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Multiparameter Testing Instrument for Oil Wells

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By applying semiconductor piezoresistance, a new sensor can be fabricated. A multiparameter testing instrument is developed using the sensor, which can be applied to measure several parameters of vapor introduced into an oil well. These parameters are quality, temperature, pressure and discharge. There are several problems to be solved in the fabrication of a sensor, such as small differential pressure and structure of the sensor. By solving these problems, the application of a diffused silicon pressure sensor to the measurement of vapor in oil wells is presented for the first time.

1. Introduction

In order to obtain dense oil from an oil well, high-pressure vapor is generally introduced into an oil well to dilute the dense oil. The states of the vapor introduced in oil well are characterized by such parameters as pressure, temperature, discharge and quality. In general, various sensors are needed to obtain these parameters, such as a pressure gauge and a flow meter for discharge, however, an important point is that quality can not be directly measured. Thus, it is necessary to develop a new sensor system, which can accurately and quickly obtain the above parameters. This instrument consists of a specially designed protective shell, a pressure sensor system and a signal processing system. In this paper we discuss in detail the measurement principles of discharge, pressure and quality, and the method for fabricating a pressure sensor system. Compared with other similar testing instruments, our system shows great advantages. First, regardless of position in the oil well, the parameters of discharge, pressure, quality and temperature can be measured simultaneously with high precision. Second, by applying the two-phase flow theory, the values of discharge and quality at any position in the oil well can be obtained from two differential pressure measurements.

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2. Measurement Principle

Vapor-flow in an oil well is a mixture of gas and liquid, and behavior of the high-pressure vapor introduced into the oil well is based on the theory of gas-liquid two-phase flow. When a rod instrument is introduced into an oil well, the cross section of the vapor-flow is reduced with the instrument, i.e., the cross section area is varied from $A = \pi (D^2/4)$ to $A_1 = \pi (D^2 - d^2)/4$, (D is the diameter of the oil well and d outer diameter of the instrument.) as shown in Fig. 1. This corresponds to the throttling model of a ring orifice-plate in the theory of the two-phase flow.(1) Based on Bernoulli's equation, because of the existing orifice-plate, the vapor-flow is speeded up, and the pressure at the back of orifice-plate will be decreased.

On the top of the instrument are placed sensitive ripple bellows A, B and C, and these bellows are joined to corresponding sensors A*, B* and C* using pipes filled with silicone oil, as shown in Figs. 2 and 3. For example, the vapor-flow exerts pressure on sensitive bellows A, and the pressure is transferred to pressure sensor A* though pipe 1. When the instrument is balanced at one position in the well, the pressure signals at that position can be obtained by sensor A*. If another differential pressure sensor is positioned at position B*, the front surface of the sensor B* chip will receive a pressure from the rear surface of the ring orifice position from sensitive bellows B though pipe 2, while its back surface will still receive pressure from sensitive bellows A. Obviously, the signals output from sensor B* are the pressure difference ΔP_1. Similarly, the differential pressure between A and C is measured by the differential pressure of sensor C*. The pressure difference ΔP_1 is caused by existence of the instrument, however, pressure difference ΔP_2 is mainly the result of friction between vapor-flow and the surfaces of the solid wall of the well and the instrument.

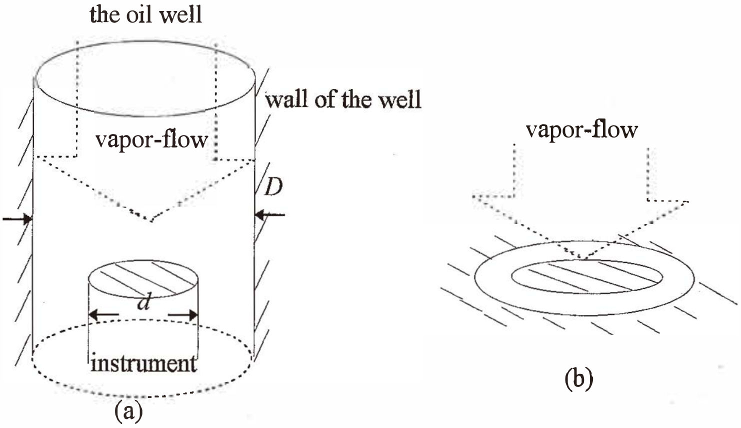

Fig. 1. Throttling model of ring orifice-plate. (a) Vapor-flow down encounters the instrument. (b) Cross section of vapor-flow is varied from a round shape to a ring shape.

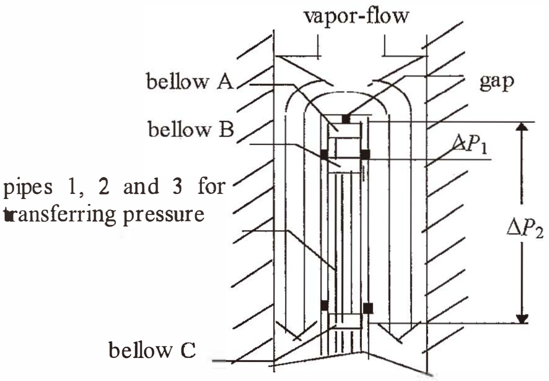

Fig. 2. Measuring principle of the instrument. Vapor-flow pressure on the sensitive bellows A, B and C, separately, the pressure is transferred to sensors A*, B* and C* correspondingly through pipes 1, 2 and 3 (sensors A*, B* and C* are not plotted in Fig. 2). ΔP_1 results from throttle, and ΔP_2 is attributed to friction.

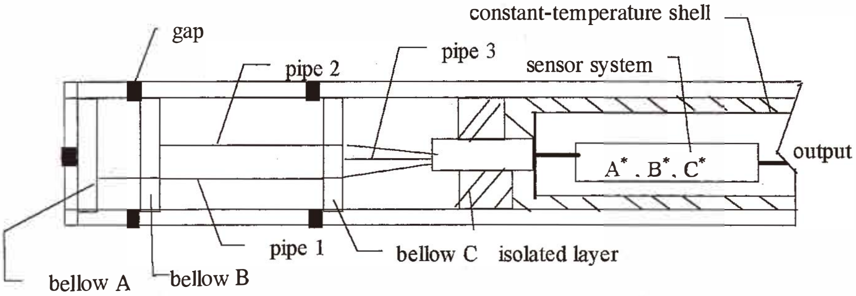

Fig. 3. Structure of the instrument. Vapor-flow acts on the bellows through gaps.

According to the gas-liquid slit phase mode,(2) ΔP_1 can be written as(3)

$$\sqrt{\Delta P_1} = \frac{W\sqrt{1-\alpha^2}}{\psi C A\sqrt{2\rho_L}}\left[\theta + X\left(\sqrt{\frac{\rho_L}{\rho_G}} - \theta\right)\right], \tag{1}$$

where ψ is thermal expansion coefficient of the shell of the instrument, C is the discharge coefficient of the ring orifice, $\alpha = A/A_1$ is the ratio of cross section of orifice to that of the well, W is the total discharge of vapor-flow introduced into the well, ρ_G is the density of the gas phase, ρ_L is the density of the liquid phase and $X = W_g/W$ is the quality, which represents the percentage of gas phase in the total gas-liquid flow.

By combining the experiment with theory, the correction coefficient can be obtained:(4)

$$\theta = 1.48625 - 9.26541\left(\frac{\rho_G}{\rho_L}\right) + 44.6954\left(\frac{\rho_G}{\rho_L}\right)^2 + \cdots\cdots\cdots,$$

where ρ_G / ρ_L can be obtained from the experiment, therefore, θ can be obtained.

When the differential pressure ΔP_1 is obtained by measurement, eq. (1) uniquely determines the relationship between the total discharge W and the quality X.

Another sensitive bellow C joined to differential pressure sensor C* is positioned at a distance L from bellows A, as shown in Fig. 3. The surface of bellow C is in contact with the measured medium at position C. The pressure at position C is transmitted to the front surface of sensor C* through pipe 3, and its back surface receives the static pressure at position A. The pressure difference ΔP_2 can be written as

$$\Delta P_2 = \Delta P_1 + \Delta P_F + \Delta P_g, \qquad (2)$$

where ΔP_g is the pressure drop caused by the gravitational difference between A and C, ΔP_F is the pressure drop caused by the friction drag between vapor-flow and wall of the well and the instrument.

After analysis,(4) the following formulas can be derived:

$$\Delta P_F = \psi'\lambda \frac{L}{DA^2}\frac{W^2}{2\rho_L}\left[1 + X\left(\frac{\rho_L}{\rho_G} - 1\right)\right], \qquad (3)$$
$$\Delta \rho_g = \rho_m g L.$$

Thus, eq. (2) can be rewritten in the following form:

$$\Delta P_2 = \Delta P_1 + \psi'\lambda \frac{L}{DA^2}\frac{W^2}{2\rho_L}\left[1 + X\left(\frac{\rho_L}{\rho_G} - 1\right)\right] + \rho_m g L, \qquad (4)$$

where ψ' is correction for the pressure difference brought about by friction drag, λ is the friction drag coefficient of a single-phase liquid, D is the diameter of the oil well, ρ_m is the average density of a vapor-liquid two-phase flow when fluid is flowing uniformly, g is gravity accelerate, and L is a distance between A and B. When ΔP_1 and ΔP_2 are obtained, we can calculate the discharge W and quality X using eqs. (1) and (4), while the temperature in the well is measured by a thermocouple detector.

3. Design of Sensor System

3.1 *Measuring conditions and requirements for sensor*

Because the temperature in the vapor-introduced well is approximately 400°C, the semiconductor piezoresistive sensor is not in direct contact with the vapor measured. Therefore, the sensor should be placed in a specially designed constant-temperature shell. The pressure-sensitive part of the sensor is separated from its signal processing part, and they are connected by a pressure transmitting pipe which is filled with silicone oil. The pressure transmitting pipe must be long and thin enough for reducing heat conduction, and it must have high strength and be able to withstand high temperatures. Thus we selected materials with low heat conductivity coefficient and good plasticity.

Because there is different pressure in different oil wells and at different parts of one well, which may range from 0–20 MPa, the measurement range of the pressure sensor is from 0 to 20 MPa. The discharge and quality are determined by differences of two pressures (ΔP_1 and ΔP_1), and the pressure difference varies from 0 to 0.1 MPa. This is a problem when measuring a small pressure difference at the high pressures. In regards to safety, the measurement range of the pressure difference is limited to 0 – 0.2 MPa. The chips of the differential sensors are designed as double-island rectangular films,(5,6) so that they are very sensitive at high pressure. Because of the limitation of the outer diameter of the entire instrument, the diameter of the constant-temperature shell is 20 mm, the outer diameter of the sensors must be less than 20 mm. The main part of the sensor is placed into the sealed cavity. The sensitive manometric bellows are exposed in the well, which should be sealed with a high-temperature-resistant material.

3.2 *Design of sensor system*

On the basis of the principle and testing conditions, the sensor system is designed as shown in Fig. 3. In the oil well, the pressure exerted on bellows A is transferred to one surface of the chips of sensors A*, B* and C* through pressure transmitting pipe 1, as shown in Fig. 4. No pressure affects the other surface of chip of A* (1 atm actually). The output from sensor A* obviously represents the pressure at the position in oil well. The pressure exerted on bellows B and C is transferred to the other surface of chips B* and C* through pressure transmitting pipes 2 and 3, separately. Thus, the output from sensors B* and C* represent the pressure difference, i.e., ΔP_1 and ΔP_2, which emerge between bellows A and bellows B and C.

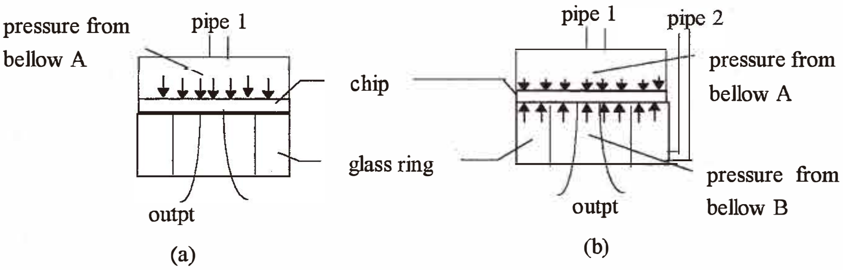

Fig. 4. Operation of sensor A* and B*. (a) One face of chip of A* receives the pressure from pipe 1, the other face receives no pressure. (b) One face of chip B* is pressured from pipe 1, and the other from pipe 2.

4. Fabrication of Sensor System and Standardization

The chips of the sensor are designed using general semiconductor piezoresistive pressure sensor technology. A circular silicon cup is used in static pressure sensors and a rectangular double-island silicon cup is used in differential pressure sensors, then the chips are packed on a glass ring using a static electricity method as shown in Fig. 4. After completion of the semiconductor technology, chips that show good stability and low temperature coefficient upon elecrothermal aging were selected.

The structure of the system and the sensor processing are very complex. The design principles are as follows. (1) The outer diameter of the sensor must be less than 20 mm. (2) The entire structure and the electrode must withstand pressures above 20 MPa. (3) Filling with oil and sealing are not easily accomplished. (4) The oil-filling technology is the most important step in manufacturing.

For a tight seal, the pressure transmitting pipe connecting the pressure-sensitive bellows to the sensor and the thermocouple must be welded in the sealed constant-temperature shell before oil is introduced. At the same time, the capillary pipe must be opened. After assembly, the sensor system is approximately 1.2 m long. We must design a vacuum cycle oil-filled apparatus which ensures that the capillary pipe and its every corner are filled with silicone oil and that no bubbles exist in the tube. Otherwise, the performance of the sensor deteriorates. A pressure-sensitive ripple membrane is welded on the basal stump using a high-frequency plasma welding machine.

The standardization test of the sensor system is divided into two phases. First, the sensor is linked with a data processing system and a microcomputer. The output characteristics of two differential pressure sensors can be measured when 0 – 0.1 MPa pressure is exerted on bellows B and C. Then the instrument is placed in a high-pressure pipe, the output of the sensor systems is shown in Table 1. According to requirements of measurement, differential pressure sensors B* and C* should more stable than static pressure sensor A*. In Table 1, three standards (nolinearity, hystersis error and repetition) are adopted to determine performance of the sensors.

5. Results and Discussion

The results of the measurement are shown in Fig. 5. From Fig. 5, we can obtain some important results about pressure P, discharge W, temperature T and quality X of the vapor-flow in an oil well, *e.g.*, P, T, W and X are approximately 13.8 MPa, 330°C, 5 ton/h and 84%, respectively. These results coincide with the data obtained using other methods. It can be proven that the entire sensor is reliable. In Fig. 5 the instrument remained in the well until 20 min after beginning the experiment. When the experiment was finished, the quality and discharge were all reduced to zero, but the pressure still remains for a while when the instrument is drawn out from the well.

Compared with other instruments used for the same purpose, this device has the following advantages.

(1) The testing equipment is very simple and compatible with other devices, and auxiliary equipment is not necessary.

Table 1
Performance of the sensors.

Sensors	Nonlinearity error (%)	Hysteresis error (%)	Repetition error (%)
A*	±0.38	0.13	0.08
B*	±0.02	±0.07	0.14
C*	±0.07	±0.07	0.14

Sensor A* is pressured to 25 MPa.
Sensors B* and C* are pressured to 0.5 MPa, (pressure difference) at a static pressure of 10 MPa.

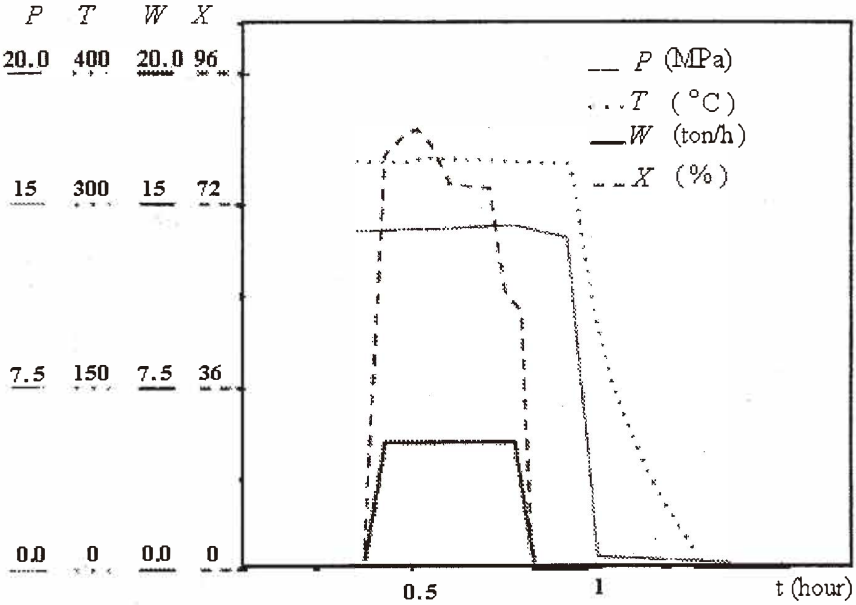

Fig. 5. The results of measurement. The X axis presents time exhausted in measurement. The unit of quality is a percentage, pressure is MPa and discharge is ton/h.

(2) The measuring time is short and the results are very accurate. Thus, automatic sampling can be performed instantly at an arbitrary position inside the oil well and the testing point is not be limited.
(3) Four useful parameters can be obtained simultaneously in one measurement with the help of a computer.

6. Conclusions

A multiparameter testing instrument is useful for measuring vapor-flow. First, because of adopting semiconductor as chip of sensor, measurement accuracy has been improved. Second, by means of a gas-liquid two-phase flow theory, all different objects to be measured can be converted into one object, i.e. pressure, which greatly simplifies the process of measurement. Third, measuring low differential pressure at high static pressure has been solved.

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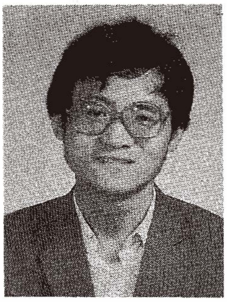

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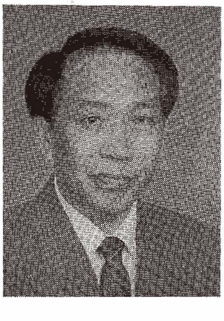

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