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Study of boiling water reactor containment temperature field underwater flooding

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Abstract: Nuclear energy, as a clean energy source with high efficiency and low pollution, is receiving more and more attention from human society, and the Fukushima nuclear meltdown in Japan in 2011 has attracted the attention of the academic community. The explosion of the Fukushima nuclear power plant was caused by the flooding of the diesel engine set by seawater, which resulted in the reactor being unable to stop and continue its reaction. The temperature inside the containment continued to rise, and the meltdown occurred due to the combination of high temperature and internal pressure, which exceeded the limit of the bearing capacity of the containment. In this paper, we study the temperature change of the boiling water reactor containment under flooding conditions and conduct an in-depth investigation based on the existing research on the temperature field of boiling water reactor containment, to derive the equation of temperature field change under flooding conditions and conduct numerical simulation on the temperature field change under flooding condition.

1. Background

Fukushima nuclear power plant is a famous boiling water reactor nuclear power plant. The nuclear reactor at Fukushima nuclear power plant is a single-cycle boiling water reactor operating as high-pressure steam driving a turbine, consisting mainly of a cooling circuit that operates in a low-pressure boiling manner with a direct cycle in which steam is generated directly from the core to drive the turbine [1], coolant boils in the reactor, water flows in the reactor in two phases, and the cooling water from the vapor mixture generated in the reactor is introduced directly into seawater. In case of an explosion, the radioactive nuclear wastewater it produces will contaminate the entire Pacific Ocean, which will not only bring the world nuclear power development to a standstill but also put the lives of all human beings at risk.

On March 11, 2011, a huge earthquake struck the northeast coast of the main island of Japan, triggering a tsunami, and under the double blow of the earthquake and tsunami, the Fukushima Daiichi nuclear power plant (NPP) was severely damaged, and in combination with the poor design solution of the plant itself and improper operation of the personnel involved, during the accident due to steam cooling and heat dissipation by radiation at high temperatures, and the hard oxide skin formed on the surface of the cladding tubes, the fuel rods retained their original shape and when they were quenched were broken into pieces and fell to the bottom of the reactor, causing the core to rupture, leading to the failure of its cooling system and thus the hydrogen explosion and core meltdown [3]. In boiling water reactors when they are not generating electricity, their fuel is still fissioning, the core melts but the generator cannot start properly affecting the cooling water circulation, and the residual heat in the reactor cannot be discharged properly, leading to high-temperature radioactive material leakage and even molten reactor explosion, which in turn leads to nuclear leakage, as shown in Figure 1 and Figure 2.

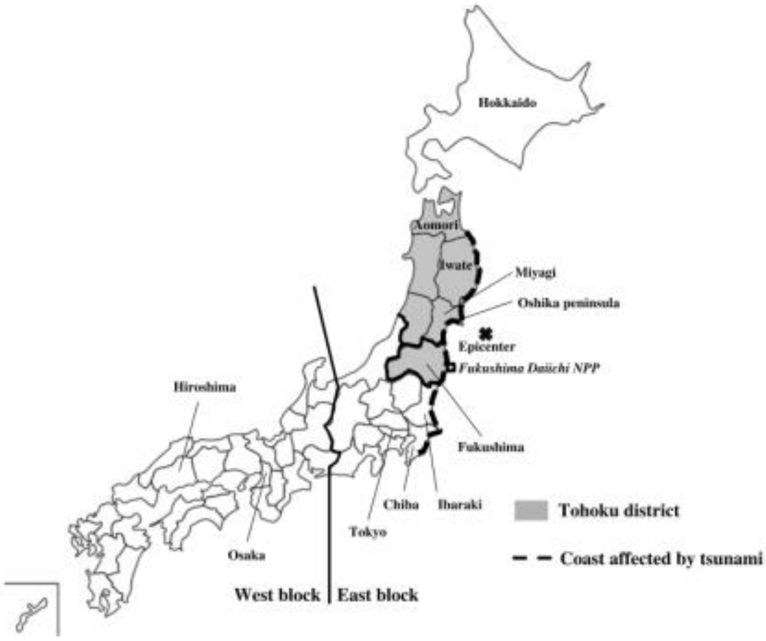

Figure 1: Location of Fukushima Daiichi nuclear power plant [2]

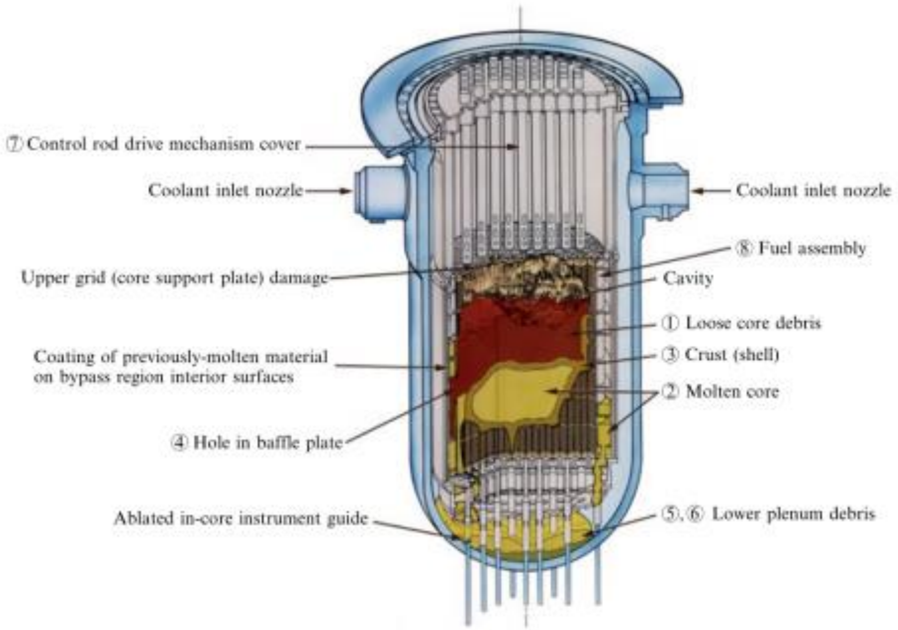

Figure 2: Internal structure of containment [2]

Nuclear power plant containment is an important enclosure structure of barrier nuclear power plant, analysis of its damage process under high temperature and pressure, as well as the temperature field changes in the flooded state, is of great significance for the prevention of nuclear leakage.

2. Status and dynamics of research

The study of nuclear power plants has been a common concern. And, there have been many studies in the academic community related to the Fukushima nuclear power plant. For the numerical simulation of the core melt on the vessel wall, Xiaoying Zhang [4] et al. used a two-layer structural model of the core melt to establish a non-stationary two-dimensional heat transfer model of the pressure vessel wall to calculate the temperature and thickness variation of the lower wall of the pressure vessel. Cheng Xiu [5] et al. proposed an improved containment atmosphere hydrogen concentration monitoring system after analyzing the penetration mandrel material and the thermocouple termination problem. Zhou Zhi [6] et al. established an accurate three-dimensional Monte Carlo model to simulate the shielding of the containment against the radiation particles under the severe accident conditions of a core meltdown. Yu Miao [7] proposed a mathematical model of heat transfer inside the steel containment, water, and steam physical property models, and simplified the physical model of the non-energetic containment cooling system. Chunlong Zhang [8] et al. used finite element software to establish a realistic and perfect containment structure to provide favorable analytical judgment conditions for later studies.

3. Temperature field model

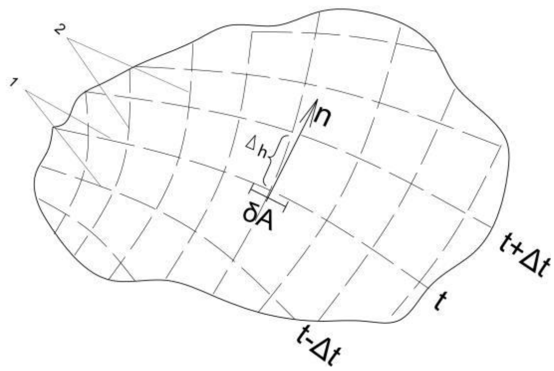

Figure 3: Schematic diagram of temperature field

The temperature field is a function of time t and spatial coordinates (x,y,z) as a collection of temperatures T at various points within a material system, and can be used to reflect the distribution of temperature T in space and time, which is mathematically expressed as$T=f(x,y,z,t)$. The analysis of the temperature field can be used to predict the temperature distribution inside and outside the structure. The phenomenon of thermal conductivity is the process of heat propagation when the individual masses of an object or individual objects of different temperatures come into direct contact. The thermal conductivity field which does not change with time is called the steady-state temperature field, and the thermal conductivity which changes with time is called the unsteady-state temperature field. Since the temperature field inside the containment varies with temperature, this paper studies the unsteady-state temperature field and applies it to the calculation of the temperature field inside the containment, as shown in Figure 3.

Heat transfer refers to the transfer from the high-temperature part of the object to the low-temperature part, in nature, as long as there is a temperature difference there will be heat transfer. The heat transfer between different objects and different parts of the object is mainly in three basic ways, which are heat conduction, heat convection, and heat radiation. Heat conduction is the main way of heat transfer in solids. Heat convection is the process of heat transfer caused by the relative displacement of masses in a fluid. The main composition of the boiling water reactor containment is reinforced concrete, in which the boiling water reactor containment will circulate due to uneven density in the fluid caused by uneven temperature during the melt explosion, so this paper mainly considers the heat conduction and heat convection phenomena in heat transfer.

Heat conduction is the phenomenon of heat transfer between two contacting objects or parts of the same object due to temperature differences. Thermal conduction coefficient = linear parameter (conduction coefficient is constant) + nonlinear parameter (conduction coefficient is non-constant). Where the thermal conductivity is used to specify the thermal conductivity parameter of a material. According to Fourier's law of thermal conductivity, the solid heat conductivity Q

$$Q = \lambda A \frac{\Delta T}{\delta}$$

Where A is the cross-sectional area perpendicular to the direction of thermal conductivity, the δ is the thickness of the flat wall, the λ is the thermal conductivity, and ΔT is the difference in wall temperature between the two sides of the flat wall.

Nowadays, considering the temperature field change in the flooded state, the heat transfer process between the fluid with relative displacement and the surface it touches needs to be considered. The heat transfer power Q is the heat passing through the heat transfer surface per unit time, known by the Newtonian cooling equation

$$Q = Ah\Delta T = Ah(T_w - T_f) = \frac{T_w - T_f}{1/hA}$$

Where A is the area of the wall in contact with the fluid, h is the convective heat transfer coefficient, ΔT is the temperature of the wall surface T_w, and fluid temperature T_f is the difference between

The boundary of the system affects the physical state of the system, and the boundary condition of the system is determined by the boundary condition, which reacts to the situation at the interface between the system and the outside world. Common boundary conditions can be divided into three categories. The first type of boundary condition gives the value of the unknown function on the boundary, i.e., the temperature distribution on the surface of the object at each instant; the second type of boundary condition gives the value of the unknown function in the normal direction on the boundary, i.e., the value of heat flow at individual points on the surface of the object at any instant; the third type of boundary conditions gives the value of the linear combination of the unknown function and the derivative of the normal direction on the boundary, i.e., the value of The third type of boundary conditions gives the value of the linear combination of the unknown function and the derivative of the normal direction at the boundary, i.e., the heat transfer law between the surface and the surrounding medium, as shown in Figure 4, Figure 5 and Figure 6.

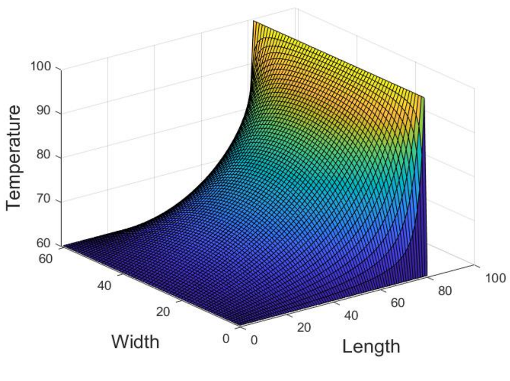

Figure 4: Temperature distribution under the first type of boundary conditions

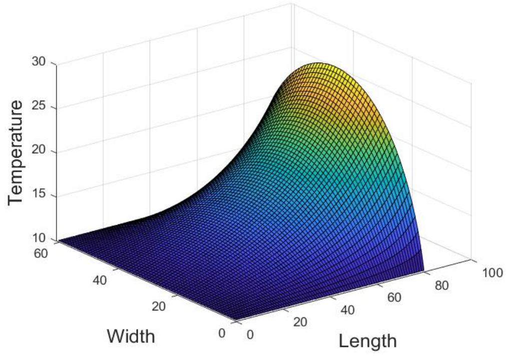

Figure 5: Temperature distribution under the second type of boundary conditions

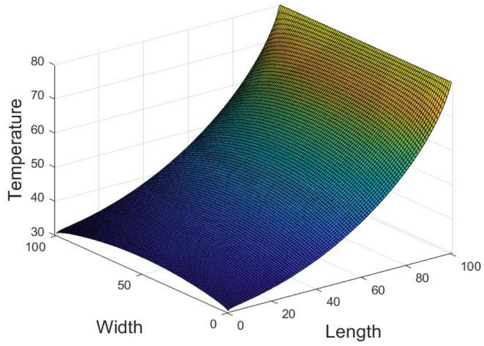

Figure 6: Temperature distribution under the third type of boundary conditions

Heat flow density is also known as heat flow, and heat flow rate represents the heat transferred per unit of time across a given surface by conduction, convection, or radiation, and is given by the following equation

$$q = Q/(S \cdot t)$$

Where Q is the heat, t is the time, and S is the cross-sectional area.

The Newton-Liechmann formula is used to describe the heat transfer process between the surface of an object and the medium, where the heat flow density q is related to the temperatureT_c of the object surface and the temperatureT_w of the surrounding medium (air temperature is considered in this paper) is related as follows

$$q = \alpha(T_c - T_w)$$

Where α is the proportionality coefficient indicating the heat transfer intensity between the surface of the object and the surrounding medium, numerically equal to the heat released (or absorbed) per unit surface area of the object at unit temperature difference.

At the same time, it is necessary to consider the heat taken away from the unit surface area per unit time due to exothermic heat and the heat transferred from the interior of the object to the unit surface area per unit time due to thermal conductivity, i.e. the energy conservation theorem.

In this paper, we consider the third type of boundary conditions and obtain the following equations by combining the Newton-Lehmann formula and the energy conservation theorem

$$(\frac{\partial T}{\partial n})_c = -\frac{\alpha}{\lambda}(T_c - T_w)$$

Where n is normal to the surface of the object and c is the temperature and temperature gradient on the surface of the object.

The containment, also known as the reactor protection shell, is a vertical cylindrical hemispherical top cover or spherical sealed metal or concrete shell that acts as a protection for the reactor's main equipment, so it can be first simplified to a simple cylindrical wall, as shown in Figure 7.

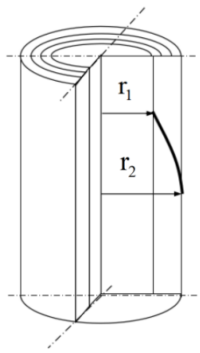

Figure 7: Schematic diagram of the circular cylinder wall

Suppose the inner and outer radii of the circular cylinder wall are r_1 and r_2, the length is L, and the surface temperatures of the inner T_1 and outer walls T_2 are kept at constant temperatures and respectively. Neglecting the heat dissipation along the axial direction, we have the following equation for the heat conduction rate of the cylindrical wall

$$Q = -\lambda S \frac{dt}{dr} = -\lambda(2\pi rL)\frac{dt}{dr}$$

Integrating the above equation by separating the variables and organizing gives

$$Q = 2\pi L\lambda \frac{T_1 - T_2}{\ln\frac{r_2}{r_1}} = \frac{T_1 - T_2}{\ln\frac{r_2}{r_1}/2\pi L\lambda}$$

Similarly, the equation for the heat transfer rate of the n-layer cylinder wall can be obtained as

$$Q_n = \frac{T_1 - T_{n+1}}{\sum_{i=1}^{n}\frac{\ln\frac{r_i+1}{r_i}}{2\pi L\lambda_i}}$$

Where T_n is the constant temperature of the surface of the nth layer of the cylinder wall.

Since the length of the cylinder wall is much greater than its wall thickness, the heat loss at the end of the wall can be neglected, while not considering the length of the cylinder wall, combined with reference [9] it is known that the equation of heat transfer through the single-layer circular pass equation is

$$\begin{cases} q = 2\pi r_1\beta_1(T_{w1} - T_{c1}) \\ q = 2\pi\lambda(T_{c1} - T_{c2})/\ln\frac{r_2}{r_1} \\ q = 2\pi r_2\beta_2(T_{c2} - T_{w2}) \end{cases}$$

Where β_1 and β_2 are the internal and external convection coefficients of the circular cylinder wall, and r_1 and r_2 are the inner and outer radii of the cylinder, and T_{c1} and T_{c2} are the inner and outer wall temperatures of the cylinder wall, andT_{w1} andT_{w2} are the internal and external air temperatures of the cylinder wall, q is the heat flow density of the cylinder wall, and is the thermal conductivity of the cylinder wall.

The equation for the heat flow density q is obtained by simplifying

$$q = \pi(T_{w1} - T_{w2})/(\frac{1}{2\beta_1 r_1} + \frac{1}{2\lambda}\ln\frac{r_2}{r_1} + \frac{1}{2\beta_2 r_2})$$

and the temperature equations for the inner and outer surfaces of the cylinder wall

$$\begin{cases} T_{c1} = T_{w1} - \frac{q}{2\pi}\frac{1}{\beta_1 r_1} \\ T_{c2} = T_{w1} - \frac{q}{2\pi}(\frac{1}{\beta_1 r_1} + \frac{1}{2\lambda}\ln\frac{r_2}{r_1}) \end{cases}$$

Similarly, the heat transfer of the double-layer cylinder about the temperature equation of the inner, middle, and outer surfaces of the cylinder can be obtained as

$$\begin{cases} T_{c1} = T_{w1} - \frac{q}{2\pi\beta_1 r_1} \\ T_{c2} = T_{w1} - q(\frac{1}{\beta_1 r_1} + \frac{1}{\lambda_1}\ln\frac{r_2}{r_1})/4\pi \\ T_{c3} = T_{w1} - q(\frac{1}{\beta_1 r_1} + \frac{1}{\lambda_1}\ln\frac{r_2}{r_1} + \frac{1}{\lambda_2}\ln\frac{r_3}{r_2})/2\pi \end{cases}$$

That is, the cylinder wall temperature is obtained Regarding, the air temperature of the cylinder wall and the heat flow density q, and the radius of the cylinder r are given by

$$T_c = g(T_w, q, r)$$

The Fukushima nuclear power plant was flooded by both the earthquake and tsunami and the meltdown of the meltdown reactor, and the generator in the basement of the plant was not working properly due to flooding, resulting in the nuclear reactor not being cooled down as usual. Consider the change in the temperature field of the boiling water reactor under flooding.

If we consider that the water flow is stationary in the case of water flooding in the containment, it can be graphically simplified as a device immersed in water, so this paper introduces a coefficient φ on top of the original heat transfer model. Therefore, this paper introduces a coefficient on top of the original heat transfer model, as the flooding coefficient.

It is known that a part of the energy is lost in the case of flooding, so the following relation of the law of conservation of energy on the surface of the object is obtained

$$(\frac{\partial T}{\partial n})_c^{'} = -\frac{\alpha}{\lambda}\varphi(T_c - T_w)$$

Where φ is the flooding factor.

In turn, the equation for the heat transfer equation of the single-layer circular pass is obtained as

$$\begin{cases} q^{'} = 2\pi r_1 \beta_1 \varphi(T_{w1}^{'} - T_{c1}^{'}) \\ q^{'} = 2\pi\lambda(T_{c1}^{'} - T_{c2}^{'})/\ln\frac{r_2}{r_1} \\ q^{'} = 2\pi r_2 \beta_2 \varphi(T_{c2}^{'} - T_{w2}^{'}) \end{cases}$$

Where β_1 and β_2 are the internal and external convection coefficients of the circular cylinder wall, and r_1 and r_2 are the inner and outer radii of the cylinder, and T'_{c1} and T'_{c2} are the internal and external wall temperatures of the cylinder wall after flooding, and T'_{w1} and T'_{w2} are the internal and external air temperatures of the cylinder wall after flooding, q' is the heat flow density of the cylinder wall, and λ is the thermal conductivity of the cylinder wall.

The equation for the heat flow density q' in the flooded state is obtained by simplifying the equation at

$$q' = \pi(T'_{w1} - T'_{w2})/(\frac{1}{2\varphi\beta_1 r_1} + \frac{1}{2\lambda}\ln\frac{r_2}{r_1} + \frac{1}{2\varphi\beta_2 r_2})$$

and the temperature equations for the inner and outer surfaces of the cylinder wall under flooding

$$\begin{cases} T'_{c1} = T'_{w1} - \frac{q'}{2\pi}\frac{1}{\beta_1 r_1} \\ T'_{c2} = T'_{w1} - \frac{q'}{2\pi}(\frac{1}{\varphi\beta_1 r_1} + \frac{1}{2\lambda}\ln\frac{r_2}{r_1}) \end{cases}$$

Similarly, the heat transfer of the double-layer cylinder in the flooded state can be obtained regarding the temperature equation of the inner, middle, and outer surfaces of the cylinder as

$$\begin{cases} T'_{c1} = T'_{w1} - \frac{q'}{2\pi\beta_1 r_1} \\ T'_{c2} = T'_{w1} - q(\frac{1}{\varphi\beta_1 r_1} + \frac{1}{\lambda_1}\ln\frac{r_2}{r_1})/4\pi \\ T'_{c3} = T'_{w1} - q(\frac{1}{\varphi\beta_1 r_1} + \frac{1}{\lambda_1}\ln\frac{r_2}{r_1} + \frac{1}{\lambda_2}\ln\frac{r_3}{r_2})/2\pi \end{cases}$$

4. Numerical simulation of temperature field underwater flooding

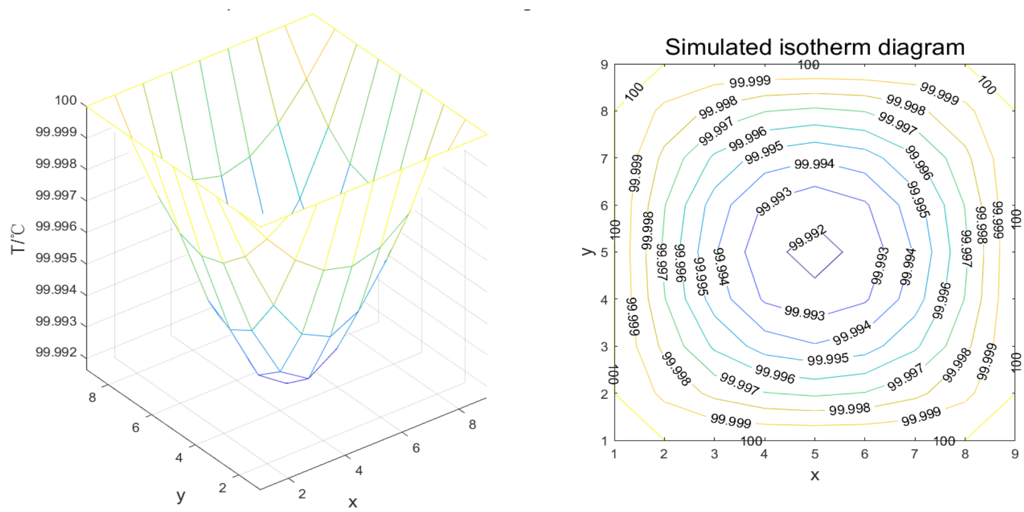

Figure 8: Two-dimensional temperature field simulation diagram

In this paper, MATLAB software is used to establish a model to numerically simulate the temperature field distribution of a single-layer cylinder wall under flooding conditions, assuming that the initial temperature of the cylinder wall is 50 ℃, the steady-state temperature is 100 ℃, and the temperature conductivity is 0.05, and the following two-dimensional temperature field simulation diagram and simulation isotherm diagram are obtained, as shown in Figure 8.

5. Conclusion

The Fukushima containment was subjected to hydrogen explosion and core meltdown due to the failure of its cooling system as a result of the core rupture. In this paper, we study the temperature field changes inside the boiling water reactor containment under flooding conditions, introduce the flooding coefficient as an innovative point, derive new heat transfer equations for single-layer as well as double-layer cylinders under flooding conditions, and numerically simulate the temperature field distribution of the cylinder wall to provide a new direction of thinking for boiling water reactor temperature field analysis research.

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