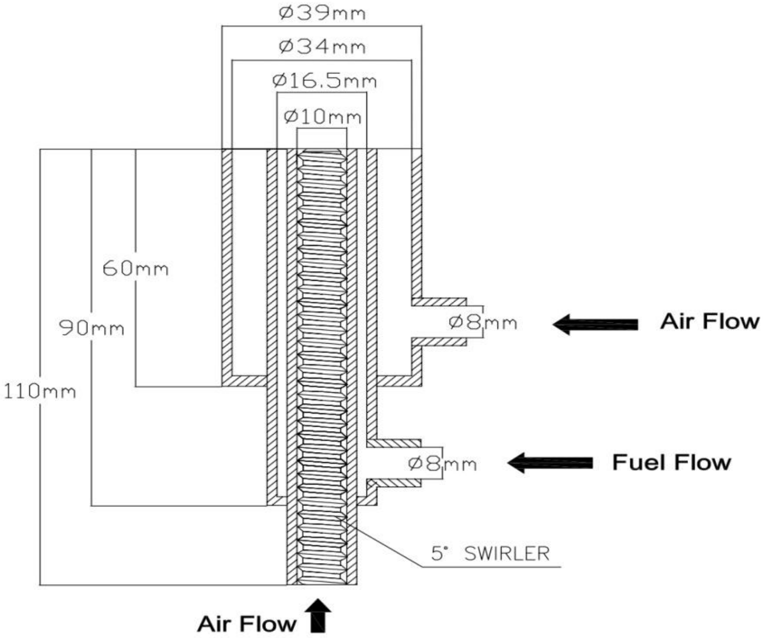



Fig. (3).Swirling TCP-IDF burner1.

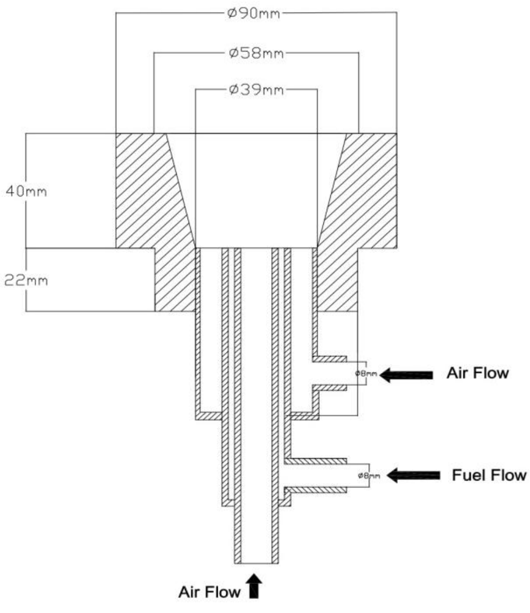



Fig. (4). TCP-IDF burner with 15°swirler.

## III. RESULTS AND DISCUSSION

***Flame shapes and color***

Flame photographs are used as an aid to illustrate and examine the different types of flames formed. The effect of the Swirling and non-swirling flame shape will be analyzed. Also, the effect of porous material will be investigated.Under the aforementioned experimental conditions figures(10), (11), (12), (13), (17) and (18) show the photographs of the TC-IDFs. The values of the air flow rate and its corresponding values of air flow rates (Qair ) and flame length are also shown in these figures. In this study, the flame length has a most commonly accepted definition which is the distance from the burner to the position on the centerline where the fuel and oxidizer are in stoichiometric proportions [28]. The flame lengths were obtained by visually averaging 10 images captured by a digital camera.For all parameters the inner tube airvelocity was fixed at 8.33m/s, with Reynolds number (Re. No.) of 8069, the outside tube air velocity was fixed at 8.84 m/s with Reynolds number of air8045, while the annular fuel velocity was fixed at 6.5 m/s, Fig (17) shows the appearance of the non-swirling TCP-IDF at these conditions, it is shown that for this case, it is shown that the flame is composed of two region, ay yellow luminous zone at the base of the flame, indicating a diffusion flame, while the tip of the flame is blue color, indicating a lean premixed flame, with a flame length of 12 cm, Fig (10) shows the appearance of the swirling TCP-IDF, it is observed that at the experiment conditions, it is shown that the flame is all blue with the flame is clearly wider with larger cross section and shorter than all other cases, with a flame length of 6cm this is the reason of the effect of swirl induced at the inner air tube, which causes recirculation of the reactants this recirculation is considered an important role inflame stabilization, because it provides a region wherethe burning speed and flow velocity are matched and it also circulates heat and active chemical species to the root of the flame for ignition of fresh reactants. Thus, for the swirling TCP-IDF, a highly stable flameis observed than non-Swirling TCP-IDF, Fig. (11) Shows the flame shape and color of TCP-IDF with 2mm porous screen, with the same length (12 cm) and cross section as the non-swirling TCP-UDF, however it is observed that the luminous yellow zone at the base of the flame is of lower size, while there is an another yellow zone at the tip of the flame, while in between the flame is blue in color indicating a more premixed flame, in lieu of the diffusion flame at the base and tip of the flame, this is because the slots of the porous screen causes a back fire that reduces the rate of reaction and decreasing the temperature of the flame, Fig (18) shows the flame shape and structure of the TCP-IDF with 1mm porous screen, the flame shape and length is the similar to TCP-IDF with 2mm porous screen, however the yellow luminous zone is much larger, comprising5cm of the 12cm flame length, this is the cause of the intensified backfire as result of the smaller 1mm slots., fig. (12) & (13). Shows TCP with 15$^{o}$ and 45$^{o}$ diffusers respectively, the flame length is 7cm for both cases, with the flame being wide with the same radial length of each diffuser, it is noted that the flame for both cases is blue,indicating a more premixed flame characteristics as a result of the wakes and eddies formed by the divergence of the diffuser, these eddies recirculates both the inner and outer air flow rates, in addition to the fuel, however it is noted that the flame of the 15$^{o}$ diffuser is more stable and intense than the 45$^{o}$ diffuser this is attributed to the fact that the wakes and eddies are close to the edge of the diffuser, for the 15$^{o}$ diffuser these areas are closer to each other than in the case of the much wider 45$^{o}$ diffuser, yielding a higher recirculation enhancing the mixing of reactantsand improving the characteristics of the combustion process.

***Thermal analysis***

Additional insight into inverse diffusion flame nature can be ascertained from temperature profiles. Fig.(5) showsradial temperature distributions for the non-swirling TCP-IDF, swirling TCP-IDF with swirl angle of 5$^{o}$, with 2mm mesh porous screen burnerand1 mm mesh porous screen burner. These radial temperature profile are conducted fromthe burner centerlineto a radial distance R= 1.9cm at the burner tip. At radial distance R=0 cm the flame temperature is low for all types of flames used in this investigation expect the swirled one. The flame temperature for the base burner used in this investigation, non-swirled TCP-IDF burner, was 171$^{o}$Cwhile it was 112 $^{o}$C,158$^{o}$C, 877$^{o}$C for TCP-IDF with porous material 1mm, porous material with 2 mm and swirled TCP-IDF respectively as shown in Fig (5). This is because the rate of mixing in swirled burner is very fast than that by any other burner. The high shear between the air jet velocity and the intermediate fuel coaxial jet increase the rate of air fuel entrainment as well as the inner core temperature is high[12], this shearing results in significant entrainment into the inner tube. Therefore, faster momentum transfer takes place between the jet and its surrounding stream for acquiring more intensified mixing, which is close to the center of the burner. the On the other hand this figure shows that the highest flame temperature values for the swirled TCP-IDF is very close to the burner centerline at radial distance R= 0.35 cm with a value of 1169$^{o}$C while it was at 0.7, 0.68 and 1.1 cm for non-swirled TCP-IDF and with porous material 2 mm, and porous material with 1 mm respectively with temperature values of 985$^{o}$C, 693oC and 540$^{o}$Crespectively. However for the non-swirling TCP-IDF as the radial distance from the centerline increases beyond 0.55cmthe temperature of the flame decreases, this is expected since the entrainment effect of the central tube so close to the burner vertically attracts much fuel to this tube than any other region of the studied boundaries causing the combustion process to be mostly located at this distance, this is shown form the start of decrease in the temperature of the TCPat this radial distance recording a temperature of 860°C, which is the temperature of the non-swirling TCP-IDF, beyond this radial distance and up to "R" of 0.7 cm the swirling TCP-IDF temperature continues to drop while the non-swirling TCP-IDF increases peaking at this location with a value of 985°C where air entrains the most amount of fuel, while for the 1mm & 2mm porous screens their temperature increases, however the 2mm screen exhibits a similar temperature profile behavior peaking at a radial distance of 0.65cm close to that of the non-swirling IDF with a temperature of 693°C, the 1mm screen temperature continues to increase, this could be related to the fact that the excessive mixing form the smaller slots of the 1mm screen causes the fuel to entrain at a further distance from the burner center where higher flow rate of turbulent air is available. After a radial distance of 1.1 cm the temperatures of all parameters starts to decrease, however it is worth mentioning thatthetemperatureprofile of the swirling TCP-IDF is always higher than that of the 1m & 2m porous screens, despite of being lower than that of non-swirling IDF as a result of almost completing the combustion at radial distance range of 0-0.55cm, where the lowest temperaturefor all parameters is at 1.9cm, with values of 614°C, 577°C, 549°C &322°C for non-swirling TCP-IDF, swirling TCP-IDF, 2mm porous screen and 1mm porous screen respectively,the decrease of the temperatures of the porous screens could be attributed to back fire that prevents the complete combustion of fuel, which is shown by the low values of average temperatures of the 1mm screen recording the lowest temperatures comparedfor all parameterstemperatures compared to other cases.The flame lengthand

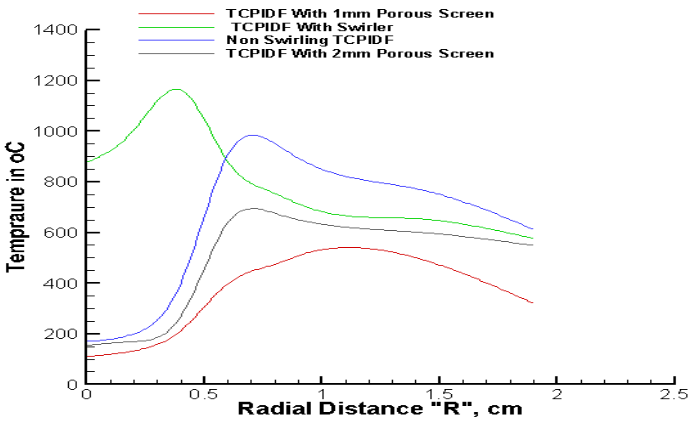



Fig. (5). Temperature analysis of different types of TCP-IDFat the tipof the burner (Z = 0) with varied radial distances.

Comparing the same radial distances discussed above, but at a higher vertical distance of 0.6cm, as shown on Fig.(6),it is clear thatAt radial distance R=0 cm the flame temperature also is low for all types of flames used in this investigation expect the swirled one recording a temperature of 580°C. The flame temperature for other parameters used in this investigation, non-swirled TCP-IDF burner, was 179°C while it was 145°C, 158°C, 179°C for TCP-IDF with porous material 1 mm, porous material with 2 mm and non-swirled TCP-IDF respectively. This is because the rate increase the rate of air fuel entrainment as discussed above, it also noted that the peak temperature values for this vertical position is at a further radial distance in comparison to that of the vertical position at the tip of the flame for all parameters, however at this vertical distance the peak value of the swirling TCP-IDF shows the most significant shift of the peak temperature value in terms of radial distance at a radial distance of 0.97 cm with a temperature of 1106°C,in lieu of 0.35cm for the measuring the peak temperatureat the tip of the flame, this shift on the peak radial position from the previously discussed vertical distance at the tip of the flame is due to the decrease of the effect of the swirling of the inner air which reduces air entrainment causing this shift away from the center of the burner. the highest flame temperature values was at 1.2, 1.33 and 1.4 cm for non-swirled TCP-IDF and with porous material 2 mm, and porous material with 1 mm respectively with temperature values of 1096°C, 1008°C and 921°C respectively,it is also worth noting that although the non-swirling TCP-IDF peaks at a shorter radial distance its temperature remains higher than other parameters (0.97cm) its temperature value is never lower than other parameters, when compared at the same radial position, where a the peak temperature value of the non-swirling TCP IDF at a radial distance 1.2cm with a recorded temperature of 1096°C, swirled TCP-IDF and with porous material 2 mm, and porous material with 1 mm respectively are with temperature values of 1189°C, 994°C and 882°C respectively, while at maximum temperature value of 2mm porous material which is 1009°Cswirled TCP-IDF and non-swirled TCP-IDFand with porous material 1 mm, respectively are with temperature values of 1163°C, 1087°C and 916°C respectively,as for the peak temperature for the 1mm porous material occurring at "R" of 1.4cm and a temperature of 921°C, swirled TCP-IDF and non-swirled TCP-IDF and with porous material 2 mm, respectively are with temperature values of 1150°C, 1075°C and 1006°C respectively,this is attributed to the desirable effect of swirling, which causes formation of a toroidal recirculation zone which allows flame stabilization to occur in regions of relative low velocity where the flow velocity and the flame speed can be matched, aided by the recirculation of heat and active chemical species [26]and because of the decreased effect of air entrainment at the inner air tube the combustion is not concentrated on this inner tube but rather is more radially distributed, as shown form the temperature profile of the TCP-IDF at this vertical position when compared to the same temperature profile at the tip of the flame. While the temperature profiles of the 2mm & 1mm porous screens continues to exhibit lower temperatures than the swirling an non-swirling TCP-IDF respectively, with the 1mm exhibiting the lowest temperatures of all parameters, as a result of the backfire discussed above, with the lowest temperature for all parameters occurring at a radial distance of 1.9 cm, with values of 811°C, 1049°C, 792°C &760°C for non-swirling TCP-IDF, swirling TCP-IDF, 2mm porous screen and 1mm porous screen respectively.

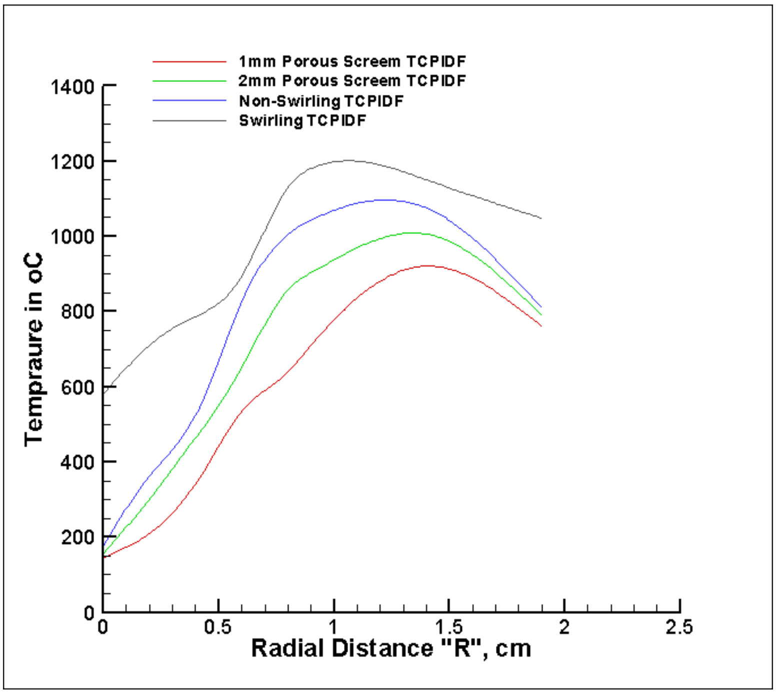



Fig. (6). Temperature analysis of different Parameters of TCP-IDFat Z = 0.6cm from the burner tip,with varied radial distances.

When studying the same parameters at a higher vertical distance of 1.6 cm, Fig (7). we find that the results are quite similar to the case of vertical distance of 0.6 cm discussed above, it is demonstrated that At radial distance R=0 cm the flame temperature of the swirled one remains the highest, however the gap between its temperature and other parameters is quite less,whereswirled one recording a temperature of 533°C. The flame temperature for other parameters used in this investigation was 237°C, 307°C, and 455°Cfor TCP-IDF with porous material 1 mm, porous material with 2 mm and non-swirled TCP-IDF respectively. This decrease of the temperature difference of the TCP-IDF at R=0, when compared to previously disused axial distances, is due to the swirling effect which causes recirculation and more uniform temperature distribution [9] of the TCP-IDF, it also noted that the peak temperature values for this vertical position is at a further radial distance from the burner center in comparison to that of the vertical position at the tip of the flame and at vertical distance of 0.6 cm for all parameters.As discussed above, due to the decrease of the effect of the inner air entrainment, the highest flame temperature values was at 1.07, 1.25 and 1.9 cm forswirled TCP-IDF, non-swirled TCP-IDF and with porous material 2 mm, and porous material with 1 mm respectively, with temperature values of 1170°C, 1053°C, 1011 and 933°C respectively., it is shown that when examining the cases with 2mm & 1mm porous screens beyond "R" of 1.25cm, their temperature values remains to increase, peaking at a radial distance of 1.9cm, this again shows the decrease of the effect of the inner air entrainment of fuel as the vertical distance increases,however this increase shift for the porous screens is as a result of the mixing and turbulence caused by the small slots of the screens, which is much more at the larger outer air tube with higher air flow rate, causing more fuel to be entrained to the outer side of the fuel as a result of the shear caused by the difference of the momentum between the outer air whit larger flow rate and that of the fuel flow rate at the edge of the burner, while the temperature value of the swirling and non-swirling TCP-IDF decreases for the same radial distance,it is again noted that although the non-swirling TCP-IDF peaks at a shorter radial distance its temperature remains higher than other parameters (1.25cm) its temperature value is remainshigher than other parameters, when compared at the same radial position, where a the peak temperature value of the non-swirling TCP IDF at a radial distance 1.25cm with a recorded temperature of 1052°C, swirled TCP-IDF and with porous material 2 mm, and porous material with 1 mm respectively are with temperature values of 1147°C, 947°C and 886°C respectively, while "R" 1.9is where maximum temperature value for1 &2mm porous materials which is 933°C and1011°C respectively, swirled TCP-IDF and non-swirled TCP-IDF, respectively are with temperature values of 1023°C, 836°C respectively, the temperature profiles of the 2mm & 1mm porous screens continues to exhibit lower temperatures than the swirling an non-swirling TCP-IDF respectively, with the 1mm exhibiting the lowest temperatures of all parameters, as a result of the backfire discussed above, however this is somewhat improved as a result from the improvement of the turbulence and hence the mixing properties for this region and the reduced effect of back fire which is shown at a radial distance of 1.9 cm, with the porous screens recording higher temperatures than non-swirling TCP-IDF with values of 863°C, 1023°C, 1011°C &933°C for non-swirling TCP-IDF, swirling TCP-IDF, 2mm porous screen and 1mm porous screen respectively,

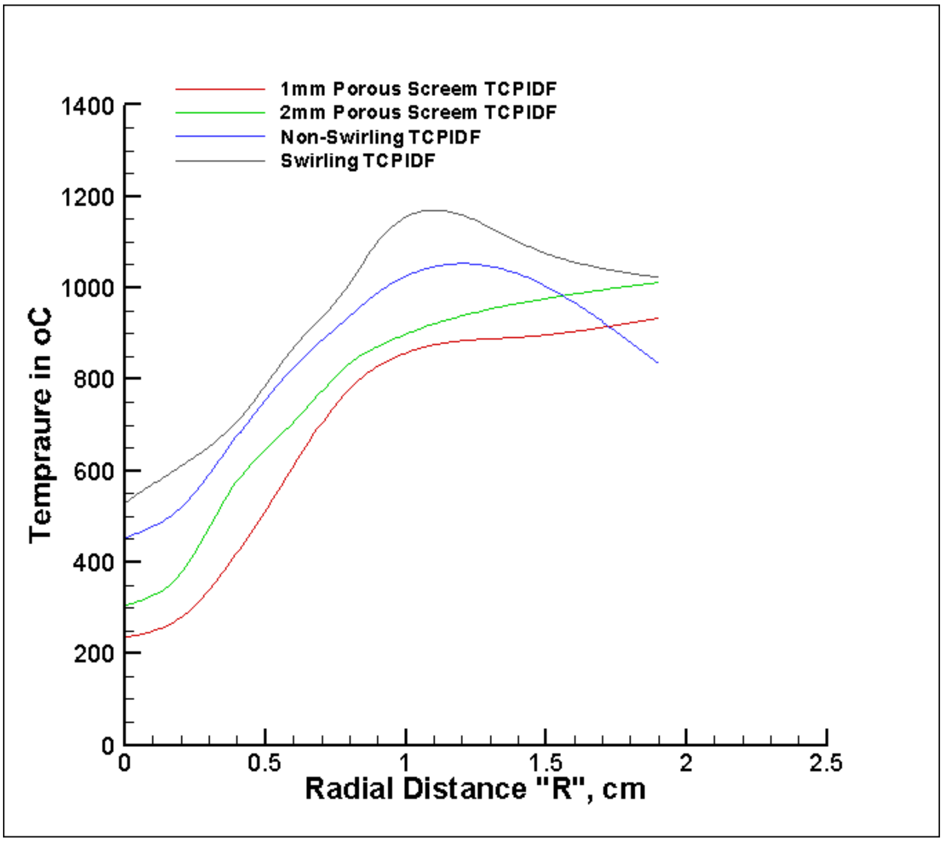



Fig. (7). Temperature analysis of different Parameters of TCP-IDFat Z =1.6cm from the burner tip,with varied radial distances.

Fig. (10). Swirling TCP-IDFFig. (11). TCP-IDFwith 2mm porous screen
At A/F ratio = 27 and Re inner air = 8069, AtA/Fratio= 27 and Re innerair =8069

Re outer air = 8045, Re outer air = 8045.

Fig. (17). Non- Swirling TCP-IDFFig. (18). TCP-IDFwith 1mm porous screen
At A/Fratio= 27 and Re inner air = 8069 At A/Fratio= 27and Re inner air =8069
Re outer air = 8045, Re outer air = 8045.

Studying the same parameters at a higher vertical distance of 4.2 cm (tip of the diffusers), as shown on Fig (8) and at this vertical distance of we start to examine the effect of applying 65°, 45° and 15° diffusers to TCP-IDF, in addition to studying swirling TCP-IDF and TCP with 2mm & 1mm mesh porous screens,
As shown at radial distance R=0, the TCP-IDF with15° diffuser indicates the highest temperature of 850°C, followed by the TCP-IDF with 45° diffuser, the non-swirling TCP-IDF, the 2mm porous screen, then the 1mm porous screen and finally the lowest temperature was that of the swirling TCP-IDF, with temperature values of 689°C, 552°C, 493°C, 466°C& 421°C respectively, the temperature of the 45° diffuser and 15° diffuser continues to increase as the radial distance increase, peaking at radial distance "R" of 2.4cm, with values of 929°C&1393°C respectively, the high temperature value recorded for these distributed is due to the eddies & wakes [16]formed as a result of flow divergence from the geometry of the diffuser these wakes causing high momentum exchange between the two co-flowing stream improving mixing [15] and thus ameliorate fuel entrainment, high turbulent energy which is cascaded down into a wide span of small scale vortices whereby dissipation occurs around corners with high Reynolds stresses, the production of stream wise vorticity alters entrainment and species mixing according to the inlet geometry [16,17]which leads to high temperatures than when using the swirler and other parameters, this is due to the improved mixing of the air of both the interior and exterior air tubes unlike with the swirler which only improves the mixing of the interior air tube results, however the 15° diffuser shows much higher temperature than the 45 ° diffuser, this is because excessive eddies resulting from lower diffuser angles causes cooling of air/fuel mixture, during the process of additional expansion of the flame [9], moreover the compact flame, of the 15° diffuser, associates with the most intensive combustion [8], which leads to higher temperature, meanwhile, it is shown that the maximum temperatures occurs near the edge of the diffusers as a result of the existence of those wakes and eddies at this location which entrains more fuel, as for the non-swirling TCP-IDF, it is examined that its temperature peaks at "R" of1.36 with a temperature value of 677°C,whilethe 15° diffuser, 45° diffuser, 2mm porous material, 1mm porous material and the swirling TCP-IDF temperatures at this radial distance are 1117°C, 878°C, 616°C, 590°C, 600°C respectively, while "R" 1.9 is where maximum temperature value for1 &2mm porous materials which is 633°C and 601°C respectively,15° diffuser and 45° diffuser, non-swirled TCP-IDF and swirled TCP-IDF, respectively are with temperature values of 1275°C, 881°C and631°C, while there is no temperature could be recorded for the Swirling TCP-IDF at this radial position,the swirling TCP-IDF, indicates its maximum temperature at "R" of 1.4 with a temperature value of 605°C, while the 15° diffuser, 45° diffuser, 2mm porous material, 1mm porous material and the swirling TCP- IDF temperatures at this radial distance are 1115°C, 876°C, 614°C, 588°C, 672°C respectively, it is shown that the peak temperature values of the swirling and non-swirling TCP-IDF are recorded at similar radial positions, indicating that the swirl is of no marginal effect, since no air is entrained to the inner air tube, the non-swirling TCP-IDF demonstrates the lowest recorded temperature profile, with lowest recorded temperature for all parameters at "R"=0 , with it values shown above, this low temperature is attributed to the fact that the combustion process is almost complete for the TCP-IDF, when compared to other parameters, which is demonstrated by the

Short flame length of TCP-IDF of only 6cm, while the non-swirling TCP-IDF, 2mm porous screen& 1mm porous screen recorded a flame length of 12cm, while the 15°& 45° diffusers measured a flame length of 11cm, when measured from the same datum of the swirling TCP-IDF, this short flame length is caused by swirling which form and internal reaction zone (IRZ),IRZ drives the transport of momentum, energy and mass. On the outer side, there also exists a shear layer between the exiting jet and ambient
air, where the jet entrains and mixes with ambient air. With an increase
in the axial distance from the nozzle exit, the annular region expands in thickness as the entrained ambient air increases the overall mass flow rate in the jet. Therefore, the gradients in temperature and species concentration become smaller with elevation [19].

It is noted that the flame 65° diffuser is so unstable at the experimental conditions that it blows off, this is because of the excessive turbulence wakes and eddies at this diffuser which causes a cooling process that is so excessive that the flame was highly unstable as a result of the extreme expansion of the flame [13],extinguishingit.

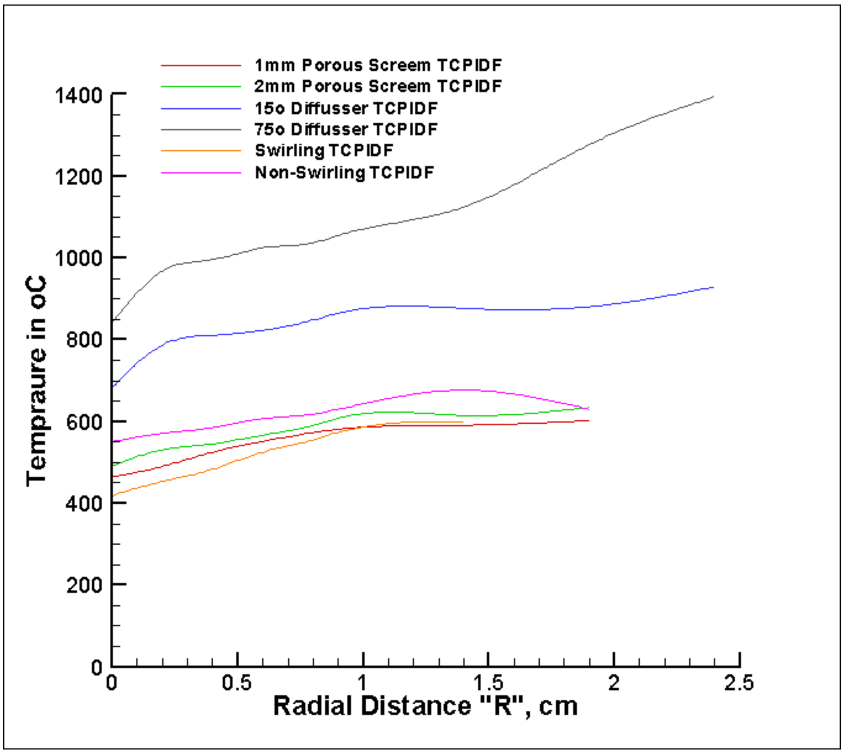



Fig. (8). Temperature analysis of different Parameters of TCP-IDFat the tip of the diffusers(atZ = 4.2cm from the burner tip) with varied radial distances.

Fig. (9) shows the same parameters at a higher vertical distance of 5.1 cm As shown at radial distance R=0, the TCP-IDF with 15° diffuser also indicates the highest temperature with a value of568°C, followed by the TCP-IDF with 45° diffuser, the non-swirling TCP-IDF, the 2mm porous screen, then the 1mm porous screen and finally the lowest temperature was that of the swirling TCP-IDF, with temperature values of 509°C, 465°C, 405°C, 356°C&304°C respectively, the temperature of the 45° diffuser and 15°diffuser continues to increase as the radial distance increase, peaking again at radial distance "R" of 2.4cm, with values of 697°C& 1284°C respectively, the high temperature value recorded for these distributed is due to the eddies & wakes as discussed above, the 15° diffuser continues shows much higher temperature than the 45° diffuser, for the same previously mentioned reason, meanwhile it is examined that themaximum temperature of for non-swirling TCP-IDF,1 &2mm porous materials occurs at 'R' of 1.9cm, whichare591°C,517°Cand 509°Crespectively,while at this radial distance the temperaturesare 1208°C and 662°C, respectively, for15° diffuser and 45° diffuser., it is noted that no temperature could be recorded for the Swirling TCP-IDF at this radial position, the swirlingTCP-IDF, indicates a peak temperature at "R" of 1.4 with a temperature value of 482°C, while the 15° diffuser, 45° diffuser, 2mm porous material, 1mm porous material and the swirling TCP- IDF temperatures at this radial distance are 1087°C, 635°C, 580°C, 522°C, 501°C respectively, it is shown that the peak temperature values of the non-swirling TCP-IDF is recorded at a radial position which is further than the peak temperature of the swirling TCP-IDF by 0.4 cm, indicating that reduction of the effect of the inner tube air entrainment with the lower flow rate.The non-swirling TCP-IDF demonstrates the lowest recorded temperature profile, with lowest recorded temperature for all parameters at”R”=0 , with it values shown above, this low temperature is attributed to the fact that the combustion process is almost complete for the TCP-IDF, when compared to other parameters, which is shown by the Shorter flame length of TCP-IDF when compared to other parameters as a result of the swirl that has been discussed earlier.

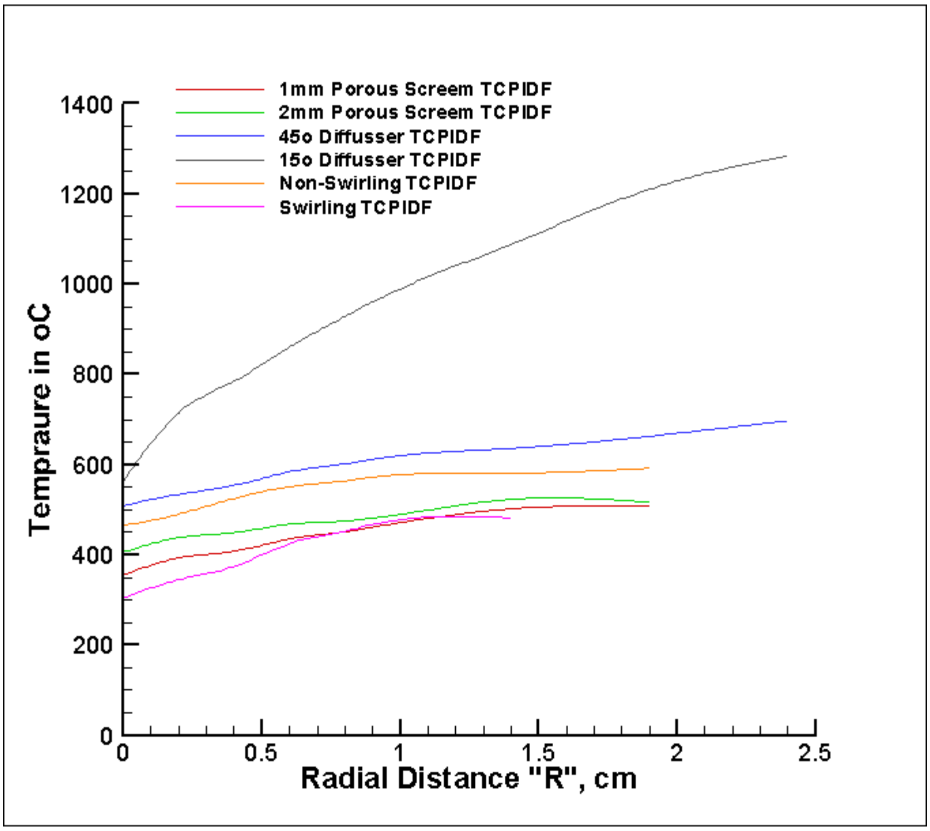



Fig. (9). Temperature analysis of different Parameters of TCP-IDFat the tip of the diffusers (at Z = 5.1cm from the burner tip) with varied radial distances

Fig. (12). TCP-IDFwithFig. (13). TCP-IDFwith
$15^{o}$ diffuser  at A/F ratio = 27, $45^{o}$ diffuser at A/F ratio = 27
Re inner air = 8069 and Re inner air = 8069,
Re outer air = 8045, Re outer air = 8045.

***Gas emissions analysis***

The below figures (14, 15 &16) indicates the CO &NOx emissions and the unburned hydrocarbons respectively, the $15^{o}$diffuser with TCP-IDF indicates the lowest CO emissions, followed by the $45^{o}$ diffuser with TCP-IDF, the swirling TCP-IDF,the non-swirling TCP-IDF, then the 2mm porous screen and the 1mm porous screen, while the 2mm porous screen demonstrates a high rate of CO emissions reduction as result of the improved mixing caused by the porous materials slots, that outweighs the backfire effect of the slots this rate is higher than that of the 1mm porous screen because the smaller slots increases the rate of back fire, which hinders the combustion process, as the vertical elevation increases beyond 5cm, it is noted for all parameters that the 2mm porous screen with TCP-IDF and finally the 1mm porous screen with TCP-IDFat a vertical distance “Z” of 3cmfrom the flame tip of each parameter, recording concentrations of 208, 480, 647, 1105, 2181 and 2309 ppmrespectively for the 15$^o$ diffuser with TCP-IDF, 45$^o$ diffuser with TCP-IDF,the swirling TCP-IDF, the non-swirling TCP-IDF, then the 2mm porous screen with TCP-IDF and finally the 1mm porous screen with TCP-IDF,the 15$^o$ diffuser records the lowest value for CO emissions for all parameters becausethe high recorded temperature of the 15$^o$ diffuser indicates that combustion is very intense, causing the CO to be more easily oxidized to be CO2 provided enough oxygen is available[18]., thus It is observed that the CO2 and temperature profiles are similar to each other, because as fuel is converted into CO2, the heat release increases the gas temperature [19],accordingly the parameters with the highest CO emissions is corresponded with having the lowest temperatures as indicated.CO emissions generally drops as we vertically depart from the center of the flame, however it is noticed that the rate of co emissions drops more steeply for the swirling TCP-IDF and the 2mm porous screen, where the swirling TCP-IDF starts to be the parameter with the second lowest CO emissions, after a verticaldistance of 5cm from the flame tip of each parameter, the CO emissions at a vertical distance of 5.5cm for all parameters is 106, 273, 315, 840, 1429 and 1880 ppm respectively for the 15$^o$ diffuser with TCP-IDF, the swirling TCP-IDF, 45$^o$ diffuser with TCP-IDF, the non-swirling TCP-IDF, then the 2mm porous screen with TCP-IDF and finally the 1mm porous screen with TCP-IDF, this is the result of the effect of swirl whereat this vertical distance the combustion process for the swirling TCP-IDF is almost complete, which is shown by the short flame length (6 cm), while other parameters experience longer flame lengths (7 cm for the 15$^o$ diffuser and 45$^o$ diffuser The CO peak is not observed at higherelevations, indicating that there is progressive combustion as theair/fuel mixture flows upwards, [19], and as a result of beyond the flame boundary zone due to dilution by entrained ambient air, where the lowest CO emissions is recorded at a vertical distance of 9cm, with values of 78, 106, 241, 574, 932 and 1342 forthe 15$^o$ diffuser with TCP-IDF, the swirling TCP-IDF, 45$^o$ diffuser with TCP-IDF, the non-swirling TCP-IDF, the 2mm porous screen with TCP-IDF and the 1mm porous screen with TCP-IDF, respectively.

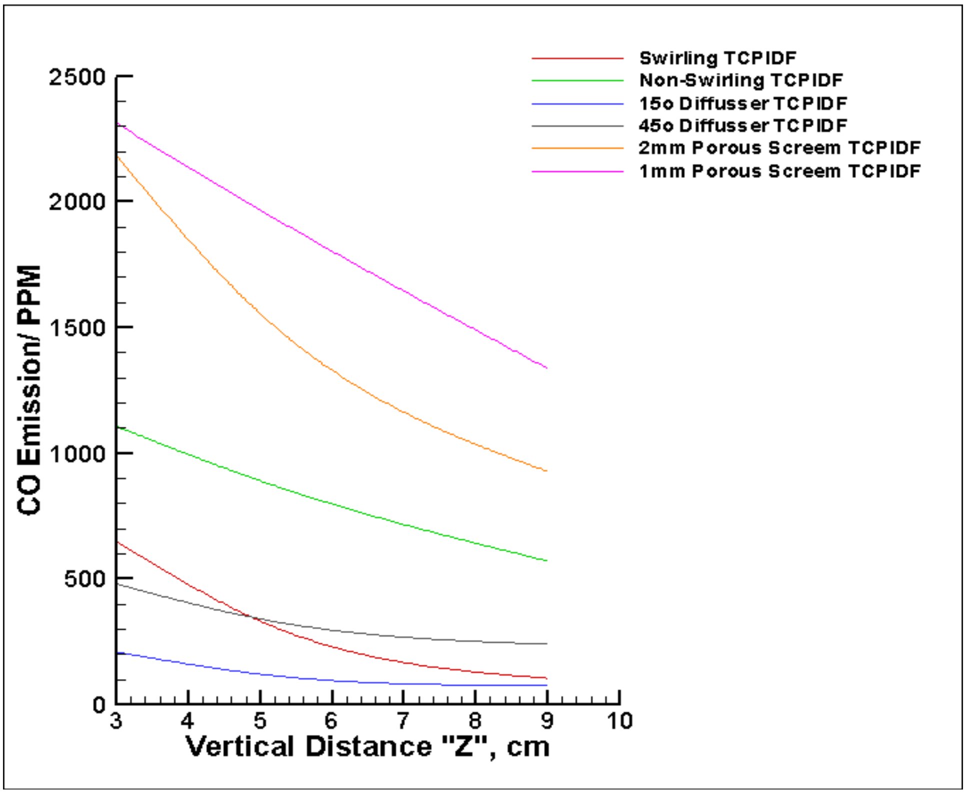



Fig. (14). Effects of TCP-IDFon CO emissions

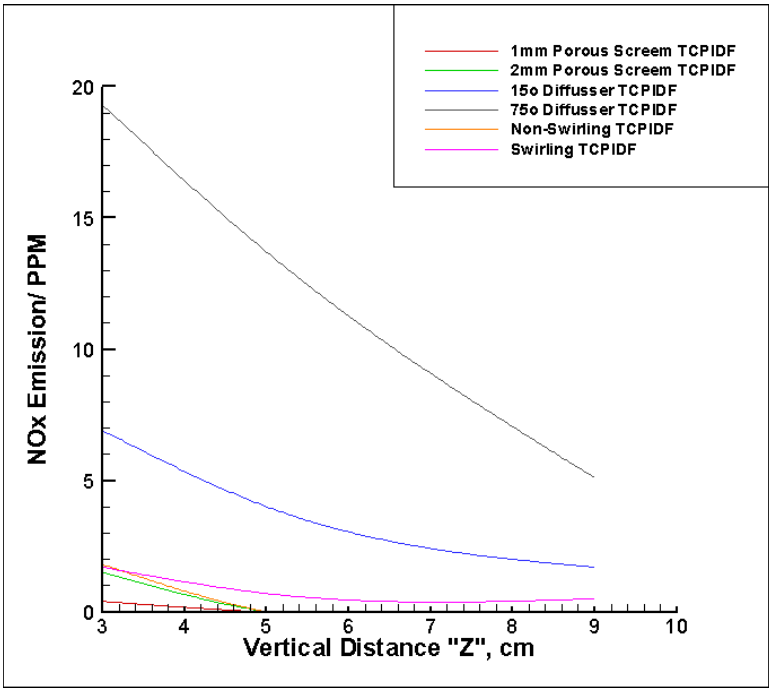



Fig. (15). Effects of Parameters of TCP-IDFon NOx emissions

Fig. (15) Represents the NOx emissions for each parameter, at z=3cm, the maximumrecorded NOxis for the 15$^{o}$diffuser, then the 45$^{o}$ diffuser, Non swirling TCP-IDF, 2mm porous screen, swirling TCP-IDF and finally the 1mm porous scree, with values of 19.2, 6.9, 1.7, 1.4, 0.5 and 0.9 ppm respectively, it is clear that NOx formation is dependent on the increase in temperature, since the highest NOx concentration is recorded for the 15$^{o}$ diffuser which represented the highest recorded temperatures at the center of the burner radially, this is because at high temperatures NOx as a result of the wakes and eddies formed by the diffusers which recirculates heat and reactants, while the swirling TCP-IDFhigher NOx are developed for the higher temperatures caused by the enhanced mixing by swirl which favors the NOx formation[20], while the non-swirling TCP-IDF flame, 2mm porous screen and 1mm porous screen, shows the lowest NOx concentrations respectively as a result of recording lower temperatures.As the vertical distance increases, combustion is more complete, moreover the ambient air starts to dilute the NOX and cools the exhaust gases hindering the formation NOxformation, the lowest NOx concentrations for all parameters is reached at a vertical distance 9cm,measuring, zeroppm for 1mm porous screen, 2mm porous screen and non-swirling TCP-IDF, while recording 0.5, 1.7 and 5.12 ppm for theswirling TCP-IDF45$^{o}$diffuser and the 15$^{o}$ diffuser, respectively.Fig. (16)., indicates the effect of various parameters on TCP-IDF, on the emission hydrocarbons, the profiles for all parameters corresponds to that of the CO emissions profile for the same reasons, except for the swirling TCP-IDF, at vertical distance of 3cm the lowest percentage is for that of the 15$^{o}$ diffuser with TCP-IDF, the swirling TCP-IDF, 45$^{o}$ diffuser with TCP-IDF, the non-swirling TCP-IDF, then the 2mm porous screen with TCP-IDF and finally the 1mm porous screen with TCP-IDF with percentages of 11.05, 13.5, 20.9, 25, 36.5 and 47.2%, respectively, however as the vertical distance “Z” increases at Z= 4 cm, the unburned hydrocarbons percentage of the swirling TCP-IDF decreases at a more drastic rate than the rate of decrease of other parameters, recording a percentage of 9.3%, while the 15$^{o}$ diffuser records 9.7 %, this the reason of the swirling which causes the recirculation and mixing of reactants, that causes a shorter flame length that indicates the conclusion of combustion at this much shorter flame length (6cm), while the flame length of the 15$^{o}$ is 7cm, thus this leads to reduction of unburned hydrocarbons percentages at a reduced vertical distance “Z” than the other parameters, this continuous to be the behavior up to the maximum measured vertical distance of 9cm where the unburned hydrocarbons percentages are, 1.1, 6.2, 14.9, 20.6, 20.8 and 24.7% respectively forthe swirling TCP-IDF,15$^{o}$ diffuser with TCP-IDF,45$^{o}$ diffuser with TCP-IDF, the non-swirling TCP-IDF, the 2mm porous screen with TCP-IDF and finally the 1mm porous screen with TCP-IDF.

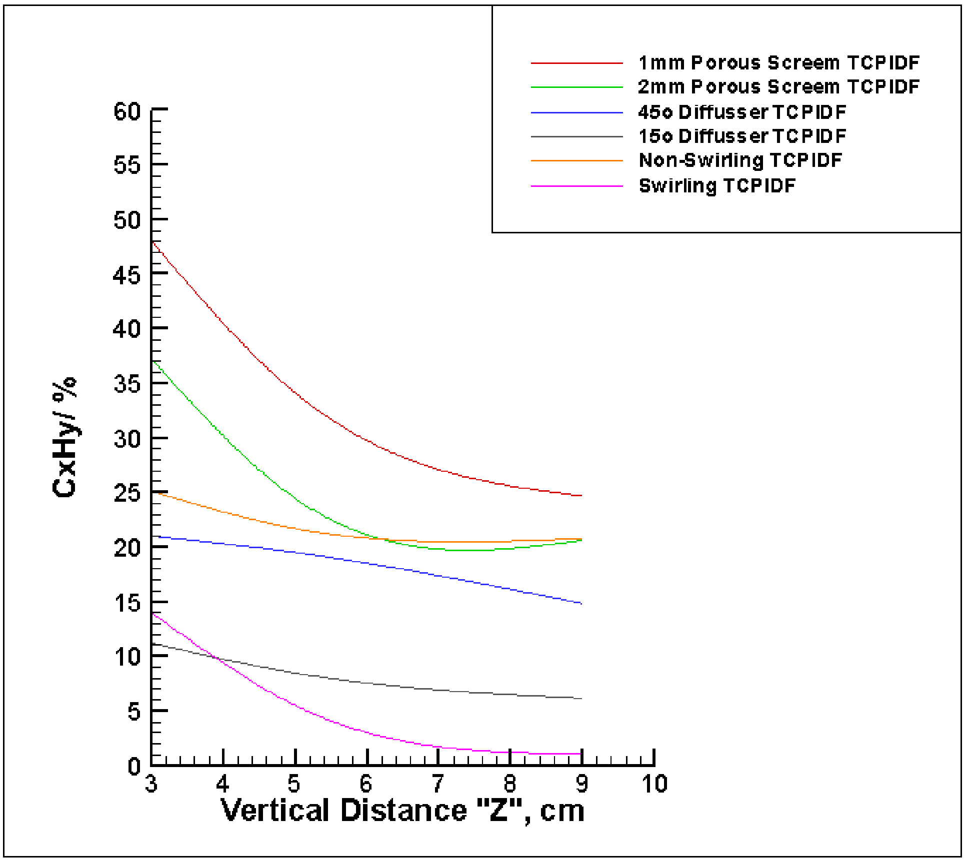



Fig. (16). Effects of Parameters of TCP-IDFon unburned hydrocarbons percentage

## IV. CONCLUSION

An TCP-IDF burner was designed, in order to compare conventional IDF with other parameters, a swirler, 45 $^{o}$diffuser, 15$^{o}$diffuser, 65$^{o}$diffuser, 2mm wide mesh porous screen and2mm wide mesh porous screen have been utilized respectively &separately, the thermal and gas emissions

Performance of these parameters have been studied under identical working conditions, the study showed the highest temperature on average have been recorded in the subsequent order, the 15$^{o}$diffuse, then the 45 $^{o}$ diffuser, the swirling TCP-IDF, the non-swirlingTCP-IDF, the 1mm wide mesh porous screen ,2mm wide mesh porous screen and finally the 65$^{o}$diffuser flame was unstable and could not be recorded.

as far as the NOx emissions the highest recorded emissions have been for the 15$^{o}$diffuser, then the 45 $^{o}$ diffuser, theswirler, the 2mm wide mesh porous screen, the non-swirling TCP-IDF and finally the least NOx emissions have been recorded for the1mm wide mesh porous screen.

While for the CO emissions the highest recorded emissions have been recorded for the1mm wide mesh porous screen, thenthe 2mm wide mesh porous screen, the non-swirling TCP-IDF, the 45 $^{o}$ diffuser thenthe swirling TCP-IDF, and at last the lowest CO emissions have been recorded for the 15$^{o}$ diffuser.

Finally when observing the unburned hydrocarbons emissions it is noted that the highest unburned hydrocarbons emissions have been shown to be for the

1mm wide mesh porous screen, then the 2mm wide mesh porous screen, the non-swirling TCP-IDF, the 45 $^{o}$ diffuser, then, the 15$^{o}$ diffuser, and finally the lowestunburned hydrocarbons emissions percentages have been recorded for the swirling TCP-IDF

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