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MODELLING AND SIMULATION OF THE COMBUSTION OF BIODERIVED FUELS IN A PT6A-27 TURBOPROP ENGINE

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ABSTRACT---
The motivation for venturing in alternative jet fuels has partly been due to the elevated level and volatility of the price of Jet A and environmental impacts on global climate change and air quality. The model of the annular combustor for the PT6A-27 engine was created using SOLIDWORKS and exported to ANSYS DESIGN MODELER. Creation of the computational mesh for the geometry using ANSYS MESHING was done in preparation for the setting up of the CFD simulation in ANSYS FLUENT. The simulation included, setting material properties and boundary conditions for a non-premixed combustion problem. Initiating the calculation with residual plotting, calculating the solution using the pressure-based solver and visually examining the flow and temperature fields using the post-processing in ANSYS FLUENT with the Standard k-ε 2 equation turbulence model used.

The fuel blend from the range of 30% bioethanol and 70% biodiesel (BE30-BD70) to 70% bioethanol and 30% biodiesel (BE70-BD30) indicated a combustion characteristic consistency with that obtained from the combustion of Jet-A1. Further, from the comparisons of the blends in terms of performance and single biofuel combustion simulation the best blend combination was 40% bioethanol with 60% biodiesel (BE40-BD60) whose adiabatic flame temperature was about 2260 Kelvins.

The blend of 40% bioethanol to 60% biodiesel was observed to have a reduced Fuel NOx footprint and the observed production rate values of Thermal NOx were a range of to Whereas a pure JetA-1 hydrocarbon fuel had a production rate of Thermal NOx ranging from to . This was indicative of a reduction in Thermal NOx when the two groups of fuels (Jet-A against 40BE & 60BD blend) were compared.

These results showed that reduction of NOx emissions is achievable for a blend of 40% bioethanol and 60% biodiesel in a combustion reaction as a substitute for the hydrocarbon JetA-1 in the PT6A-27 turboprop engine.

KEY WORDS—*PT6A-27, nonpremixed Combustion, NOx, Turbulence model*---

1.0 INTRODUCTION

THE aviation sector currently accounts for around 2% of man-made global greenhouse gas emissions. Though this represents a relatively small share compared to other modes of transport such as road transport. However, aviation is the fastest growing transport mode and is projected to grow by around 4% to 5% annually by 2050, [1], [2], [3].

The motivation for venturing in alternative jet fuels has partly been due to the elevated level and volatility of the price of Jet A (a kerosene-based aviation gas turbine fuel) and environmental impacts on global climate change and air quality, [4], [5].

In 2008 aviation industry was the first transport sector to set targets for cutting its carbon emissions. They set out their short, medium and long-term goals. Sustainable alternative fuel will play a significant role in achieving the industry's long-term emissions reduction goal, [6].

The engine and commercial aircraft research and development communities have been investigating the practicality of using alternative fuels in near, mid, and far-term aircraft. Presently, it appears that an approach of using a "drop in" jet fuel replacement, which may consist of a kerosene and synthetic fuel blend, will be possible for use in existing and near-term aircraft. Future mid-term aircraft may use a bio-jet and synthetic fuel blend in ultra-efficient airplane designs. Future, long-term engines and aircraft in the 50-plus year horizon, may be specifically designed to use a low or zero-carbon fuel, [7].

Jonathan *et al* (2013) simulated the use of alternative fuels in a turbofan engine. As the push to make the use of biofuels becomes more pervasive in the airline industry continues, it is important to understand their broader impact, [8]. A positive example of the engine performance simulations using C-MAPSS40k had demonstrated the thermodynamic compatibility of biodiesel with existing engines. In this study the 100% biodiesel combustion simulation equally showed thermodynamic stability, however, due to the expected higher levels of NOx emissions from biodiesel, [9].

The experimental study by Saifuddin *et al* (2017) on the performance and emission characteristics of micro gas turbine engine fueled with bioethanol-diesel-biodiesel blends proposed B80E20 (80:20 of biodiesel-bioethanol) blend to be selected as an ideal blended fuel. The performance test in the micro gas turbine was limited up to 20% blend of biofuel, which showed improved thermal efficiency during the test. Subsequently, the emission test carried out in this work also showed significant enhancement in emissions, except nitrogen oxides (NOx) which contributed to the higher formation in comparison with the distillate diesel, [10].

The ratio to be applied in micro gas turbine engine due to its adaptability to replace diesel fuel, while showed better performance and emission properties as compared to the pure petroleum diesel,[10]. This research however proposes that the ratio of 40% bioethanol and 60% biodiesel blend is suitable for use in the PT6A-27 annular combustor as a substitute for Jet A1 hydrocarbon fuel.

The scope of this research did not take into account the phase separation in the proposed blends and any precipitation presence in the blend nor did the research attempt to modify fuel lines, nozzle configurations and perforations as proposed by Laranchi *et al* (2013), who concluded that a modified injector and the dilution air holes overall area were sufficient to achieve a comparable power and efficiency in relation to substituting Natural gas with bioethanol, [11].

2.0 OBJECTIVES

To determine engine combustion performance characteristics if powered by bio derived fuels, without any modification to the PT6A-27 gas turbine engine annular combustor through the following specific objectives.

- To model and simulate combustion properties of bio-derived fuels in a PT6A-27.
- To determine the adiabatic flame temperature and compare the performance of the simulated results to those obtained in practical situations.
- To determine the levels of NOx emissions from bioethanol, biodiesel and compare with emissions produced from Kerosene based jet fuels as obtained from similar literature results.

3.0 METHODOLOGY

3.1 Overview

The modelling and simulation of combustion of bioethanol and biodiesel blend in a PT6A-27 Turboprop annular combustor involved two general procedures of, modelling the annular combustor in SOLIDWORKS CAD Software and subsequently running ANSYS-FLUENT. The specific parameters to be assessed included: Thermal stability, Adiabatic flame temperature and Emissions.

3.2 Simulation Methods

The PT6A-27 Turboprop annular combustor simulation was done using a non-premixed model. The reaction was modeled using the non-premixed combustion model. The combustion simulation approach for bioethanol, biodiesel and their blends using the non-premixed combustion model for the reaction chemistry as outlined by,[12] Tu et al (2008), were used.

Step 1: Creation of geometry

The first step was to create a 3-D geometry of the annular combustor in SOLISWORKS based on the equations as proposed by Melconian and Modak (1985) [13]. The other input data which included the gravimetric flow rate of air and fuel, the turbine inlet temperature and compressor exit temperature was obtained from the operating parameters of the PT6A-27 engine [14]. The created geometry was sectioned at 25 degrees, for the purpose of computational economy.

Step 2: Mesh Generation
The Mesh was created in ANSYS MESH, [15] with number of elements and nodes at 2.639487×10^6 and 5.00298×10^5 respectively.
Step 3: Selection of physics and fluid properties
The selection of physics and fluid properties included the activation of different models to aid in running a non-premixed combustion simulation. The energy equation was activated as well as the standard k-εpsilon (2 equation) under the viscous model coupled with the enhanced wall treatment.
Step 4: Specification of boundary conditions
To obtain a unique solution to this combustion simulation, the boundary conditions were set as shown in table 3.1. The gravimetric fuel flow rate, and air flow rate was set at 0.142 kg/s and 2.0 Kg/s respectively. The turbulent kinetic energy and turbulent dissipation rate were set to 1 m^2/s^2 and 1 m^2/s^3
respectively.

Table 3. 1 : Boundary condition parameters for unique solution

parameter	value	units
$\dot{m}_3$ (Air flow rate)	2.0	Kg/s
T_3 (Fuel inlet temperature)	315	K
P_3 (Combustor initial pressure)	1.0	Pa
$\dot{m}_f$ (Fuel flow rate)	0.142	Kg/s

Step 5: Initialization and solution control
The fifth step of the simulation involved two prerequisite processes within the solver, which are initialization and solution control. Firstly, the iterations were set at 1000 iterations with a backflow temperature of 1000 K to avoid shut down of the software during simulation. The relaxation factors were set at 0.2 and 0.8 for density and body forces respectively.
Step 6: Monitoring convergence
The iteration converged at 500 iterations from the commanded 1000 iterations. All the indicative lines including governing equations such as the continuity line, energy equation line converged at half the commanded iterations.

4.0 RESULTS AND DISCUSSION

The sectioned combustor at 25 degrees as shown in fig. 1. With the resulting meshed geometry in fig. 2. are presented. The varying combustion simulation proportions of biofuels ranging from 100% bioethanol and 0% biodiesel to 100% biodiesel and 0% bioethanol were used. The biofuels were varied at 10% reduction intervals in bioethanol and 10% increment in the biodiesel.

Fig 3. shows the simulated combustion of JetA-1 via surrogates. The recirculation and primary zones show a high-level activity of combustion with adiabatic flame temperature around 2320 K. This model's adiabatic flame temperature result can be considered a safe reference for the biofuel blends used in this study based on experimental studies undertaken by Xu et al (2015) for the National Jet Fuel Combustion Program where they tested 9 different Kerosene based Aviation fuels and reported the range of adiabatic flame temperature of 2280 K to 2300 K, [16]. these experiment results on adiabatic flame temperature by were used as validation.

The combustion simulation for a non-blend of 100% bioethanol as shown in fig. 4. with temperature contours in the recirculation zone did not show higher temperatures distribution as expected for the recirculation zone. This can be attributed to the low specific heat content of bioethanol. Similarly for the 80% bioethanol and 20% biodiesel blend, the temperature distribution was observed to be higher in the dilution zone and recirculation zone. The primary zone temperature distribution was not consistent with the annular combustor temperature distribution. Blending of biofuels from the range of 70% bioethanol and 30% biodiesel (70BE-30BD) to 30% bioethanol with 70% biodiesel (30BE-70BD) including 100% non-blend fig. 6. biodiesel had the temperature contours distribution and the adiabatic flame temperatures showing a consistence in comparison with the combustion of JetA-1.

This research, however, proposes for the blend ratio of 40% bioethanol and 60% biodiesel blend with a reported adiabatic temperature value of 2260 K as substitute fuel for JetA-1 hydrocarbon fuel.

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The levels of NOx emissions were determined through consideration of the different types of NOx emissions namely: Thermal NOx, Fuel NOx and Prompt NOx. From the fuel composition, Fuel NOx is evidently higher in the conversional Jet fuels. However, it was observed that an increase in the Adiabatic Flame Temperature directly increased the levels of Thermal NOx. The blend of 40% bioethanol to 60% biodiesel was observed to have a reduced Fuel NOx footprint. It was further observed that the rise in the calorific energy content of the fuel blend due to the presence of biodiesel in the mixture contributed to the increase in Thermal NOx production, albeit still less than that obtained from a pure hydrocarbon fuel of JetA-1 as shown in figures 7 and 8.

In another study Silitonga *et al* (2018) published the findings of their study. They stated "the effect of bioethanol-diesel blends on engine performance characteristics had been studied, and it is found that these blends significantly reduce the exhaust emissions of compression ignition engines. It has been proven in previous studies that these blends improve the cetane number (and thus, ignition quality), which reduces the carbon monoxide (CO) and NOx emissions, as well as smoke opacity, [17]. Despite this study by Silitonga *et al* (2018) not being a study on gas turbine engines, the combustion characteristics remain the same irrespective of the reacting chamber geometry. This study validates, the numerical simulations of this research on the NOx emissions

A pure JetA-1 hydrocarbon fuel had a production rate of Thermal NOx ranging from $0.002699526\ \mathrm{Kgmol/m^3\ s}$ to $0.002705489\ \mathrm{Kgmol/m^3\ s}$. Whereas for the biofuels blend at the proportions of 40% bioethanol and 60% biodiesel, the observed production rate values of Thermal NOx range of $4.798448 \times 10^{-6}\mathrm{Kgmol/m^3\ s}$ to $5.01322 \times 10^{-6}\mathrm{Kgmol/m^3\ s}$ shown in figures 7 and 8. This was indicative of a reduction in Thermal NOx when the two groups of fuels (Jet-A against 40BE & 60BD blend) were compared.

4.1 Implications of results

The adiabatic flame temperature is an important combustion characteristic. Part of the objectives of this research was to determine the adiabatic flame temperature for different percentage compositions of the bioethanol and biodiesel blends. The implication of the reported adiabatic temperature value of 2260 K for 40% bioethanol and 60% biodiesel blend is key in conducting actual experimental tests. This result entails that.

- The blend is suitable for use in the PT6A-27 annular combustor.
- For any modifications and scaling up procedures, this blend ratio is still suitable for use in the PT6A-27 annular combustor.
- The fuel blend can be used as a replacement to the pure hydrocarbon Jet fuel in the PT6A-27 annular combustor.
- At this reported blend ratio, the level of thermal NOx production is lower than that produced by the pure hydrocarbon Jet fuel.

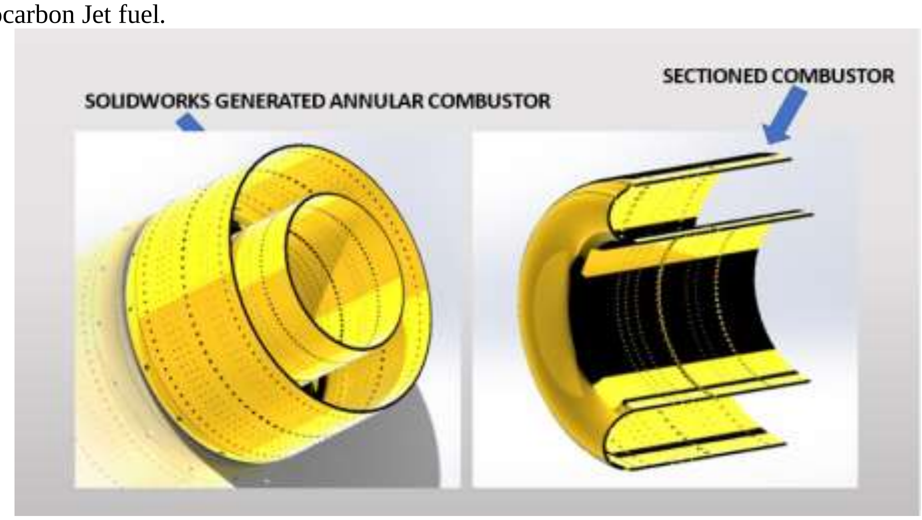

Fig. 1.: SOLIDWORKS sectioned combustor geometry

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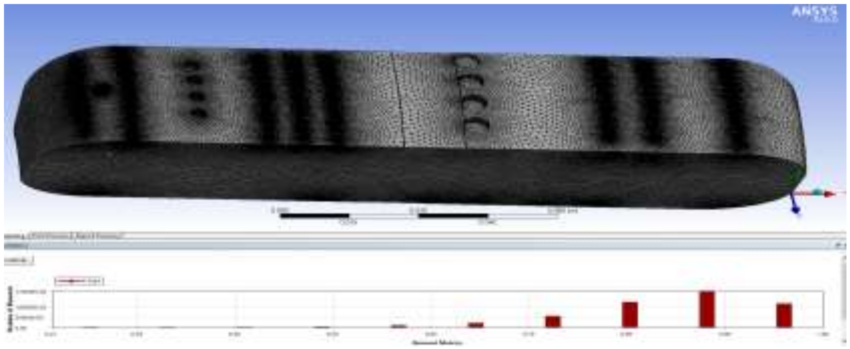

Fig. 2. Mesh generation in ANSYS MESH

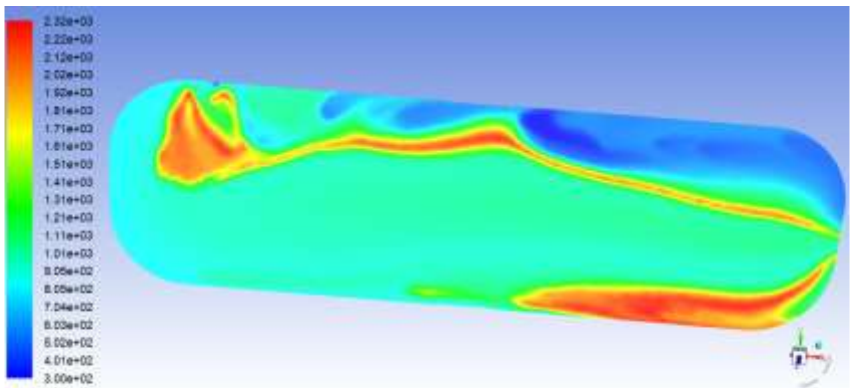

Fig. 3. Jet-A non-premixed temperature 2D contour non-premixed combustion.

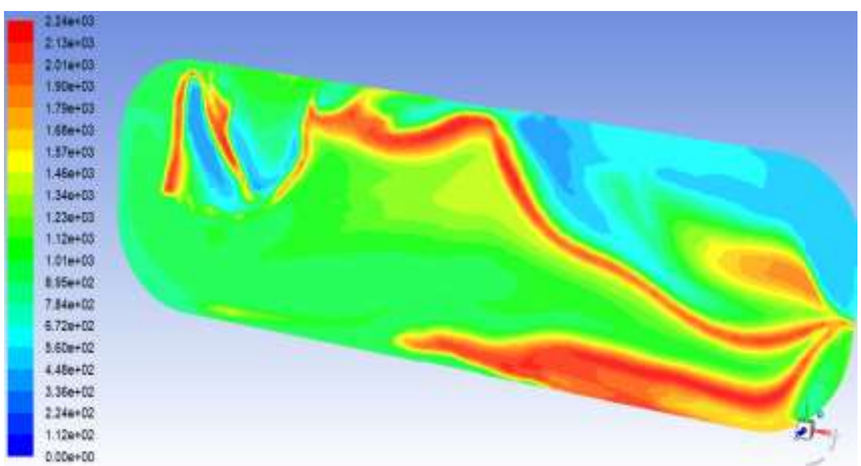

Fig. 4. 100% bioethanol 2D temperature contour non-premixed combustion

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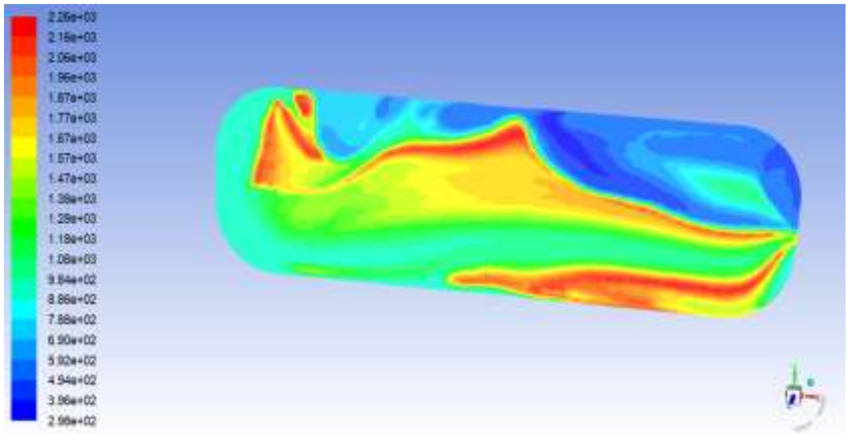

Fig. 5. 40% bioethanol, 60%biodiesel 2D nonpremixed combustion

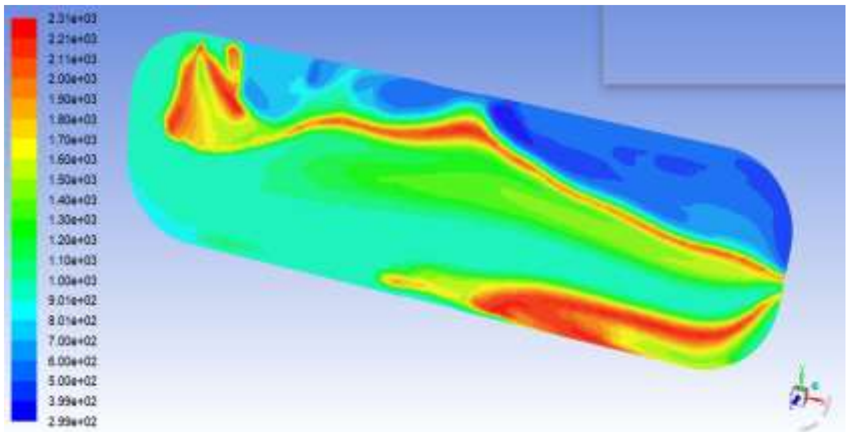

Fig. 6. 100% biodiesel 2D temperature contour non-premixed combustion

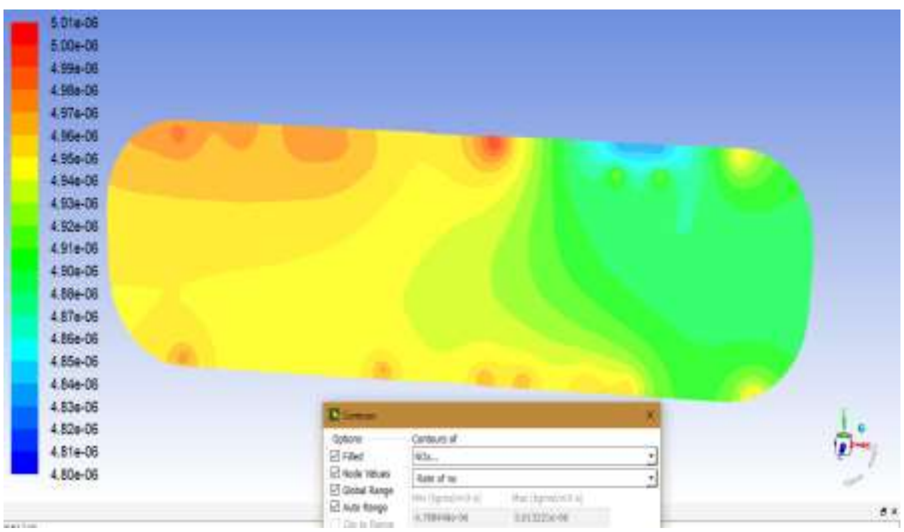

Fig. 7. Biofuels Blend Thermal NOx production rate $Kgmol/m^3\ s$

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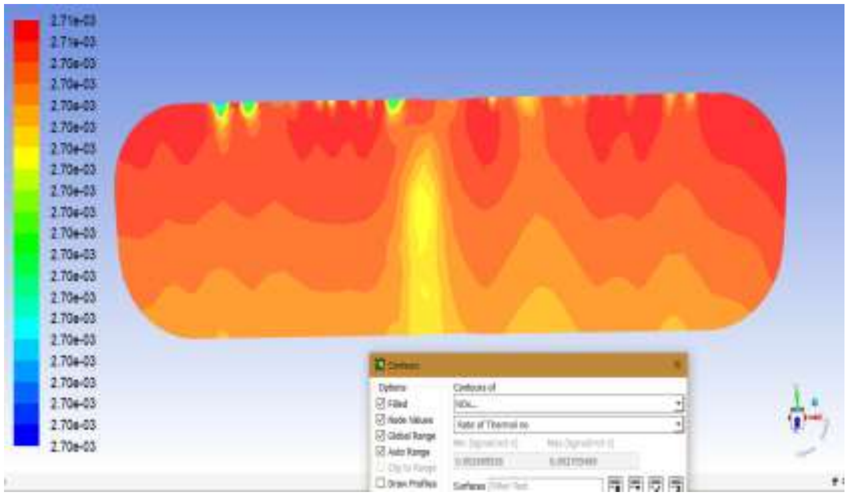

Fig. 8. JetA1 NOx production rate $Kgmol/m^3\ s$

5.0 CONCLUSION

Modelling and simulation of combustion of bioethanol and biodiesel in the PT6A-27 annular combustor was done. The implication of the reported adiabatic temperature value of 2260 K for 40% bioethanol and 60% biodiesel blend is key in conducting actual experimental tests. This result entails that the quality of the fuel is good enough at the reported blend ratio of 40% bioethanol and 60% biodiesel. The blend is suitable for use in the PT6A-27 annular combustor. For any modifications and scaling up procedures, this blend ratio is still suitable for use in the PT6A-27 annular combustor. The fuel blend can be used as a replacement to the pure hydrocarbon Jet fuel in the PT6A-27 annular combustor and at this reported blend ratio, the level of thermal NOx production is lower than that produced by the pure hydrocarbon Jet fuel.

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