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MATHEMATICAL MODELLING ON IMPACT OF COMPRESSION AND EQUIVALENCE RATIO ON LEAN BURN SPARK COMBUSTION ENGINE BASED ON EXTENDED EXPANSION

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ABSTRACT

The energy crisis, brought on by the rapid depletion, price increases, uncertain supplies, and ever-increasing demand for petroleum fuels, has prompted a worldwide search for fuel alternatives as well as methods of extracting more useful work from conventional fossil fuels. Internal combustion engines have undergone continuous improvement in terms of fuel consumption and exhaust emissions since their inception. One of the most significant challenges that engineers and scientists in the automotive industry and its partners are currently facing is improving fuel efficiency while maintaining or even improving exhaust gas emissions. In order to increase thermal efficiency while simultaneously reducing exhaust emissions and fuel consumption, lean operation is an appealing operational method. Lean operating limits can be improved by using gaseous fuels because they are clean, economical, and abundant. One of the primary objectives of this research is to examine the Extended Expansion Lean Burn Combustion Engine. Based on the findings of this study, it can be concluded that the simulation results are in excellent agreement with the experimental results. The mathematical model that has been developed can be used as an effective analytical tool to predict the effect of engine design and operating parameters on engine performance and emissions in a short period of time and at a low cost.

Keywords *– Extended, expansion, lean, burn, combustion, engine etc,*

1. INTRODUCTION

Before the 1970s, only a few experimental works were conducted to investigate the lean combustion technology used in SI engines. This technology was first investigated in 1908, with the goal of demonstrating the benefits of higher thermal efficiency. When the need for emission control and fuel economy improvement became apparent, lean combustion technology was developed to meet these requirements. It produces lower emissions, higher thermal efficiency and improves fuel economy.

The use of lean operation in homogeneous-charge spark-ignited engines lowers peak combustion temperatures, which in turn lowers NOx emission levels. Lean operation is typically limited by the air-to-fuel ratio, which cannot be exceeded without causing ignition to be impossible or combustion to be incomplete. Because of the reduced mixture burning rate, operating under lean conditions can result in increased spark advance and lower thermal efficiency. A four-stroke lead burn engine with

extended expansion concept is being investigated for its performance and emission characteristics, taking into consideration the advantages of a lean burn engine and the extended expansion concept.

The lean burn technology is one of the viable techniques for internal combustion engines that can be used to achieve complete and clean combustion while also reducing emission levels. Lean burn technology burns the air-fuel mixture completely or almost completely in an efficient manner, resulting in reduced fuel consumption and pollutants levels that are within acceptable limits for the environment. Lean combustion, as a result, is a preferred concept for reducing exhaust emissions in order to comply with stringent emission regulations. Applied to a lean burn engine, the extended expansion concept is investigated in this work in order to determine the impact on performance and exhaust emission characteristics.

1.1 Lean Burn Combustion Engine

These are engines that use a higher air-to-fuel ratio than is chemically necessary to burn all of the fuel in order to achieve full combustion. Designed to improve fuel efficiency without sacrificing power or driveability, the lean burn combustion engine is a high-performance engine.

There are numerous issues associated with the use of homogeneous lean burn mixtures in practise, including reduced flame propagation, the occurrence of misfire, poor mixture distribution quality in multi-cylinder engines, and a high amount of unburnt HC in the exhaust stream, among others. However, to a certain extent, these issues can be resolved by:

- Adopting low heat loss combustion systems
- Increasing swirl and turbulence level in combustion chamber
- Use of additives
- Use of Catalytic Coating
- Use of high compression ratio
- Use of Higher Energy Ignition System

The following are the advantages of using a lean burn engine:

When the mixture is made leaner, the thermal efficiency increases due to the following reasons:

- ✓ Higher ratio of specific heats as the mixture properties approach those of air as the mixture is made leaner
- ✓ Because the burned gas temperature is lower, dissociation losses are reduced, and heat transfer losses to the coolant are reduced as a result of the lower burned gas temperature.

1.2 Extended Expansion Engine

The efficiency of any conventional engine is limited by two factors:

- ✓ It is the pumping loss, which increases with the reduction of the load, that acts as a negative force. This loss is a significant factor in the urban driving cycle, and it contributes significantly to increased fuel consumption.
- ✓ The expansion ratio is the same as the compression ratio in that the value of the expansion ratio is not fixed in order to achieve the highest efficiency. Its value is determined by the maximum compression ratio that the mixture is capable of producing.

Many automobile manufacturers are currently concentrating their research efforts on this issue. The primary goal is to either completely eliminate the throttle valve or to operate it as wide open as possible regardless of the load conditions.

2. LITERATURE REVIEW

Ankur Kalwar and Avinash Kumar Agarwal (2021) - When compared to identical port-fuel injected spark-ignition (SI) engines, gasoline direct-injection (GDI) engines are known for their superior fuel economy and higher power output. When operated in stratified combustion mode or lean homogeneous mode, GDI engines undergo overall lean-burn combustion of the charge, resulting in a significant reduction in fuel consumption. The combustion of a lean mixture lowers the peak in-cylinder temperature while also lowering the formation of NOx emissions. Although the combustion of the stratified mixture or the overall lean mixture has several advantages, there are some drawbacks to consider. The chapter discusses the factors that contribute to combustion variability, which results in partial burn and misfire cycles in the combustion process. Misfire and cyclic variations are caused by the non-repeatability of the mixture formation process. It has been proposed that detailed optical studies covering the distribution of the fuel–air mixture equivalence ratio, charge motion inside the combustion chamber, flame front propagation, and radical formation that is responsible for emissions be carried out in order to investigate the mechanism for combustion instability. It is discussed in this chapter how to improve and extend the operating range of stratified combustion modes in GDI engines in order to achieve superior gas economy and reduce exhaust emissions. Various areas such as ignition parameters, spray characteristics of different nozzles, injector strategies, cylinder charge control, and the use of alternate fuels are discussed.

Javad Kheyrollahi, et al (2021) - It is possible to improve engine performance and efficiency by using lean burn combustion of natural gas in spark-ignited engines. This can be accomplished by reducing pollutant emissions while also achieving better fuel consumption. Excessive lean mixture introduced into the engine, on the other hand, causes the combustion to become unstable, and misfire occurs in a significant number of cycles. Pre-chamber ignition technology is a practical solution that can improve the efficiency of spark-ignition engines. In this study, the combustion of a lean mixture was empirically investigated in a one-cylinder engine powered by natural gas using a new prechamber spark plug. Tests were carried out at compression ratios of 11.5, 13.5, and 16 as well as a wide range of air-to-fuel ratios. Because of the use of pre-chamber spark plugs, the lean operating limit is increased by 10 to 45 percent, and the average in-cylinder pressure and exhaust gas temperature are reduced by 4 and 3 percent, respectively, compared to the conventional spark ignition system, respectively. By using a pre-chamber spark ignition system, it was possible to reduce brake specific fuel consumption by 4 to 11 percent. The formation of HC, CO, and NOx is approximately 11 percent, 16.3 percent, and 10 percent lower than that of conventional spark ignition usage, respectively.

Sulaiman(2013)presented a paper in which the performance of a single cylinder spark ignition engine operating on liquefied petroleum gas (LPG) as a fuel was examined and discussed. Because of volumetric efficiency and reduced specific fuel consumption, they discovered that power output can be reduced by up to 4% when compared to gasoline.

MehrnooshDashti, et al (2012) - Because CNG enriched gasoline has a higher octane number than regular gasoline, using CNG as an additive for gasoline is a wise choice because it reduces emissions. As a result, it is possible to run the engine on gasoline with a lower octane number. This would also imply an increase in the compression ratio of SI engines, which would result in increased performance while simultaneously lowering gasoline consumption. As a result of the use of simulation codes to model the thermodynamic cycle of an internal combustion engine, tools for more efficient engine designs and fuel combustion have been developed over the years. A thermodynamic cycle simulation of a conventional four-stroke spark-ignition engine has been developed in this research. Engine performance parameters and emission characteristics of a CNG/gasoline blend fuelled engine are investigated using this model. A spark ignition engine cycle simulation based on the first law of thermodynamics has been developed by performing stepwise calculations for the compression process, the ignition delay time, the combustion process, and the expansion process, among other things. The conservation equations for mass and energy serve as the model's building blocks, respectively. It was not necessary to solve the equations analytically because the Newton-Raphson method was used to solve them numerically. As shown in the diagram below, the cylinder is divided into two zones that are separated by a thin flame front in this model.

A. Manivannan, et al (2004) - Numerical study of a 4-stroke, single-cylinder, spark-ignition engine with extended expansion and lean burn is the subject of this paper. Thermodynamic and global modelling techniques are used to simulate the engine's internal combustion processes. The following processes are taken into consideration in the simulation study: compression, combustion, and expansion. Sub-models are used to account for the effects of the gas exchange process, heat transfer, and friction, among other things. The Wiebe heat release formula was used to predict the cylinder pressure, which was then used to determine the amount of work that had been done as indicated. In order to predict the brake, mean effective pressure, brake thermal efficiency, and brake specific fuel consumption, the heat transfer from the cylinder, friction, and pumping losses were also taken into consideration. The results of the simulation show that there is an increase in thermal efficiency up to a certain limit in the timing of the intake valve closure. Excessive delay in the intake valve closure (IVC) timing reduces the engine performance further delaying the intake valve closure (IVC) timing results in less overall performance.

3. RESEARCH METHODOLOGY

- ✓ In order to predict the performance and emission characteristics of an extended expansion lean burn spark ignition engine operating on gasoline fuel, a mathematical model for compression, combustion, expansion, gas exchange processes, NOX emission, UBHC emission, and CO emission has been developed.
- ✓ Extensive research into the performance and emission characteristics of a gasoline-powered extended expansion lean burn spark ignition engine is underway.
- ✓ Experiment with various air-fuel ratios and ER/CR ratios as well as different speeds and loads to determine how they affect performance and emission characteristics.
- ✓ Comparison of simulation results with experimental data allows for the validation of the mathematical model that has been developed.

3.1 Gas Exchange Process

As described by Ganesan and Ashely S. Campbell, the gas exchange process is modelled in accordance with the procedure outlined in their paper. The following equation takes into account the variations in pressure that occur during the exhaust and intake processes. It is possible to calculate the flow rates using the following relationship. It is necessary to consider the flow in two different regimes: subsonic and supersonic. The critical pressure ratio that distinguishes the two regimes is referred to as P_{Rcrit}, and it is determined solely by the value of the gas's k.

$$\frac{dp}{dt} = K_p p\left(\frac{1}{M}\frac{dM}{dt} - \frac{1}{V}\frac{dv}{dt}\right) exhaust \qquad (1)$$

$$\frac{dp}{dt} = K_\Gamma\left(\frac{RT_m}{V}\frac{dM}{dt} - \frac{p}{V}\frac{dv}{dt}\right) intake \qquad (2)$$

It is beneficial to consider two points regarding the treatment of equations above. It is the first of these that is concerned with what occurs at the end of the exhaust stroke. At TDC, the mass of exhaust in the working volume is M_{tdc}, which represents the residual gases that will remain in the engine during the following cycle calculation. It is more than or equal to the intake manifold pressure p_m at TDC when the cylinder pressure is at the top of the compression stroke. The increase in volume will result in a decrease in the pressure in the working space, and, at the same time, exhaust gas will flow back into the intake manifold, displacing fresh charge, if the intake valve is allowed to open.

The flow chart of the integration procedure is depicted in the figure.

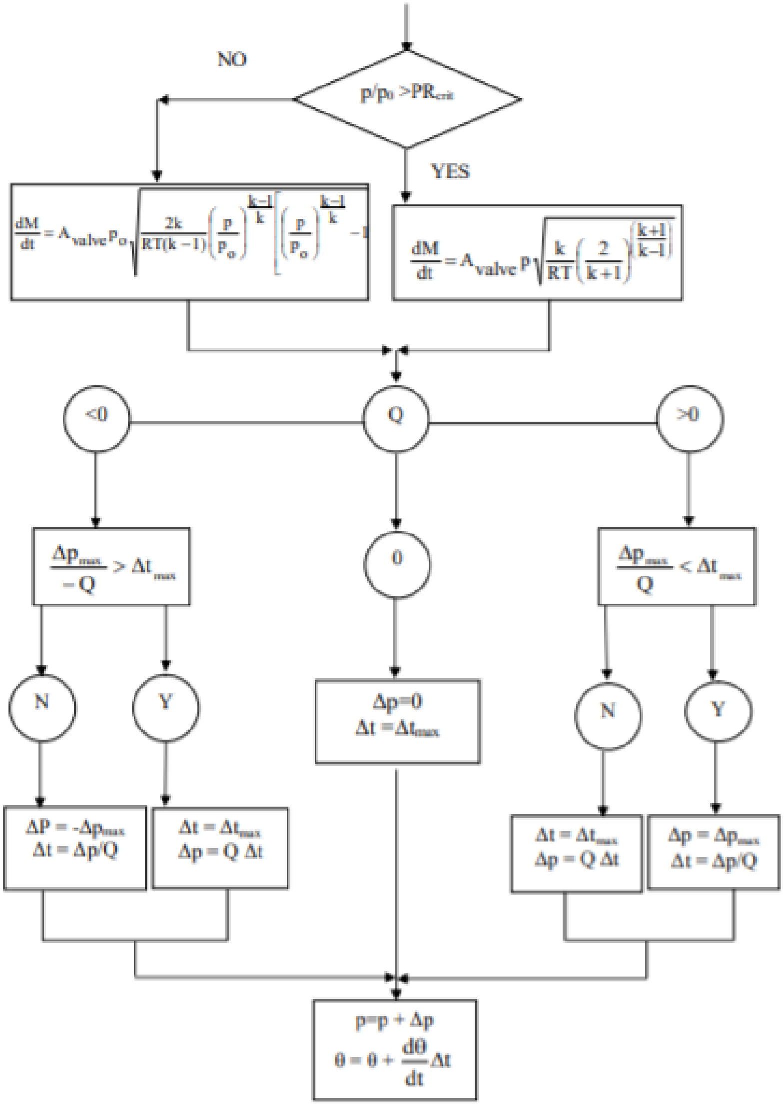

Figure 1: Flow Chart for Integration of Equations

It is more than or equal to the intake manifold pressure pm at TDC when the cylinder pressure is at the top of the compression stroke. Increases in working space volume will result in a decrease in pressure, while exhaust gas will flow back into the intake manifold and displace fresh charge if the intake valve is allowed to open fully.

3.2 Equilibrium Calculation of Species

In order to determine the NO concentration, argon is separated from atmospheric nitrogen. The molar fraction of these species, denoted by X_i, was used to calculate the composition. One mole of total products is made up of 'ae' moles of fuel multiplied by the stoichiometric quantity of air:

$$ae\,(C_nH_m) + \frac{ae}{\phi}\left(O_2 + \frac{78}{21}N_2 + \frac{1}{21}Ar\right) \longrightarrow X_{CO}CO + X_{CO2}CO_2 + X_{H20}H_2O + X_{H2}H_2 + X_{OH}OH + X_H H + X_{N2}N_2 + X_{NO}NO + X_N N + X_{O2}O_2 + X_0 O + X_{Ar}Ar \qquad (3)$$

$$\phi = \frac{Actual\ Fuel\ air\ ratio}{Chemicallycorrect\ fuel\ airratio} \qquad (4)$$

The preparation of equilibrium constants is the first step in the calculation. These are fixed for one state (P,T), the values of 'ae' and 'b' are chosen, and all Xi values are evaluated.

4. DATA ANALYSIS AND RESULTS

The main reason for choosing this engine was that it could safely operate at compression ratios that SI engines couldn't handle. To measure the cylinder pressure, a piezoelectric pressure transducer was mounted flush with the cylinder head surface. In addition, piezoelectric pressure sensors are installed in the intake and exhaust manifolds to measure pressure.

4.1 Specification of the Engine

The majority of the mechanisms either use a complex system that necessitates major engine modifications or are prohibitively expensive. A simple approach has been taken in this work to minimise modification, simplify the design, and reduce cost. The primary goal of this study was to look into the effects of extended expansion with constant CR. Rather than designing and developing a continuously variable valve timing (VVT) system. The requirement for valve timing is to delay IVCT, which was accomplished using a simple approach.

Table 1: Specification of the Engine

Type	**Four stroke, water-cooled CI engine modified to run in SI mode**
Make	KIRLOSKAR
Number of Cylinder	One
Bore X Stroke	80mm X 110 mm
Displacement volume	552.92cc
Compression ratio	16.5
Connecting rod length	230 mm
Rated Power (original diesel engine)	5BHP@1500rpm
Valve Timing	
Inlet Valve Opening (IVO)	13°bTDC
Inlet Valve Closing (IVC)	30°aBDC
Exhaust Valve Opening (EVO)	20°bBDC
Exhaust Valve Closing (EVC)	14°aTDC

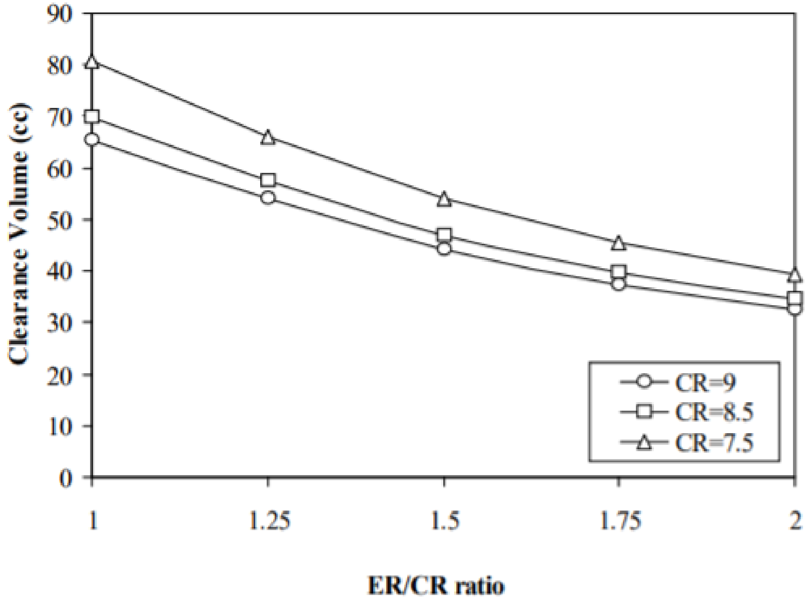

Figure 2: Variation of Clearance Volume with ER/CR Ratio

4.2 Effect of ER/CR Ratio on Brake Power

The test engine selected has a maximum effective compression ratio of 9. Because slight knock was observed when the engine was operated with CR of 9 at low loads (i.e., when the air-fuel ratio was less than 20), the test was stopped at air-fuel ratio 18 and no significant improvement in lean limit was observed when compared to CR of 8.5. After an air-fuel ratio 24, the brake power of CR 9 and CR 8.5 drops dramatically.

The simulation and experimental results are very similar. The percentage difference between simulation and experimental values ranges from 3 to 12%. This discrepancy is the result of theoretical assumptions made during the simulation process. Pressure variation of a conventional lean burn engine (ER/CR ratio 1) with respect to crank angle, as simulated. The simulation results are very close to the experimental values. The differences between the simulated and experimental values range from 2 to 13%. The peak pressure simulated value is 34.24 bar.

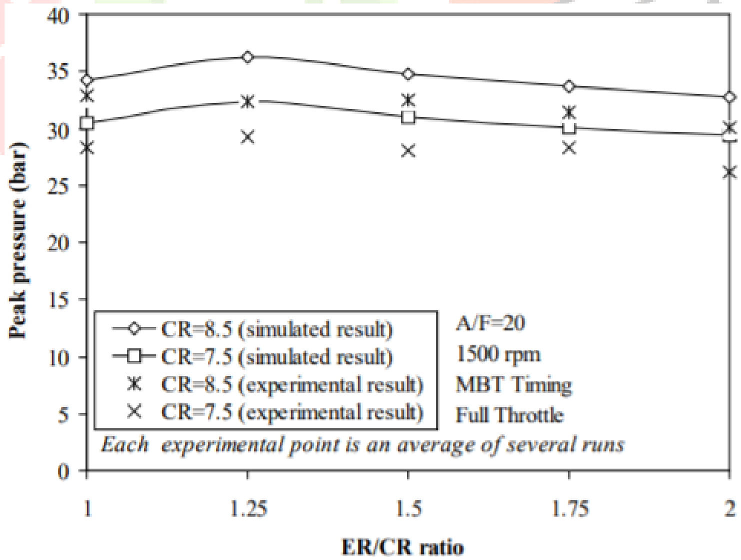

Figure 3: Variation of Peak Pressure with ER/CR Ratio

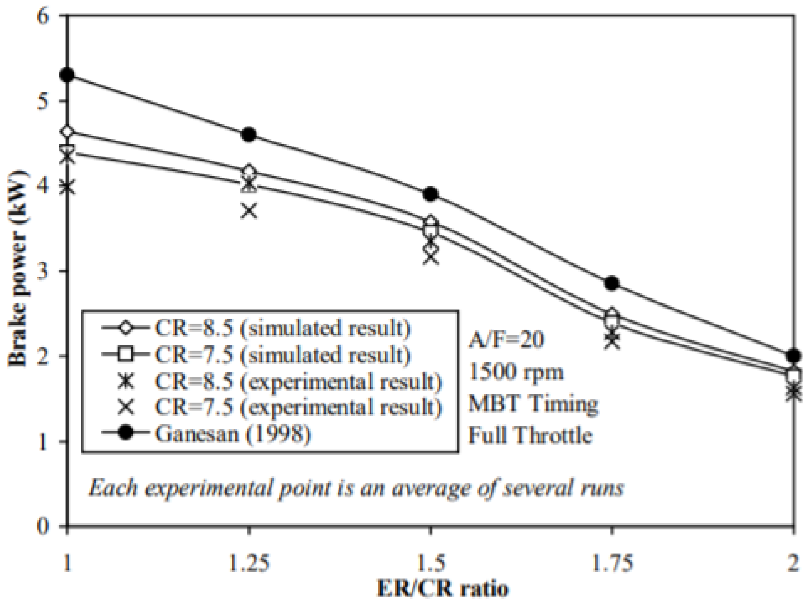

Figure 4: Variation of Brake Power with ER/CR Ratio

The effect of the ER/CR ratio on brake power is shown in Figure 4. The brake power decreases as the ER/CR ratio rises, and this decrease is due to a decrease in volumetric efficiency as the ER/CR ratio rises. Because the intake valve closes late as the ER/CR ratio rises, the charge is pushed back. The piston on the charge must expand some amount of work to push the charge in the opposite direction. This could be the cause of the decline in power. In simulation, the brake power for ER/CR ratio 1 is about 4.64 kW, and in experiment, it is about 4.35 kW; for ER/CR 1.5, the brake power is about 3.58 kW and 3.35 kW, respectively. The percentage decrease in brake power due to extended expansion is 22.84 percent in simulation and 22.99 percent in experiment. When other operating parameters improve, the reduction in brake power can be scarified to the point where the ER/CR ratio is 1.5. When the ER/CR ratio exceeds 1.5, the brake power is drastically reduced.

In Figure 4, brake power variations with ER/CR ratio are compared to those of Ganesan (1998). The current results' trends have been found to be comparable to that of other researchers' work. Due to increased air-fuel ratio operation or different make engine used by other researchers, the numerical value of brake power is comparatively less in the current study.

As the compression ratio rises, the peak pressure developed rises as well, resulting in increased brake power. The increase in brake power due to a compression ratio increase from 7.5 to 8.5 is 5.69 percent for the base engine and 3.76 percent for the EEE with an ER/CR ratio of 1.5. In comparison to the base engine, the results show that increasing the compression ratio has less of an effect on brake power in the EEE. This is due to the EEE's volumetric efficiency being reduced.

5. CONCLUSION

- For the extended engine, an ER/CR ratio of 1.5 was found to be optimal for maximum brake thermal efficiency and minimum BSFC.
- When the CR is increased from 7.5 to 8.5, the lean limit is increased from 21 to 24. When the CR is increased to 9, there is no significant improvement in the lean limit.
- At 1400 rpm, the maximum brake thermal and volumetric efficiency was observed. At this speed, BSFC was also found to be the smallest.
- EEE has a greater advantage in improving brake thermal efficiency at part loads by combining variable intake valve closing and variable compression.

5.1 Further research

- More research into lean burn EEE with other fuels, such as CNG and LPG, can be done.
- Because the advantages of lean burn EEE are so promising, it could be used in conjunction with a variable compression ratio (VCR)-variable valve timing (VVT) engine.
- Other methods for achieving lean combustion may be used in conjunction with the extended expansion concept.

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