Capacitive Pressure Sensor With Integrated Signal-Conversion Circuit for High-Temperature Applications

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ABSTRACT In this paper, a capacitive pressure sensor for high-temperature application is proposed. This sensor includes three parts: a capacitive pressure-sensitive chip fabricated from green tapes using lamination technology, a C–V conversion circuit fabricated using high-temperature-resistant electronic components and a PCB board, and a thermal-insulation shell fabricated from a high-temperature-resistant alloy and aerogel. Due to the aerogel, which is a thermal-insulation material, being filled between the circuit board and the rear-end shell, when the air intake temperature reaches 350°C, the temperature transmitted to the C–V conversion circuit board can be kept below 60°C; this ensures normal operation of the C–V converter circuit. The developed sensor can record pressure values from room temperature to 350 °C. According to the pressure–voltage curves at different temperatures obtained from tests, the sensor's sensitivity is 38 mV/bar, and its repeatability error is less than 1.948%. The results show that the proposed sensor has a high operating temperature and is more reliable and linear than existing sensors.

INDEX TERMS Capacitive pressure sensor, ceramic sensitive chip, thermal insulation, high temperature environment application.

I. INTRODUCTION

With advancements in scientific research, aerospace, and other fields, high-temperature pressure sensors are being widely used in various applications [1]–[8], especially those that involve oil wells, ships, water conservancy and hydropower, aerospace, and military satellites. Sensors used in such applications must be able to withstand high temperatures and provide accurate measurements, which is critical for normal operation of other subsystems. Therefore, it is necessary to develop a pressure sensor that can function stably for a long duration in high-temperature environment.

Recently, several studies have focused on high-temperature pressure sensors. For example, in 2018, Tan *et al.* [9] studied an infinite passive high-temperature pressure sensor based on HTCC (High Temperature Co-fired Ceramics)technology.

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This sensor functions normally from 70 kPa to 120 kPa in a temperature range of 20–1100 °C; it has a maximum pressure sensitivity of 92.98 kHz/kPa and an average temperature sensitivity of 11.33 kHz/°C. However, this sensor has some disadvantages, such as signal attenuation with increasing test temperature and a short reading distance. In 2018, Liang *et al.* [10] developed a diaphragm-less pressure sensor based on the fiber optic interference principle; this sensor was tested at a temperature of 800 °C. Its sensitivity is 14.8 pm/C, and its nonlinearity is less than 1.5% at different temperatures. Although the two aforementioned types of sensors can function stably under a high-temperature environment, their signal demodulation system is highly complex and bulky. Thus, these sensors cannot satisfy the requirements of engineering applications. In 2016, Yao *et al.* [11] proposed a piezoresistive pressure sensor with an integrated signal-conditioning circuit. This sensor can perform pressure measurements at temperatures from -50 °C to 220 °C and
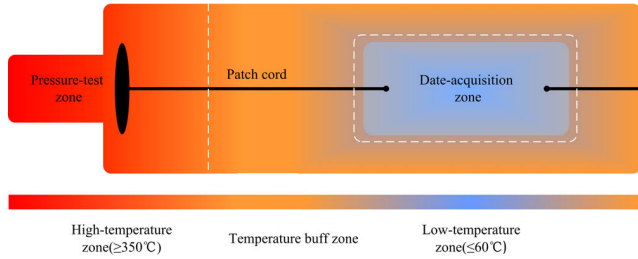
FIGURE 1. Schematic diagram of the temperature partitioning of the as-designed sensor.

pressures of 0–2 kPa, and has a sensitivity of 21 mV/MPa. However, due to limitations in terms of its material properties, this sensor can function only at low temperatures. Therefore, it is necessary to develop a type of high-temperature pressure sensor that can be used in engineering applications.

In recent years, capacitive pressure sensors [12]–[17] have attracted increasing research attention because of their high sensitivity, low power consumption, and good high temperature adaptability. Specifically, several experimental studies have focused on capacitive pressure sensors fabricated using alumina ceramics [18]–[20] due to their excellent characteristics, such as low cost, high sensitivity, and simple processing. However, a ceramic capacitive high-temperature pressure sensor with an integrated signal conversion circuit, capable of functioning in an actual high-temperature environment, is yet to be developed. In this study, a capacitive pressure sensor fabricated using ceramic material is designed and verified experimentally. The sensor includes three parts: a capacitive ceramic varistor chip to realize highly sensitive acquisition of pressure signals, a C–V conversion circuit for converting capacitance signals to stable, easy-to-measure voltage signals, and an integrated thermal insulation shell for protecting the chips and circuit boards from high temperatures. Due to aerogel, a thermal insulation material, being filled between the circuit board and the rear-end shell, when the air intake temperature reaches 350°C, the temperature transmitted to the C–V conversion circuit board can be kept below 60°C. This ensures normal operation of the C–V converter circuit. As a result, the entire high-temperature pressure sensor is divided into a high-temperature pressure-test area, a temperature buffer zone, and a low-temperature signal-processing area. The sensitive capacitance chip is located in the high-temperature pressure-test area. The capacitance signal is transmitted to the low-temperature signal-processing area through the temperature buffer and is converted to a voltage signal. Figure 1 shows a schematic diagram depicting the temperature partitioning of the as-designed sensor.

II. DESIGN AND MANUFACTURE OF CAPACITIVE HIGH-TEMPERATURE PRESSURE SENSOR
A. DESIGN OF PRESSURE-SENSITIVE CHIPS
The capacitive pressure-sensitive chip designed in this study has an elastic-thin-plate-and-cavity structure. The elastic deformation of the thin plate and the air tightness of the
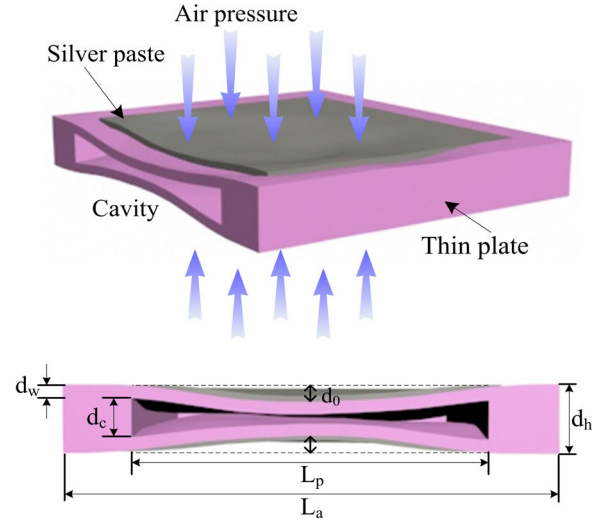
FIGURE 2. Cross-sectional view of pressure-sensitive chip.

cavity are the necessary conditions for normal operation of the pressure-sensitive chip. When the external air pressure is greater than the internal air pressure of the cavity, the elastic thin plate will deform and bend inward. As shown in Figure 2, the thickness of the upper and lower surfaces of the thin plate is d_w, and the shape variable at the center, which is denoted as d_0, is the largest. The side length of the square plate is denoted as L_p, and the height of the cavity is denoted as d_c.

According to the classical thin-plate theory, when a pressure is uniformly applied on the surface of a thin plate, its bending stiffness can be calculated as follows:

$$D = \frac{E d_w^3}{12 \left(1 - v^2\right)} \quad (1)$$

where E is the Young's modulus of the thin plate, and v for the Poisson's ratio of the thin plate. When a uniform pressure P is applied, the maximum deflection generated at the center of the thin plate can be expressed as

$$d_0 = 0.00126 \frac{P \cdot (L_P)^4}{D} \quad (2)$$

As shown in Figure 2, there are two layers of thin plates and an air in a cavity between the plates. When no pressure is applied, the initial capacitance is

$$C_0 = \varepsilon_0 \frac{\pi L_p^2}{d_c + \frac{2 d_w}{\varepsilon_r}} \quad (3)$$

where ε_0 is the vacuum dielectric constant and ε_r is the relative dielectric constant of elastic thin plate material. When a pressure P is applied, elastic deformation occurs in the upper and lower plates, and the distance between the plates changes. Under this condition, the working capacitance can be expressed as [21]

$$\begin{cases} C_S(P) = \frac{C_0}{\sqrt{\gamma}} \arctan\left(\sqrt{\gamma}\right) \approx C_0 \left(1 + \frac{\gamma}{3} + \frac{\gamma^2}{5}\right) \\ \gamma = \frac{2 d_0}{d_c + \frac{2 d_w}{\varepsilon_r}} \end{cases} \quad (4)$$
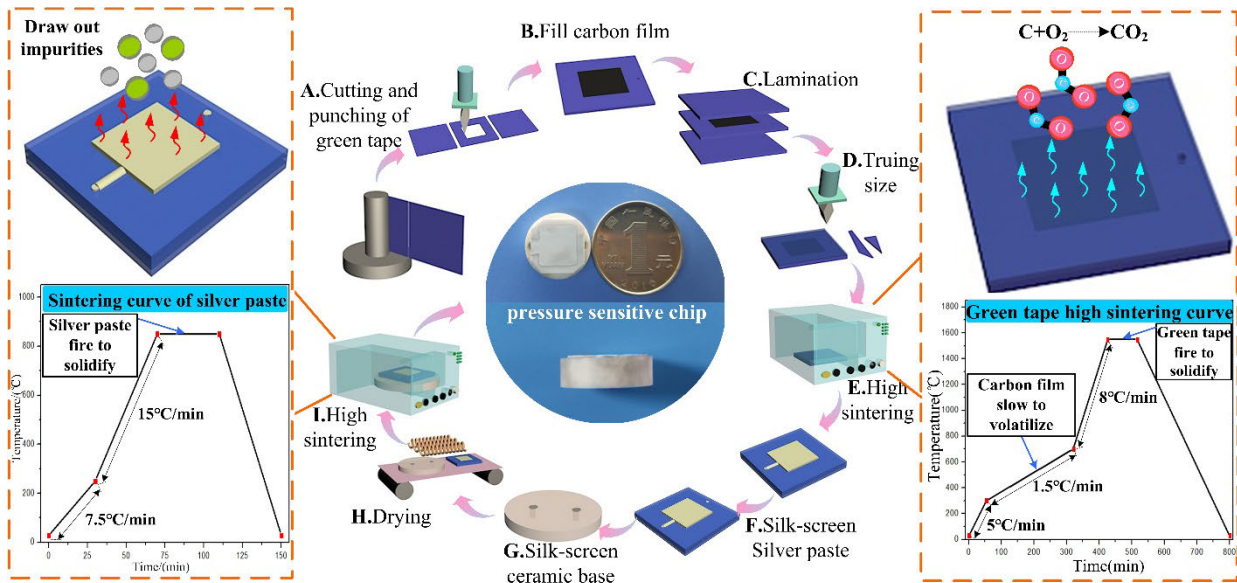
FIGURE 3. Fabrication process of the pressure sensitive chip as-prepared.

B. PREPARATION OF PRESSURE-SENSITIVE CHIP

The capacitive sensitive chip designed in this study was fabricated via high-temperature firing using green tape. Green-tape lamination, screen printing, and high-temperature welding were used in the production process. Figure 3 shows the steps followed for preparing the pressure-sensitive chip, as well as an image of the chip. The steps are as follows:

A The primary processing of the three-layer green tape according to the required size, including the cutting of the tape and the punching and opening of the cavity, is completed;

B A carbon film with the same thickness as that of the green tape is placed within the cavity of the second green tape;

C The three layers of green tape are placed inside the laminating machine and are laminated into a single unit;

D The laminated green tape is processed further according to the designed size to trim the burrs generated during lamination;

E The green tape is placed in a high-temperature furnace. A temperature curve is set. First, the temperature inside the furnace is raised from room temperature to 300 °C at a rate of 5 °C/min; the carbon film volatilizes at this time. Then, the furnace temperature is raised to 700°C at a rate of 1.5 °C/min; the CO_2 is slowly discharged through the gaps in the green tape, and the tape is gradually cured during this period. Finally, the furnace temperature is raised to 1550 °C at a rate of 8 °C/min, and this temperature is maintained for 90 min; the furnace is then cooled down naturally. During this period, the endogenous porcelain is completely cured, and the thin plate of the pressure-sensitive chip is prepared;

F The silver paste is uniformly printed on the upper and lower surfaces of the thin plate structure via screen printing. The silver paste on the upper surface is connected to the blank part of the lower surface through the hole to form the welding spot;

G The ceramic base is processed according to the size, and silver paste is smeared on the channels and welding spots of the ceramic base;

H The ceramic base coated with silver paste and the thin plate structure are placed in a high–low temperature test chamber and are dried at 150 °C to facilitate the step operation;

I The thin-plate structure is placed on the ceramic base. The welding points of the pressure-sensitive chip and the ceramic base are butted. The chip and base are then placed in a high-temperature furnace. A temperature curve is set. The furnace temperature is raised from room temperature to 250 °C at a rate of 7 °C/min. Then, the temperature is raised to 850°C at a rate of 15 °C/min. Subsequently, the temperature is kept constant for 40 min, and then, the furnace is cooled down naturally. This completes the production of the pressure-sensitive chip.

C. DESIGN OF C–V CONVERSION CIRCUIT

The C–V conversion circuit of the proposed sensor was designed using a CAV444 capacitance-to-voltage integrated circuit and an AD8221 instrumentation amplifier. CAV444, based on CAV424, has been recently launched by AMG (Analog Microelectronics Gmbh) Its most important feature is its ability to directly measure the capacitance change of a capacitance sensor and convert it to a linear voltage signal output. The working principle of CAV444 is as follows: The measuring capacitance (sensor) as a capacitor of integrated measuring oscillator, generates oscillation period through charging and discharging, and the oscillation period
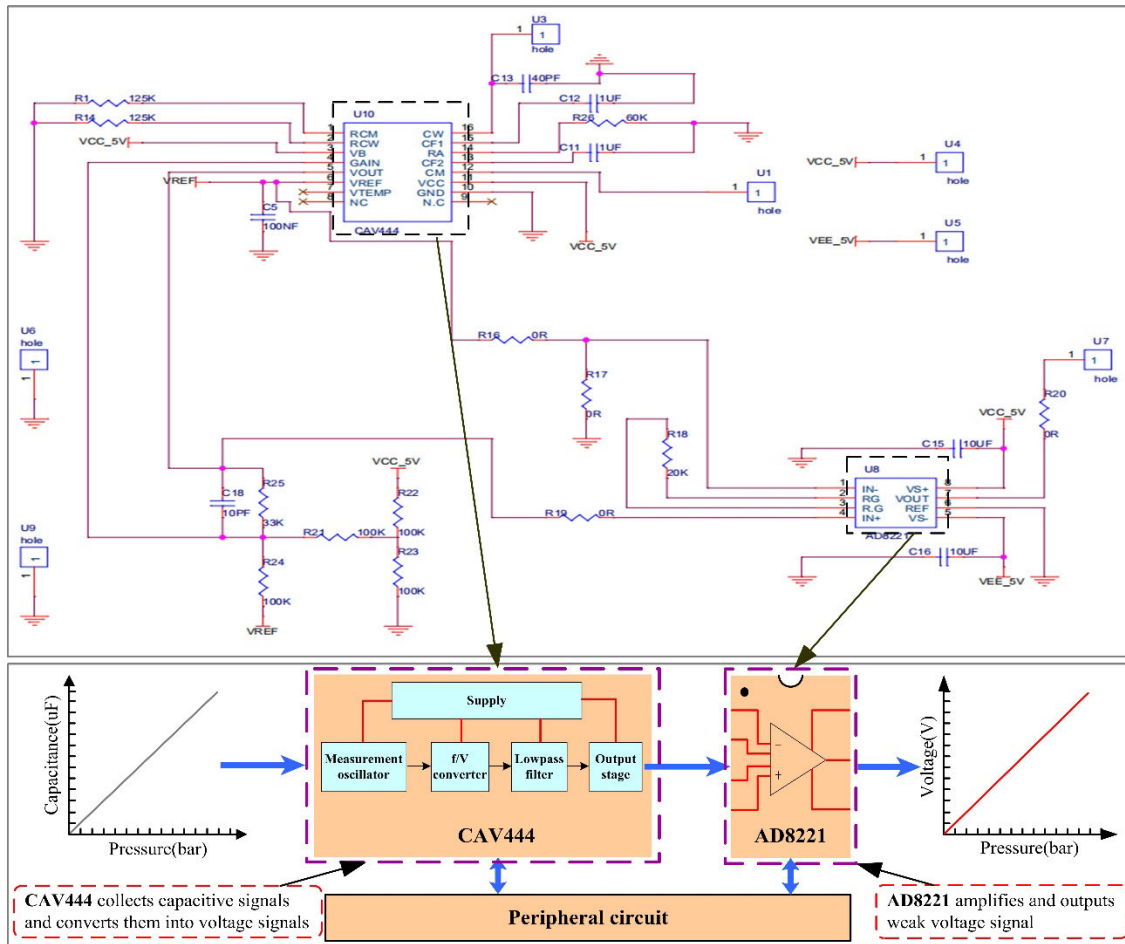
FIGURE 4. Schematic diagram of C–V conversion circuit.

is linearly related to the measuring capacitance. The DC voltage signal is output through a frequency/voltage circuit and a low-pass filter. After a zero-point and full-scale adjustable output stage, the desired voltage signal output is obtained, and the output voltage and reference voltage become a differential voltage output. AD8221 is a gain-programmable, high-performance instrumentation amplifier. Compared with similar products, it has a higher common-mode rejection ratio (CMRR) with respect to frequency. In addition, the CMRR of other instrumentation amplifiers is attenuated at 200 Hz, whereas AD8221 maintains a minimum CMRR of 80 dB when the gain is 1 and at frequencies of up to 10 kHz. The high CMRR in terms of frequency allows AD8221 to suppress broadband interference and linear harmonics, which considerably simplifies the filtering requirements.

The C–V conversion circuit of the proposed sensor functions as follows: First, the CAV444 integrated circuit collects the varying capacitance signal from the capacitance-sensitive chip. Then, after processing, it linearly converts the capacitance signal to a voltage signal. The weak voltage signal is filtered and output to the AD8221 instrument-amplifying module. The AD8221 module amplifies the weak voltage

signal and outputs a strong voltage signal. A schematic diagram of the circuit is shown in Figure 4.

D. PACKAGING OF HIGH-TEMPERATURE PRESSURE SENSOR

The integral heat-insulating shell of the proposed sensor comprises a front-end ventilation shell, a high-temperature-resistant connector, a rear-end shell, and heat-insulating aerogel. The front-end ventilation shell and the rear-end shell of the outermost layer are fabricated using high-temperature alloys. The aerogel can effectively insulate heat from the air inlet to the circuit board to ensure normal operation of the circuit board. The packaging of the pressure sensor is performed from inside to outside and from front to back, following the installation steps listed below (the numbers in parentheses correspond to the numbered components shown in Figure 5):

A Using the through-hole of the pressure-sensitive chip (2) and the double-pin structure of the high-temperature-resistant connector (3), the chip is connected with the connector;

B The high-temperature-resistant connector is installed in the front-end ventilation shell (1) through a thread structure;
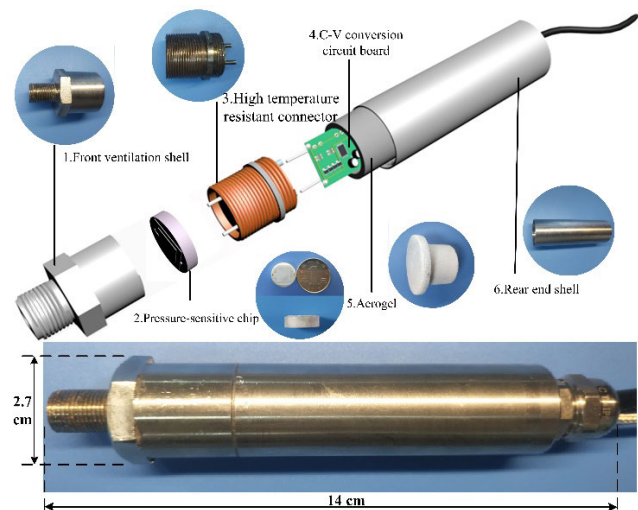
FIGURE 5. Schematic and image of the high-temperature pressure sensor.

C Two pins at the front end of the C–V conversion circuit board (4) are inserted into the jack at the rear end of the high-temperature-resistant connector. This ensures stable electrical connections at high temperatures;

D The heat-insulating aerogel (5) adheres to the inner wall of the rear-end shell (6) and is connected to the front-end ventilation shell via the threaded structure of the rear-end shell.

Figure 5 shows a diagram of the components and an image of the packaged high-temperature pressure sensor. In the functional state, the airflow reaches the capacitive pressure-sensitive chip through the air passage in the front-end ventilation shell, and the sealing effect of the pressure sensor is achieved at the high-temperature-resistant connector. The varying capacitance signal reaches the front end of the C–V conversion circuit through the connector. Finally, the capacitance signal is processed and is converted to a voltage signal through the conversion circuit, and the voltage signal is output through a cable.

III. MEASUREMENT AND RESULTS

A. VARIABLE-PRESSURE TEST UNDER NORMAL-TEMPERATURE ENVIRONMENT

The normal-temperature pressure-testing system used in this study consists of a pressure tank, a high-precision voltmeter, a power supply, a pressure controller, and a nitrogen tank. Before testing, the pressure controller program, including the pressure-control range and the number of segments, is set. The pressure-control valve of the nitrogen tank is opened, and the pressure is set to 3 bar. The power supply and voltmeter are switched on; then, the voltage-supply value is set, and the voltage is output. When the pressure stabilizes, the voltage indicator of the voltmeter records the voltage. After the maximum pressure is reached, the pressure-relief process is started, and the corresponding voltage value during this process is recorded. The measurement is repeated three times. Figure 6 shows a structure diagram
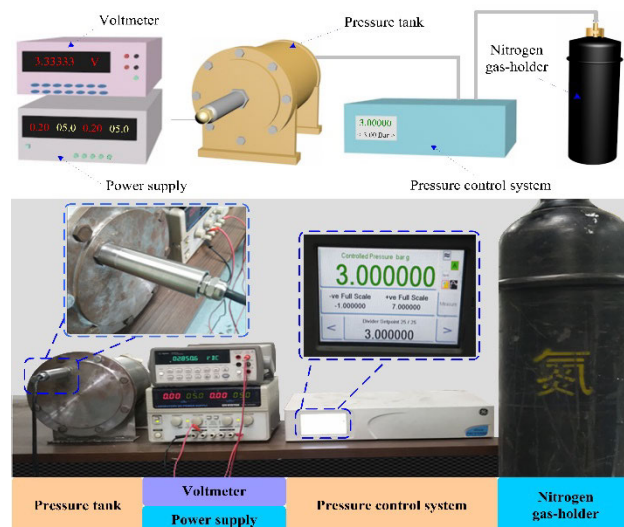

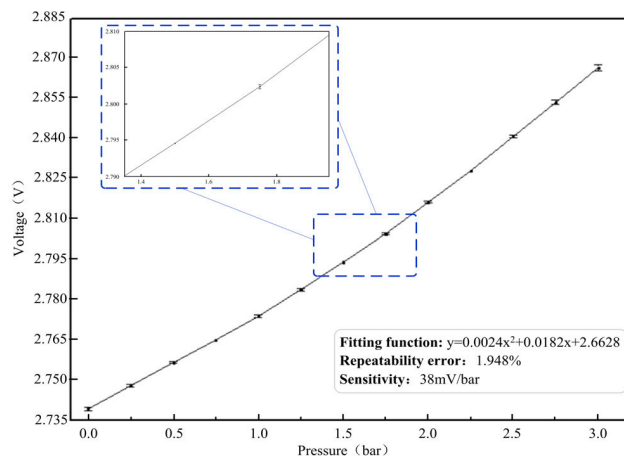**FIGURE 6.** Structure diagram of pressure-test system under normal-temperature environment.

FIGURE 7. Pressure–voltage curve with error bar at room temperature.

of the pressure-test system under a normal-temperature environment.

Figure 7 shows the pressure–voltage curve with error bar plotted using Origin. The static sensitivity of the sensor was calculated to be 38 mV/bar. In addition, the pressure–voltage variation of the sensor is continuous and monotonous, with high linearity, low hysteresis, and high repeatability.

B. TEST UNDER HIGH-TEMPERATURE–HIGH-PRESSURE COMPOSITE ENVIRONMENT

The high-temperature and high-pressure composite environment testing system used in this study consists of a high-temperature pressure furnace, a controller, a power supply, and a high-precision voltmeter. Firstly the high temperature pressure sensor is installed in the furnace. Then, the power supply is connected to a high-precision voltmeter. Finally, by controlling the test system appropriately, pressure–voltage curves at different temperatures were obtained. The test was repeated, and the data were recorded. Figure 8 shows
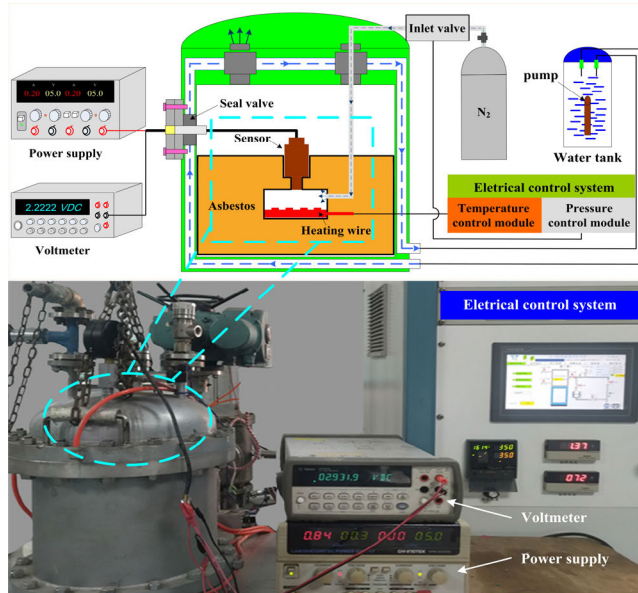
FIGURE 8. High-temperature and high-pressure composite environment testing system.
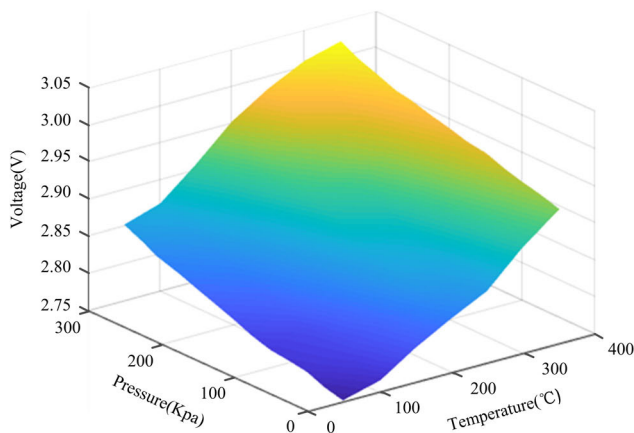
FIGURE 9. 3D temperature–pressure–voltage graph of high-temperature pressure sensor.

the structure of the high-temperature–high-pressure composite test system. Figure 9 shows the three-dimensional temperature–pressure–voltage graph in the composite test environment.

IV. CONCLUSION

In this study, a capacitive high-temperature pressure sensor was designed. A ceramic pressure-sensitive chip, a C–V conversion circuit, and an integrated thermal-insulation shell, which constitute the proposed sensor, were designed and fabricated. Finally, the developed pressure sensor was tested repeatedly under normal temperature and high-temperature–high-pressure composite environments, and the pressure–voltage conversion curve was plotted. The tests results show that the sensor can function in a high-temperature environment, over a temperature range of 0–350 °C. It has a measurable pressure range of 0–300 kPa,

a static sensitivity of 38 mV/bar, and a repeatability error less than 1.948%. The sensor is highly linear and reliable and can be used for pressure measurement in high-temperature environments.

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