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ВЛИЯНИЕ РАСПРЕДЕЛЕНИЯ ГОРЕЛОК НА ХАРАКТЕРИСТИКИ ГОРЕНИЯ И ВЫБРОСЫ ОКСИДОВ АЗОТА В КАМЕРЕ СГОРАНИЯ ПАРОГЕНЕРАТОРА, ИСПОЛЬЗУЮЩЕГО ПРИРОДНЫЙ ГАЗ ПРИ ЧАСТИЧНОЙ НАГРУЗКЕ

Аннотация: *В этой статье с использованием кода Ansys Fluent для моделирования процессов горения было выполнено вычислительное гидродинамическое (CFD) моделирование горения природного газа в камере сгорания парогенератора с вихревыми горелками, расположенными на стенке камеры сгорания, при пяти различных схемах сгорания при частичной нагрузке. Модель была использована для изучения влияния распределения горелок на параметры камеры сгорания, которые включают распределение температуры и концентрации (*CO_2, CO, NO_x*) в камере сгорания.*

Исследование показало, что размещение горелок на более низком уровне привело к лучшей теплоотдачи к трубам испарителя, в результате чего снизилась температура на выходе из камеры сгорания. А также был достигнут однородный температурный градиент в несмежном распределении горелок по сравнению с другими распределениями и уменьшилась концентрация оксидов азота.

Ключевые слова: *вычислительная гидродинамика, природный газ, вихревая горелка, распределение тепла.*

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THE EFFECT OF BURNERS DISTRIBUTION ON THE COMBUSTION AND NOX EMISSION CHARACTERISTICS IN STEAM BOILER COMBUSTION CHAMBER USING NATURAL GAS AT PARTIAL LOAD

Abstract: *In this paper, computational fluid dynamics (CFD) modeling was performed for combustion of natural gas in the combustion chamber of a steam generator with swirl burners located on the wall of the combustion chamber at five different combustion distribution under partial load. Ansys Fluent code has been used to model combustion processes. The model was used to study the effect of distribution of burners on combustion chamber parameters, which include temperature distribution, and (CO_2, CO, NO_x) concentrations in the combustion chamber.*

The study showed that placing the burners at a lower level led to a decrease in the temperature at the outlet of the combustion chamber, as a result of better heat transfer to the evaporator tubes. And to achieve a homogeneous thermal gradient, in the non-contiguous distribution of the burners compared to the other distributions. As well as, decreasing the concentrations of the nitrogen oxides.

Keywords: *CFD, Natural gas, Swirl burner, Temperature distribution.*

1- Introduction:

Steam generators are an essential part of any power plant or cogeneration system and in many industrial facilities. Although steam parameters such as pressure and temperature, have been rising steadily over the past few decades. However, the main function of a steam generator remained the same, generating steam according to the required conditions with high efficiency and a low operating cost. While meeting emissions regulations and environmental recommendations, achieved by the combustion chamber, where the burners inside of it, provide complete combustion of the fuel, and the appropriate distribution of the resulting heat. It also facilitates the heat transmission process into the working agent efficiently, which will have a positive effect on the performance of the boiler at large. Thus, choosing the placement of the burners in the combustion chamber is considered to be crucial, when designing a boiler [1].

2- Research problem, purpose and importance:

The power plant steam generator in the Homs Refinery, is currently operating most of the time at various partial loads. Making it hard to determine, the distribution of the working burners and their appropriate order. And there were noticed, that some indicators of the boiler function differed when operating the same number of burners, but with different distribution within the combustion chamber. Whereas, the rest of the indicators were hard to determine, especially the combustion chamber variables. This research aims at studying the effect of the distribution of burners on the variables of the combustion chamber of the studied steam generator, when operating three burners (The most used state currently). The variables include:

1. The distribution of the temperatures, within the combustion chamber.
2. The concentration of carbon monoxide, carbon dioxide and nitrogen oxides, in the combustion chamber.

The importance of this research comes from trying to determine the appropriate performance of the burners at partial loads, simulating the practical reality of the conditions, under which the steam boiler operates. Also, determining the optimal cases depending on the obtained results.

3- Methods of Research and its Materials:

The study depends on modeling using computational fluid dynamics (CFD), on a model that simulates the combustion chamber of the studied steam boiler. In order to study the effect of the distribution of burners, under different operating conditions, using commercial code (ANSYS Fluent 19.0). Which makes this model capable of evaluating the performance of these burners. Also, providing the information and values, related to the variables of the combustion chamber of the studied steam generator, for each one of the distribution cases, of the burners operating inside the steam generator.

3-1- Description of the studied steam generator and the geometrical model:

The studied steam generator has natural circulation, with a dual-passage drum. Its nominal capacity is 190 t / h of superheated steam, at a pressure of 9.41 MPa. And the temperature is 540 degrees Celsius. The combustion chamber occupies the lower part of the boiler, which is located on the front of the combustion chamber, where nine burners are within a common cover [2]. The combustion air stream is directed towards the swirling blades, while the fixed air swirling blades swirl the combustion air, to mix the air with the fuel. Also to fixate the flame at the outlet of the burner. In addition to that, swirling has a fundamental effect on flame formation and combustion [3].

(Figure 1) shows a three-dimensional illustration of the swirling burner, used in the studied steam generator. The parts of the burner were modeled and assembled using the SolidWorks environment. (Figure 2) shows the geometric dimensions of the burner in [mm].

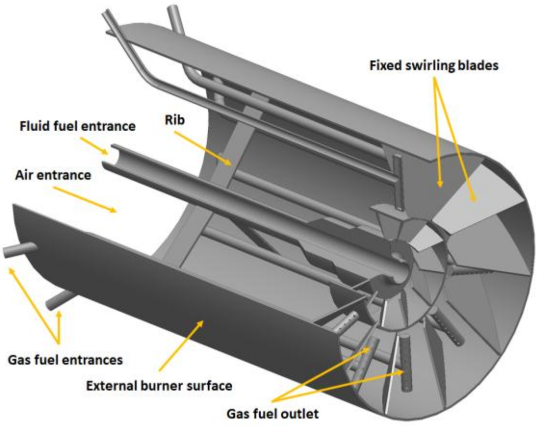


Figure 1: Three-dimensional illustration of the swirl burner

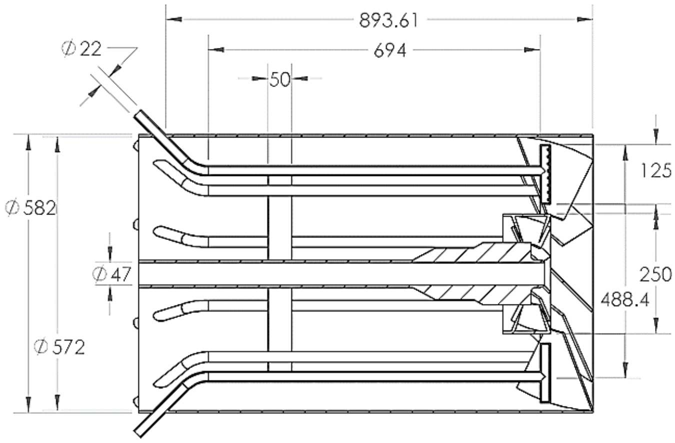


Figure 2: Geometric dimensions of the swirl burner

(Figure 3) shows the swirl burner and a front section of it, after simplification, where the parts before the fixed swirling blades were cut, in order to reduce the number of the elements in the burners mesh, which has a large number of areas being cut. The cut areas don’t relate to the studied subject. (Figure 4) shows a magnified section of the gas fuel outlet slots. (Figure 5) shows a three-dimensional illustration of the burner stream field created using SolidWorks, and a front section of it prior to the mesh generation.

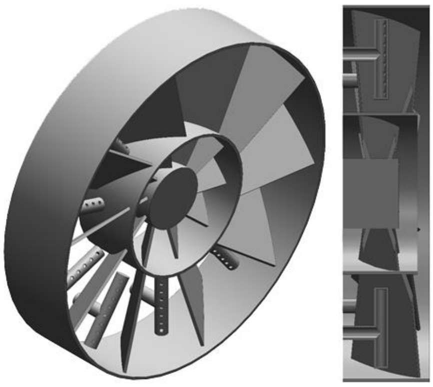


Figure 3: Three-dimensional illustration of the swirl burner

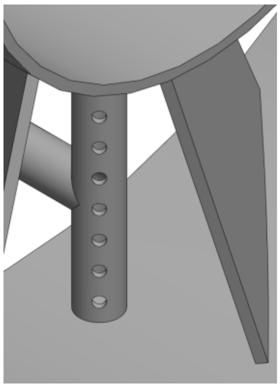


Figure 4: Magnified section of the gas fuel outlet slots

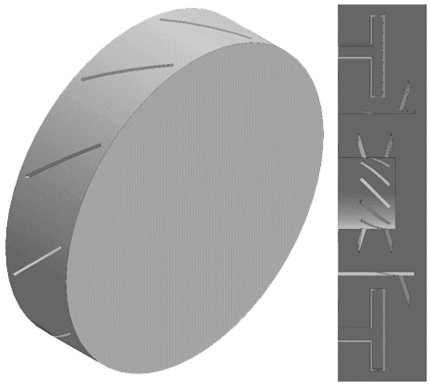


Figure 5: Three-dimensional illustration of the swirling burner stream field

(Figure 6) shows a three-dimensional illustration of the combustion chamber with swirling burners, while (Figure 7) shows the dimensions of the main combustion chamber in [mm] and the numbering of the swirl burners.

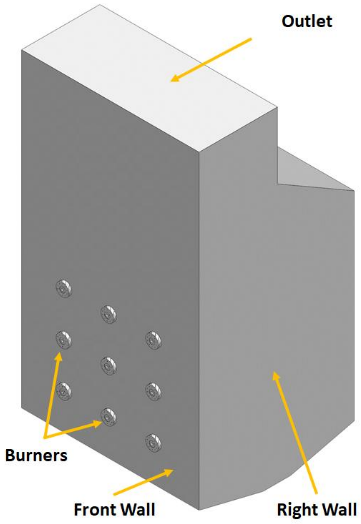


Figure 6: Three-dimensional illustration of the combustion chamber with swirl burners

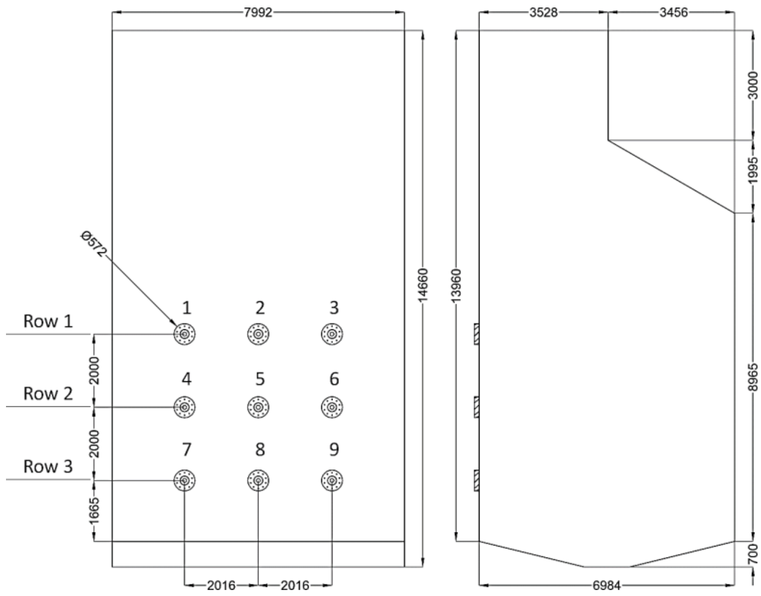


Figure 7: Dimensions of the main combustion chamber, and the numbering of the swirl burners

3-2- Numerical mesh:

The mesh was generated using the Ansys ICEM 19.0 application, in which the burners' blocks were separated and the dimensions of the rest of the blocks were adjusted, to increase the density of the elements in the area of the burners, in order to increase the accuracy of the solution in the area opposite the burners. Hexahedral mesh was generated for the combustion chamber, and tetrahedral for the burners, and (Figure 8) shows the numerical mesh of burner.

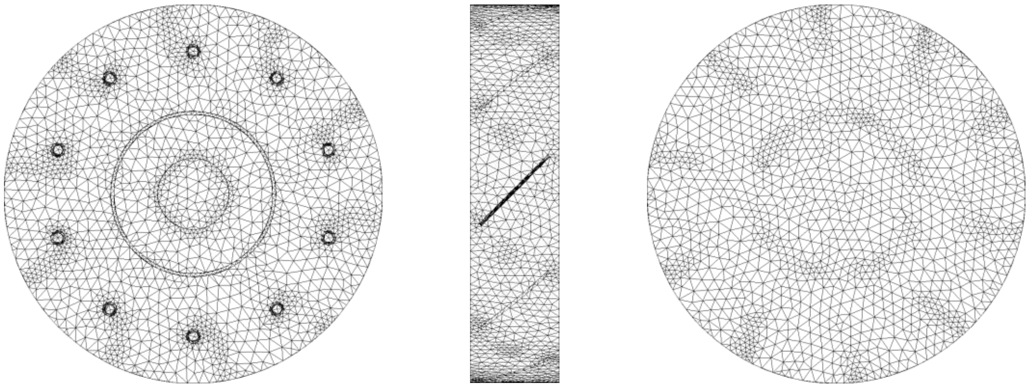


Figure 8: The numerical mesh of burner. Fuel and air entrances (left), front view projection (center), inteface between burner and combustion chamber from the burner side (right)

(Figure 10) shows a side view of the combustion chamber. While (Figure 11) shows a gradual front view of the combustion chamber passing from the axes of the burners. In it, we observe the density of the elements of the mesh in the area of the burners, and the average number of elements in the mesh was (1.7) million elements.

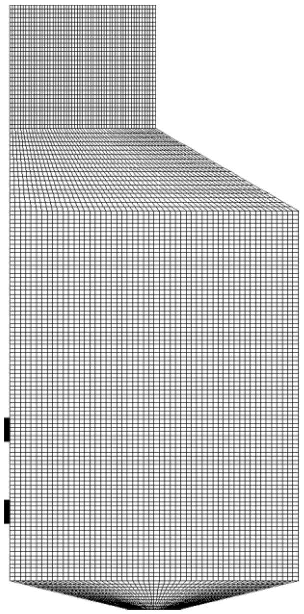


Figure 9: Front section of the combustion chamber, after creating the elements mesh

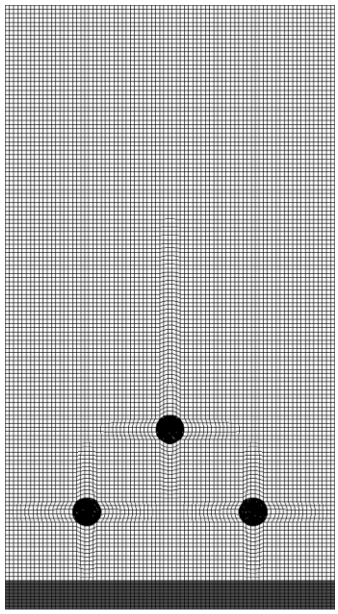


Figure 10: Side view of the combustion chamber, after the elements mesh generation

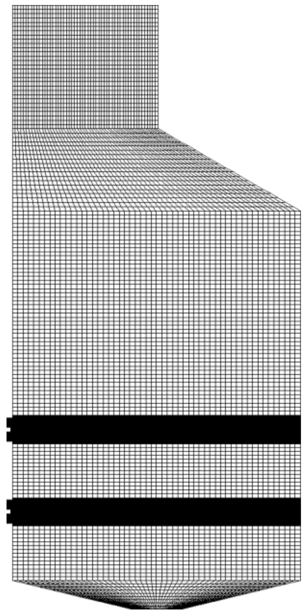


Figure 11: A gradual front view, passing through the axes of the burners

3-3- Physical model and boundary conditions:

3-3-1- Physical model:

Navier - Stokes' three-dimensional flow equations were solved in the steady state. And the Realizable k−ε model is employed for the turbulent modeling. The discrete ordinates (DO) model is selected for the radiation modeling, and the emissivity of flue gas was calculated by weighted-sum-of-gray-gases model (WSGGM), and the non-premixed combustion model is selected for the combustion modeling. (SIMPLE) algorithm was used to get a relation between velocity and pressure corrections.

3-3-2- Boundary conditions

The mass flow rate of combustion air is 13.799 kg/s, and the mass flow rate of fuel is 1.130 kg/s. The air temperature is 376 K, the fuel temperature is 293 K, and the average temperature of the walls of the combustion chamber is 479 K, and wall emissivity is 0.8. (Table 1) shows the composition of the used fuel, which was obtained from the central laboratory of the General Company for Homs Refinery.

Table 1: The composition of used fuel

Component	(CH_4)	(C_2H_6)	(C_3H_8)	(C_4H_{10})	(C_5H_{12})
Percentage	93.3	3	3.2	0.3	0.2

3-4- Validation of the model:

Data and readings including hourly measurements of the main parameters were obtained by actual operating of the steam generator at several partial operating states, in order to benefit from it in our research. Where part of the limit conditions were determined based on these readings, as it is almost impossible to collect sufficient operating data to provide the detailed information needed for modeling using a CFD. Therefore the main parameters available from the manufacture company and from the repeated measurements by the operator, assisted the validation of the model [4].

The average temperature of the flue gases at the outlet of the combustion chamber, obtained from simulation, was compared to the calculated temperature at the outlet of the combustion chamber, based on the measurements provided by the operator. As shown in (Table 2), there is an acceptable proximity between the calculated temperature value based on measured values, and the temperature value obtained from the simulation.

Table 2: Comparison between the calculated and the measured temperature of flue gases

The temperature of the flue gases, while operating three burners	
The temperature determined by the experimental measurements	$T_{outlet} = 977.65\ K$
The temperature obtained from the simulation	$T'_{outlet} = 1004\ K$
Error percentage	2.695%

4- Results and discussion:

4-1- Temperature distribution:

Temperature distribution is a key indicator for evaluating the performance of the combustion chamber. It should be homogeneous inside the combustion chamber as much as possible, avoiding the formation of hot spots, and reducing the thermal stresses on the boiler tubes. Which helps the heat to be transferred to all the tubes in the steam generator equally, and reduces the possibility of nitrogen oxides formation. The graph in (Figure 12) shows the average total temperatures of the flue gases, along the combustion chamber height, for the five studied arrangements, when operating three burners. Where the numbers in the illustration indicate the numbering of the operating burners, and also illustrated in (Figure 7), where we notice the differentiation of the case 579 from the rest of the cases (The operating burners are the fifth, seventh and ninth), where the temperature was high below the combustion chamber, and decreased significantly going upward.

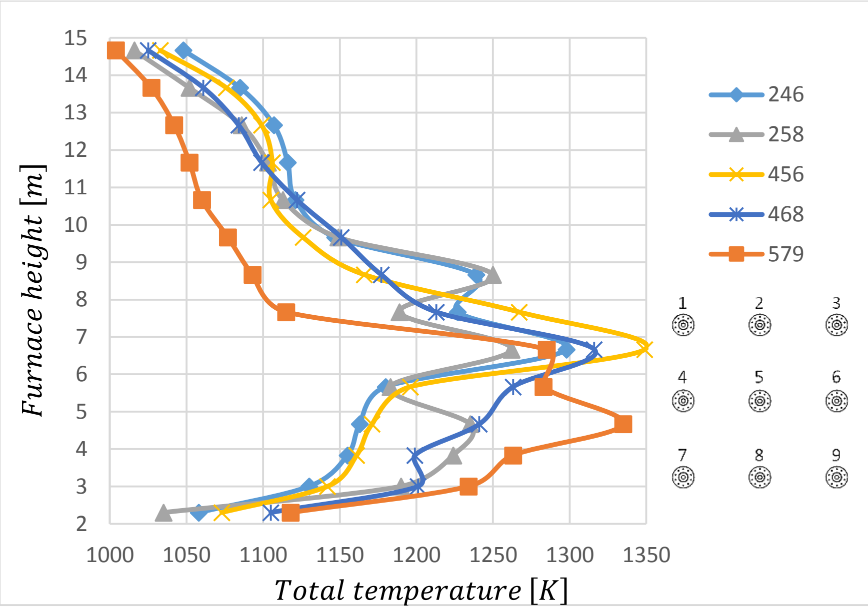
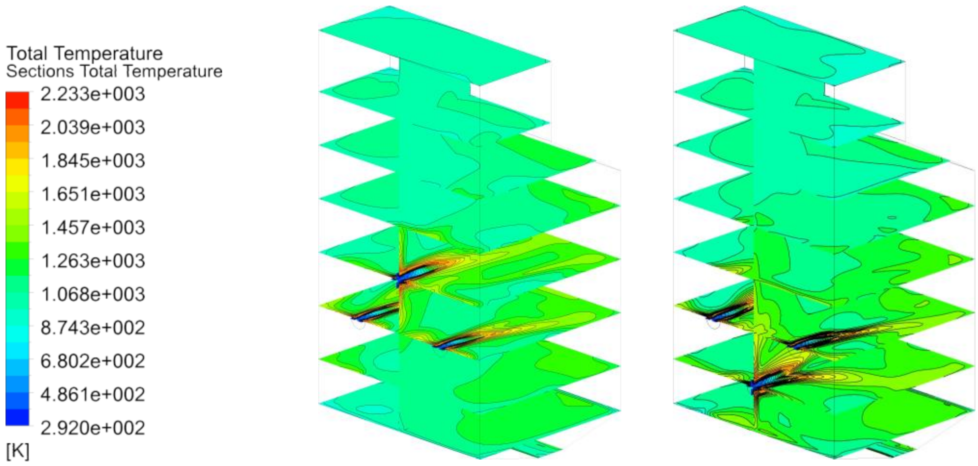


Figure 12: The relation between the average total temperature and the combustion chamber height, when three burners are in operation

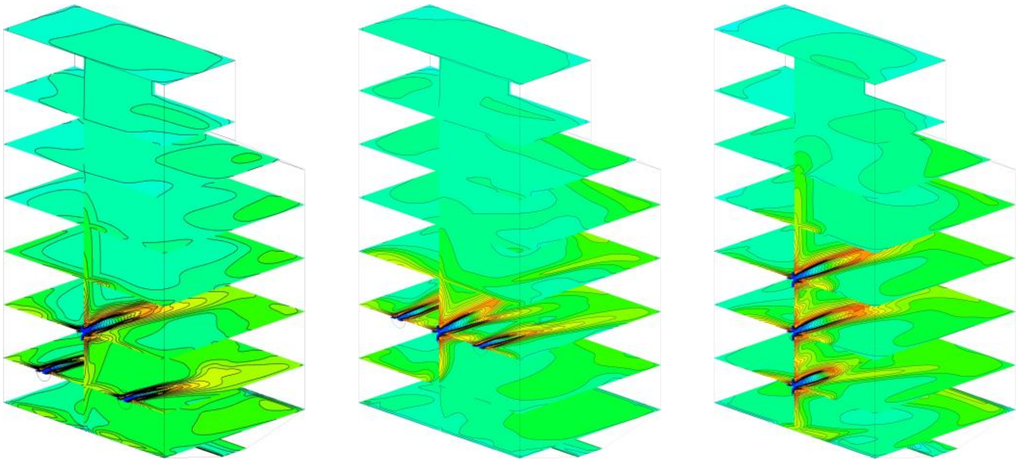
(Figure 13) shows the total temperature distribution inside the combustion chamber, at the front section and several horizontal sections. The thermal homogeneity is observed in the case 579 of burners operation, compared to the other cases that contained some hotspots. The reason for this is that part of the heat produced by the combustion process, has been transferred to the side walls near the burners. While it is clear when the operating the burners in one vertical line in case 258, that the average temperatures in the combustion zone are almost homogeneous, since there is only one burner in each row. However, we excluded the vertical operation cases of the burners 147 and 369, similar to the case 258. Because in these two cases the burners are located near the two side walls, which leads to thermal stresses and a non-homogeneous distribution of the heat within the combustion chamber.

When operating the burners in one line horizontally in the case 456, we found a significant increase in the temperature in the burners working area in the second row, as shown in (Figure 12). It is the highest average temperature among all other operating cases. Causing localized heat concentration on the evaporator tubes. Therefore, this distribution is not appropriate.

Also, the cases of horizontal burner operation 123 and 789, similar to the case 456, were excluded. We observe a big difference in the temperature distribution according to the operating mode of the burners, either in a vertical or in a horizontal line.



Operating burners 246 Operating burners 468



Operating burners 579 Operating burners 456 Operating burners 258

Figure 13: The total temperatures distribution inside the combustion chamber, when three burners are in operation

We found from (Table 3) that the highest value of the average flue gases temperature, was in the case of operating burners 246 compared to other operating cases. The reason for this is that the burners are placed on the first and second rows, as the combustion gases could not lose a large part of their heat to the steam generator tubes (Due to the short passage distance). Whereas the temperature of the flue gases in the operating cases 258 and 579 was lower at the outlet of the combustion chamber, because burners are placed on the second and third rows, near the bottom of the combustion chamber, which helped heat transfer to the steam generator tubes better. This hypothesis is supported by the homogeneous distribution of the burners at the angles of a triangle in the cases 246 and 579. However, their placement at a different height led to this difference in performance, where placing the burners 579 at a lower level resulted in a lower temperature of the flue gases at the outlet of the combustion chamber. Thus, we find that case 579 is optimal compared to the rest of the cases, as the thermal homogeny within the combustion chamber was the best. This corresponds to [5], [6], therefore it is recommended to use the non-contiguous burners distribution 579 during operation.

Table 3: The average temperature of the flue gases, when operating three burners

Operation cases	Average temperature of flue gases [K]			
	outlet	First row	Second row	Third row
Burners 246	1048	1239	1298	1163
Burners 258	1016	1250	1262	1235
Burners 456	1033	1166	1349	1171
Burners 468	1025	1177	1316	1241
Burners 579	1004	1093	1285	1335

4-2- Concentration of carbon dioxide gas when operating three burners:

The concentration of carbon dioxide is considered to be a key indicator for evaluating the quality of the combustion process. (Figure 14) shows the values of the average mole fraction of carbon dioxide gas, along the height of the combustion chamber, for the five studied distributions. Where we notice the differentiation of case 579 also, from the rest of the cases.

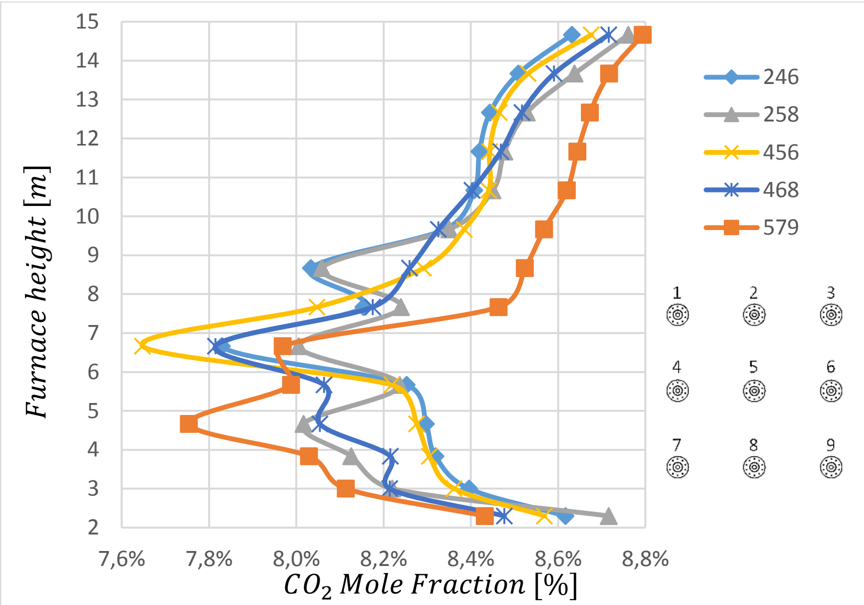


Figure 14: The relation between the mean mole fraction of carbon dioxide and the height of the combustion chamber, when three burners are in operation

(Figure 15) shows the molar concentration of carbon dioxide inside the combustion chamber at different distributions. Where we notice that the mean concentration of carbon dioxide at the outlet of the combustion chamber is the highest in the operating condition 579. As shown in Table 4, the value of (CO_2) concentrations was about 2% higher compared to case 246, which means the combustion process was better in this case compared to other cases. Probably the reason for this is that the burners are placed at the bottom of the combustion chamber, providing sufficient time to complete the combustion process. Because the lower the burner, the longer the fuel particles stay in the combustion chamber. Thus, the chance of completing the fuel combustion process increases, and this corresponds to [5], [6].

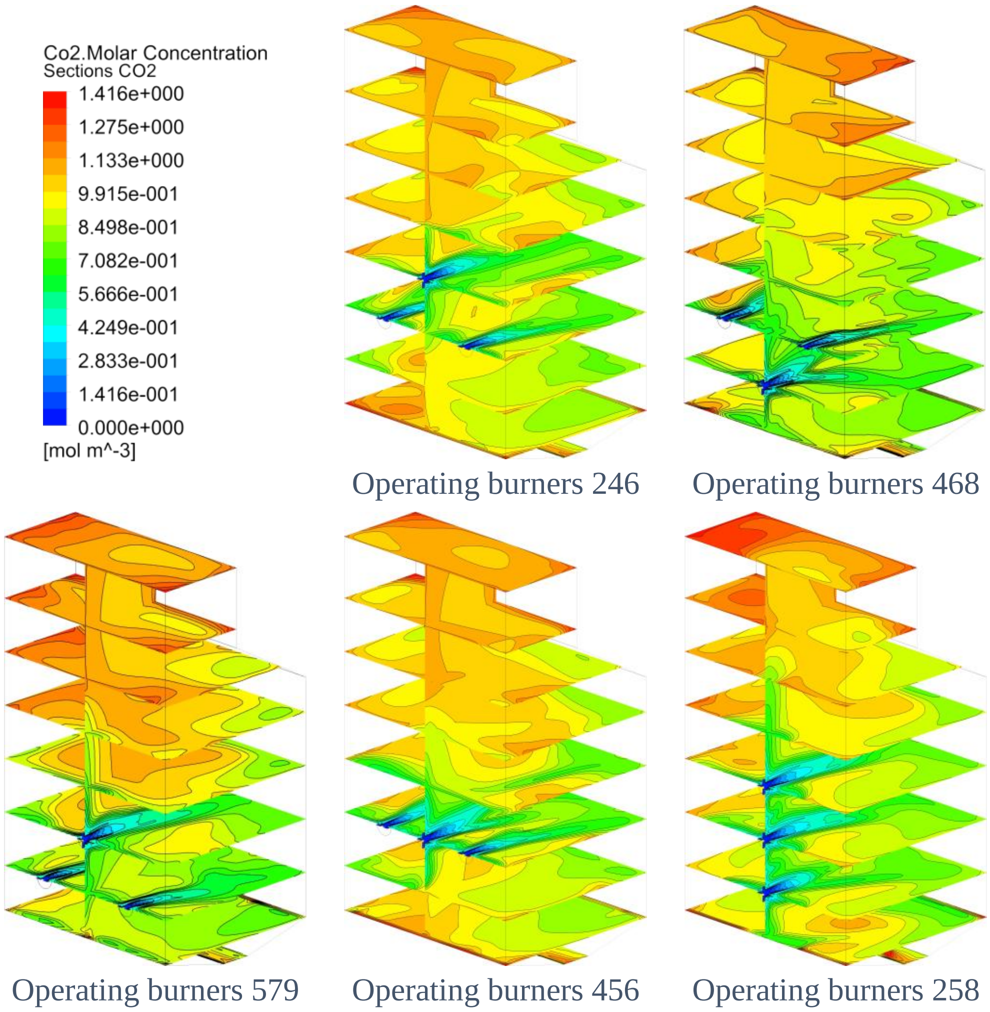


Figure 15: The molar concentration of carbon dioxide inside the combustion chamber, at different distributions of three burners

(Table 4) shows the mean molar fraction of carbon dioxide, when three burners are in operation.

Table 4: The mean mole fraction of carbon dioxide, when three burners are in operation

Operation cases	Mean mole fraction of carbon dioxide [%]			
	outlet	First row	Second row	Third row
Burners 246	8.632	8.034	7.83	8.297
Burners 258	8.761	8.059	8.006	8.016
Burners 456	8.676	8.291	7.648	8.276
Burners 468	8.716	8.260	7.815	8.050
Burners 579	8.794	8.524	7.969	7.754

4-3- Concentration of carbon monoxide gas when operating three burners:

Carbon monoxide concentrations are considered to be a key indicator for evaluating the performance of burners, as low carbon monoxide levels indicates a high quality of combustion. And the combustion is complete when it is equal to zero. The graph in (Figure 16) shows the mean mole fraction values of carbon monoxide, along the height of the combustion chamber, for the five studied distributions.

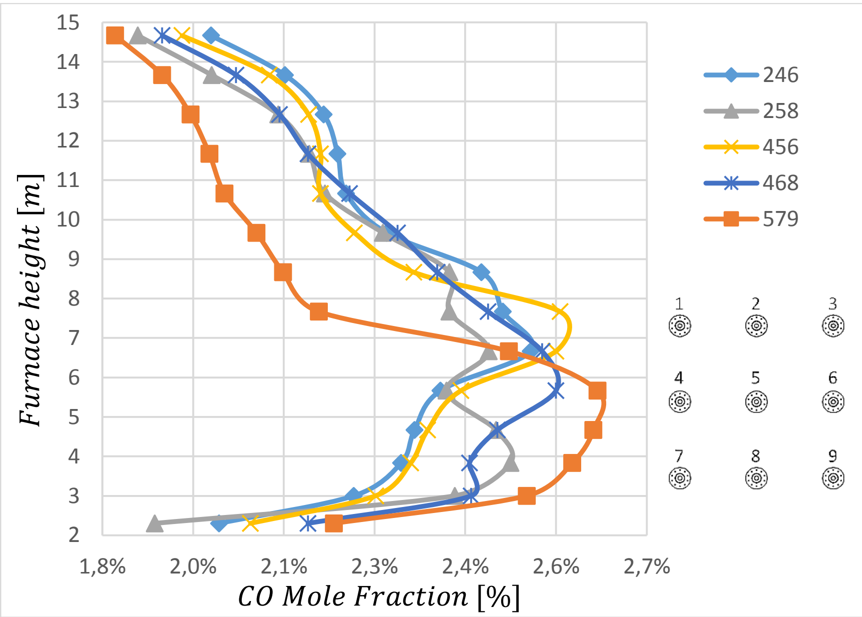


Figure 16: The relationship between the mean mole fraction of carbon monoxide, and the combustion chamber height, when three burners are in operation

Table 5: The mean mole fraction of carbon monoxide when operating three burners

Operation cases	**Mean mole fraction of carbon monoxide (%)**			
	outlet	**First row**	**Second row**	**Third row**
Burners 246	1.980	2.427	2.508	2.316
Burners 258	1.859	2.374	2.439	2.451
Burners 456	1.932	2.315	2.550	2.338
Burners 468	1.899	2.354	2.527	2.453
Burners 579	1.821	2.099	2.472	2.612

From (Table 5), we find that the value of the mean concentration of carbon monoxide, at the outlet of the combustion chamber, is the lowest in the 579 operating case. Which indicates a better combustion process in this case compared to the other cases, despite the fact that carbon monoxide concentrations were high in the burners' operation area, however, it decreased towards the top as a result of the completion of the combustion process, that is, the transformation of CO into CO_2 , which corresponds to our previous conclusion results. While we notice a high average concentration of carbon monoxide in the case of operation 246, indicating that the combustion process was worse compared to other cases, although the burners were placed at the corners of a triangle, in a similar shape to the best case 579. But placing it at a higher height led to this variation in performance. Where the value of (CO) concentrations in the operating case 246, was about 8% higher compared to case 579. (Figure 17) shows the molar concentration of carbon monoxide inside the combustion chamber, with different distributions of the three burners. As we note the opposite situation of the previous carbon dioxide concentrations, as expected, because the relation between the two is inverse.

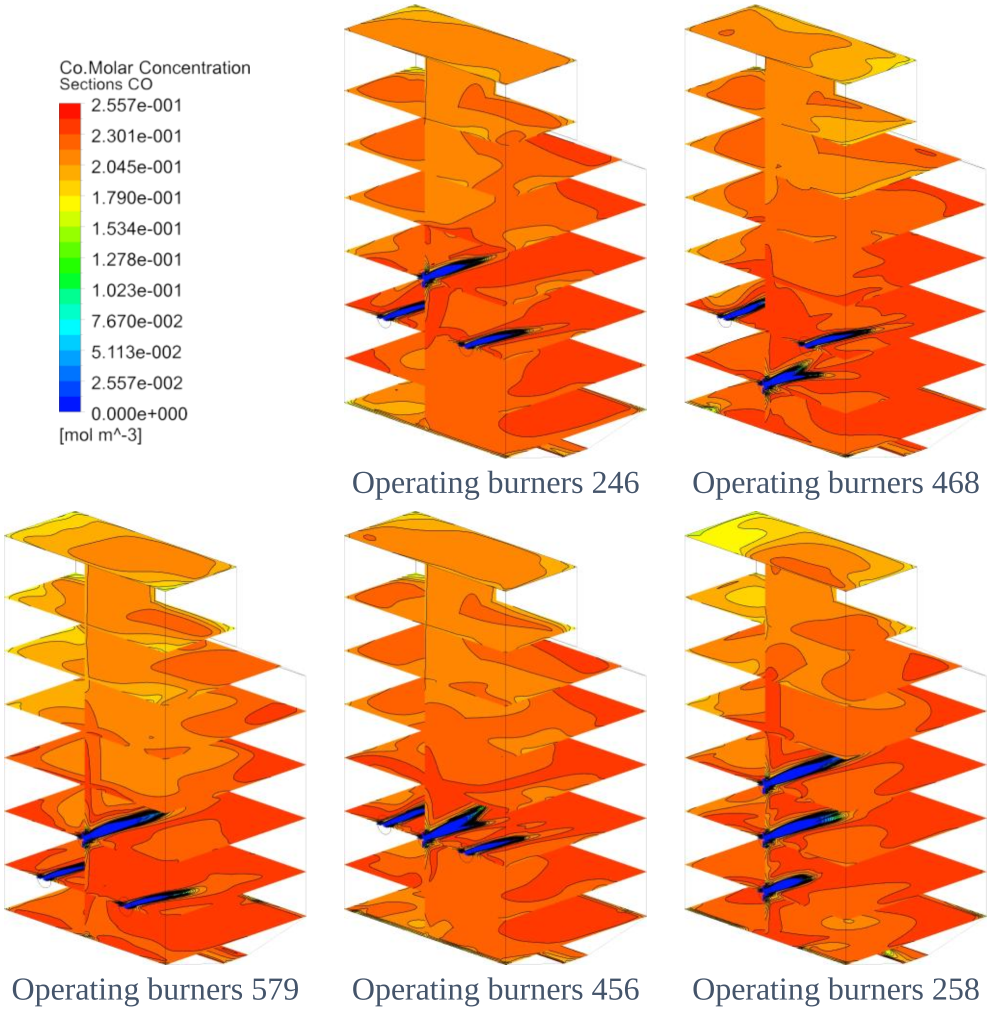


Figure 17: Molar concentration of carbon monoxide in the combustion chamber in the different operating cases of the burners

4-4- The molecular concentration of nitrogen oxides when operating three burners:

The concentrations of nitrogen oxides are important indicator, for evaluating the performance of gas fuel burners, as a result of the formation of thermal nitrogen oxides according to the Zeldovich principle. The graph in (Figure 18) shows the values of the mean molecular concentration of the nitrogen oxides, along the height of the combustion chamber, for the five studied distributions. Where we see again, the differentiation of case 579 from the rest of the cases.

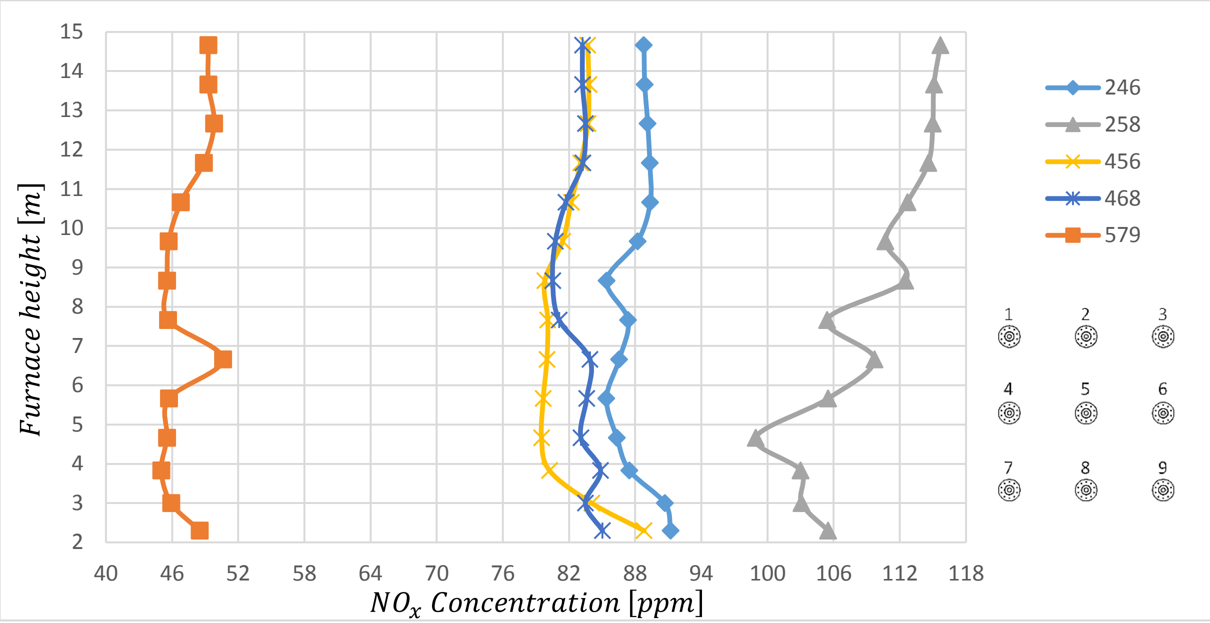


Figure 18: The relation between the mean molecular concentration of nitrogen oxides, and the combustion chamber height, when three burners are in operation

We found from (Table 6), that the value of the mean molecular concentration of nitrogen oxides at the outlet of the combustion chamber is the lowest in the operation case 579, then case 468, followed by case 456. The reason for this is the thermal homogeneity in the nitrogen oxides formation area. Whereas the concentrations were the greatest for case 258, where the three burners are placed on top of each other, in one line vertically. As a high thermal concentration is formed in that small sector, in contrast to case 456, in which the three burners were in one line horizontally, where the same thermal concentration was not achieved due to the upward movement of gases, and there was not enough time for thermal nitrogen oxides to form in this area. Which corresponds to the Zeldovich principle. Comparing the two similar operation cases 579 and 246 (Burners are placed on the corners of a triangle), but different by placing them at a different height, resulting in this difference in performance, where we see that placing the burners at a lower level decreased the mean concentration of nitrogen oxides, at the outlet of the combustion chamber, about 44.6%. This is due to several factors, the most important of which is the thermal homogeneity in the nitrogen, and the absence of heat foci, in addition to the lack of the sufficient amount of oxygen, as a result of almost complete combustion in this case.

Table 6: The mean molecular concentration of nitrogen oxides when operating three burners

Operation cases	Mean molecular concentration of nitrogen oxides (ppm)			
	outlet	First row	Second row	Third row
Burners 246	90.94	87.84	89.11	88.73
Burners 258	118.30	115.60	112.90	101.80
Burners 456	85.69	82.00	82.38	81.72
Burners 468	83.22	80.52	83.90	83.08
Burners 579	50.40	46.70	52.09	46.94

(Figure 19) shows the molecular concentration of nitrogen oxides inside the combustion chamber, at the different distributions of the three burners. Where it seems clear the advantage of case 579.

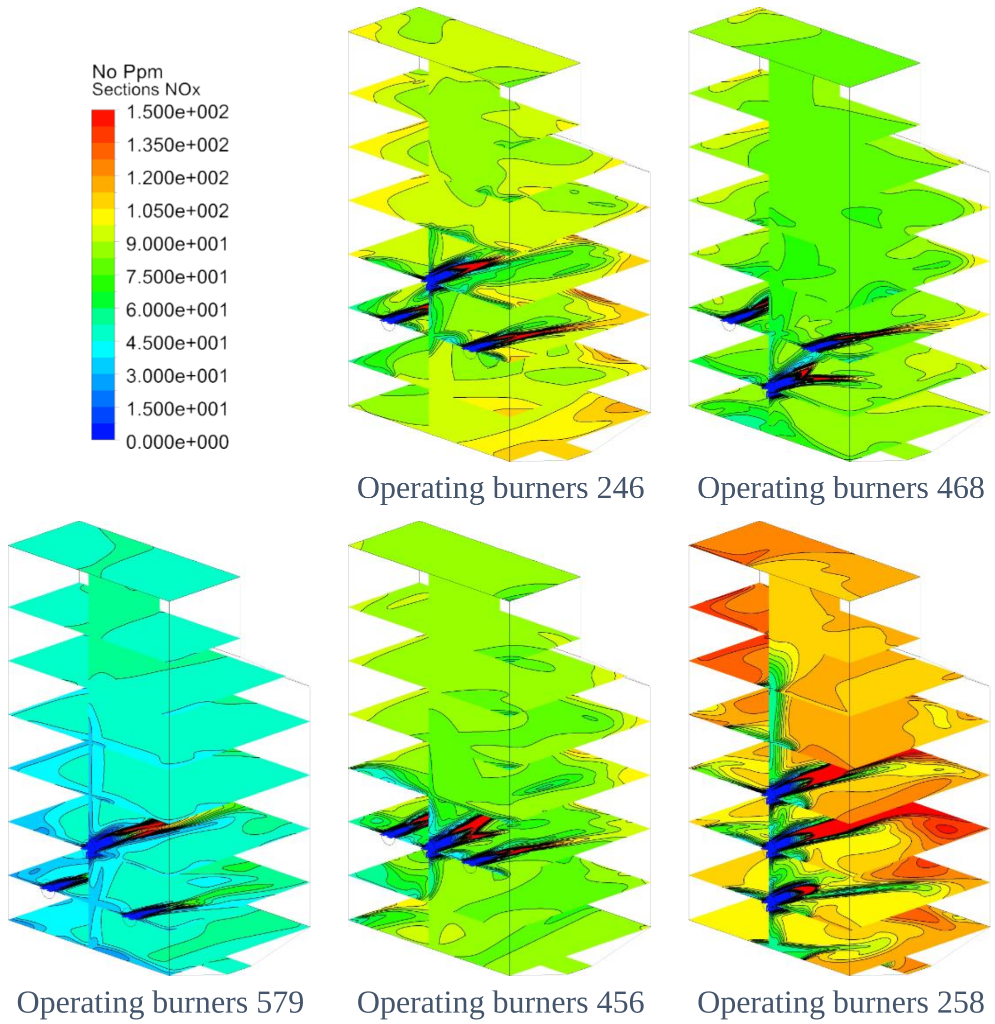


Figure 19: Molecular concentration of nitrogen oxides, inside the combustion chamber, when operating three burners.

5- Conclusions:

1. Operating the burners at a low level near the bottom of the combustion chamber, leads to, decreasing the total temperatures of the flue gases, as well as, decreasing the carbon monoxide concentrations at the outlet of the combustion chamber. As case 579 is considered to be optimal compared to the rest of the cases in general, and also the similar case 246 (The burners are placed on the corners of a triangle) in particular. Where the temperature at the outlet of the combustion chamber, was in this case the lowest among the other operating cases. This indicates that the heat transfer rate into the steam generator tubes was the best. Also, the values of (CO_2) concentrations were higher by about 2%, and (CO) was lower by about 8%, which indicates that the combustion process was the best as well. Thus, it is recommended to distribute the burners according to case 579 when operating.
2. The contiguous distribution of burners, in one horizontal line, leads to an increase in temperature at the working area of the contiguous burners. This causes a localized heat concentration on the evaporator tubes, where it was observed in the operating condition 456, a significant increase in temperature at the working area of the burners in the second row. It was the highest in that area, 1349 K, compared to the other operating cases. Therefore, this distribution is considered to be inappropriate.
3. Operating the burners at a low level, near the bottom of the combustion chamber, leads to lowering the mean molecular concentration of nitrogen oxides, at the outlet of the combustion chamber. Where the operating case 579 was the optimal one, compared to the rest of the cases, where the mean molecular concentration of nitrogen oxides at the outlet of the combustion chamber, in the operating case 579, was 44.6% lower than the similar operating case (The placement of the burners on the corners of a triangle, but at a higher height).
4. The contiguous placement of the burners in one vertical line increased the mean molecular concentration of nitrogen oxides at the outlet of the combustion chamber. The concentrations of nitrogen oxides were the highest at the outlet of the combustion chamber, in the case 258, compared to the rest of the cases. Where the three burners are placed on top of each other, in one vertical line. Leading to the formation of a high

thermal concentration in this small sector. In contrast, in case 456, the three burners were also placed next to each other, but in a horizontal line. Where the same thermal concentration did not occur, due to the upward movement of gases.

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