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Design and Research of Power Line Carrier Communication System for In-situ Micro High Pressure Hydraulic Station Controlling the Opening and Closing of Safety Valves

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ABSTRACT
In order to meet the requirements of stable transmission of signals for several kilometers above and below the wellbore using a new type of in-situ micro high-pressure hydraulic station system that controls the opening and closing of safety valves, a long-distance communication system suitable for oil extraction environments has been designed. Select narrowband power line carrier signal transmission method based on the high-temperature and high-pressure working environment and functional requirements underground; Based on the principle of impedance matching, a resistor with the same equivalent impedance value is connected at the end of the transmission line to avoid reflection of the transmission signal along the wire and ensure stable signal transmission; When different power supplies are used for ground and underground systems, the relative zero points between different power modules are different, leading to signal transmission distortion. The negative electrodes of the ground and underground power supplies are grounded together, so that the power supply has a common relative zero point, which preserves the carrier signal; Aiming at the interference of high order harmonics in the power line circuit of the hydraulic station caused by electric submersible pumps on the carrier signal, a fine-tuning inductor is connected in series on the input zero line and the live line of the total circuit, and low-pass filtering is used to shield the high order harmonics in the circuit; Based on heat conduction research, the long-term high-temperature working environment heat resistance of narrowband power line carriers is studied, and simulation verification is conducted using Flotherm XT software. Finally, the experiment verified that the designed communication system can achieve long-distance stable communication both in the well and underground.

Keywords-Safety valve; Power line narrowband carrier communication; Fine tune the inductance; Common negative electrode, equivalent impedance matching, heat resistance simulation

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I. INTRODUCTION

A downhole safety valve is a safety device placed in the wellbore and connected to a set position on the oil pipe, which prevents blowout and environmental pollution when the wellhead device loses control [1]. The traditional safety valve opening and closing hydraulic control system is located on the ground, which remotely controls the opening and closing of the underground safety valve. The hydraulic control pipeline has a long transmission distance, and the control has a certain degree of delay. For the newly proposed in-situ micro hydraulic station, which is located approximately 1000 meters underground near the safety valve, in-situ control of the safety valve can be carried out. The comparison between the two is shown in Figure 1.1. In order to achieve real-time opening and closing of safety valves, it is particularly important to design a communication system that can achieve stable transmission of signals above and below the wellbore, which can greatly improve the safety of oil extraction operations and avoid the occurrence of blowout accidents.

Due to the high temperature and harsh environment underground, wired communication is generally used as the signal transmission method. Fiber optic communication and power carrier communication are mainly used in wired communication [2-3]. The in-situ micro hydraulic station system is used in conjunction with the intelligent composite continuous casing [4-5], and the intelligent composite continuous casing adopts a winding manufacturing process to ensure mechanical performance. Laying optical fibers in it can easily cause fiber breakage. Therefore, power line carrier transmission without the need for additional transmission lines is chosen as the communication method.

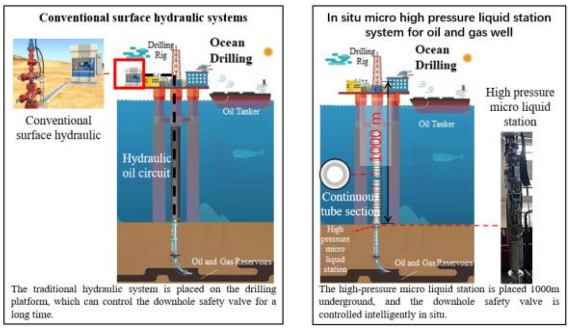


Figure 1.1 Comparison between traditional safety valve opening and closing hydraulic control system and in-situ micro hydraulic station system

However, the underground working environment of high temperature and high pressure, and the submersible oil pump and other high power electrical appliances will cause interference to the communication signal, the existing power line carrier transmission mode can not realize the stable transmission of signals. In view of this, narrow-band power line carrier is selected as signal transmission mode for underground high-temperature working environment in this paper. To solve the problem of equivalent impedance matching, based on the principle of impedance matching, a resistance is connected at the end of the transmission line to avoid the reflection of the transmitted signal along the wire and ensure the stable transmission of the signal. In order to avoid signal distortion and interference, the negative pole of the ground and underground power supply is common grounded to achieve common zero, and the fine-tuning inductor is connected in series on the neutral line and live line of the input end of the equipment power supply to prevent high harmonics, and the anti-interference module is built to realize the signal fidelity transmission in high temperature environment. Finally, the feasibility of power narrow-band carrier communication is determined by heat resistance analysis.

II. Determination of narrowband carrier signal transmission method

The carrier wave is generally electromagnetic wave, which can load ordinary signals (sound, image) onto high-frequency signals of a certain frequency. According to the signal frequency, the carrier signal can be divided into narrowband carrier communication and broadband carrier communication. Its characteristics are shown in Table 2.1:

Table 2.1 Classification and characteristics of carrier Signal

Carrier signal	Narrowband carrier signal	Broadband carrier signal
Transmission frequency	10kHz-500kHz	2MHz-20MHz
Low signal transmission power	√	
Suitable for high temperature environment	√	
Faster transmission rate		√
Lower cost	√	

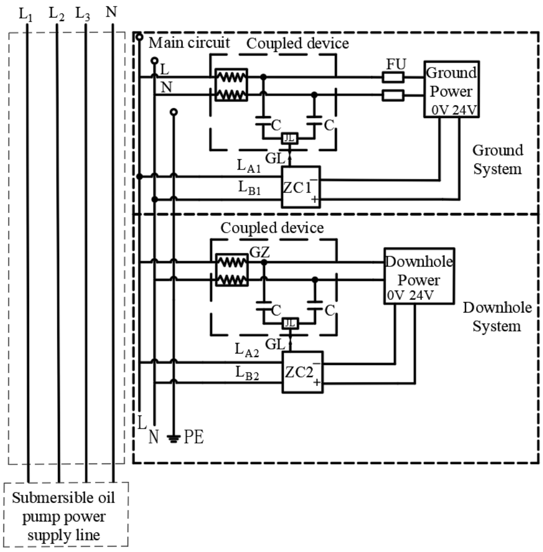
Due to the high power of broadband transmission, it is difficult to adapt to high-temperature environments in oil wells. Therefore, narrowband carrier signal transmission is chosen as the transmission method.

III. Design of Narrowband Carrier Communication System and Stable Signal Transmission

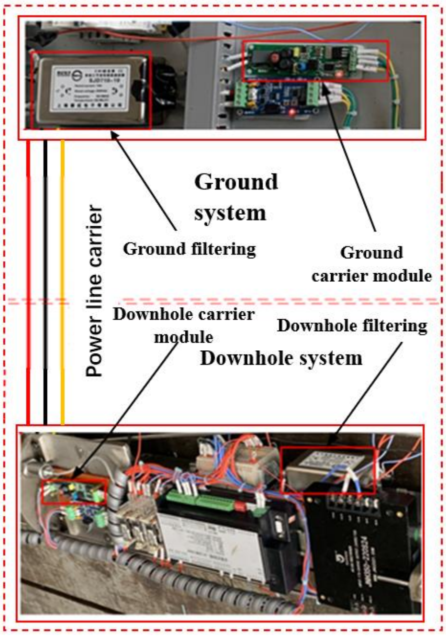
By constructing the carrier and TTL-485 modules, connecting resistors in series in the narrowband carrier power line, a common ground wire for ground and underground power sources, and a fine tuned inductor connected in series on the zero line and live line of the main circuit input, stable transmission of signals above and below the well is achieved.

3.1 Construction of Carrier and TTL-485 Signal Transmission Modules

The system designed in this article includes a well system and an underground system, with a distance of 1000 meters between them. Considering the working environment and functional requirements of the system, a narrowband carrier communication system suitable for deep well high temperature transmission is constructed that only uses power lines for long-distance signal transmission. The composition of the power line narrowband carrier communication system is shown in Figure 3.1 (a), and an optoelectronic isolation module TTL-485 is added to the physical connection, making the carrier signal transmission more stable, The actual wiring diagram is shown in Figure 3.1 (b).



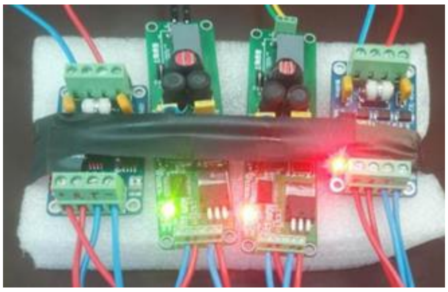
C is the high-voltage coupling capacitor; GL is a high-frequency cable;
ZC1/ZC2 are surface and well wave controllers respectively;
L_{A1}/L_{B1} (L_{A2}/L_{B2}) is the carrier signal terminal for ground transmission/reception (underground transmission/reception)
(a)Schematic diagram of the principle



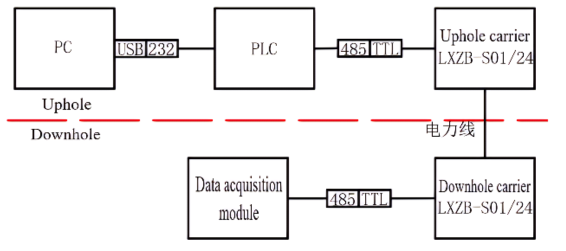
(b) Physical wiring diagram
Figure 3.1 Power line carrier communication system

The function of a carrier controller is to achieve modulation and demodulation of signals and meet the requirements of communication quality. The function of a filter is to pass high-frequency carrier signals and prevent the power frequency voltage and current on the power line from entering the carrier equipment, ensuring personal and equipment safety.

The surrounding environment of the micro high-pressure hydraulic station communication system is relatively harsh. A high-temperature carrier module and a signal conversion module are added to the system, as shown in Figure 3.2 (a). The carrier module is used to transmit signals between the ground and underground, that is, the 485 signal from the ground PLC is converted into a TTL signal through the TTL-485 module, and then the signal is converted into a carrier signal by the ground carrier module and transmitted to the well download wave module through the power carrier line, Finally, the TTL signal from the download wave module is connected to the 485 signal input terminal of the I/O module through the underground TTL-485 module. The schematic diagram of the communication principle is shown in Figure 3.2 (b):



(a) Physical wiring diagram between carrier module and TTL to 485 module



(b) Connection diagram of narrowband carrier communication system

Figure 3.2 Physical connection diagram of carrier module and connection diagram of narrowband carrier communication system

3.2 Equivalent Impedance Matching Design

Based on the impedance matching principle [6] analysis, when the load impedance does not match the internal impedance of the excitation source, that is, the impedance does not match, the transmission signal will reflect back along the wire, affecting signal communication in the well and underground. The schematic diagram is shown in Figure 3.3. When R=Z (z), the transmitted energy is just absorbed by the resistance R at the end, and no energy is reflected back. To address this issue, a resistor is connected at the end of the line to match the load impedance with the internal impedance of the excitation source, ensuring stable transmission of signals above and below the wellbore. The resistor connection method is shown in Figure 3.4. The schematic diagram of the communication system after adding impedance matching is shown in Figure 3.5. Another key problem to be solved is to determine resistor R in Power Line Carrier system.

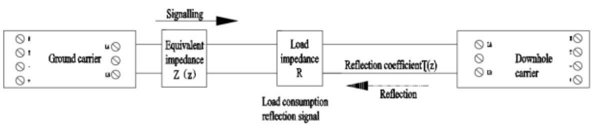


Figure 3.3 Schematic diagram of impedance matching

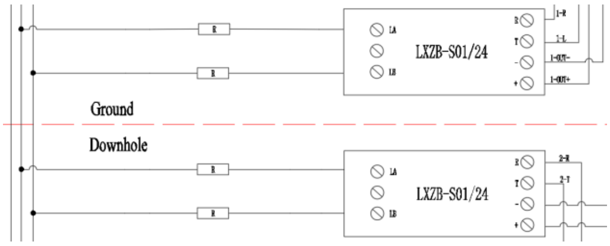


Figure 3.4 Impedance matching resistance connection

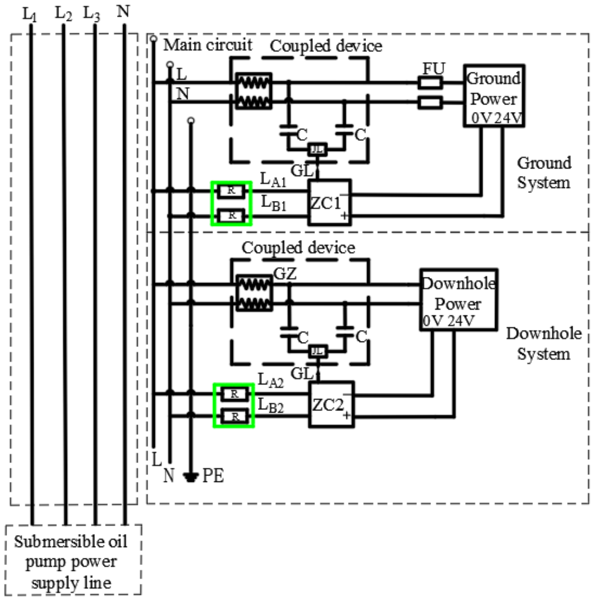


Figure 3.5 Schematic diagram of communication system after adding impedance matching

The power line in the selected narrowband carrier communication method is arranged in a flexible continuous sleeve, as shown in Figure 3.6. Due to the parallel distribution of the wires, the characteristic impedance calculation formula of the wires is:

$$Z_0 = 276log_{10}\frac{2S}{d} \qquad (1)$$

In the formula, S: the center distance between two conductors in mm; d: The diameter of the conductor mm; The unit of characteristic impedance is Ω.

The signal wire adopts a copper conductor with a diameter of 1.8mm and an outer diameter of 2.1mm, including an insulation layer. It is spiral wound with a winding angle of 15 °, and the distance between the wires is greater than or equal 1 time the wire diameter (2.1mm). There are a total of 3 single wires (1 as a backup), located on the same side of the pipeline. Therefore, the characteristic impedance is:

$$Z_0 = 276log_{10}\frac{3.9}{1.8} = 92.68Ω。 \qquad (2)$$

FIG. 3.6 Power line layout in the novel-flexible long tube in narrow-band carrier communication system

The characteristic impedance is the ratio of the incident wave or the reflected wave, and the equivalent impedance is the ratio of the incident wave and the reflected wave superimposed at a given location. This is a function of position. For lossless transmission lines, the characteristic impedance is fixed, while the equivalent impedance varies from position to position. The following equation shows the relationship between the equivalent impedance and the characteristic impedance.

$$Z(z) = Z_0 \frac{1+\Gamma(z)}{1-\Gamma(z)} \quad (3)$$

According to equation (3), the equivalent impedance Z(z) can be calculated by the characteristic impedance Z_0 and the reflection coefficient Γ(z) of the transmission line. Reflection coefficient Γ(z) is 0.1, so

$$Z(z) = Z_0 \frac{1+\Gamma(z)}{1-\Gamma(z)} = 92.68 \times \frac{1.1}{0.9} = 113.28\Omega \quad (4)$$

Therefore, according to Equation (4), in order to meet the impedance matching, the load R should be equal to the equivalent impedance Z(z). So, R=Z(z)

3.3 The Common Negative Pole of the Power Supply Ensures that the Signal Level Reference Value is the Same

When the ground system and underground system are powered by different power sources, the transmission of carrier signals will be affected due to the different relative zeros between the power modules, resulting in abnormal signal transmission. In order to avoid this phenomenon, the negative pole of the ground and underground power supply is connected to the ground wire when the system is working, so that the power supply has a common relative zero point and reduces the influence on carrier signal transmission. Its schematic diagram is shown in the red line in Figure 3.7.

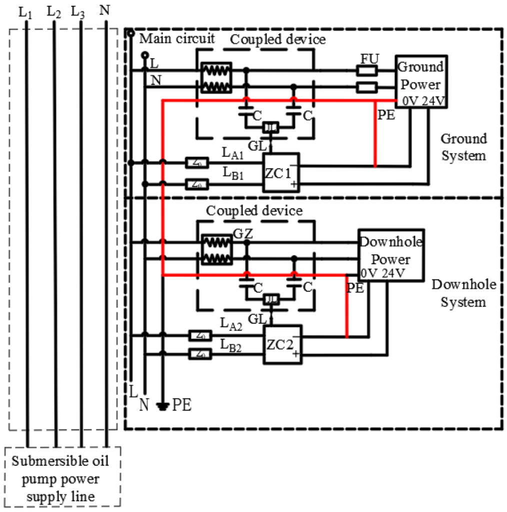


Figure 3.7 Schematic diagram of negative common ground wire of ground and underground power supply

3.4 Shielding High-order Harmonics Through Series Inductance

The high-order harmonics generated in the circuit can interfere with the carrier signal, leading to abnormal signal transmission. To avoid this phenomenon, a fine-tuning inductor is connected in series on the input zero line and the live line of the main circuit during testing. The inductor has the function of DC resistance AC, effectively preventing high order harmonics in the circuit, avoiding the impact of external electrical appliances on the current in the carrier circuit, and playing a role in anti-interference the transmission of the carrier signal. The anti-interference solution diagram is shown in the blue box in Figure 3.8.

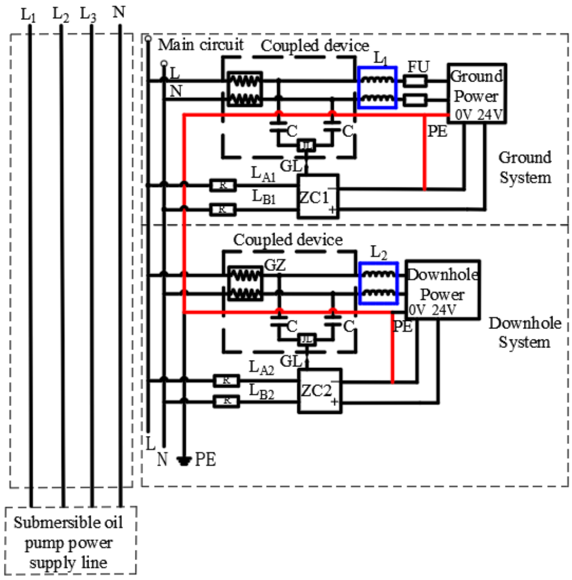


Figure 3.8 Schematic diagram of carrier signal anti-interference solution

IV. Power Line Carrier Communication Test

4.1 Power Line Borne Wavelength Distance Communication Test

To verify whether the carrier signal can transmit normally at a distance of 1000 meters, a simulation test was conducted, as shown in Figure 4.1:

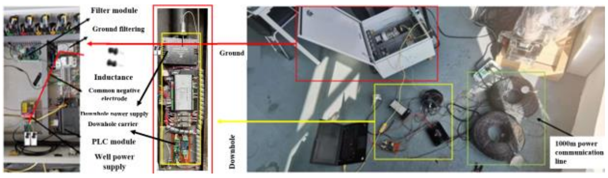


Figure 4.1 Long distance communication test

In the experiment, the ground system is connected to the underground system through two 1000 meter power communication lines, with one end of the power communication line connected to the ground 220V AC (one connected to L and one connected to N), and the other end connected to the underground power input terminal; The LA and LB ports of the ground carrier wave and the downhole wave are respectively connected to two power carrier lines to achieve signal transmission between the two carrier communication modules.

After testing, the signal transmission between the ground system and the underground system is normal and the communication is stable. That is, the 1000 meter power line can supply power to the underground power supply normally. The underground I/O module can receive the switch signal sent by the ground PLC, and the ground PLC register can correctly read the analog signal received by the underground I/O module.

4.2 Communication Tests in Electromagnetic Field Environments

In order to verify the normal operation of the carrier signal in an environment with electromagnetic fields, a high current device was used to simulate the magnetic field environment and conduct carrier signal anti-interference testing, as shown in Figure 4.2:

High current cable

(a) High current armored cable interference environment

High-power motor

(b) High power motor interference environment

Figure 4.2 Anti interference test of carrier signal for underground micro high pressure hydraulic station system

(1) Place three armored cables with a current of 60A near the underground system to simulate the electromagnetic effect on the carrier signal generated by the current in the underground high-voltage line, as shown in Figure 4.2 (a);

(2) Place the underground system near the high-power motor in operation, with a running current of approximately 90A, to simulate the electromagnetic effect on the carrier signal generated by the current in the underground high-voltage line, as shown in Figure 4.2 (b).

Through experiments, it has been found that the system can operate normally in the magnetic field generated by high currents when an inductance module is added to the circuit.

V. Analysis of the Temperature Resistance of the Carrier Communication Module for Long Term Underground Operation

5.1 Heat Dissipation Principle of the carrier Module

The ambient temperature of the underground hydraulic station is 80℃, which verifies the long-term safe temperature range of the carrier module in this environment and ensures that the working temperature of the carrier module in the system will not exceed the temperature borne by the device, so as to prevent the system from being unable to work due to excessive temperature [7].

In order to prolong the working life of the control system in high temperature environment as far as possible, one of the methods is to carry out thermal design of the carrier module (high temperature resistance design) [8]. It is necessary to carry out thermal design of the carrier module to minimize the heat emitted by the carrier module. Reduce the thermal resistance between the carrier module and the environment, and improve the heat dissipation effect.

The control system works continuously in downhole for a long time and belongs to the steady-state heat transfer type. Since the entire control system is placed in a sealed pressure cylinder, it is a steady-state heat transfer problem in an enclosed space.

The main mode of heat transfer in this project is heat conduction. Physicist Fourier once proposed the famous law of heat conduction:

$$q = -\lambda \cdot gradt \qquad (5)$$

$$\phi = -\lambda \cdot A \cdot gradt \qquad (6)$$

According to Fourier's law, in order to calculate the heat transfer and heat conduction flow of an object, it is necessary to know the temperature gradient of the object at each point:

$$t = f(x, y, z, \tau) \qquad (7)$$

In order to obtain the temperature field, the differential equation of heat conduction, which describes the general law of temperature field, must be established.

The differential equation of heat conduction is derived from the energy conservation and Fourier law of the infinitesimal control volume selected in the heat conducting body.

$$\rho c \frac{\partial t}{\partial \tau} = \left[\frac{\partial}{\partial x}\left(\lambda \frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right)\right] + \dot{\Phi} \qquad (8)$$

When the thermal conductivity λ is constant, the heat conduction differential equation can be simplified as follows:

$$\rho c \frac{\partial t}{\partial \tau} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}\right) + \frac{\dot{\Phi}}{\rho c} \qquad (9)$$

For steady-state heat conduction, the heat conduction differential equation is further simplified as follows:

$$\frac{\lambda}{\rho c}\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}\right) + \frac{\Phi}{\rho c} = 0 \qquad (10)$$

Where: ρ —— density of the object, kg / m3;

c —— specific heat capacity of the object, J / (kg · K).

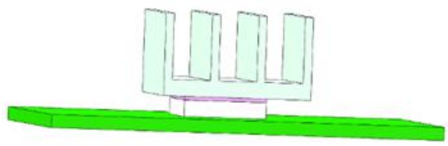
5.2 Thermal simulation analysis and model building

Because the downhole temperature gradually increases with the decrease of depth, it is difficult to calculate by analytical solution, so we use simulation software to solve. FloTHERM XT[9] is a 3D thermal simulation and optimization design software in the field of electronic heat dissipation, which is mainly used in the heat dissipation simulation analysis of packaging components, PCB boards, system equipment and data centers at different levels. Before purchasing electronic components, modeling and simulation analysis can be conducted to predict the air flow, temperature distribution and heat transfer process inside the environment where electronic components are located, as well as the final temperature reached by electronic components. Thermal risks of products can be identified according to the simulation results, so that more reliable electronic components can be selected or designed. The ambient temperature in this project is 80℃. A more reliable carrier module can be selected according to the simulation results.

According to the thermal resistance theory, the device in the process of heat transfer can be expressed as thermal resistance. A smaller chip can be equivalent to a uniform heat source, and an irregularly shaped device can be abstracted into a similar geometry. The setting of boundary conditions also needs to be simplified.

Numerical calculation analysis: After modeling the thermal design scheme that has been determined, thermal simulation can be carried out in FloTHERM XT software. The temperature field and velocity field can be obtained by simulation, and the appropriate carrier module can be selected according to the simulation results.

In the process of establishing the thermal simulation model, the reasonable simplification of the model and the accurate setting of the boundary conditions have great influence on the reliability of the simulation results. Therefore, in the process of model building, the simplification of the model should be as realistic as possible, such as the dissipated power and size of the chip, PCB materials and thermal conductivity, thermal resistance of components, etc. The model built in FloTHERM XT is shown in Figure 5.1 (a).



(a) Heat dissipation model of carrier module

(b) Test diagram of carrier module in an 80℃ incubator

Figure 5.1 Heat dissipation model of carrier module and test diagram of carrier module in 80℃ incubator

5.3 Setting boundary parameters and simulation results

The heat transfer process of the control system of this project includes heat convection and heat conduction. The ambient temperature of the control system is 80℃, so the temperature of each component of the control system is generally above 80℃. According to experience and rules, according to theoretical analysis, after a certain period of heat dissipation, the temperature of the system will eventually tend to steady state, so we only need to solve the steady-state temperature.

According to the actual situation of the project, the control system is placed in the underground safety valve, which is sealed, so the fluid in the solution domain is 80℃ air. (1) Boundary conditions: the ambient temperature is 80℃, the pressure is 1 atmosphere, and the fluid is 80℃ air. The grid is divided in the best way. (2) heat convection mode: natural air flow; (3) Heat conduction mode between the chip and the heat sink.

The carrier module chip is the main heating source, the chip size of PCB board is 20×10×2mm, and the power is 0.25W. Modeling, simulation and optimization of the circuit board. The three-dimensional shape of the modeled chip model is shown in Figure 5.1 (a). The PCB is the carrier chip, which is coated with thermal grease, and the heat sink is above the thermal grease.

As shown in Figure 5.2, the modeling and simulation analysis results show that the highest temperature element is 88.067℃ for the chip. The carrier module is put into an 80℃ incubator for test, as shown in Figure 5.1 (b), and the miniature high-pressure hydraulic station system can work normally. The experience shows that the carrier module meets the requirements of the device, and the selected carrier module LXZB-S01/24 high temperature carrier (temperature resistance 110℃) is applicable.

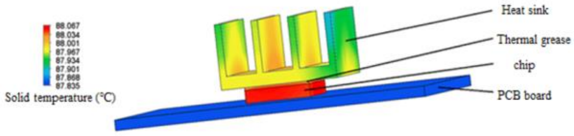


Figure 5.2 Simulation result of carrier module

VI. Conclusion

For a new type of in-situ micro high-pressure hydraulic station system that controls the opening and closing of safety valves, this paper designs a long-distance power line narrowband carrier communication system suitable for oil extraction environments. After experimental verification and thermal simulation analysis, it has been proven that the designed communication system can achieve stable signal transmission for thousands of meters in high-temperature and high-pressure environments.

(1) The selected long-distance narrowband power line carrier signal transmission method can meet the usage conditions of the in-situ micro high-pressure hydraulic station underground system;

(2) Based on the principle of impedance matching, a resistor is connected at the end of the transmission line to prevent the transmission signal from reflecting back along the wire, ensuring that the signal does not generate self interference;

(3)By connecting the negative electrodes of the ground and underground power supplies together to the ground wire and constructing an anti-interference module, the carrier signal fidelity transmission is achieved;

(4)Connect fine-tuning inductors in series on the zero line and live line of the ground and underground control circuit power supply ends, effectively preventing the electric submersible pump from causing high-order harmonics in the power line circuit of the hydraulic station, improving the stability and signal reliability of long-distance transmission;

(5) Based on the theory of heat conduction and the simulation and experimental verification of Flotherm XT software, it has been determined that the designed communication system can achieve stable transmission of power and signals over thousands of meters in high-temperature and high-pressure environments.

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