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# NUMERICAL METHODOLOGY FOR ANALYSIS AND CHARACTERIZATION OF THE FUEL SPRAY IN A COMBUSTION ENGINE

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**Abstract.** *The computational simulation for the spray characterization of an internal spark ignition internal combustion engine presents a great challenge to new technologies and systems that seek better fuel utilization and a lower level of emissions. New technologies such as direct injection of fuel into spark ignition engines have emerged in the face of strong environmental appeal and the limitation of fossil fuel sources, which require increasingly efficient and less polluting vehicles. With the increasing insertion of this technology in the automotive market, the characterization of fuel spraying by the injector is important to increase combustion efficiency and avoid abnormal or incomplete combustion. For the numerical analysis of the spray there are several commercial CFD software, Computational Fluid Dynamics, which can be applied in this study, but there is an increasing and substantial need for less expensive software. Within this context, this work has as main objective to propose a methodology for numerical characterization of the spray in an internal combustion engine of direct injection. Taking into account academic and industrial interests in the manipulation of open CFD codes the OpenFOAM software for the characterization of the spray was used in this work. Spray dispersion models such as LISA, TAB, Reitz-Diwakar and KHRT were used and modified to converge with the experimental data obtained in dynamometer tests. Important parameters of the spray, such as break-up length, cone angle, penetration, droplet diameter, droplet dispersion, velocity fields, among others, were calculated and analyzed in this work. The main results showed that the spray dispersion models are well implemented in the software compared to the literature. The work also demonstrates that the Rosin Rammler model reproduces better the distribution of Spray drops by comparing the results of the simulation with the experimental results.*

**Keywords:** CFD, OpenFOAM, Spray-Fuel, GDI

## 1. INTRODUCTION

The internal combustion engine has been used for more than one hundred and forty years to drive cars and vehicles in general. However, the strong environmental appeal and the limitation of fossil fuels are demanding increasingly efficient and less polluting vehicles. Because of these requirements, new technologies and systems are being applied to internal combustion engines to achieve better fuel utilization and lower emission of contaminants. Among the new technologies, the use of direct injection applied in spark ignition engines is highlighted. With the increasing insertion of this technology in the automotive market, the fuel spray is a prime factor since spray formation can occur in an irregular manner, with a wide variety of droplet size, cone angles, penetrations, droplet size distributions, velocity fields and break-up.

In this context, the mathematical models applied to computer simulation are an important tool to meet engineering needs in the improvement and development of new products. It can be noticed that the mathematical models have been used in conceptual projects of new equipment and processes, allowing a reduction in costs in relation to laboratory tests and increase of scale. In addition, its use allows a reduction in the response time in launching or adapting projects.

## 2. NOTATION AND RELEVANT DEFINITIONS

Recent work (Sherman, 2017) half of the United States fleet of automobiles and trucks are equipped with the direct fuel injection system. The concept is quite straightforward, the fuel injector is no longer in the inlet of the intake system and is positioned directly in the combustion chamber. The fuel is injected at the exact moment that combustion is needed instead of having to mix with incoming air and flowing around an inlet valve.

(Baumgarten, 2006) still signals that there are different types of cones, due to variations in the mechanisms of operation of the injectors. The main structures are full cone and hollow cone sprays. A schematic description of a full-cone high-pressure spray is given in Fig. 1.

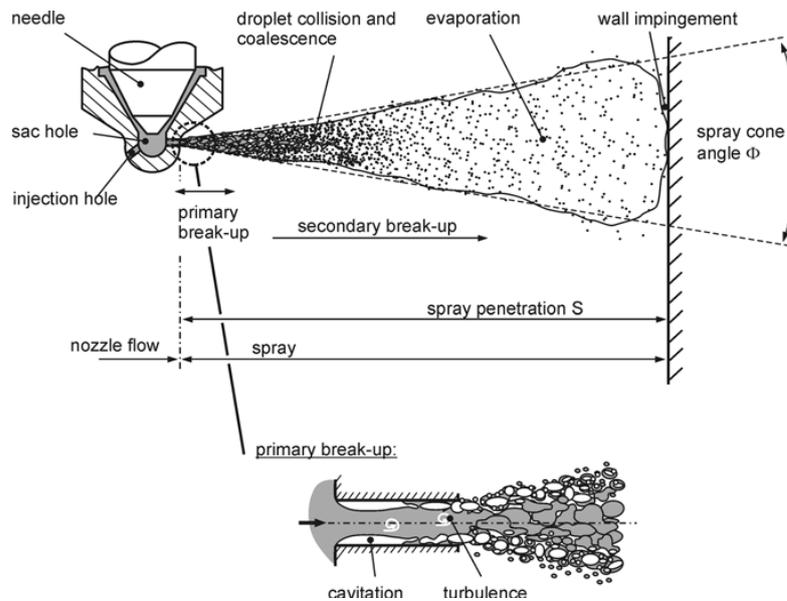


Figure 1. A schematic description of a full-cone high-pressure spray  
Author: Baumgarten (2006)

### 2.1 Dispersion

Recent work (Guzzo, 2017) shows that when at a given instant the volume of liquid within the cone is known, the dispersion of a break can be expressed quantitatively. The degree of dispersion can then be expressed as the ratio of the volume of the spray to the ratio of the volume of liquid contained therein. To achieve maximum dispersion of the liquid at moderate injection pressures and low ambient pressures, hollow conical sprayers are typically used. They are commonly known to produce droplets having small diameters, effective mixing formation, reduced penetration and hence high breaking efficiency. Recently, Lefebvre (2017) has shown that in general, the factors that influence the increase of cone angle also tend to increase spray dispersion.

### 2.2 Penetration

Penetration is defined as the maximum distance reached when the spray is injected into a static atmosphere. As soon as the liquid jet of the atomizer passes through the outlet orifice thereof, external forces of the medium compete with the internal forces of the liquid and surface tensions, and then a destructive process of the liquid film formed in this outlet channel begins. The penetration characteristics of the sprays are important and variable according to the geometry of the combustion chamber. According to Zhao (2002), the penetration characteristics of direct injection gasoline injectors are influenced by some operational parameters, among them are the pressure and density inside the combustion chamber, the injection pressure, the injector temperature and the volatility of the fuel.

### 2.3 Cone Angle

According to Baumgarten (2006), the factor of greatest influence on the cone angle of the conical hollow spray and penetration is the density of the gas with which it comes into contact. However, experiments (Gindele, 2001 and Homburg, 2002) showed that environments of high pressures can considerably decrease cone angle and penetration, in addition to contributing to the increase in the mean diameter of droplets. This behavior is extremely unfavorable for the use of swirl injectors in direct injection engines. Depending on the timing of the injection, the pressure in the

combustion chamber can vary greatly, so that various spray structures can be formed from the same injector, which may compromise the quality of the mixture.

## 2.4 Breakup

The second Fajgenbaum (2013) break-up is characterized by the parameter that measures the distance from the injection orifice to the point where the liquid film begins its rupture in ligaments and ceases to be continuous. Baumgarten (2006) reports that, depending on the relative velocity and properties of the liquid and the surrounding gas, the breaking length of a liquid jet can be controlled by different mechanisms. These different mechanisms are usually characterized by the distance between the orifice of the injector and the first point of formation of the drops, this distance is called break-up.

## 2.5 Mean diameter of the droplets

Recent work (Lefebvre, 2017) shows that sprays droplets of fuel injectors have varying sizes due to interactions between them and their own heterogeneous nature. In order to create a breaking parameter related to spray droplet diameters, a mean diameter was established that could represent a sampled drop group. In this sense, (Mugele and Evans, 1951) proposed a general relationship to determine the mean diameter of spray droplets formed by injectors, according Eq. (1).

$$D_{ab} = \left( \frac{\sum_{i=1}^{\infty} N_i \cdot D_i^a}{\sum_{i=1}^{\infty} N_i \cdot D_i^b} \right)^{\frac{1}{a-b}} \quad (1)$$

Where D is the representative diameter, a and b are the indices that depend on the type of average to be calculated and N is the number of drops of a given sample containing the diameter D.

Recent work (Lefebvre and McDonell, 2017) and (Bayvel and Orzechowski, 1993) the mean diameter is a parameter that provides an assessment of the quality of the break and does not provide information about the drop itself.

## 3. COMPUTATIONAL APPLICATION

This chapter describes the methodology for obtaining results of an investigation into the characterization of the fuel spray of an internal combustion engine using the OpenFOAM software. The models of breaking, evaporation, penetration, droplet dispersion, droplet collision and path definition are set forth and thus intend to predict the main properties of the hollow cone spray of fuel discharged by an injector into the atmosphere. The simulations were performed on a computer with 4 cores, Intel I7-4500U CPU @ 2.39GHz.

As the experimental air velocity is very low, ie around 0.06m/s according to Hemdal (2009), the initial air velocity in the computational domain was estimated at 0m/s. The initial turbulent kinetic energy  $k$  and the turbulence length scale  $lt$  were not measured in the experiments, but the initial  $k$  and the initial turbulent dissipation rate  $\varepsilon = C\mu/lt^{1.5}/lt$  are required input parameters for the  $k - \varepsilon$ . Due to the slow movement of the air in the combustion chamber, the initial was estimated at  $0.1m^2/s^2$ , while the initial  $\varepsilon$  was estimated at  $10 m^2/s^3$  (as shown in Tab. 1). Sensitivity studies will be performed to determine the initial values of  $k$  and  $lt$  due to uncertainty in the above estimates.

The values of the constants in the spray models, the initial and contour conditions used in the present thesis and other standard numerical parameters used in the simulations are presented in Tab. 1.

Table 1. Simulation Conditions.

	TYPE	NAME	CONSTANTS
Mathematical Models	Injetor	Injetor Pintle	$d_{inj}=4mm; d_g=30\mu m; C_d=0.418$
	Primary breakup	Rosin-Rammler	$rm=15\mu m; q=2; q=3$
		LISA	$Cl=1; C\tau=12; Q=0.001; J=1.5E-4$
	Secondary breakup	TAB	$y0=0; \dot{Y}0=0; C\mu=5; C\omega=8; We_{crit}=12$
		Reitz-Diwakar	$Cb=6; Cb=0.785; Cstrip=0.5; Cs=40$
		KHRT	$B0=0.61; B1=40; C\tau=10; Crt=0.1$
Turbulence	k- $\varepsilon$	$C\mu=0.09; C1=1.44; C2=1.92; C3=-0.33; \sigma k=1.0; \sigma\varepsilon=1.3; Prt=1.0$	

	initial internal field	Boundary type	Numerical div-schemes
$K [m^2/s^2]$	1	kqRWallFunction	Gauss limitedLinear 1
$\epsilon [m^2/s^3]$	10	epsilonWallFunction	Gauss limitedLinear 2
$T[K]$	350	zeroGradient	
$p[bar]$	6	buoyantPressure	Gauss linear
$U[m/s]$	0	fixedValue	Gauss limitedLinearV 1
Other Parameters	number of parcels	656.100	
	Spray cone angles	Inner cone angle $40^\circ$	
		Outer cone angle $60.1^\circ$	
	Time step	$5 \mu s$	
	Maximum Courant number	0.5	
Mesh	40x100x40 mm		

To analyze the Rosin-Rammler, RR model, implemented in OpenFOAM, a comparison with the literature is shown in Fig. 2 shows that the results of the OpenFOAM model agree with those presented by Reis (2015).

Both indicated the same behavior and almost the same time penetration, demonstrating that spray simulation models are well implemented as expected.

Table.1. Initial Conditions

Chamber Temperature (K)	300
Chamber Pressure (Pa)	1.0E05
Injection Temperature (K)	320
Injection Pressure (bar)	100
Inner Cone Angle ( $^\circ$ )	40
Outer Cone Angle ( $^\circ$ )	60.1
Mean Mass Flux (g/s)	12.65
Parcels per second	8,000,000

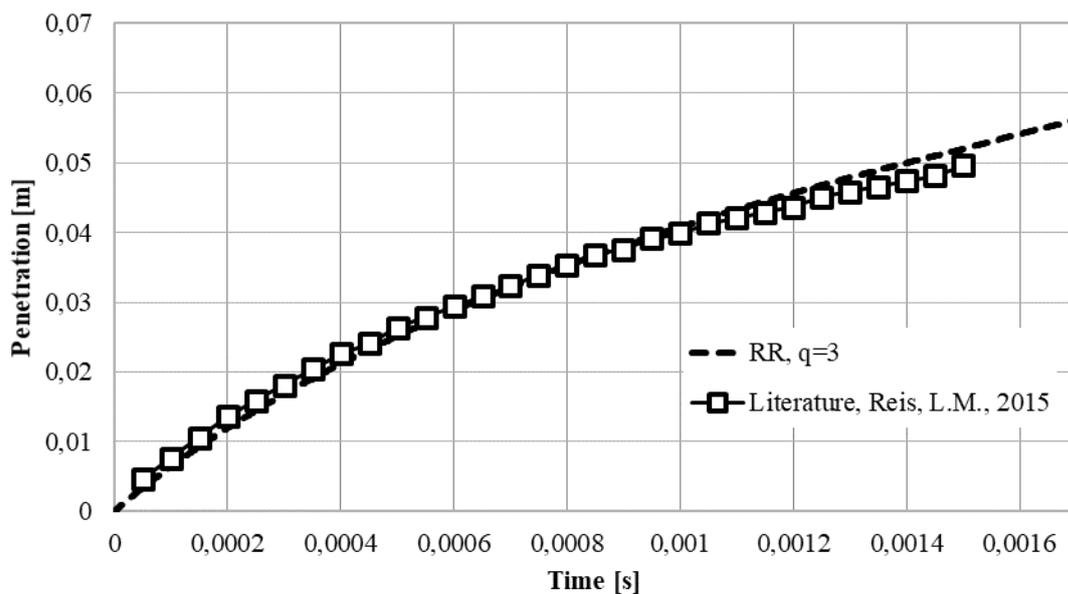


Figure 2. Penetration by time, comparing with the literature.

## 4. RESULTS

This section presents the results of the mesh analysis in a combustion chamber and the numerical results of the fuel spray characterization. These numerical results are compared with experimental data.

### 4.1 Mesh Analysis

The moving mesh technique adopted in this paper has considered that the mesh can be extended or compressed in one direction and the shorter and longer edges can be changed. When using unstructured meshes, aspect ratio is considered an important feature of the mesh. In order to study the sensitivity of the CFD results three sets of meshes were generated with 15, 30 and 45 grid layers in the linear zone of the cylinder. The results obtained in the simulations were little sensitive to the mesh aspect ratio and Reynolds volume-weighted average progress variable and cylinder pressure were not affected by the mesh aspect ratio, as shown in Fig. 3. While Fig. 4 demonstrates the volumetric mesh of the combustion chamber and the gantries.

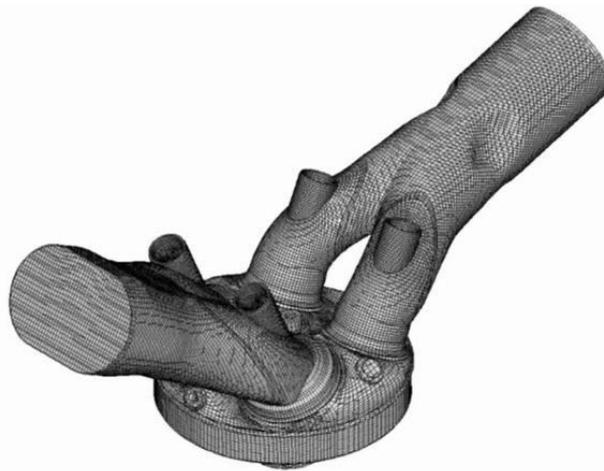


Figure 3. Volumetric mesh of the combustion chamber and gantries.

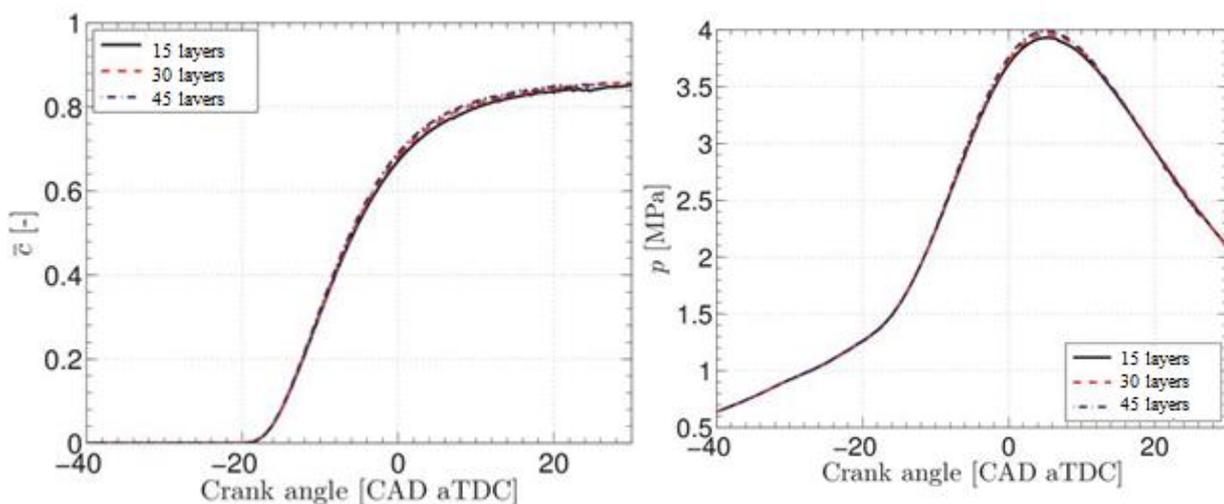


Figure 4. Impact of mesh change on (a) Reynolds local mean progress variable and (b) mean cylinder pressure.

### 4.2 Spray Characterization

Figure 5 shows the results of the analyzed models compared to the experimental data. This graph shows the agreement of numerical data and experimental data. However, the final behavior of the exponential function model indicates overestimated penetration. The curve of the three models suggests an underestimation of penetration in the region between 0.3 and 0.9 milliseconds, mainly due to the experimental behavior of the spray that presented pre-spraying. This pre-spraying is not modeled, therefore, there is some disagreement with the experimental data.

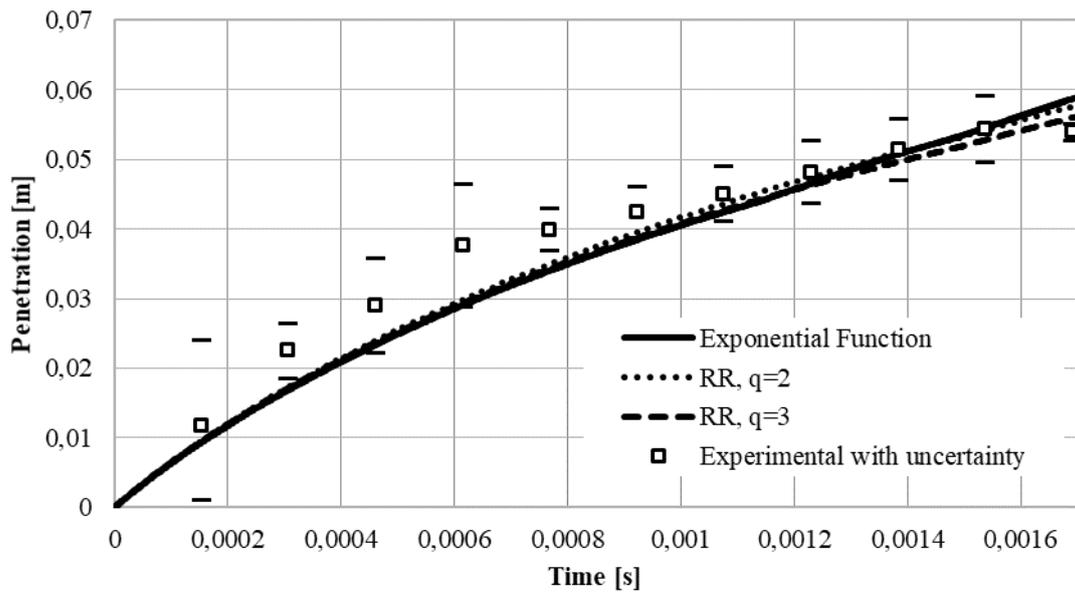


Figure 5. Spray penetration by time, comparison of models with experimental data.

Figure 6 shows the initial drop distribution results for the ethanol spray. This chart shows the different approaches to PDF functions used in the analyzed models. As can be seen, the behavior of Exponential Function and RR are quite different. The dominant droplet diameter in both cases is different, since in the exponential function the frequency peak is close to 0 and the RR function is close to  $30\mu\text{m}$  or  $20\mu\text{m}$  depending on the variable  $q$ .

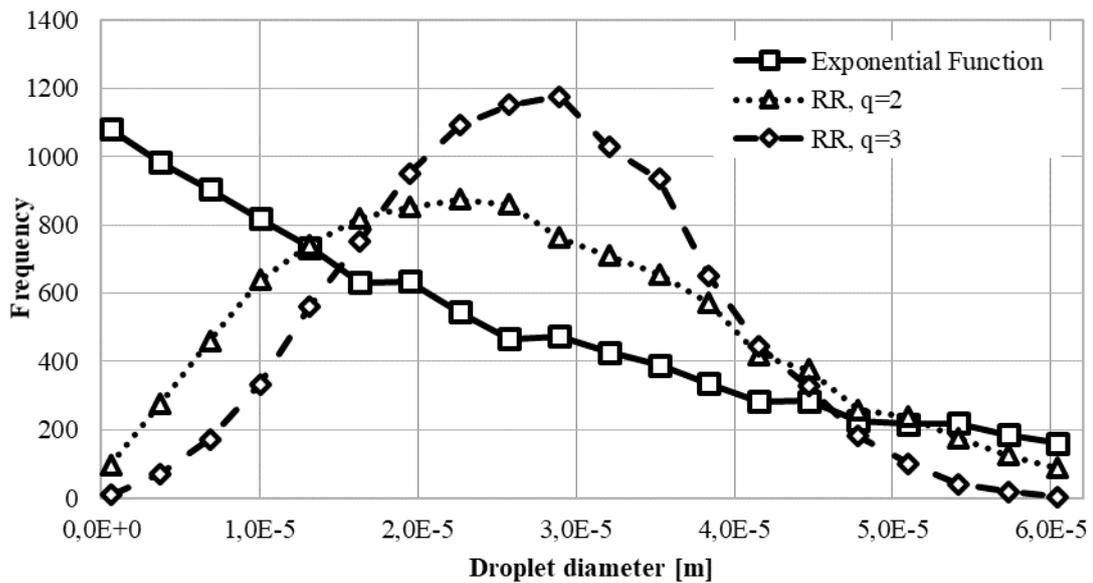


Figure 6. Droplet diameter in the spray plots (Rosin-Rammler,  $q = 2$ ).

Figure 7 illustrates the comparison between the experimental results and the numerical results obtained. In this figure it can be observed that the numerical results are consistent with the experimental data, with a good approximation between them.

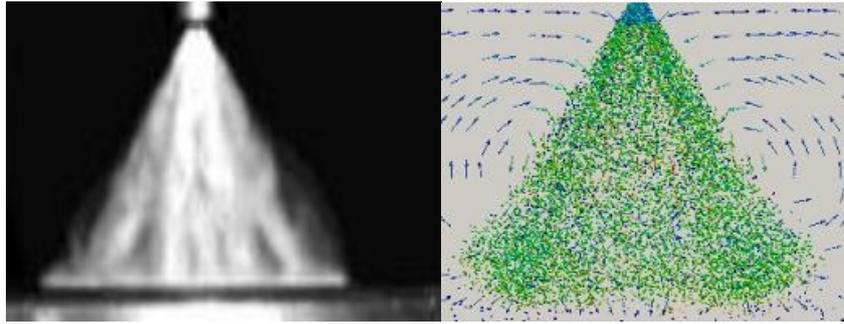


Figure 7. Comparison between spray behavior, numerical and experimental evaluations

## 5. CONCLUSIONS

It was possible to identify the mathematical models present in OpenFoam that describe the spray behaviors. You could see that OpenFOAM is written in object-oriented language in C++ and the hierarchies of its classes are not easy to understand.

Working with the combustion chamber geometry within OpenFoam is difficult and has become unfeasible, so a complementary program has been used to facilitate 3D modeling.

By simulating the models that characterize the spray behavior, it was concluded that the Rosin-Rammler and Exponential methods achieved a good penetration curve compared to the experimental data. The Rosin-Rammler model had the best fit at the end of the curve as the Exponential curve tends to increase, so it is recommended to use this PDF method for spray simulations.

## 6. ACKNOWLEDGEMENTS

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