

COMPUTATIONAL FLUID DYNAMICS SIMULATION OF A SINGLE CYLINDER RESEARCH ENGINE WORKING WITH BIODIESEL

by

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The main objective of the paper is to present the results of the computational fluid dynamics simulation of a direct injection single cylinder engine using diesel, biodiesel, or different mixture proportions of diesel and biodiesel and compare the results to a test bed measurement in the same functioning point.

The engine used for verifying the results of the simulation is a single cylinder research engine from AVL with an open engine control unit, so that the injection timings and quantities can be controlled and analyzed.

In Romania, until the year 2020 all the fuel stations are obliged to have mixtures of at least 10% biodiesel in diesel. The main advantages using mixtures of biofuels in diesel are: the fact that biodiesel is not harmful to the environment; in order to use biodiesel in your engine no modifications are required; the price of biodiesel is smaller than diesel and also if we compare biodiesel production to the classic petroleum based diesel production, it is more energy efficient; biodiesel assures more lubrication to the engine so the life of the engine is increased; biodiesel is a sustainable fuel; using biodiesel helps maintain the environment and it keeps the people more healthy.

Key words: *computational fluid dynamics simulation, single cylinder research engine, biodiesel, rapeseed oil.*

Introduction

In the last years, computational fluid dynamics (CFD) modeling was improved to simulate 3-D flows, mixture formation, burning and pollutant formation for direct injection engines.

In the engine development process, CFD modeling of direct injection engine is used to analyze the interaction between the fuel and the motion of the intake air inside the combustion chamber. The scope is to minimize the prototyping time and to identify solutions with high success rate, in an early stage of the project. The success is based on the capability to make numerous studies, including different shapes for the combustion chamber, for the piston, for the admission pipes, in a relatively short time, based on the computational power [1-11].

In the last years, due to an intense world request, a lot of simulation models have been developed using CFD code. The continuous request for answers regarding direct injection engines, the characteristics, and performance of calculation systems, in many cases can't be satisfied with own codes. In this context, AVL FIRE is a world leader for the CFD simulation solutions, and can always be upgraded with own generated code.

The program used for simulation is AVL FIRE, and for the simulation, for the combustion model, Eddy break-up model was used, for the auto-ignition model Diesel_MIL (multiple ignition location), and for NO formation the original Heywood model.

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The Eddy break-up model is the typical example of mixed-is-burnt combustion model. It is based on the works [12-16] and can be found in all commercial CFD packages. The model assumes that the reactions are completed at the moment of mixing, so that the reaction rate is completely controlled by turbulent mixing. Combustion is then described by a single step global chemical reaction:



in which F stands for fuel, O for oxidizer, and P for products of the reaction. Alternatively we can have a multistep scheme, where each reaction has its own mean reaction rate.

In AVL FIRE the mean reaction rate is written:

$$\overline{\rho \dot{r}_{fu}} = \frac{C_{fu}}{\tau_R} \bar{\rho} \min \left(\bar{y}_{fu}, \frac{\bar{y}_{O_x}}{S}, \frac{C_{Pr} \bar{y}_{Pr}}{1+S} \right) \quad (2)$$

The first two terms of the “minimum value of” operator “min” simply determine whether fuel or oxygen is present in limiting quantity, and the third term is a reaction probability which ensures that the flame is not spread in the absence of hot products. C_{fu} and C_{Pr} are empirical coefficients and τ_R is the turbulent mixing time scale for reaction.

The value of the empirical coefficient C_{fu} has been shown to depend on turbulence and fuel parameters. Hence, C_{fu} requires adjustment with respect to the experimental combustion data for the case under investigation [17].

Boundary definition

The simulations were made in order to understand in more detail the processes that occur and the behavior of the air-fuel mixture inside the combustion chamber.

The objectives are structured in the following way:

- investigation of the air flow inside the combustion chamber, to understand the effects that the intake pipes shape have on the flow and the effects of the bowl of the piston on the air-fuel mixture and on the flow structure,
- the study on the shape of the injection, and
- study of the swirl coefficient, injection parameters, pressure, temperature, and the combustion equivalence ratio in the combustion chamber.

All investigations were made in AVL FIRE, and the verification of the results was made in the Technical University of Cluj-Napoca, on the test bed from the automotive department.

The point chosen for simulation is 4000 rpm and an IMEP of 4 bar because it best represents the engine operation points.

The accuracy of the simulations depends on the prediction capability of the used models, adopted for injection simulation, propagation of the injection, burn, and pollutant formation.

The initial data regarding the dimensions of the single cylinder engine are presented in tab. 1. Table 2 presents the timings and quantities of the injected fuel.

In conformity with tab. 2, fig. 1 presents the injection laws for pilot and main injection. Due to the injector needle lift, the real injection law has looks a little different than the theoretical one; and because of the delay between the energizing of the injector and the actual needle lift, the injection used in the simulation is delayed, but the injected quantity remains the same (the area between the graph and the horizontal axis).

Table 1. Engine specifications

Type	Value	Unit
Bore	85	mm
Stroke	90	mm
Fuel system	Natural aspirated	–
Injection system	Common rail	–
Maximum speed	4200	rpm

Table 2. Injection timings

Injection time	SOI	EOI	Quantity [mm ³]	Quantity [mg]
Pilot	692	695	2.9	2.5
Main	701	725	23.83	20.1

SOI – start of injection; EOI – end of injection

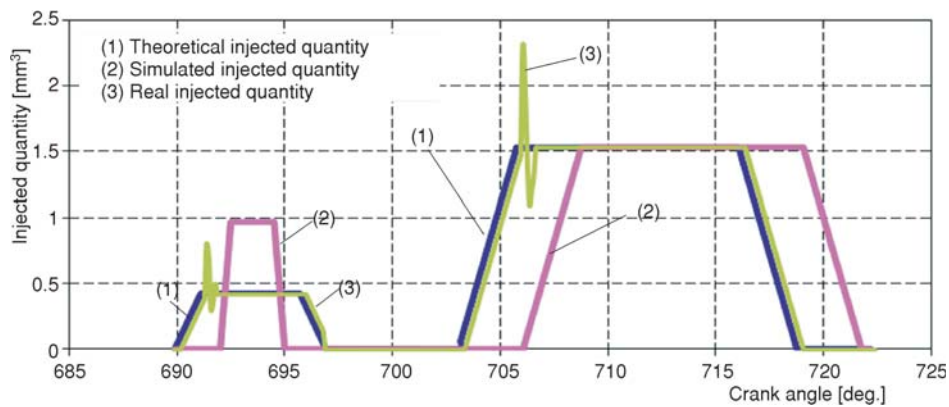


Figure 1. Theoretical, simulated, and real injection laws for pilot and main injection

The combustion chamber geometry and the created mesh are presented in fig. 2. The maximum number of cells in the moving mesh is 1.5 million.

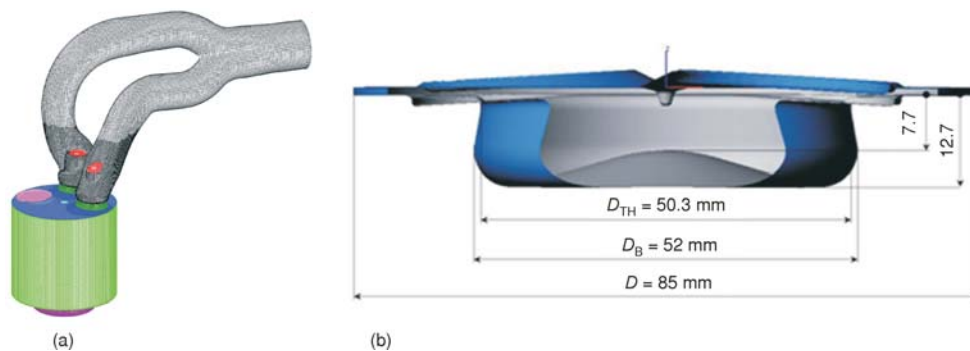


Figure 2. Used moving mesh (a) and the combustion chamber geometry (b)

Results and discussions

The obtained results were processed with the post-processing module AVL IMPRESS, using user defined programs and MS Excel.

Flow speeds

The flow speed of the air entering the combustion chamber is important to monitor for the filling of the chamber, to notice the air currents and to improve the flow parameters. Also the swirl coefficient was studied because it has a great influence on the injection process.

The results are presented in figs. 3 and 4, for the maximum opening of the intake valves.

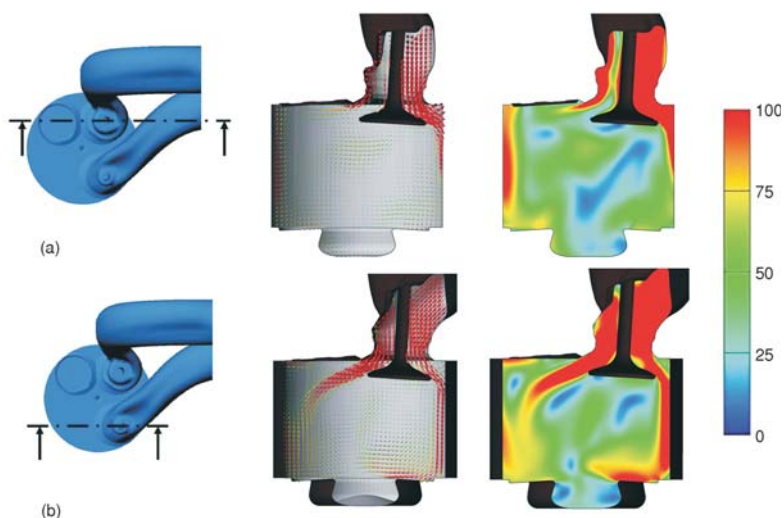


Figure 3. Vectorial and surface views of the flow velocities at 450° CA
(a) in the helical port, (b) in the tangential port
(for color image see journal web site)

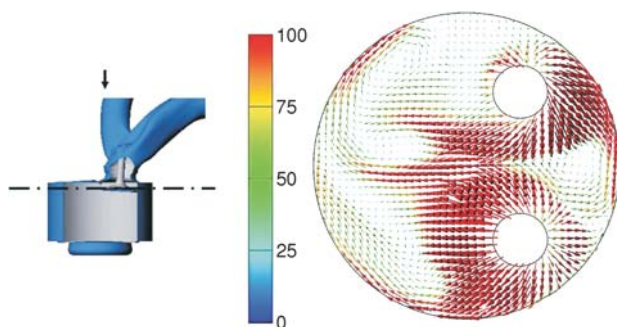


Figure 4. Top vectorial view of the flow velocities at maximum intake valves opening
(for color image see journal web site)

The role of the helical port can be seen better in the vectorial view, fig. 4:

- to create the proper swirl;
- and the role of the tangential port (better seen in the surface view, fig. 3):
- to ensure the correct air flow;
- that is why in the tangential port the red area with the speed of 100 m/s is bigger.

Swirl coefficient

The swirl coefficient data were generated with the help of a function implemented in AVL FIRE. The swirl coefficient rises from 0° CA to 480° CA to a value of 2.4 and then decreases to 1.9 at 680° CA.

The most important points of the swirl coefficient are:

- intake valve closing (580° CA), where the swirl coefficient is 2.04, and
- injection start (692° CA), where the swirl coefficient is 2.09.

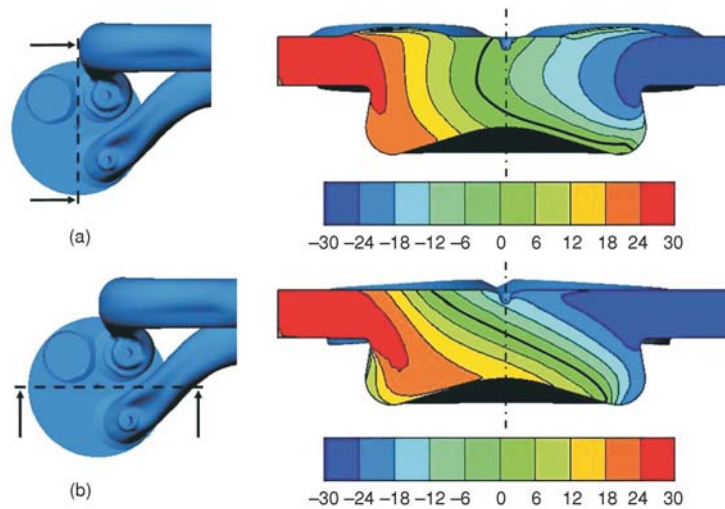


Figure 5. Swirl analysis (flow velocities) at 690 deg CA
(a) section perpendicular on Oy axis (b) section perpendicular on Ox axis
(for color image see journal web site)

It is important to know the shape of the flow at maximum intake valves opening (fig. 5), and to know the axis around which the air is swirling because this axis should coincide with the cylinder axis [18]. The axis analysis is presented in fig. 6.

By studying the swirl coefficient we can see that the swirl axis almost coincides with the cylinder axis, which is good, because it influences equally all the injection cones; fact also confirmed with the cuts perpendicular on the cylinder axis in fig. 6.

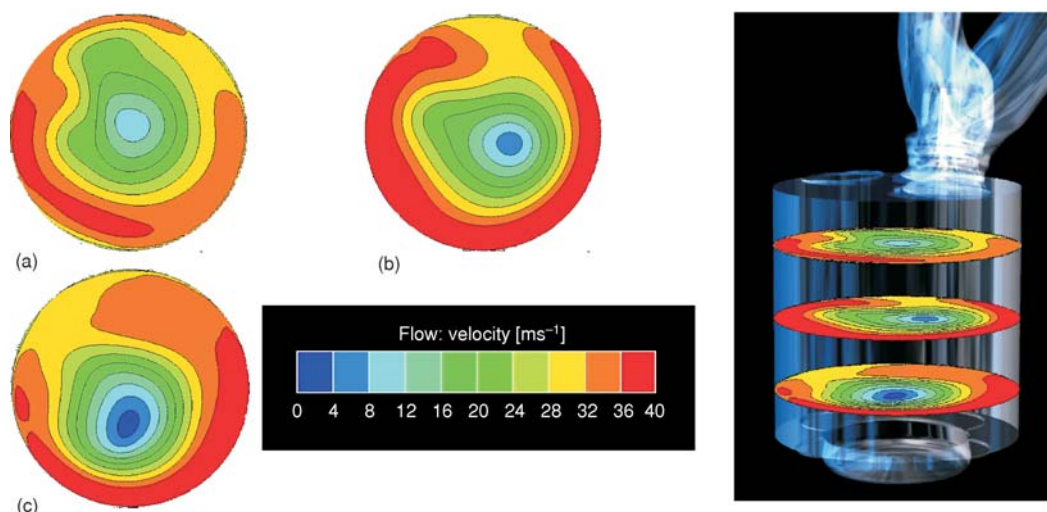


Figure 6. Rotation axis of the air flow in the combustion chamber; cut at (a) 1/4 stroke, (b) 1/2 stroke, and (c) 3/4 stroke (for color image see journal web site)

Combustion equivalence ratio

Figure 7 represents the variation of the combustion equivalence ratio during the pilot and main injection. The effect of the swirl can be seen, as the injection cones tend to rotate clockwise, which ensures a better air-fuel mixture, and there for a better combustion.

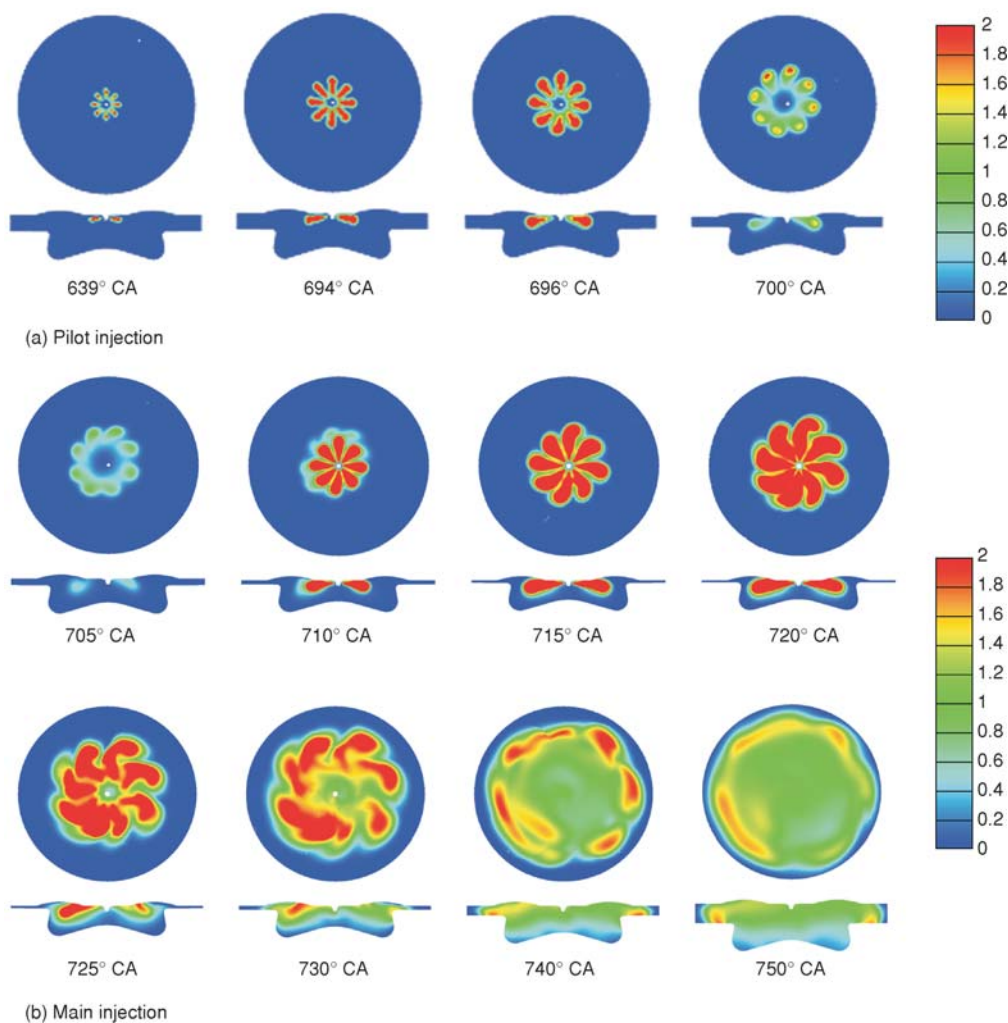


Figure 7. Evolution of the combustion equivalence ratio of the pilot and main injection
(for color image see journal web site)

Jet penetration

Simulations were made using diesel, B10 (10% rapeseed oil + 90% diesel), B20, and B50, the biodiesel blends have different lower calorific values and different densities, which are presented in tab. 3.

Because the density rises for B50, B20, and B10 in comparison to diesel, the penetration of the fuel, for the same injection pressure, is different, and it is presented in fig. 8. It can be

Table 3. Lower calorific value and density of different blends of biodiesel in comparison to diesel [19]

Fuel	Composition	Lower calorific value [kJkg ⁻¹]	Density [kgm ⁻³]
Diesel	Diesel 100%	43200	830
B10	10% rapeseed + 90% diesel	42780	835
B20	20% rapeseed + 80% diesel	42360	840
B50	50% rapeseed + 50% diesel	41100	855

seen that the maximum penetration of the fuel jet when using B50 is 18 mm, in comparison to 15.2 mm for B20, 14.8 mm for B10, and 13.6 mm for diesel. Comparing the obtained results with the experimental research made by Mariasiu [19], it seems that the biofuels penetration is directly influenced by the turbulence of engine fluid inside the combustion chamber. The immediate effect is reducing of the smoke pollutant emissions.

Cylinder pressure

The cylinder pressure is presented in fig. 9. The differences between diesel and biodiesel blends can be seen, because if the mixture contains more rapeseed oil, the lower calorific value of the obtained biodiesel decreases.

The cylinder pressure was measured with a piezoelectric sensor placed in the combustion chamber and results were collected with an INDI Module from AVL.

The pressure inside the combustion chamber using pure diesel is 63.29 bar, for B10 it is 62.18 bar, for B20 it is 62.32 bar, and for B50 it is 61.26 bar; so the pressure decreases to 97% using B50 in comparison to pure diesel.

Temperature in the combustion chamber

The temperature inside the combustion chamber during the diesel and biodiesel burn is presented in fig. 10.

The temperature inside the combustion chamber reaches from 1761 K (when using die-

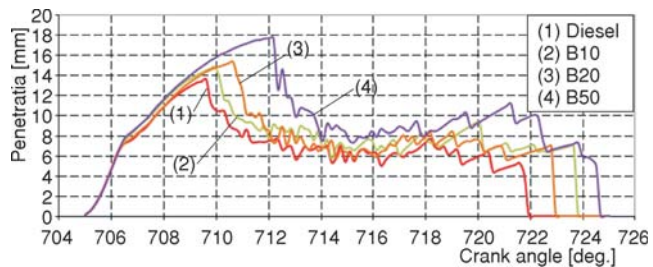


Figure 8. Fuel jet penetration using different blends of biodiesel

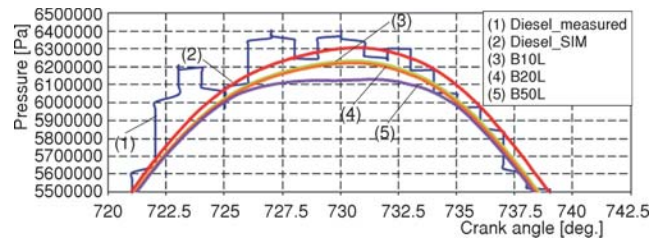


Figure 9. Cylinder pressure for diesel, B10, B20, and B50

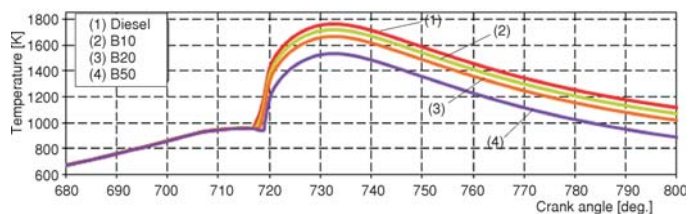


Figure 10. The temperature inside the combustion chamber using the biodiesel blends

sel) to 1534 K (when using B50), so the temperature decreases to 87% when using B50, to 94% when using B20, and to 97% when using B10 in comparison to diesel.

Conclusions

In the present study the flow velocities during the intake were analyzed. The role of the tangential and helical intake port were underlined, the swirl axis was also analyzed. The axis of the swirl is well centered so the influence on the fuel injection cones is uniform.

Also the diesel, B10, B20, and B50 combustion has been simulated and the equivalence ratio, cylinder pressure, cylinder temperature and fuel jet penetration were investigated.

The cylinder pressure for the diesel fuel was also measured on the test bed, because of the A and B constants from the Eddy break-up model used for the combustion. The constants were kept and the simulation was restarted using B10, B20, and B50, respectively; the pressure and temperature curves were extracted.

When using biodiesel blends, due to the higher density, the penetration increases with the percentage of biodiesel in diesel. But due to the decrease of the lower calorific value, the cylinder pressure drops to 97% and the temperature also drops to 87%. But the advantage when using biofuels is mainly the lower emissions [20-22].

The authors wanted to underline the importance of test bed measurements before simulating the processes inside the single cylinder research engine. The methodology of the research followed a few logical steps: first, the measurements on the test bed were made in a very well chosen working point, in order to obtain the best views for the movement of the air inside the cylinder; secondly, the surface of the cylinder head, piston head, injector tip, valves and other important surfaces were measured and built in a computer aided design software and imported in AVL FIRE; thirdly, the boundaries were named in order to create different cell sizes for different selections like the valve tips; fourth step, we created the solver steering file where the inputs were the temperatures, pressures from the test bed in order to create the real simulation conditions.

After the simulation was done, all the necessary data were extracted and processed in order to be presented in a traditional way.

Also, the authors wanted to underline the advantages of using a simulation based on test bed measurements, like: by measuring the cylinder pressure, atmospheric pressure and temperature, and the sizes of the engine elements, the simulation was able to generate including the movement of the air inside the cylinder, and much more needed data, also the fuel can be changed easily and the simulation should run again to generate a new set of data.

Acknowledgments

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Nomenclature

CA	– crank angle	deg.	– degrees
C_{fu} , C_{Pr}	– empirical coefficients	F	– fuel quantity
D	– piston diameter	O	– oxygen quantity
D_B	– piston bowl diameter	P	– products of reaction quantity
D_{TH}	– piston throat diameter	τ_R	– the turbulent mixing time scale for reaction

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