International Journal of Scientific & Engineering Research Volume 11, Issue 6, June-2020
ISSN 2229-5518

Numerical analysis of supersonic nozzle using method of Characteristic

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Abstract— Nozzle is a device in which pressure energy is converted in to kinetic energy and this supersonic nozzle can be used for different application includes aerospace, materials science, automobile many more. Present study involves study of flow parameter of a supersonic nozzle for different divergence angle. Convergent area is assumed be a constant but in divergent section area is changing with respect to divergence angle. Flow parameter is observed for the different divergence angle and they are Mach number, static pressure , velocity, turbulent kinetic energy, the diverge angle is used for the 11°,13°.

Index Terms— Method of Characteristics, supersonic nozzle, divergence angle.

1 Introduction

The performance of a rocket depends heavily on its nozzle's effectiveness in converting thermal energy to kinetic energy. To increase the vacuum performance of classical convergent-divergent rocket nozzles, it is desirable to achieve high expansion rate. Modern rocket nozzles are designed to operate over a wide range of altitudes and are typically with large area ratios to ensure high efficiencies at high altitudes. A nozzle's design altitude is where its exit pressure is equal to the ambient pressure. Above that altitude, the nozzle flow is 'under expanded and below it over expanded. In both conditions the nozzle produces thrust less than the possible maximum value. Usually the nozzle design altitude is well above sea level, leaving the nozzle flow in an over expanded state for its startup as well as ground testing. Overexpansion in a rocket nozzle presents the critical, and sometimes design driving, problem of flow separation induced side loads.

2 MATERIALS AND METHODS

Extensive study of existing literature on experimental and numerical analysis of expansion through convergent–divergent nozzles has been done. Nozzle geometry, expansion ratios, flow and boundary conditions have been drawn on the basis of the literature survey. Creation of two-dimensional geometry of the nozzle and meshing is done on Workbench of ANSYS 14®. Simulation of expansion is carried on ANSYS FLUENT 14®software using different levels grid refinement and turbulent models.

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Grid independence test is carried for each of the cases studied to select appropriate number of elements for the computational domain. Validation of simulated results with that of experimental is done and the numerical approach, which resulted in acceptably proximate predictions, is adopted for further study of the cases taken in this work. Post processing features of ANSYS FLUENT are used to generate static pressure, total pressure and velocity contours and Mach number plots for all cases. Parameters that are essential for detailed analysis of expansion like flow exit velocity, pressure at exit and position of occurrence of shocks are obtained from post processor generated contours and plots.

2.1 Geometrical Description

A two-dimensional geometry of the nozzle has been created using Workbench ANSYS 14. Diameters at inlet, throat and exit have been maintained same for all cases considered in this work. Dimensions of the conical nozzle for 15^0 of divergent angle are

Table 1: Boundary Conditions

Particulars	**Dimension**
Inlet width (Diameter) (m)	1.000
Throat width (Diameter) (m)	0.304
Exit width (Diameter) (m)	0.861
Throat radius of curvature (m)	0.228
Convergent Length (m)	0.640
Convergent angle (deg)	30
Divergent angle (deg)	15

2.2 Validation

Experimental results cited by C.A. Hunter et al on AIAA **[2]** have been used to validate the numerical approach adopted in this work. Experiments were conducted on conical nozzles for different pressure ratios. Plots depicting the variation of non-dimensional pressure against non-dimensional distance on the axis from the inlet of the nozzle have been used for the validation. Expansion had been simulated for same NPR for conical nozzle as of experimental adopting both k-ω and k-ε turbulent models. Figure 1 shows the comparison of simulated results with the experimental results. It can be clearly observed that predictions using k-ε model were closer to experimental results when compared with that of with k-ω model. The numerical approach resulted in most proximate results to that of experimental are employed for the further analysis of cases undertaken for both conical and contour nozzles.

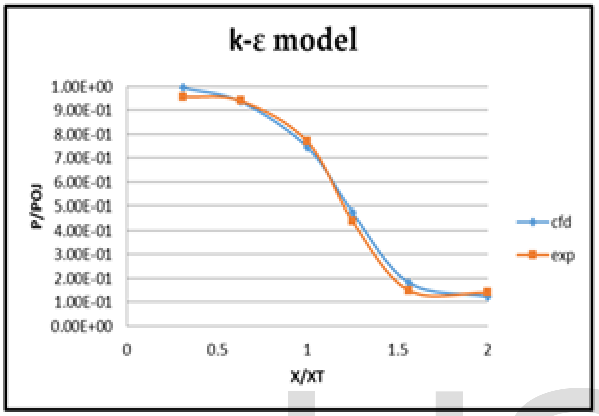


Fig. 1. Validation using K-€ model

2.4 Method of Characteristics

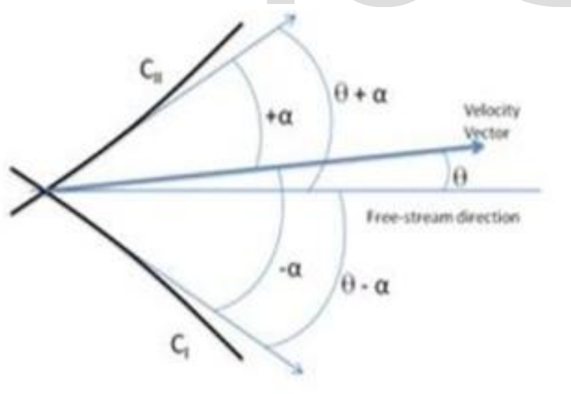


Fig.2. Method of Characteristics

Method of characteristics is method to calculate the nozzle divergence angle based on partial differential equations. To fix the nozzle divergence angle nozzle dimension.

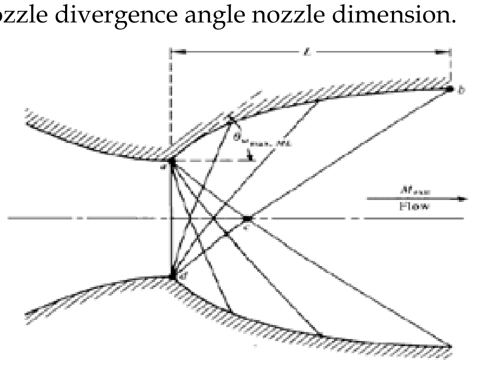


Fig.3. Minimum Length of a Supersonic nozzle

3 Result and Discussion

Case 1: Divergent angle=11° -Conical Nozzle

1. **Contour of Mach Number**

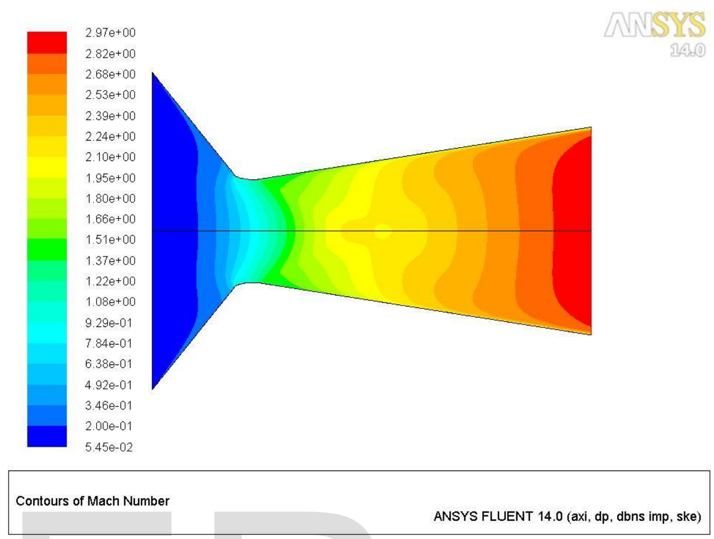


Fig.4 Mach number contour for conical nozzle with divergence angle 11°

The Mach contour of the CD nozzle when the divergent angle is made 11° is shown in the figure 9. It is clear that there is no shock occurred inside the divergent section of the nozzle. The inlet section has a velocity of 5.45e-02Mach and it increases to a value of 1.08e+00 Mach at the throat section. The velocity is found to be increasing as it passes through the divergent section. At the exit section, the velocity is found to be 2.82e+00Mach.

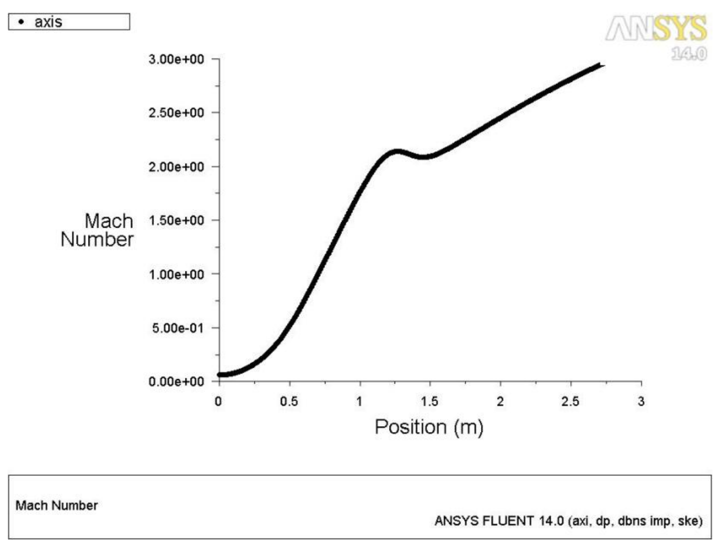


Fig.5 Plot of Mach number v/s Position for Conical Nozzle with Divergent angle 11°

In this case, no shock is observed, resulting in higher exit velocity of 2.82e+00 Mach around the axis. It can also be observed that although exit Mach number is fairly high, a higher degree of flow separation occurs from almost 2.0m from the inlet, which is far sooner than when compared to previous case of contour nozzle.

2. Contour of Static pressure

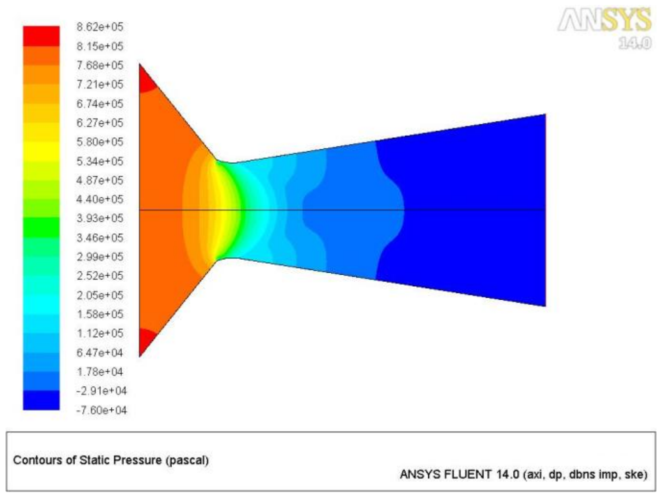


Fig.6. Static Pressure contour for conical nozzle with divergence angle 11°

The static pressure contour shows a reduction in the static pressure throughout the nozzle. At the inlet, the static pressure is found to be 7.68e+05Pa. At the throat it has reduced to 5.34e+05Pa. This value again reduces to a value of -2.91e+04Pa and remains constant till the exit section.

Case 2: Divergent angle=11° -Contour Nozzle

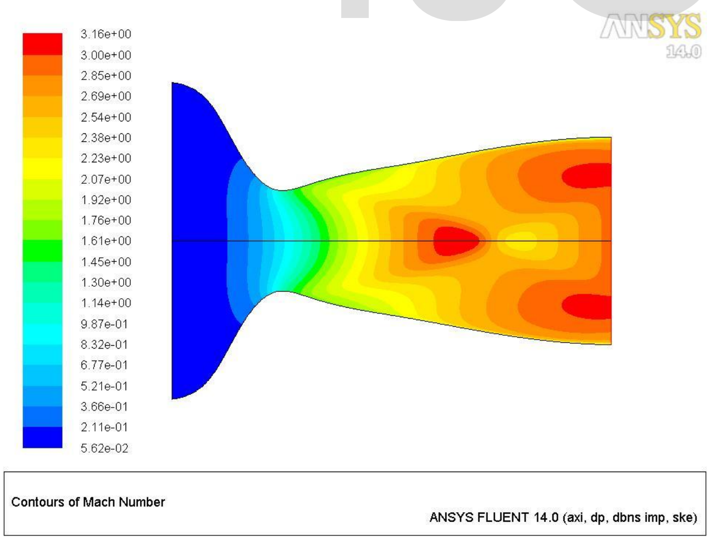


Fig.7. Mach number for Contour Nozzle with Divergent angle of 11°

The variation in the Mach contour for Contour nozzle can be observed from figure 11. Here no shock has occurred inside the divergent section. The inlet section has a velocity of 5.62e-02 Mach. At the throat the velocity varies from 9.87e-01 and 1.14e+00Mach. The exit velocity is found to be 2.69e+00 Mach along the axis of the nozzle.

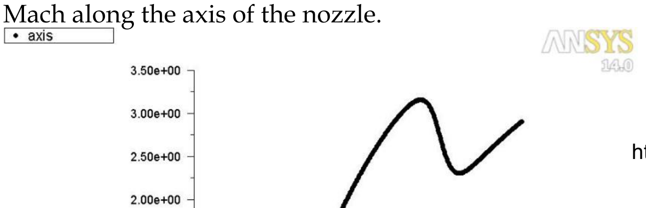


Fig.8. Plot of Mach number v/s Position Contour Nozzle with Divergent angle of 11°

In this case, shock is observed, resulting in higher exit velocity of 2.69e+00 Mach around the axis. It can also be observed that although exit Mach number is fairly high, a higher degree of flow separation occurs from almost 2.54m from the inlet, which is far sooner than when compared to previous case of contour nozzle.

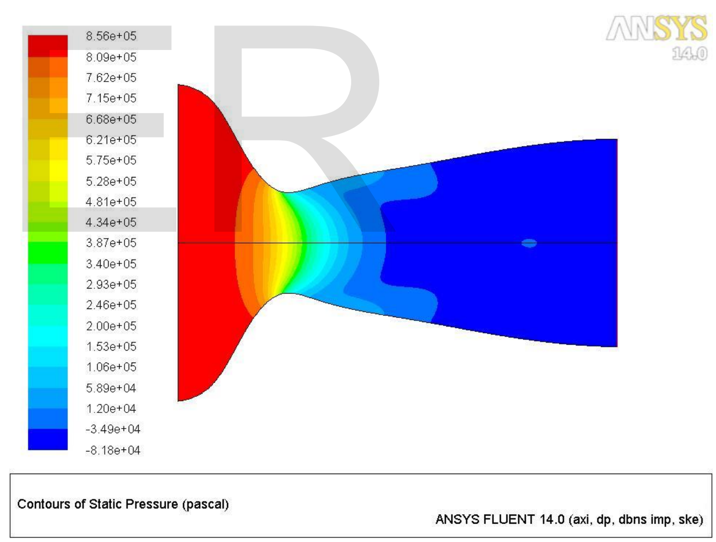
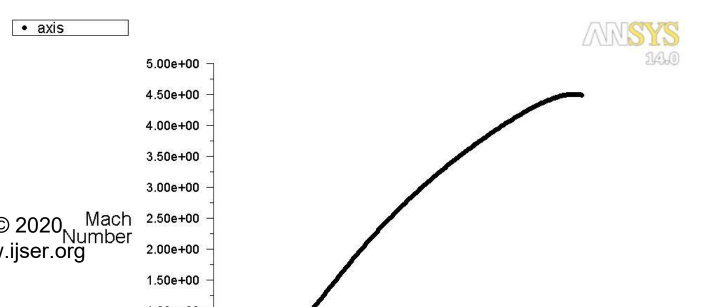


Fig.9.Static Pressure contour for contour nozzle with divergence angle 11°

The pressure dropped from 7.62e+05 to 5.28e+05Pa at the throat section, which is larger in magnitude when compared with 11˚ conical. The expansion almost completely happens to a value of -3.49e+04Pa at the exit.

Case 3: Divergent angle=13° -Conical Nozzle



International Journal of Scientific & Engineering Research Volume 11, Issue 6, June-2020
ISSN 2229-5518

Fig.10.Mach number contour for conical nozzle with divergence angle 13°

The Mach contour of the CD nozzle when the divergent angle is made 13° is shown in the figure 13. It is clear that there is no shock occurred inside the divergent section of the nozzle. The inlet section has a velocity of 5.46e-02Mach and it increases to a value of 1.08e+00 Mach at the throat section. The velocity is found to be increasing as it passes through the divergent section. At the exit section, the velocity is found to be 2.96e+00Mach.

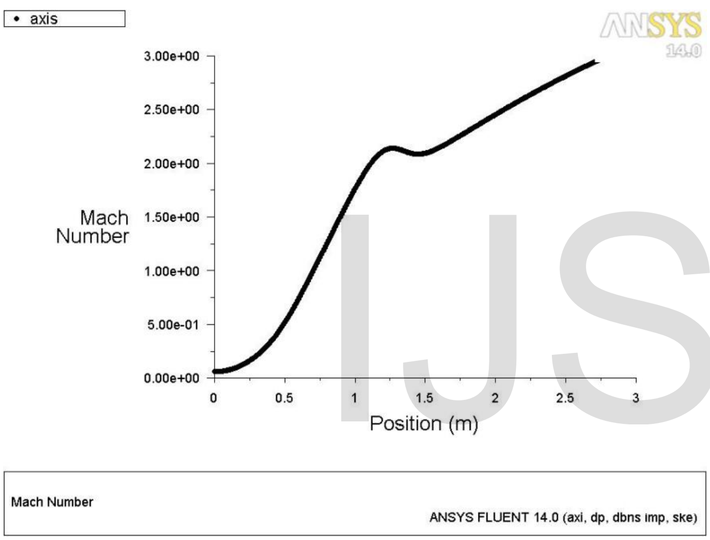


Fig.11. Plot of Mach number v/s Position for conical nozzle with divergence angle 13°

Contour of Static Pressure

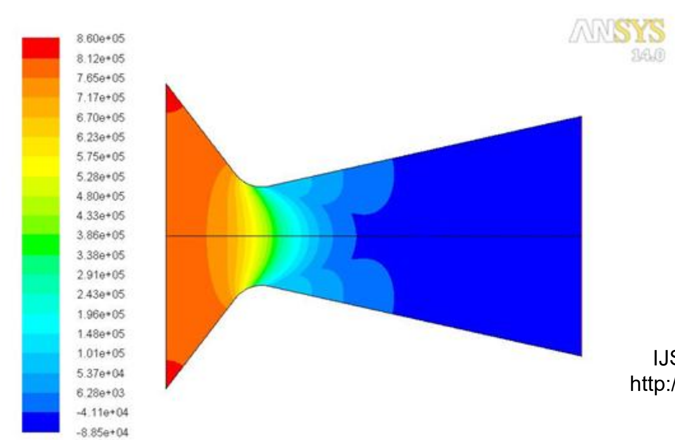


Fig.12. Static pressure for conical nozzle with 13˚ divergent angle

The static pressure contour shows a reduction in the static pressure throughout the nozzle. At the inlet, the static pressure is found to be 8.12e+05Pa. At the throat it has reduced to 5.75e+05Pa. This value again reduces to a value of -4.11e+04Pa and remains constant till the exit section.

Case 4: Divergent angle=13° -Contour Nozzle

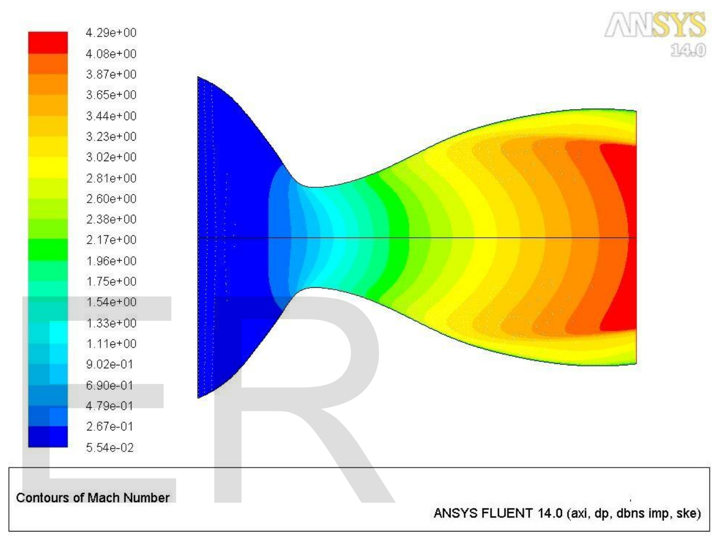


Fig.13.Mach number contour for contour nozzle with divergence angle 13°

The Mach contour of the CD nozzle when the divergent angle is made 13° is shown in the figure 15. It is clear that there is no shock occurred inside the divergent section of the nozzle. The inlet section has a velocity of 5.54e-02Mach and it increases to a value of 1.11e+00 Mach at the throat section. The velocity is found to be increasing as it passes through the divergent section. At the exit section, the velocity is found to be 4.29e+00Mach.

In this case, no shock is observed, resulting in higher exit velocity of 4.29e+00 Mach around the axis.

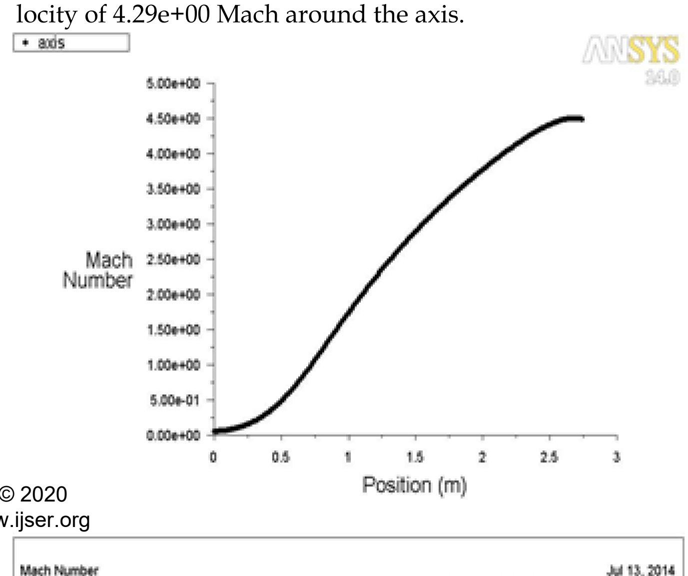


Fig.14. Plot of Mach number v/s Position for conical nozzle with divergence angle 13°

Contour of Static Pressure

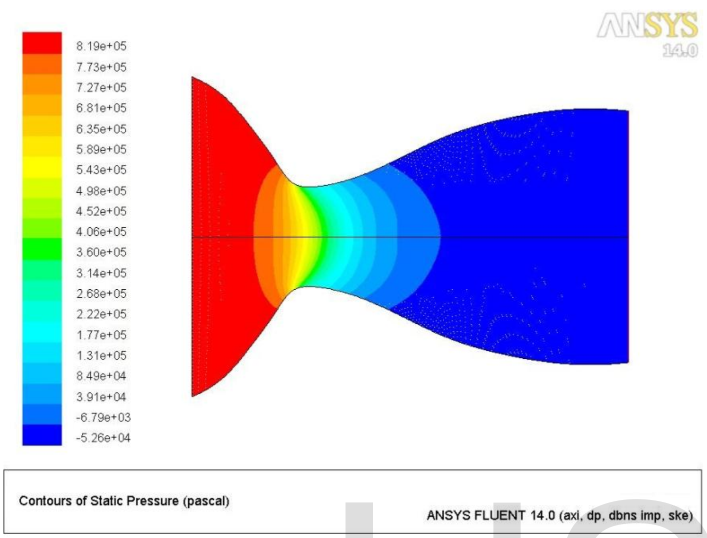


Fig.15. Static pressure for contour nozzle with 13˚ divergent angle

4. CONCLUSION

a. Validation of numerical results show that even by restricting the computational domain to exit of the nozzle acceptable results can be obtained.
b. Among the turbulence models available in the commercial software, k-ε model resulted in most proximate results to that of experimental.
c. From the Mach number plots it evident that distance of occurrence of first shock from the inlet increases with divergent angle.
d. Shocks of higher intensity are observed with polynomial contour nozzles at lower divergent angles when compared with respective conical nozzles with similar end geometry.
e. Contour nozzles resulted in higher exit Mach numbers for all divergent angles when compared with respective conical nozzles with similar end geometry.
f. Absence of occurrence of shocks was observed with higher divergent angles both in the case of conical and divergent C-D nozzles.
g. Higher degree of turbulence and flow separations are observed with contour nozzles when compared with respective conical nozzles with similar end geometry.

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