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Analysis of the Cooling Performance of the Scramjet Regenerative Cooling Channel according to the Aspect Ratio using the Conjugate Heat Transfer Analysis

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Abstract

This study conducted a basic study on the cooling performance of the scramjet regeneration cooling considering the aspect ratio (AR) for the optimal design. The cooling performance according to the aspect ratio of the regenerative cooling channel was checked by reflecting the aerodynamic heating and combustion heat generated from the flow during the flight at Mach 6 for 600 seconds. The regenerative cooling channel inside the scramjet aircraft was reflected in one dimension, and the heat transfer model was applied to calculate the heat transfer coefficient. The heat transfer analysis method was verified by comparing it with the cooling channel experimental data, and finally, the cooling performance was compared considering the regenerative cooling channel AR of 1, 2, and 4.

Keywords: *Scramjet, Regenerative cooling, Conjugate heat transfer analysis, Supercritical fluid*

Nomenclature

A – Area (m^2)
AR – Aspect ratio
C_p – Specific heat at constant pressure (J/kg-K)
e – Internal energy (J/kg)
H – Channel cross-section height (mm)
h – Specific enthalpy (J/kg)
h^* – Modified heat transfer coefficient of flow
$\dot{m}$ – mass flow rate (g/s)
N – Number of channel
Nu – Nusselt number
P – Pressure (Pa)
Pr – Prandtl number
q'' – Heat flux (W/m^2)
Re – Reynolds number

T – Temperature (K)
u,v,w – velocity (m/s)
W – Channel cross-section width (mm)
ρ – density (kg/m^3)

Subscripts
ad – Adiabatic
avg – Average value
cw – Isothermal
max – Maximum value
sum – Sum value
t – Total value
w – Wall

1. Introduction

In the scramjet aircraft, the structure of the aircraft is exposed to a high-temperature environment by aerodynamic heating and combustion heat. In this situation, a regenerative cooling channel that reuses fuel is applied to cool the scramjet aircraft. In the case of a regenerative cooling channel, fuel is used

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as a coolant, so when the fuel flows along the channel, the heat generated from the structure is absorbed and the temperature of the fuel increases. At this time, there is an advantage of enhancing combustion while reusing the fuel with a higher temperature for combustion. In order to properly design these regenerative cooling channels, it is necessary to comprehensively determine the temperature inside the regenerative cooling channel and the temperature of the structure in flight situations. Since it is difficult to efficiently identify various situations experimentally, the physical thermal environment should be checked through computational analysis. Studies are being actively conducted to complexly check the thermal environment of the regenerative cooling channel in consideration of the flight environment.

Jang et al. [1] confirmed the temperature change of the regenerative cooling channel through a quasi-one-dimensional heat transfer analysis. However, the flow and structure were considered as quasi-one-dimensional situations, and only fixed situations were considered in the shape information of the cooling channel. Han et al. [2] established a conjugate heat transfer analysis method reflecting the regenerative cooling channel in consideration of the flight situation of the scramjet aircraft. However, only cases with limited fuel properties and heat transfer coefficients of the cooling channel were considered.

In this study, a conjugate heat transfer analysis was conducted by generalizing the properties of fuel and heat transfer coefficients inside the regenerative cooling channel in consideration of the flight situation of the scramjet aircraft. In the case of regenerative cooling channels, a quasi-one-dimensional analysis was performed in the same way as Han's study for the efficiency of calculation. Here, the fuel properties inside the regenerative cooling channel were applied by the physical properties prediction program used in previous studies [3], and the heat transfer coefficient was calculated using a commonly used heat transfer model. The validity of the conjugate heat transfer analysis method was compared with the referenced experimental data [4]. Finally, the characteristics according to the aspect ratio (AR) of the regenerative cooling channel were analyzed.

2. Methodology

2.1. Conjugate heat transfer analysis

The same method as in previous studies was used for the governing equation of the conjugate heat transfer analysis, including aerodynamic heating, thermal structure, and cooling channels. The thermal aerodynamic analysis used the general Navier-Stokes equations and is shown in Eqs. 1-3. Thermal structure analysis considers only the heat transfer equation and is given in Eq. 4-6. And for the cooling channel analysis, a quasi-one-dimensional equation was applied, as shown in Eq. 7-8. The flow chart of the conjugate analysis is shown in left of Fig. 1. In the flight situation considered in this study, it is not necessary to consider the chemical reaction of air. Therefore, for the efficiency of the conjugate heat transfer analysis, the thermodynamic analysis part and the thermal structure analysis part are analyzed separately. And in the thermal structure analysis, the unsteady calculation is performed including the cooling channel. First, the isothermal condition analysis and the adiabatic condition analysis are performed in the thermodynamic analysis part, respectively. In addition, the heat transfer coefficient was modified as shown in Eq. 9 to reflect the temperature change over time on the surface of the aircraft. And based on the modified heat transfer coefficient, the heat transfer amount boundary condition was set on the surface of the aircraft. Then, the calculation was repeated including the regenerative cooling channel inside the aircraft structure. Three-dimensional analysis was performed for the thermal aerodynamic and the thermal structure part, and quasi-one-dimensional analysis was performed for the cooling channel. In the case of cooling channels, since several cooling channels are arranged based on the combustion chamber area, the cooling channel was considered quasi-one-dimensional for the efficiency of analysis. A generally used Dittus-Boelter heat transfer model was used for the cooling channel, as shown in Eq. 10. The Dittus-Boelter heat transfer model may be somewhat less accurate depending on the type of fuel or the supercritical situation. Therefore, research on a heat transfer model with high accuracy according to the fuel type or supercritical situation is planned to be conducted.

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+\frac{\partial G_v}{\partial z}+S \tag{1}$$

$$Q=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ \rho e_t\\ \rho_i\\ \vdots\\ \sum_i \rho e_{vib,i}\end{pmatrix},E=\begin{pmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (\rho e_t+p)u\\ \rho_i u\\ \vdots\\ \sum_i \rho e_{vib,i}u\end{pmatrix},F=\begin{pmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (\rho e_t+p)v\\ \rho_i v\\ \vdots\\ \sum_i \rho e_{vib,i}v\end{pmatrix},G=\begin{pmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ (\rho e_t+p)w\\ \rho_i w\\ \vdots\\ \sum_i \rho e_{vib,i}w\end{pmatrix},S=\begin{pmatrix}0\\ 0\\ 0\\ 0\\ 0\\ W_i\\ \vdots\\ \sum_i W_{vib,i}\end{pmatrix} \tag{2}$$

$$E_v=\begin{pmatrix}0\\ \tau_{xx}\\ \tau_{xy}\\ \tau_{xz}\\ -\left(q_x+\sum_s q_{vx,s}\right)+\Phi_x+\sum_s\left(\rho D_s\frac{\partial c_s}{\partial x}\right)\\ \rho D_i\frac{\partial c_i}{\partial x}\\ \vdots\\ \sum_i\left(\rho e_{vib,i}D_i\frac{\partial c_i}{\partial x}-q_{vx,s}\right)\end{pmatrix},F_v=\begin{pmatrix}0\\ \tau_{xy}\\ \tau_{yy}\\ \tau_{zy}\\ -\left(q_y+\sum_s q_{vy,s}\right)+\Phi_y+\sum_s\left(\rho D_s\frac{\partial c_s}{\partial y}\right)\\ \rho D_i\frac{\partial c_i}{\partial y}\\ \vdots\\ \sum_i\left(\rho e_{vib,i}D_i\frac{\partial c_i}{\partial y}-q_{vy,s}\right)\end{pmatrix}$$

$$,G_v=\begin{pmatrix}0\\ \tau_{xz}\\ \tau_{yz}\\ \tau_{zz}\\ -\left(q_z+\sum_s q_{vz,s}\right)+\Phi_z+\sum_s\left(\rho D_s\frac{\partial c_s}{\partial z}\right)\\ \rho D_i\frac{\partial c_i}{\partial z}\\ \vdots\\ \sum_i\left(\rho e_{vib,i}D_i\frac{\partial c_i}{\partial z}-q_{vz,s}\right)\end{pmatrix} \tag{3}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=0 \tag{4}$$

$$Q=\rho h_t=\rho C_p T \tag{5}$$

$$E=q_x=-k\frac{\partial T}{\partial x},F=q_y=-k\frac{\partial T}{\partial y},G=q_z=-k\frac{\partial T}{\partial z} \tag{6}$$

$$\frac{\partial}{\partial t}(\bar{A}Q)+\frac{\partial E}{\partial x}=H \tag{7}$$

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho C_p T\end{bmatrix},E=A\begin{bmatrix}\rho u\\ \rho u^2+p\\ (\rho C_p T)u\end{bmatrix},H=\begin{bmatrix}0\\ p\frac{\partial A}{\partial x}-\bar{D}\tau_w\\ \bar{D}q''_w\end{bmatrix} \tag{8}$$

$$h^*=\frac{q''_{cw}}{(T_{ad}-T_{cw})} \tag{9}$$

$$Nu=0.023Re^{0.8}Pr^{0.4} \tag{10}$$

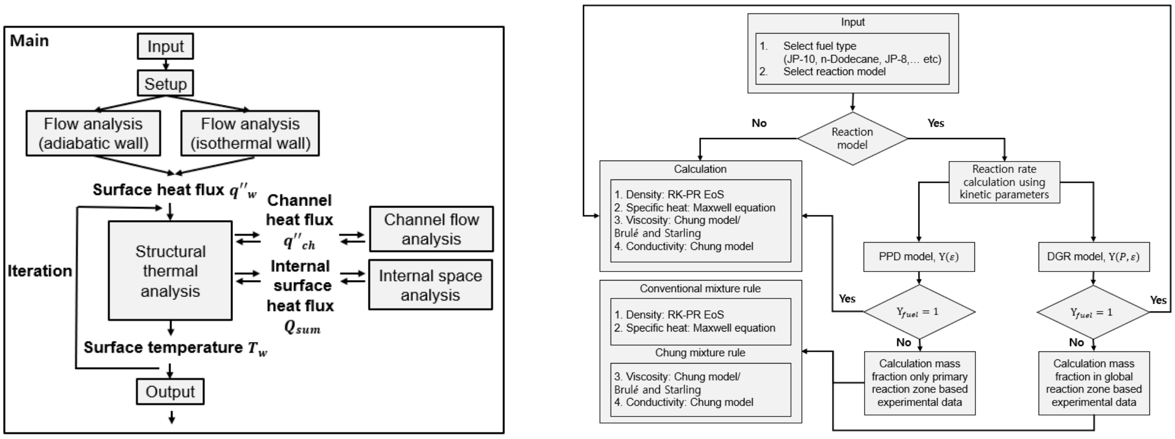


Fig 1. Flow chart of conjugate heat transfer analysis and prediction of fuel properties [2,3].

2.2. Prediction of Cooling Channel Fuel Properties

In order to consider the general situation, the three-parameter state equation and transport property model used in previous studies were used for the cooling channel fuel properties [3]. These prediction methods can reasonably consider the fuel properties of hydrocarbon fuel series used as fuel for scramjet aircraft to the supercritical region. For the fuel property prediction part applied in this study, the method of solving the singularity problem of the thermodynamic equation performed in the previous study of this researcher was applied. The RK-PR EoS, a 3-parameter equation of state applied in this study, has a limit value of the predictable critical compressibility factor of fuel. Critical compressibility factors are determined for each fuel, and an equation that corrected the singularity problem was presented in previous studies to predict stable properties when predicting fuel that exceeds the limit value of the critical compressibility factor [3]. In addition, even when considering pyrolysis, physical properties were stably predicted by applying the rule of mixture. These prediction methods can reasonably consider the properties of hydrocarbon fuel series used as fuel for scramjet aircraft up to the supercritical region. For fuels with pyrolysis information, fuel properties can be predicted by reflecting pyrolysis. The flow chart of the fuel property prediction program is shown in right of Fig. 1.

2.3. Validation of analysis methods

The conjugate heat transfer analysis method including cooling channels was verified by referring to the study in which experimental data exist. The experiment of the preceding study is a situation in which a single circular cooling channel is arranged inside a cylindrical structure, and the pyrolysis of fuel in the supercritical area is considered. It was compared with the data of previous studies that conducted cooling channel experiments with n-decane fuel [4]. The above-mentioned property prediction method was applied for the properties of the n-decane fuel, and the property prediction result is shown in Fig. []. The property prediction result was calculated with an accuracy of approximately 2.3 to 14.6% of the deviation compared to the NIST REFPROP data [5]. For n-decane fuel, the product proportional distribution (PPD) model was applied to pyrolysis by referring to previous studies. At this time, products generated during pyrolysis are presented in previous studies, and properties during pyrolysis are calculated using the rule of mixture. Fig. 3 shows the verification results. The temperature measurement data of the outer surface of the cylindrical structure were compared with the results of the conjugate heat transfer analysis. Comparing the experimental data and the analysis results, the average deviation was 1.9% and the maximum deviation was 5.6%. In addition, the fuel outlet temperature and fuel conversion rate at the cooling channel outlet were compared and shown in Table 1. It was confirmed that the results of the conjugate heat transfer analysis of this study were calculated within a reasonable error range when compared with the experimental data. When comparing the accuracy with the results of the axisymmetric analysis in previous studies, it was confirmed that the analysis results of this study were also calculated with similar errors and were valid.

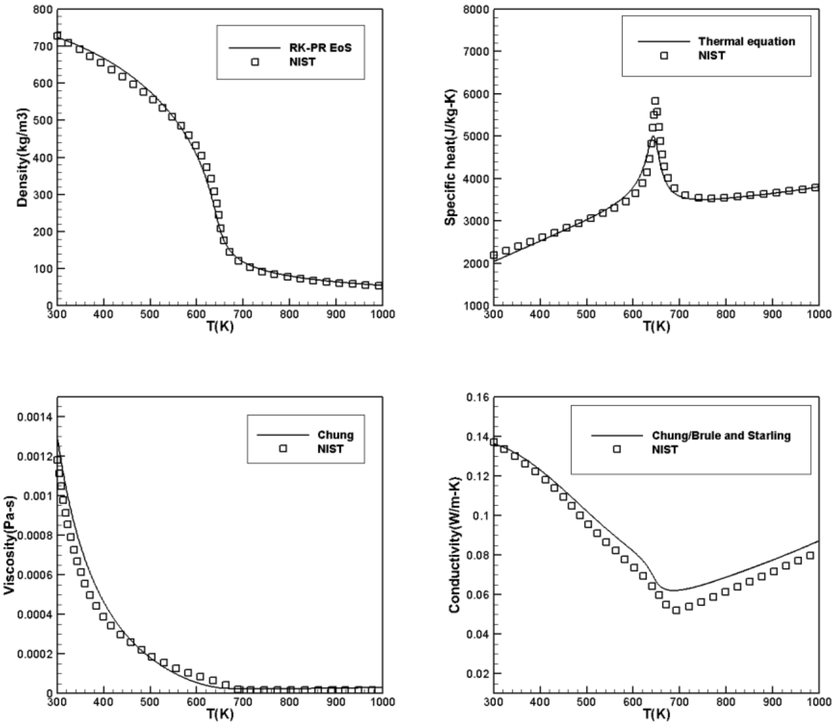


Fig 1. Comparison of NIST data and predicted fuel property results for n-decane fuel.

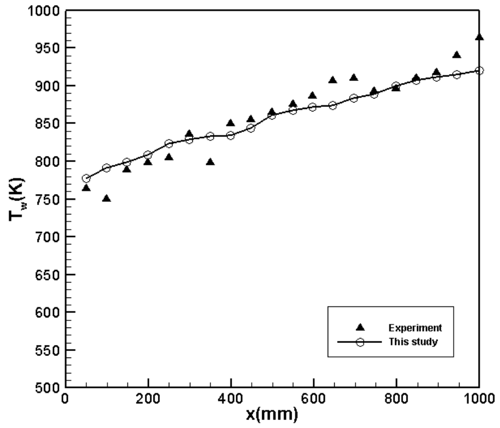


Fig 2. Comparison of numerical analysis result and experimental data.

Table 1. Channel exit temperature result compared with experimental data.

	Experiment	**Numerical result**		**Deviation**
Channel exit temperature (K)	893	887	Deviation (%)	0.7
Conversion (%)	34.36	31.70	Deviation (%)	7.7

2.4. Analysis conditions

In this study, the shape of a scramjet aircraft similar to the X-51A was considered. It is assumed that the aircraft cruises for 600 seconds at Mach number 6 at an altitude of about 23 km. The actual flight trajectory is not a cruise flight, but the concern of this study is the prediction of the cooling performance of the cooling channel. Therefore, the thermodynamic analysis situation assumes the flow environment with the most severe heat load during the flight section. A cooling channel was arranged in one dimension along the shape of the internal flow path of the scramjet aircraft. The AR of the cooling channel is 1, 2, and 4, and the cross-sectional shape information is shown in Table 2 in consideration of the combustion chamber area and total mass flow rate. The fuel is assumed to be n-decane. The cooling channel condition is assumed to be a total mass flow rate of 300 g/s considering the equivalent ratio of the flight mode, and the operating pressure is assumed to be 3 MPa considering the supercritical situation. The initial inlet temperature is 300 K. In addition, the material of the structure was set to Inconel X-750, which is considered a heat-resistant material in the combustion chamber [6].

Table 2. Cooling channel information.

AR	W(mm)	H(mm)	N	$\dot{m}/\mathrm{N}$(g/s)
1	1.445756	1.445756	156	1.92
2	0.928562	1.857125	182	1.65
4	0.62118	2.484719	204	1.47

2.5. Results and discussions

Fig. 3 shows the results of the temperature outside the fuselage of the scramjet aircraft. Parts such as the sharp leading edge rose to the adiabatic temperature and were calculated to be approximately 1,258 to 1,544 K. Fig. 4 shows the structure temperature result near the combustion chamber, which generates the most heat due to combustion heat. Since the vicinity of the combustion chamber is greatly affected by the cooling channel, the surface temperature was compared according to the cooling channel AR. The lower the AR, the lower the structure temperature was calculated at the same point in the combustion chamber. The cooling channel results are shown in Fig. 5, and the highest temperature at the outlet temperature was calculated to be approximately 1,022-1,039 K, depending on the AR. When comparing the temperature of the structure near the combustion chamber with the cooling channel results, the lower the aspect ratio, the better the cooling performance. In the case of a predetermined combustion chamber area, the smaller the aspect ratio, the higher the mass flow rate per channel, resulting in better cooling performance. In addition, the average temperature and total pressure drop of fuel at the cooling channel outlets with the aspect ratios of 1, 2, and 4 were calculated as shown in Table 3. In terms of combustion, there is an advantage in promoting combustion because high-temperature fuel is easily pyrolyzed. The total pressure drop in the cooling channel was calculated to be the lowest when the AR was 1. Considering the average outlet temperature of a cooling channel, the surface temperature of the structure, and the total pressure drop of the cooling channel, the lower the AR, the better the performance. As a result, the structure was calculated with a temperature distribution of 2,000 K or less. If heat-resistant materials having a high melting point are properly utilized in the structure of the aircraft, the aircraft can sufficiently withstand the situation. In addition, since pyrolysis actively occurs at the temperature of the fuel from about 800 K, combustion efficiency is advantageous when the fuel is injected at a temperature of at least 800 K or higher at the cooling channel outlet. In the flight situation assumed in this study, the maximum temperature of the fuel is about 1,000 K and the average outlet temperature is about 800 K, so it was confirmed that the fuel sufficiently rises to the temperature at which pyrolysis occurs.

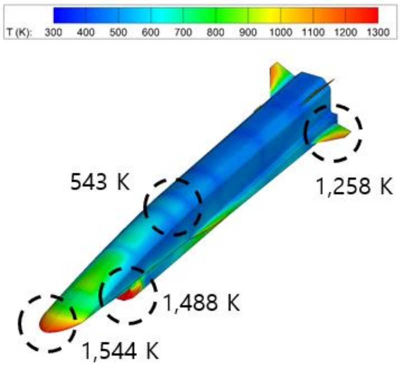


Fig 3. Temperature contour of fuselage.

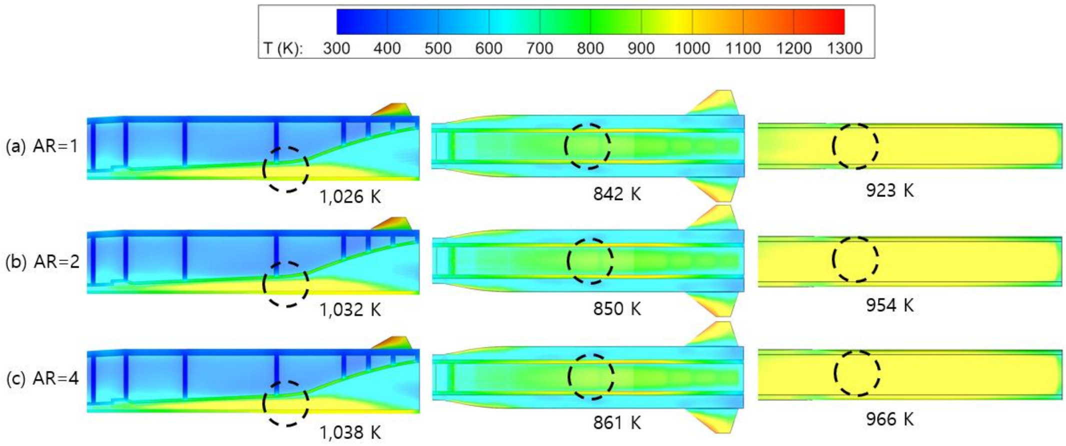
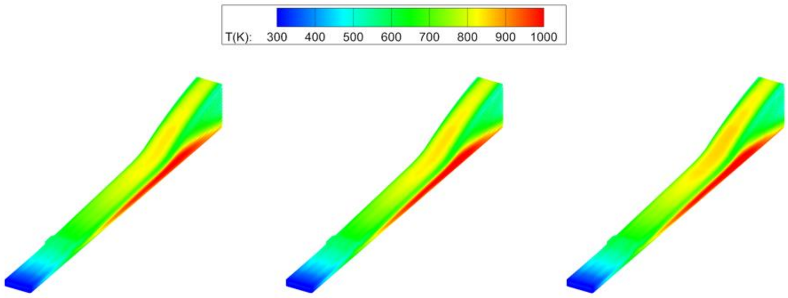


Fig 4. Temperature contour from combustion chamber to nozzle (left: side, middle: upper, right: lower).



(a) AR=1 (b) AR=2 (c) AR=4

Fig 5. Temperature contour of cooling channel.

Table 3. Results of cooling channel.

AR	$\mathbf{T_{max}}$**(K)**	$\mathbf{T_{avg}}$**(K)**	$\mathbf{\Delta P_{sum}}$**(kPa)**	$\mathbf{u_{avg}}$**(m/s)**
1	1,022	792	673	10.5
2	1,037	797	876	11.0
4	1,039	795	1,134	11.1

3. Conclusion

This study used computational analysis to confirm the characteristics of the regenerative cooling channel of the scramjet aircraft. JP-8 was considered as the fuel inside the cooling channel. The properties of fuel were calculated using a general three-parameter state equation and transport property model, and the Dittus-Boelter model was applied to the heat transfer model. It was confirmed that the sharp leading edge of the outer fuselage of the scramjet aircraft rose from 1,258 to 1,544 K. And the maximum temperature of the fuel outlet was calculated to be approximately 1,022-1,039 K depending on the AR. The total pressure drop of the cooling channel was the lowest when the AR was 1. In addition, when the cooling channel AR was low, the temperature of the combustion chamber structure was calculated to be lower. Overall, considering the outlet temperature of the cooling channel, the temperature of the structure, and the total pressure drop of the cooling channel, the lower the AR, the better the performance.

Acknowledgments

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