A Numerical Study on the Influence of Temperature on the Measurement Performance of liquid lead-bismuth-eutectic (LBE) Electromagnetic-flowmeter

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Abstract

Liquid lead-bismuth eutectic (LBE) is one of the preferred materials for accelerator driven subcritical(ADS) transmutation targets and coolants in fourth-generation nuclear reactors. Due to the complex and interacting physical and chemical factors in the measurement process of LBE in high temperature operating environment, it is very difficult to control the flow and on-line calibration, resulting in the slow development of LBE flow meter technology, which hinders the fourth Generation nuclear reactor technology development. Electromagnetic flowmeter is currently recognized as one of the most suitable LBE flow measuring instruments in the world. In this paper, the measurement characteristics of LBE electromagnetic flowmeter at high temperature are numerically analyzed and studied, the influence of temperature on magnetic field strength and flow field distribution is quantitatively given, and the measurement linearity of LBE electromagnetic flowmeter is analyzed. The research conclusions provide a certain reference for the detection of lead-bismuth alloy flow parameters and the on-line calibration of LBE electromagnetic flowmeters in the nuclear industry control process.

1. Introduction

Nuclear energy is one of the most promising clean, economical and high-efficiency energy sources because it does not produce greenhouse gases during the energy conversion process and effectively reduces the harm to the environment. According to the medium and long-term development plan of China's nuclear power, by 2020, the total installed capacity of nuclear power in my country will reach 4 billion watts (operation) and 1.8 billion watts (under construction), and the annual spent fuel will exceed 1,000 tons. 10,000 tons, and the total will reach more than 14,000 tons in 2025[1]. The limited uranium resources and the difficulty in properly disposing of nuclear waste are obstacles to the development of my country's nuclear technology. Accelerator Driven subcritical system (ADS) is an innovative technical route for transmuting nuclear waste, and it is an effective solution to the bottleneck of nuclear energy utilization.

LBE has a series of advantages such as low melting point, high boiling point, radiation resistance, stability, good thermal conductivity and good fluidity, so it has become one of the preferred materials for ADS core coolant. Accurately obtaining the flow information of LBE is the key core technology to ensure the safe operation and control of the nuclear reaction loop. LBE has special physical and chemical properties, and the flow meter has been operating in harsh conditions of high temperature, high pressure and strong radiation for a long time, resulting in slow development of LBE flow measurement technology.

The electromagnetic flowmeter based on Faraday's electromagnetic induction principle is a velocity-type flowmeter. Electromagnetic flowmeter has the advantages of simple structure, strong signal stability, no internal resistance parts, and little influence by the flow characteristics of lead-bismuth fluid during measurement. Therefore, it is one of the most important methods of lead-bismuth flow measurement in the world[2-3]. The ambient temperature of the traditional electromagnetic flowmeter is (5~35)°C, and the temperature of the measured medium is (4~35)°C. However, the ambient temperature in the ADS reactor loop is (200~400)°C, and the temperature of LBE is (200~500)°C.

In order to develop a LBE electromagnetic flowmeter that can operate stably for a long time and maintain measurement accuracy under actual high temperature conditions, many scientific research institutions and scholars have carried out a lot of research. The CHEOPE and LECOR circuits in Italy, the LISOR circuit in Sweden and the THESYS circuit in Germany all use permanent magnet electromagnetic flowmeters to detect flow, but no clear research conclusions have been given for the accuracy and stability of the instruments after long-term operation[4]. Switzerland and Sweden also use electromagnetic flowmeters as lead flow measurement instruments, but have not published relevant results of in-depth research. The flowmeter used by the magnetohydrodynamic device MaPLE (Magneteohydrodynamic PbLi Experiment) built by UCLA University in the United States is a custom-made permanent magnet electromagnetic flowmeter. It can be seen from the experimental data that 0.09m3/h is measured. The minimum flow point obtained is about 3m^3/h[5]. The permanent magnet electromagnetic flowmeter designed by KIT in Germany is used in the PICOLO circuit. The working temperature of the flowmeter is 350 °C, and the flow range is (0.0072~0.72) m^3/h [6]. The stability of the flowmeter has been reported. The experimental platform of the Brasimone Research Center TBE of ENEA in Italy uses three electromagnetic flowmeters with a maximum flow rate of 1.027m^3/h, but during the actual flow experiment, the output of the flowmeter is unstable[7]. LBE electromagnetic flowmeters are also used in nuclear reactors in many laboratories in India and Japan[8-10]. When Indian researchers tested the electromagnetic flow performance on the experimental device, they found that the percentage error between the simulated value and the actual value of the electromagnetic flowmeter they designed was about 2%[11]. Russia has studied including ADS-related coolant flow parameter experiments, and related instrument optimization design theory and control software development[12]. The technology is relatively mature, but the LBE instruments in the system need to be disassembled and calibrated repeatedly.

China has carried out research on the concept of ADS since the 1990s.In 2011, the Chinese Academy of Sciences launched the strategic pilot science and technology project of "Future Advanced Nuclear Fission Energy-ADS Transmutation System", dedicated to completing the independent research and development of all core technologies and system integration technologies of the ADS system from test devices to demonstration devices. In addition, The FDS team is a multi-disciplinary advanced nuclear energy research team established by the Institute of Plasma Physics, Chinese Academy of Sciences and the School of Nuclear Science and Technology, University of Science and Technology of China. The ADS transmutation demonstration device uses an electromagnetic flowmeter independently developed by my country, but under long-term operation The measurement of LBE electromagnetic flowmeter has deviation, and the maximum linear deviation is -0.14% respectively[13-19]. After long-term research by scientific researchers in China, many achievements have been made in the measurement principle and measurement characteristics of LBE electromagnetic flowmeters. Flow measurement technology is not perfect and mature.

The research focus of this paper is the influence of high temperature on the measurement characteristics of lead-bismuth electromagnetic flowmeter, especially the relationship between the induced magnetic field and flow field and the measurement characteristics of the electromagnetic flowmeter at high temperature, and further analyzes the influence of temperature on the linearity of the electromagnetic flowmeter. The research conclusions obtained have certain reference significance for promoting the LBE flow instrument technology and the development of the fourth-generation nuclear reactor.

2. Background theory

The basic principle of the lead-bismuth electromagnetic flowmeter is Faraday's law of electromagnetic induction. Permanent magnets are used to form a uniform and constant magnetic field (**B**) around the pipeline(The diameter of the measuring tube is D). When the LBE flows through the measurement pipeline, the induced magnetic field is cut to generate an induced potential (U). The magnitude of the induced electromotive force is proportional to the fluid flow rate (average velocity $\bar{v}$). The measurement principle of the LBE electromagnetic flowmeter is shown in Figure 1.

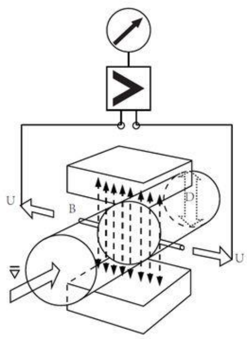


Figure 1: Principle diagram of LBE electromagnetic flowmeter.

In order to further discuss the measurement characteristics of LBE electromagnetic flowmeter, we have summarized and analyzed the measurement equation of electromagnetic flowmeter on the basis of previous research[20-21].

According to Ohm's law,

$$\vec{j} = \sigma\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{1}$$

$\vec{j}$ is the current density vector, $\vec{E}$ is the electric field strength, $\vec{v}$ is the fluid average velocity; $\vec{B}$ is the magnetic induction.

Introduce potential *U*,

$$\vec{E} = -\nabla U \tag{2}$$

Since the angular frequency of the excitation current is very low, the displacement current is ignored and only the conduction current is considered, and the divergence of the current density $\vec{j}$ is obtained to be equal to zero.

$$\nabla \cdot \vec{j} = 0 \tag{3}$$

Substitute formula (2) and formula (3) into formula (1) to get,

$$\nabla \cdot \vec{E} + \nabla \cdot (\vec{v} \times \vec{B}) = 0 \tag{4}$$

Combining formula (2), we get,

$$\nabla^2 U = \nabla \cdot (\vec{v} \times \vec{B}) \tag{5}$$

In the formula U is the electromagnetic flow sensor output induced electromotive force; ∇^2 is the Laplace operator. It can be seen from equation (5) that the sensor output signal depends on the movement of the fluid and the induced magnetic field.

3. Theoretical analysis

The excitation mode, insulating lining, electrode installation and signal processing methods of general electromagnetic flow sensors cannot meet the high temperature environment requirements of LBE flow measurement. According to the actual working conditions of the LBE flow measurement loop, the LBE electromagnetic flow sensor optimizes the structure of the general-purpose electromagnetic flow sensor. The LBE electromagnetic flow sensor adopts DC excitation, the measuring tube wall is made of stainless steel and has no insulating lining, and the electrode can be directly connected to the outer wall of the stainless steel measuring tube[22]. Therefore, the measurement characteristics of LBE electromagnetic flowmeters are very different from general-purpose electromagnetic flowmeters, especially the impact of high-temperature environments on the measurement characteristics of lead-bismuth flowmeters, which will be the focus of this paper.

Under the actual working conditions of LBE flow measurement, high temperature not only refers to the temperature of the measured medium, but also includes the high temperature of the measurement environment. As shown in formula (5), the change of the temperature field will cause the (gradient) change of the magnetic field and the flow field, and then affect the sensor output signal.

The factors that cause the change of the magnetic field and flow field gradient include the expansion coefficient and conductivity of the sensor's measuring pipe material, the material of the excitation module, the conductivity and the dynamic viscosity coefficient of the measured fluid. In order to further quantitatively analyze the high temperature for the analysis of the sensor measurement characteristics, the construction temperature (*T*) is from (100~600) °C relative to the stainless steel 316 pipe size (*L*) at 20 °C, the magnet remanence (B_r), and the measured fluid. The rate of change of conductivity (σ_f), wall conductivity (σ_w), and dynamic viscosity ($\bar{v}$). Combined with the actual working conditions, the selected lead-bismuth alloy fluid is $Pb_{44}Bi_{56}$, and the excitation magnetic steel material is AlNiCo. The analysis results are shown in Figure 2.

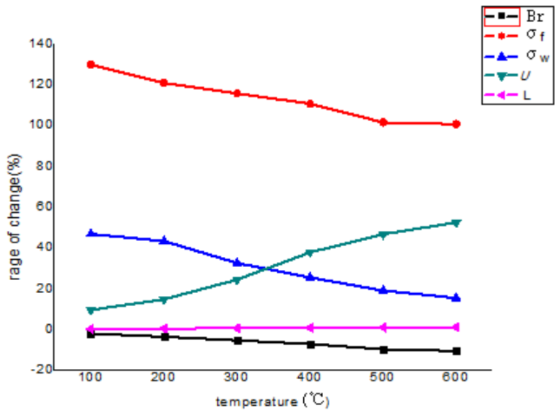


Figure 2: Variation of influence quantity with temperature.

As shown in Figure 2, the change rate of each physical property at temperature (100~600)°C was analyzed. It can be seen from the analysis that,

1. σ_f, σ_w, and Br decreased with the increase of temperature, and the change rates were 25.1%, 42.3%, and 9.8%, respectively. That is to say, as the temperature increases, the conductivity of the measured medium and the conductivity of the measuring tube wall both decrease, and the conductivity of the tube wall decreases more significantly. Therefore, the influence of the conductivity of the tube wall on the output signal must be analyzed during high temperature measurement. Because when the conductivity of the pipe wall is closer to the conductivity of the measured fluid, the short-circuit effect of the output signal is more significant. As the temperature increases, the magnetic field strength will decrease, which can be qualitatively judged. As the temperature increases, the magnetic field strength will decrease.

2 The change rates of υ and L increase with the increase of temperature, and the change rates are: 47.2% and 0.87%, respectively. It can be seen that the change rate of L with temperature changes has little effect, so it will not be considered in the follow-up research. With the increase of temperature, υ increases, and the change of kinematic viscosity will directly affect the distribution of the measured fluid, which in turn affects the output signal of the sensor. Therefore, the subsequent analysis will further quantitatively analyze the influence of the flow pattern and output signal.

4. Modeling and results analysis

According to the analysis in the previous section, among the factors affecting the measurement performance of the flowmeter, the magnetic field strength and flow field distribution are most significantly affected by high temperature. The following will analyze the measurement performance of the LBE electromagnetic flowmeter from these two aspects.

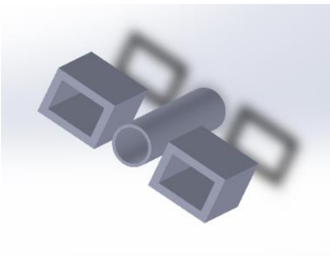
4.1 Analysis and modeling of LBE electromagnetic flow sensor

According to the actual working conditions, the analysis parameters are shown in Table 1.

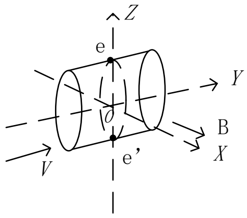
Table 1: Analysis parameters.

Sensor diameter	DN30
Measuring tube length	150mm
Medium temperature	（100~500）℃
Measuring tube wall material	316L
Permanent magnet material	AlNiCo
Measured medium	$Pb_{44}Bi_{56}$
Maximum flow rate	3m/s

The excitation module of the LBE electromagnetic flowmeter adopts DC excitation. The actual working space is limited, and the square and angular permanent magnet structures are used. Compared with angle magnets, the induced magnetic field of square magnets is more uniform. In this paper, square magnet steel is used, the air gap width is 35mm, and the overall volume of the magnet is 170mm×140mm×40mm. The model is shown in Figure 3.



a. 3D model



b. measuring pipe coordinate map

Figure 3: Modeling of LBE electromagnetic flowmeter.

4.2 The effect of temperature on the strength of the magnetic field

When discussing the influence of temperature on the magnetic field strength, if the measured fluid is a fully developed flow, the flow velocity distribution is axisymmetric. The finite element calculation results are shown in Figures 4, 5. Figure 4 is the result of measuring the change of the magnetic field strength at the geometric center of the tube wall with temperature. Figure 5 shows the distribution of the magnetic field intensity in the tube measured at 300°C.

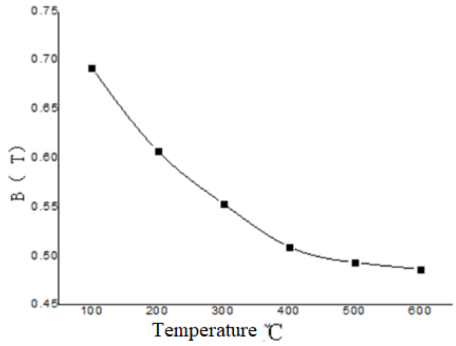


Figure 4: The effect of temperature on the strength of the magnetic field.

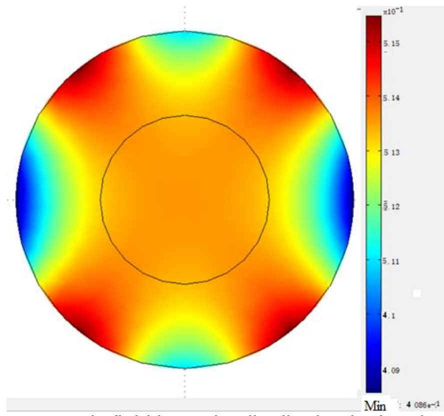


Figure 5: Magnetic field intensity distribution in the pipeline at 300℃ (X0Z plane).

According to the calculation results, it can be known that:

1. As shown in Figure 4, since the magnetic field strength within the measurement tube wall is not uniformly distributed, the magnetic induction intensity at the geometric center of the measurement tube wall is taken here. As the

temperature increases, the magnetic field strength at the center of the measuring tube wall decreases, and the output signal of the lead-bismuth flow sensor decreases at this time.

2. As shown in Figure 5, the distribution of the magnetic field intensity in the pipeline is not completely uniform, and the closer to the edge of the magnetic steel, the more significant the change. However, when the square magnet steel is used, the distribution of the magnetic field in the center of the pipeline is relatively uniform, and the maximum and minimum change rates of the magnetic field strength are relatively low.

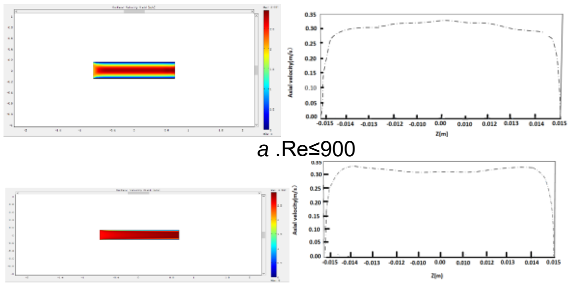
3. Combining with Figures 4 and 5, it can be seen that in the direction perpendicular to the magnetic pole surface, from the two pole surfaces to the center of the flow channel, the distribution is decreasing. In the direction perpendicular to the horizontal plane, that is, the direction of the flow velocity, the magnetic induction intensity decreases from the axis to both sides, and the magnetic induction intensity is the largest at the axis. In the axial direction of the flow velocity, the magnetic induction intensity decreases from the middle of the flow channel to both sides, and there is a gentle area in the middle of the flow channel.

4. In the direction of flow velocity, the magnetic field strength is the largest at the center position, and it shows a downward trend along the measuring tube. Usually, the output signal of the sensor is calculated under the assumption that the magnetic field is uniform, but it can be seen from the analysis that the magnetic field strength of the cross section of the measuring tube can be assumed to be uniform (the gradient of the magnetic field strength is not large) when the magnetic steel structure design is reasonable. However, the magnetic field strength gradient along the direction of the flow velocity is large, that is, the change is large. According to the measurement principle of electromagnetic flowmeter, the output signal of the sensor will be affected, and the linearity of the flowmeter will also be affected.

4.3 The effect of temperature on the flow field of the measured fluid

From the theoretical analysis in the previous section, it can be seen that the flow state of the fluid will affect the output signal of the sensor, and the influence of temperature change on the kinematic viscosity, which in turn affects the flow field distribution of the measured fluid, which will be discussed in detail in this section.

From the analysis in Figure 2, it can be seen that with the increase of temperature, the kinematic viscosity of the fluid changes, and the change of kinematic viscosity will affect the flow pattern distribution of the flow field. When the temperature of the measured fluid is less than 100℃, it has almost no effect on the measurement characteristics of the flowmeter. The temperature variation range discussed in this paper is (100~500)℃. According to the variation range of temperature, the Re value of the measured medium is calculated, and the flow field distribution in the measurement pipeline is obtained, as shown in Figure 6.



a .Re≤900

b. Re≥2900

Figure 6: Effect of temperature change on flow field distribution.

According to the calculation results in Figure 6 and in combination with Equation (6), it can be seen that under the action of the Lorentz force, the flow field will change with the change of temperature. Under laminar and turbulent flow, the axial velocity near the tube wall will drop to 0, and the velocity near the central axis of the tube wall will be the largest. Compared with the turbulent flow, the axial velocity gradient near the measuring tube wall is steeper in laminar flow, that is, the influence on the sensor output signal is more significant at this time.

5. Linear analysis

The linearity of the meter is very important for the measurement performance. High linearity is one of the advantages of electromagnetic flowmeters, but only under a uniform magnetic field and a symmetrical flow field. In the previous analysis, we know that as the temperature changes, both the magnetic field and the flow field distribution are affected by the temperature, and these changes will affect the linearity of the flowmeter. This section will further discuss the effect of temperature on the linearity of the flowmeter, based on the results of the previous analysis.

Because below 100 ℃ has little effect on the measurement characteristics of lead-bismuth electromagnetic flowmeter, the linearity of the instrument when the medium temperature is from (200~500)℃ is analyzed here. Assuming that the flow field is fully developed and the measuring tube is located in the center of the excitation range, the relationship between the flow rate of the instrument and the output signal of the sensor is as follows.

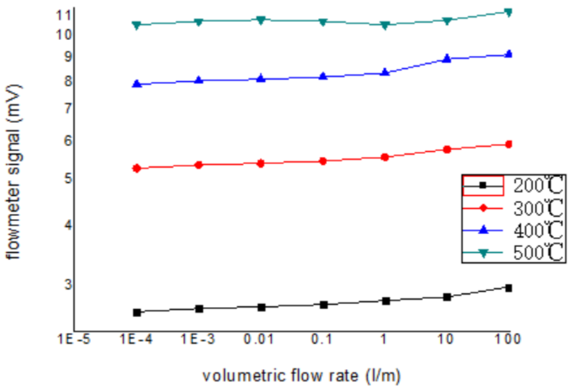


Figure 7: The relationship between the flow rate and the sensor output signal when the flow field is evenly distributed.

As shown in Figure 7, when the design of the magnetic steel structure is reasonable, that is, the influence of the magnetic field distribution on the coupling field in the measurement space is negligible, when the temperature of the measured medium is from (200~500) °C, the output signal of the sensor increases with The flow rate of the meter increases and increases. When the flow rate is less than or equal to 0.1l/m, the sensor output signal does not change significantly with the flow rate. When the temperature is greater than or equal to 400°C and the flow rate is greater than or equal to 0.1l/m, the output signal of the sensor changes significantly with the flow rate. This shows that the high temperature has a significant effect on the linearity of the flow meter.

It can be seen from the analysis in the previous section that high temperature has a significant impact on the flow field distribution. The analysis of the influence of the flow field on the linearity of the sensor output signal is shown in Figure 8.

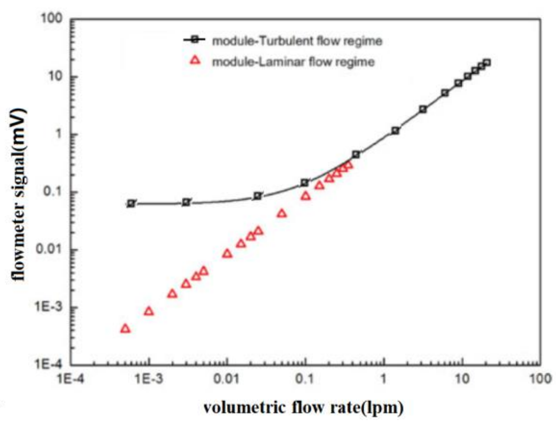


Figure 8: Relationship between flow rate and sensor output signal when the magnetic field is evenly distributed.

As shown in Fig. 8, when the influence of the flow field distribution on the coupled field in the measurement space is negligible, the sensor output signal decreases with the decrease of the flow rate, because with the decrease of the average fluid velocity, the Lorentz force has a The effect of velocity distribution becomes significant. When the flow field distribution is in a turbulent state, a linear relationship is established between the sensor output signal and the flow rate.

In practical applications, we want to know the threshold value at which the flow is linearly related to the sensor output signal. In the turbulent flow state (>4L/m), the linearity between the flow rate and the sensor output signal is significant; while the flow rate is less than or equal to 1 L/m, in the turbulent flow state, the nonlinearity is significant. Therefore, it is not recommended to use experimentally obtained linear equations established in turbulent flow regimes (>4 L/m) for estimating flow velocity in practical conditions.

6. Conclusion and outlook

According to the actual working conditions, the measurement performance of lead-bismuth electromagnetic flowmeter at high temperature is analyzed from the angle of coupling field, and the following conclusions are obtained:

1 When the temperature is between 100°C and 600°C, the change rate of the flow field and the magnetic field has a significant impact on the measurement performance of the LBE electromagnetic flowmeter. In the design and actual use of the LBE electromagnetic flowmeter, the magnetic steel and the measured medium should be considered. Influence of flow field distribution on measurement performance of flowmeter.

2 The distribution of the magnetic field intensity in the pipeline is not completely uniform, and the closer to the edge of the magnetic steel, the more significant the change. However, the distribution of the magnetic field in the center of the pipeline is relatively uniform, and the rate of change of the magnetic field strength is low. When the design of the magnetic steel structure is reasonable, the influence of the magnetic field strength on the output signal of the sensor is limited, but when the measurement environment or the temperature of the measured medium changes significantly, the influence of the magnetic field cannot be ignored, because the magnetic steel material will be affected by high temperature. thereby weakening the sensor output signal.

3 The change of temperature will cause the change of Lorentz force, the flow field in the pipe will change,

and the change rate of the flow field distribution along the pipe wall direction is significant.

4 Linearity is one of the issues that must be considered in the use of LBE electromagnetic flowmeters, which is not only related to subsequent online calibration, but also related to the design of subsequent converters and the calculation of flow rate based on flow conversion. When the medium temperature is greater than or equal to 400°C and the flow rate is greater than or equal to 1L/m, the magnetic field strength has a significant impact on the linearity of the sensor output signal; when the flow rate is greater than or equal to 4L/m, the flow field distribution has a significant impact on the linearity of the sensor output signal.

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