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Theoretical Modeling and Design of a Coaxial-Swirl Injector and Thruster Components for MMH/NTO-Based Upper Stage Thrusters

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Abstract: Coaxial swirl injectors solve the major problem when it comes to liquid propulsion, which is the mixing of the fuel and oxidizer. It helps by mixing the fuel at an atomic level and making sure that the mixture is even. This paper focuses on the design of an engine with coaxial swirl injector faceplate using hypergolic propellant. The major problem with the hypergolic propellant is that it ignites on contact, but with the help of a coaxial swirl injector we can take it as an advantage by modifying the spray cone angle so that the contact point is at an optimal distance. The work entails the design of a modified coaxial swirl injector for hypergolic propellants which is then integrated into a faceplate with multiple injectors. Then, with the help of the dimensions of the faceplate, the combustion chamber is designed to withstand the simultaneous instant combustion from the multiple injectors, which is then focused onto the custom-designed nozzle to maximize the output thrust.

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1. Introduction

Among the multiple types of bipropellants used in spacecrafts, MMH/NTO is unique due to its ability to ignite spontaneously and be stored long-term and provide greater thrust than a normal propellant. These features make MMH/NTO ideal for spacecraft tasks, such as orbital adjustments and attitude corrections. Their hypergolic behavior (self-igniting) minimizes the need for additional ignition components, which helps in simplifying the design of the chamber and nozzle and enhance overall reliability in crucial vacuum and outer space missions. Even though these propellants are widely used, the heat flux characteristics within the hypergolic thrusters remain complex and not fully understood and characterized. The chamber walls face extreme temperatures during operation, and predicting the thermal load is crucial and vital for material selection and design optimization, which contributes to stable and efficient combustion. Understanding how and where heat builds up helps engineers select appropriate materials, ensure the stability of the structure, and integrate effective thermal control systems. With the development of the CFD tools, it is possible to model the chemical reactions and heat distribution with outstanding precision and accuracy, and they can be simulated in 3D, which helps in a better understanding of the fuel properties. Even though multiple CFD simulations are developed, many simulation efforts rely on assumptions of heat transfer and steady combustion, missing out on how heat concentrates around the injector during the swirl and recirculation effects. It is rare to see studies that combine chemical reactions, flow dynamics, and material behavior in one complete model that can truly guide the design process. This paper presents a 3D simulation about how hypergolic propellants react and combust and studies their flow behavior using Ansys Fluent. A coaxial swirl injector is introduced to enhance the propellant mixing rate, hence improving the combustion stability. The primary objective is to study how the heat flux spreads across the injector faceplate and the walls of the chamber and nozzle under

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realistic conditions. These findings are intended to help in the support of better thermal design of compact bipropellant rocket engines and guide future efforts in developing durable, sustainable, efficient rocket engines integrated with hypergolic propellants.

2. Case Studies

The performance parameters of bipropellant thrusters which use MMH/NTO as an oxidizer and fuel combination are a subject of deep investigation as they are critical in the role of spacecraft propulsion. Various studies have contributed valuable insights into injector flow dynamics, combustion analysis and exhaust flow behavior, each of them elaborating on high-temperature hypergolic combustion.

2.1 Fuel Properties

The study performed by Noor Muhammad, elaborates that MMH (874 kg/m^3) provides high thermal stability and NTO (1431 kg/m^3) is an oxidizer that is highly dense and easily stored in the spacecraft's volume as it is very compact and has a very low boiling point. The optimum oxidizer-fuel ratio range is about 1.6 to 2.46 and high combustion temperatures of up to 3385K generate heavy heat flux near the injector and throat. High-temperature alloys like C-103 (Columbium) and Inconel 718 are chosen to withstand thermal stress (Hou.et.al.2018, Zhao.et.al.2024).

Table 2.1. Fuel Properties of MMH and NTO propellant combination

Details	**Values**
Propellant Combination	
Optimum O/F Ratio	1.6 – 2.46
Combustion Temperature	3385 K
Density	1200 kg/m^3
I_{sp} (sea level)	2825 N-s/kg
I_{sp} (vacuum)	3296 N-s/kg
N_2O_4	
Density	1431 kg/m^3
Freezing Temperature	11°C
Boiling Temperature	21°C
Viscosity	0.00043 kg/m-s
Thermal Conductivity	0.153 W/m-K
Specific Heat (Cp)	0.743 kJ/kg-K
MMH	
Density	874 kg/m^3
Freezing Temperature	-52°C
Boiling Temperature	87°C
Viscosity	0.00087 kg/m-s
Thermal Conductivity	0.205 W/m-K
Specific Heat (Cp)	2.235 /kg-K

2.1 Combustion Chamber

The study done by a similar research paper (Muhalim.et.al.2009), explained that the combustion chamber is designed to produce 450N thrust using MMH/NTO as fuel and oxidizer. A simple cylindrical chamber design seemed optimal and efficient in manufacturing. Columbium alloy (C-103) has been used as the chamber material due to its outstanding temperature tolerance and oxidation resistance under simultaneous combustion. Initial wall thickness of 2 mm was considered using a basic pressure determination formula. These design parameters affect the heat transfer in high stress regions such as the throat, nozzle and the injector faceplate, which are critical to determining thermal loads in the chamber design.

Table 2.2. Formulae used to calculate Combustion Chamber and Propellant Tank Dimensions

Parameter	**Formula**
Throat Diameter	$d_t = \sqrt{4F/\pi C_{F\,exp} P_C}$ ---> (Eqn 2.2.1)
Combustion Chamber Wall Thickness	$t_c = P_C R_C FS/\boldsymbol{\sigma_y}$ ---> (Eqn 2.2.2)

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Nozzle Expansion Ratio	$\varepsilon = (D_e/D_t)^2$ ---> (Eqn 2.2.3)

2.3 Thruster Simulation

A related paper (Lee.et.al. 2019) explained the disadvantages of assuming the equilibrium conditions during combustion and came up with a more optimal four-step global kinetic reaction model for hypergolic combustion. The flow was studied by simulating with a solver that combined Navier-Stokes equations within the chamber and Direct Simulation Monte Carlo (DSMC) techniques for expanded flow in vacuum. This approach identified crucial deviations in species distribution and thermal when compared to perfect and ideal conditions. This created a need for a chemical kinetic model clearly when solving flow impingement effects and mitigating spacecraft risks.

2.4 Coaxial Swirl Injector

This research paper by (Kim.et.al.2011) carried out an in-depth conceptual study of dual liquid coaxial swirl injectors to estimate the dimensions and oxidizer fuel ratio, which affects the propellant mixing rate and mass flow rate and the internal flow. Using non-reactive flow tests considering water as a simulation fluid, they observed fluid sheet thickness and analyzed flow characteristics in the combustion chamber and nozzle exit area. Their results revealed that accurately modifying the offset length leads to lean and steady fluid sheets and enhances the spray breakup point. At the other extreme, excessive offsets caused unsteady behavior, and there was deviation in ignition stability. This work highlights the crucial role of refining the injector configuration to maintain continuous, uniform, stable mixing and combustion in spontaneously igniting propulsion systems (Song.et.al.2021, Ohminami.et.al.2009, Nagesh.et.al.2024)

Table 2.3. Formulae used for Injector Design

Parameter	**Formula**
Injector Mass Flow Rate	$\dot{m} = \rho A V$ ---> (Eqn 2.3.1)
Discharge Velocity	$V = C_d \sqrt{2\Delta P/\rho}$ ---> (Eqn 2.3.2)
Mass Flow Rate per Injector	$\dot{m}_{inj} = \dot{m}_{total}/N$ ---> (Eqn 2.3.3)
Tangential Slot Mass Flow Distribution	$\dot{m}_{slot} = \dot{m}_{inj}/N$ ---> (Eqn 2.3.4)
Area of Rectangular Tangential Slot	$A = w \times h$ ---> (Eqn 2.3.5)
Oxidizer/Fuel Velocity from Mass Flow	$V = \dot{m}/\rho A$ ---> (Eqn 2.3.6)

2.5 Nozzle

This research provided the essential groundwork in nozzle engineering and design through their analysis and study of bell-type profiles using the Method of Characteristics (MoC). This study offers performance optimization charts across various expansion ratios, which enables engineers to identify nozzle shapes that help in the enhancement of thrust while mitigating energy losses and physical design constraints. The insights from this study are highly relevant in the context of vacuum-related propulsion systems, where nozzle geometry directly affects the specific impulse, efficiency and thermal stress handling (Tuttle.et.al.1983).

3. Methodology

This section elaborates about the structured approach that combines design, calculation, simulation procedures to study how the heat is distributed in an MMH/NTO based hypergolic rocket thruster. The objective is to generate 80 kN of thrust while studying and understanding the pressure and temperature effects using Ansys Fluent analysis.

3.1 Estimation of Thrust Required

The design process started by defining a target thrust of 80 kN which is appropriate for upper stages or satellite control units. This was inspired by the Superdraco engine developed by SpaceX that produces a comparative level of thrust in the same type of hypergolic system. It demonstrated the capability for rapid ignition and greater thrust in a compact configuration. This was the main benchmark for this study. This value of 80 kN aligns with the standard mission objectives, demands and realistic propulsion parameters.

3.2 Mass Flow Calculation

With the output thrust determined, the necessary mass flow rate of the fuel and oxidizer were obtained using standard propulsion formulae. The O/F ratio was set at 1: 2.46, which was found to be similar with multiple published papers and data, and used to divide the total mass flow into its respective components. The breakdown of the mass flow determination is as follows:

Taking the thrust value to be 80 kN and converting it into kilograms (kg) for ease of calculation, which enables straight-forward calculation of mass flow rate. From the literature survey, the sea level specific impulse is 285 seconds, which was chosen. This value depicts the efficiency of MMH/NTO engines under atmospheric conditions.

Table 3.1. Formulae used in Mass flow calculation

Parameter	**Formula**
Mass flow rate of Propellant	$\dot{m}_p = F/I_{sp}$ ---> (Eqn 3.2.1)
Mass flow rate of Fuel	$\dot{m}_f = \dot{m}_p/1+O/F$ Ratio ---> (Eqn 3.2.2)
Mass flow rate of Oxidizer	$\dot{m}_o = \dot{m}_p - \dot{m}_f$ ---> (Eqn 3.2.3)
Mass of Fuel	$M_f = \dot{m}_f \cdot \Delta t$ ---> (Eqn 3.2.4)
Mass of Oxidizer	$M_o = \dot{m}_o \cdot \Delta t$ ---> (Eqn 3.2.5)

Using eqn 3.2.1 from table 3.1, we get the total mass flow rate of propellant as $\dot{m}_p$ = 28.623 kg/s. Considering the oxidizer and fuel ratio (O/F Ratio), we find the mass flow rate of fuel and oxidizer using eqns 3.2.2 and 3.2.3 from table 3.1. Assuming the O/F Ratio as 2.46 from fuel properties table 2.1, we get $\dot{m}_f$ = 8.275 kg/s and $\dot{m}_o$ = 20.348 kg/s. Typically, in the middle stages of rocket engines, the burn time (Δt) is in between the range of 140s-180s. As this is the optimal range for the rocket engine we have designed, we assumed the value of burn time (Δt) to be around 160 seconds. Considering this burn time value, we estimated the mass of fuel and oxidizer separately using the eqns 3.2.4 and 3.2.5 from table 3.1. The values obtained are M_f = 1324 kg and M_o = 3255 kg. Adding up these values we get the total propellant mass as M_p = 4579 kg. The calculated mass flow rates and total propellant masses were used to determine the tank pressure, number of injector elements, combustion chamber dimensions and volume. These values are used as input in Ansys Fluent simulations.

3.3 Propellant Tank Volume and Wall thickness Estimation

Table 3.2 Formulae used for Fuel Tank Pressure and Wall Thickness

Parameters	Formula
Volume of Oxidizer	$V_o = M_o/\rho_o$ ----> (Eqn 3.3.1)
Volume of Fuel	$V_f = M_f/\rho_f$ ----> (Eqn 3.3.2)
Density kg/m^3 to kg/l Conversion	1 kg/m^3 = 0.001kg/l ----> (Eqn 3.3.3)
L to m^3 conversion	1L = 0.001 m^3 ----> (Eqn 3.3.4)
Volume of Cylinder	$V= \pi r^2 h$ ----> (Eqn 3.3.5)
Thickness of Tank Wall	$t = P_{T1}RFS/\sigma_y$ ----> (Eqn 3.3.6)

Before the volume calculation, the density of both the fuel and the oxidizer was converted from kg/m3 to kg/l based on eqn 3.3.3 from table 3.2. Considering the mass of propellant found in the steps before and the known density of MMH and NTO from table 2.1, the volume of each propellant was separately calculated using eqn 3.3.1. The values obtained were 1514.87 L and 2253.66 L for MMH and NTO respectively.

The obtained volume values are now converted from L to m3 using eqn 3.3.4 in order to determine the fuel tank dimensions. Considering that each propellant is stored separately in their respective cylindrical tanks, the radius and height of the cylinder were found by rearranging the eqn 3.3.5 from table 3.2 with respect to the obtained volume value. After multiple iterations and solving to estimate the optimal radius and height for the fuel tanks, r = 0.5m and h = 4.5 m for the oxidizer tank and r = 0.5m and h = 3.2m for the fuel tank are the chosen values.

To make sure that the structural integrity of the tank under load, the wall thickness was evaluated using eqn 3.3.6 from table 3.2. After studying the material meticulously, the values for Factor of Safety, Tank pressure and Yield Strength of Aluminum 7075 were approximated and assumed to be 1.5, 3.5 MPa and 505 MPa respectively.

3.4 Injector Design Calculations

To ensure better mixing and stable combustion, coaxial swirl injectors were selected. The total mass flow rate is divided equally between all the injectors. For the mass flow rate considered, we are using 4 injectors positioned on a face plate (Lee.et.al.2024, Lecourt.et.al.2024) The fuel and oxidizer outlets were calculated using basic geometric formulae and fluid equations. The total mass flow rate of fuel and oxidizer to produce 80 kN thrust is 8.275 kg/s and 20.348 kg/s respectively, which was obtained in the mass flow calculation section. This total mass

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flow rate value is evenly distributed. As we are using 4 injectors, the mass flow rate of each injector is obtained to be 2.06875 kg/s and 5.087 kg/s for fuel and oxidizer respectively, using the eqn 2.3.3 from the table 2.3.

The exit velocity of the both fuel and oxidizer was calculated using the eqn 2.3.2 and was found out to be 63.462 m/s and 49.59 m/s respectively. With the existing values of mass flow rate, density and exit velocity, the exit area was found by rearranging the equation 2.3.1 from the table 2.3, which gave us the outlet area of the fuel as 0.0000372 m^2 and outlet area of oxidizer as 0.0000716 m^2.

Using the area of circle, the fuel outlet diameter was calculated to be 6.88 mm. As this is a coaxial swirl injector, the oxidizer flows around the fuel region and the oxidizer area is the area between outer and inner diameters. The inner diameter which includes the fuel outlet and wall thickness which is taken as 9.88 mm. The total outer diameter required to get the oxidizer area was estimated to be 13.74 mm.

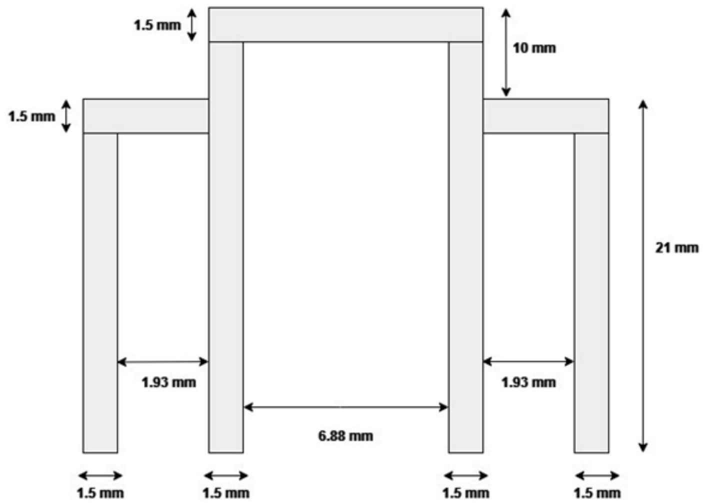

Fig 3.4.1 2D Sketch of the estimated Coaxial Swirl Injector Design

3.4.1 Injector's Fuel & Oxidizer Slot Design and Velocity Calculation

To achieve efficient mixing and proper flow of the propellant in the coaxial swirl injector, rectangular slots were added into the fuel and oxidizer inlet regions of each injector. Each injector is cylindrical, and the slots are placed into the curved surface of the cylinder. Each injector contains 4 fuel slots and 6 oxidizer slots which are placed equidistant from each other. The mass flow rate of each slot was calculated using eqn 2.3.4 from table 2.3. The calculated values of fuel and oxidizer slot's individual mass flow rates are 0.517 kg/ s and 0.847 kg/ s independently. For these estimated values of mass flow rate, we need to determine the rate at which the fuel and oxidizer have to be injected. The velocity through each slot was set up using eqn 2.3.2 from table 2.3. The velocity values were set up to be 63.462 m/ s and 49.59 m/ s for fuel and oxidizer independently.

Using eqn 2.3.6 from table 2.3, the area of the fuel slot and oxidizer slot were determined individually. The values are 9.34 mm^2 and 11.7 mm^2 for fuel and oxidizer respectively. Assuming the slot width is 1.5 mm, the required length of the slot was computed by rearranging the eqn 2.3.5 from table 2.3, we get 6.2 mm for the fuel slot and 7.96 mm for the oxidizer slot.

The injector is made up of 2 concentric cylinders in which the inner cylinder is the path of the fuel and the outer cylinder is the oxidizer path. The total injector length is 31 mm, the outer cylinder (oxidizer) length is 21 mm and the inner cylinder (fuel) extends 10 mm above the outer cylinder, which makes its total length 31 mm. The fuel slots placement is located within the lower 6mm of the 10 mm extended region. The oxidizer slots are placed 16 mm above the injector's exit. This ensures the separation of fuel slots for safer flow and swirl connection.

3.5 Face Plate Design Description

The design process for the injector commenced with the determination of the spray cone angle. This angle is of critical importance for the computation of inter-injector spacing, which is necessary to preclude spray overlap and subsequent flow interference. Such interference can result in incomplete and unstable combustion processes. Four injectors were arranged symmetrically in a square configuration to ensure optimal propellant distribution within the combustion chamber. An outer diameter of 300mm was selected to correspond with the dimensions of the combustion chamber, coupled with an inlet diameter of 250mm. Each injector incorporates designated fuel and oxidizer ports, possessing diameters of 9.88mm and 13.74mm, respectively. These ports are precisely positioned on the injector faceplate. The faceplate is constructed of three inner layers, measuring 2mm, 2mm, and 3mm, respectively, and an outer wall with a thickness of 5mm. The fuel inlet is offset 0.9mm superior to the center layer, while the oxidizer inlet is situated 5mm inferior to the same. The total height of the oxidizer compartment, inclusive of all material layers, is 21mm. The injector nozzles extend 1.04mm from the faceplate (Yu.et.al.2024).

3.6 Combustion Chamber and Nozzle Design Calculation

This segment covers the process of designing and sizing the combustion chamber and nozzle based on the Characteristic Length (L*), Nozzle Expansion Ratio (ε) and pressure constraints. The parameters such as chamber length, throat and exit diameter and wall thickness were calculated, ensuring the structural integrity and thermal stability of the body. The chamber and nozzle design were based on the standard calculation using a characteristic length which is assumed to be 1m, that contributes to sufficient time and volume required for complete combustion. This length must be thrice the chamber diameter, so that we get the chamber diameter of 0.3m. The characteristic length is separated into two different sections; the combustion chamber section, which is 0.55m, and a converging section, which is 0.45m. Continuing this step, the diverging section of the nozzle from the throat to exit was designed with a length of 0.35m. The throat diameter is calculated using eqn 2.2.1 from table 2.1. The nozzle expansion ratio was assumed to be 25 as that is the optimum value, so the exit diameter was calculated using eqn 2.2.3 from table 2.2 with the throat diameter value obtained from the previous step. The values for exit and throat diameters are 0.44m and 0.088m respectively. The total engine length includes both the chamber and nozzle section, which is 1.35m in total. To maintain the structural strength, the thickness of the chamber and nozzle was determined using eqn 2.2.2 from table 2.2. Based on the pressure and yield strength of the material chosen, the required thickness was found to be 10mm.

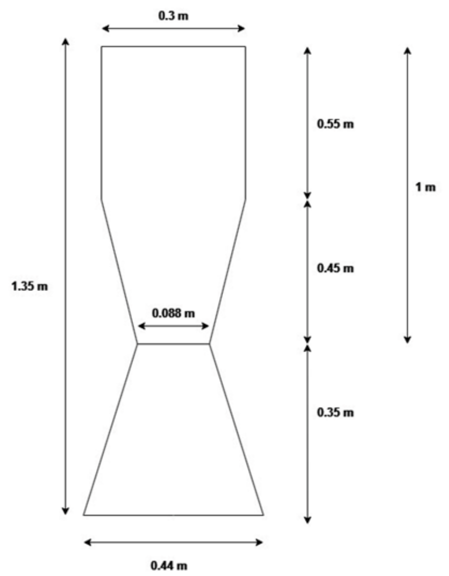

Fig 3.6.1 2D Sketch of the estimated Combustion Chamber and Nozzle Design

4. Result and Discussion

To control hypergolic MMH/NTO propellant flow, the swirl-coaxial injector was developed analytically using a combination of empirical and momentum-based equations. The chosen diameters of the inner oxidizer and outer fuel orifices considered the desired mass flow rates and swirl intensity. The swirl number, which influenced the cone angle and the quality of atomization, was established through a theoretical examination of the tangential and axial velocity components within the swirl chamber. Calculations indicated that an ideal swirl number ranging from 0.6 to 1.0 produced a consistent hollow cone spray. The resulting swirl cone angle ensures sufficient spray distribution and prevents sprays from adjacent injectors, arranged in a square layout from intersecting. The cone angle is found to be approximately 60 to 65 degrees. In the constrained upper-stage chamber design, this configuration reduces the risk of combustion instability and enhances effective mixing. Further research of the propellant flow through the injector assembly was conducted to ensure the accurate prediction of static and dynamic pressure drops. From the predicted pressure drop values and chamber inlet conditions, it was determined that the injectors can provide consistent mass flow rates required for the thrust output of typical upper-stage applications. The design supported a chamber pressure of 8.1 MPa, with flow velocities in the injector outlet reaching supersonic speeds post-spray. These theoretical results matched well with previous experimental injector performance datasets from the literature, confirming the reliability of the model. The O/F ratio was kept at 2.46, ensuring standard combustion efficiency while reducing hot spot formation along the chamber walls. This theoretical model lays a solid groundwork for adapting the injector system to suit the demands of middle-stage rocket engines, where higher thrust and stronger combustion stability are essential. By adjusting orifice diameters and increasing the number of injector elements, while retaining the optimized swirl cone angle—the design can manage greater propellant flow without compromising spray uniformity. As it can adjust to different chamber pressures, it is ideal for a range of mission types. In larger combustion sizes, the symmetrical square arrangement of the injectors facilitates uniform flame distribution and decreases the likelihood of interference between neighboring flows. This study provides essential insights into the injector's performance capabilities for advanced propulsion systems before advancing to CFD models and experimental testing.

5. Conclusion

Theoretical models were calculated to design a coaxial-swirl injector for MMH/NTO-based propellants, producing safe and efficient combustion in upper-stage thrusters. The injector parameter values were determined analytically and mathematically, by considering the swirl cone angle, orifice dimensions, and mass flow conditions to assure the complete mixing of propellants and maintain ignition stability. Design constraints were evaluated, and MMH/NTO is hypergolic, allowing for no external energy input during ignition to meet these design constraints. Calculations of swirl-induced flow dynamics provided information about the spray behavior and mixing quality within the chamber. It supports a compact and efficient design for the injector, which can optimize thrust performance. These findings form the basis on which this injector configuration can be adapted to use in middle-stage engines, and with future studies using CFDs and experiments, may improve performance.

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7. Conflict of Interest

The author declares no competing conflict of interest.

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