Improvement of P-V Diagram Measurements

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ABSTRACT

This paper presents how much experimental errors are caused by the characteristics of pressure transducers in P-V measurements. In addition, the accuracy of the balanced pressure valve (the B.P.V.) of a free disc type, which determines the cylinder absolute pressure level, is shown.

Namely, the indicated gas work was calculated by the following two methods: (a) Sensitivity method (the calibrated sensitivities of pressure transducers were used.) (b) B.P.V. method (two points of the Cylinder absolute pressure level, which were determined by the B.P.V., were used.) In this paper two values of the indicated gas work were compared under several compressor speeds and several loads.

As a result, it was made clear that the characteristics of pressure transducers affected the accuracy of P-V diagram measurements considerably, and it was also confirmed that the B.P.V. was very effective in improving the accuracy of P-V measurements.

INTRODUCTION

Generally, as the indicated gas work, oversuction loss and overcompression loss are calculated from P-V diagram measurements, the conceivable experimental errors depend on the accuracy of measuring instruments, crank angle readings, pressure transducers and determining the cylinder absolute pressure level as discussed in reference [1] - [5].

As an A/D converter and a computer have become indispensable for high accuracy measurements such as those used in P-V diagrams, we used this computer measuring system in this study.

To detect the crank position, a rotary encoder with 360 pulses per revolution was installed and instantaneous crank speed was measured precisely. This signal was used when the cylinder pressure data were associated with the correct cylinder volume.

There are many different brands, types and sizes of pressure transducers, which are the most important devices in P-V measurements. However, it is difficult to evaluate the quantitative effects of transducer characteristics on the accuracy of P-V measurements. The reason is based on the fact that the 'ideal' pressure sensor does not exist, so it is impossible to compare the 'real' one, as Alyea and et al.[3] said. Nevertheless they also said that comparing 'real' pressure transducers gives us valuable information, so we investigated what kinds of pressure transducers should be used to improve the accuracy of P-V diagram measurements.

The evaluating points of pressure transducers are as follows:

1) The sensitivity variations should be as small as possible in the quasi-static calibration test.
2) The difference of two indicated gas works calculated by (a) Sensitivity method and (b) B.P.V. method should be small.
3) The relation between the indicated gas work, suction and discharge overshoot losses and the compressor running conditions should have no discrepancy.

PRESSURE TRANSDUCER

Table 1 shows the specifications of the four pressure transducers used in this study. A and B are a piezoelectric type. C is a semiconductor strain-gage type and D is a water cooled strain-gage type.
### Table 1 Specifications of Pressure Transducers

These pressure transducers have been used for P-V measurements of engines or compressors in our company. The difference between A and B is that B has a built-in amplifier, and as shown in Table 1, A is superior to B in low frequency response. C is the smallest of these transducers, and is suitable for small compressors such as those used in car air conditioners. D, which was originally used for engines, is the largest of them and is water cooled.

### CALIBRATION TEST

Fig. 1 shows the calibration test apparatus and measuring instruments. Various signals are acquired by the measuring system and are processed by the analysing system. Wave Memorizer (W/M), which is a kind of A/D converter in the measuring system, has 10 bits, 4 ch., 1 kword/ch. and 5 μsec. as a minimum sampling time. The digital data stored in the W/M, are fed into a personal computer as letters and are recorded on a data cartridge tape. The analysing system, which consists of a desktop computer and a plotter, translates the letters data on the tape into dimensional data, calculates the indicated gas work, oversuction and over-compression losses and plots these results.

In this test, we took the following into account:

1) The transducers have the tendency to change their sensitivity because of their mounting torque. To avoid this effect, they were mounted from the beginning in the same valve plate used in P-V measurements, and were tested.
2) The temperature of this test vessel was controlled using an electric oven. C-C thermocouples were fitted in each transducer to measure the temperature.
3) The sensitivity was measured when the nitrogen gas in the test vessel,

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<table>
<thead>
<tr>
<th>Item</th>
<th>Type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td></td>
<td>6.4</td>
<td>6.4</td>
<td>3.2</td>
<td>10.0</td>
</tr>
<tr>
<td>Range (MPa)</td>
<td></td>
<td>24.6</td>
<td>7.0</td>
<td>3.5</td>
<td>9.9</td>
</tr>
<tr>
<td>Resonant Frequency (kHz)</td>
<td></td>
<td>130</td>
<td>500</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Low Frequency Response (Hz)</td>
<td></td>
<td>9 x 10^{-2}</td>
<td>5 x 10^{-3}</td>
<td>DC-</td>
<td>DC-</td>
</tr>
<tr>
<td>Linearity (%)</td>
<td></td>
<td>±0.8</td>
<td>±1.0</td>
<td>±0.5</td>
<td>±1.5</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td></td>
<td>-240</td>
<td>-73</td>
<td>-45</td>
<td>-175</td>
</tr>
</tbody>
</table>

---

4) The pressure of the supplied nitrogen gas was read using a high accuracy piezo-vibration digital pressure transducer having the accuracy of ± 0.37 (kPa).

5) This quasi-static test was run twice under the following conditions:
   - Temperature: 14°, 40°, 70°, 100°, and 120°C
   - Pressure: from 2.45, 1.67, 0.98 and 0.49 (MPa) to atmospheric pressure

The sensitivity was obtained by averaging 8 values at each temperature.
Fig. 3 shows the results of the normalized transducer sensitivity as a function of the temperature. Not only is the sensitivity variation of type A within 0.3%, but also the sensitivity change between 14°C to 120°C is within 0.5%. The sensitivity of type B, on the other hand, having a large variation of 9.3% at 100°C, decreased incredibly as the temperature raised. The sensitivity above 100°C decreased to less than half of the manufacturer's calibrated value. These results show that the low frequency response is influenced greatly by temperature, so we judged it was impossible to calibrate type B using the quasi-static test. The pressure curves of this test are shown in Fig. 4. Type A, C and D pressure curves were drawn with the minimum point equal to atmospheric pressure, but type B's was drawn using the manufacturer's calibrated sensitivity. The type C pressure curve shows a distortion below 1 MPa, also as demonstrated in Fig. 4. Since its distortion affects the linearity, the sensitivity variation is 5.4% and is larger than the manufacturer's specifications value. (The manufacturer said it seemed to be caused by the over-tightening torque, but we had the same results when the other three transducers of the same type were tested.) Type D pressure curve is very similar to A's and the sensitivity variation is within 1.2%. D is inferior to A in noise.

Balanced Pressure Valve

Fig. 5 shows the structure of the B.P.V., which was manufactured for trial in this test. The B.P.V. of a free disc type has an eddy-current gap sensor to detect the small movement of the valve to indicate the time at which the cylinder pressure equals an accurately measured reference pressure. The valve has a diameter of 8 mm, a thickness of 0.2 mm and a running clearance of 200 μm. The measuring instruments are the same as those in Fig. 1.

In Fig. 5, P_0 is the pressure in the test vessel and is higher than the reference pressure P_0. When the solenoid valves were opened suddenly, the change of P_0 was indicated by using the A type transducer, because it had the best accuracy in the quasi-static test. P_0 was read by a bourdon tube pressure gage calibrated by the digital high accuracy pressure transducer.

The experimental waves are shown in Fig. 6. Here P_0 looks like steps due to the W/M resolution of 0.1%. The valve delay time is defined as Δτ, which means the time required from X_0 to X_1. X_0 is the point at which P_0 is equal to P_0. X_1 is the point at which the running distance of the valve is equal to 2 μm.
Fig. 5 Schematic of the B.P.V.

Fig. 6 Experimental Results of the B.P.V.

Fig. 7 Relation between $\Delta T$ and $\alpha$ of the B.P.V.

Fig. 8 Relation between $\Delta P$ and $\alpha$ of the B.P.V.

It is 1% of the total valve running clearance and can be resolved sufficiently by the W/M. The experimental data of $\Delta T$ were plotted as a function of the pressure gradient $\alpha = \frac{dP_c}{dt}$ as shown in Fig. 7. In Fig. 7, the theoretical curve ($T$) is based on equation (1):

$$ t = 3 \sqrt{\frac{2P}{\alpha}} $$

where: $t =$ time required from $X_0$ to $X_1$
$x =$ running distance of the valve
$g =$ acceleration of gravity
$h =$ thickness of the valve
$\gamma =$ specific gravity of air
$\alpha =$ pressure gradient ($= \frac{dP_c}{dt}$)

The results are subject to large variations, but apparently the experimental delay time $\Delta T$ is larger than the theoretical one. This may be caused by the viscosity of the oil used to seal the free valve.

Now, it is a problem of how accurate the B.P.V. is in determining the absolute pressure level. In this case, the pressure error $\Delta P$ was got by the equation $\Delta P = \alpha \Delta T$ as shown in Fig. 8. The pressure error $\Delta P$ increases as the pressure gradient $\alpha$ increases.

To determine the absolute pressure level, the cylinder pressure gradient $\alpha$ should be as small as possible. As examples, the following points in the compressor crank angle were chosen due to the small gradient of approximately 5 - 20 kPa/msec.

1) near B.D.C.
2) compression stroke while the discharge valve is opening.
To minimize the pressure errors, the valve delay time $\Delta T$, which is shown as an experimental curve (E) in Fig. 7, is taken into account. Namely, as shown in Fig. 6, if the point $X_1$ can be measured, the point $X_0$ can be determined by taking the delay time $\Delta T$ based on the curve (E) into account. According to this rule, the pressure of the point $X_0$ may be equal to the reference pressure $P_0$. The curve (E) in Fig. 8, which corresponds to the curve $CE_1$ in Fig. 7, shows that the maximum variations in the experimental data from this curve are less than $\pm 3.0$ kPa, so that it is the accuracy of the B.P.V. that determines the absolute pressure level.

P-V DIAGRAM MEASUREMENTS

The M101C compressor produced by Mitsubishi Heavy Industries was used in this test. The M101C is a reciprocating open type compressor, having a bore diameter of 82 mm and a displacement volume of 422.5 cc/rev. It originally had two cylinders, but was modified to have only one. Six different compressor running conditions are summarized in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Compressor Speed (rpm)</th>
<th>Discharge Pressure (MPa)</th>
<th>Suction Pressure (MPa)</th>
<th>Suction Gas Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>1.353</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>750</td>
<td>(CT=35°C)</td>
<td>0.296</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>970</td>
<td>(CT=40°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>1.533</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>750</td>
<td>(CT=40°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>970</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Compressor Running Conditions (R-22)

To determine T.D.C. and to observe the instantaneous crank speed, the rotary encoder was connected to the crank shaft. This encoder has a disc with 360 slits. It detects the slits optically and generates a square wave per 1 degree precisely. It also generates one pulse per revolution used as a triggering signal for the W/M. By using the gap sensor, which detects the displacement of the piston under the air running, the difference between one pulse of the rotary encoder and the signal of the gap sensor at T.D.C. was checked at three rotational speeds, 500, 750, 970 rpm. Its variation was within only $\pm 0.02$ degree.

The 360-pulse signal is translated into the instantaneous crank speed (=d$\theta$/dt) by the fluctuation counter, which measures the time-interval between two square waves. As the crank speed signal of the fluctuation counter causes a phase lag of 1 degree because of its own mechanism, the delay time of this signal d$\theta$/dt is rectified in the data processing. Furthermore, the crank angle $\theta$ is calculated by the integral of this signal.

RESULTS AND DISCUSSION

Indicated Gas Work

There are two methods to calculate the indicated gas work by P-V measurements. One uses (a) the calibrated sensitivity and the other uses (b) the two points of the absolute pressure level determined by the B.P.V.

In order to see the difference between the indicated gas works, the results were shown as a mechanical efficiency $\eta_m$, which is defined as the ratio of the indicated gas work $W_0$ to the compressor input power $W_{in}$,

$$\eta_m = \frac{W_0}{W_{in}}$$

The results at the operating condition of CT/ET=35°/-15°C and CT/ET= 40°/-15°C are shown respectively in Fig. 9. As shown in Fig. 9, type C shows the largest difference between the (a) and (b) methods. However, remembering the large variation in sensitivity in the quasi-static test, it may be a natural result.

Fig. 9 Difference of Mechanical Efficiencies Calculated by the (a) and (b) Methods
The sensitivity of type B could not be measured in the calibration test, so that the manufacturer's calibrated value was used in the (a) method. In spite of this, type B shows only a small difference, as does type D. Type A shows the smallest difference (within 1.5%), because it had the smallest variation of its sensitivity. From these facts, it must be concluded that both the results of the calibration test and the results of determining the absolute pressure level were correct.

\( \eta_m \) is also shown directly in Fig. 10 and 11. The important things are that variations among them are with 6-8% and that \( \eta_m \) of type B has the discrepant tendency that \( \eta_m \) increases as the compressor speed increases.

Fig. 12 shows the cylinder pressure curves, which demonstrate the difference between waves. To make comparison easier, the pressure curve of type A was chosen as a fundamental wave, because it had the smallest variation between the (a) and (b) methods.

Having a poor low frequency response, the pressure curve of type B is different from A's at the suction stroke. The curve of type C is distorted in the low pressure region. That is the same phenomenon recognized in the calibration test. The curve of D type is very similar to A's. However, the indicated gas work of type D is always smaller than A's. The difference of the indicated gas work between A and D increases as the compressor speed increases. It is caused by the limitation of the high frequency response of 5 kHz, which is a characteristic of D's dynamic strain meter.

**Oversuction and Overcompression Losses**

The oversuction loss \( W_s \), and the overcompression loss \( W_d \), are divided by \( W_{in} \) as shown in Fig. 13 and 14. To calculate \( W_s, W_d \), we needed to determine the absolute pressure level, therefore, \( W_s, W_d \) were calculated by the (b) method.

As shown in Fig. 13 and 14, the differences of \( \eta_d = W_d / W_{in} \) are within 1%. On the other hand, the differences of \( \eta_s = W_s / W_{in} \) are greater (within 4-5%). Therefore, it must be pointed out that the characteristics of transducers mainly affect the suction stroke.
In addition, only type C shows the discrepant tendency that γs decreases as the compressor speed increases, because C's distortion in the low pressure region became smaller as the compressor speed increased. Likewise, type B shows the discrepant tendency that γs is not proportional to the volumetric efficiency. If the compressor is run at the same speed, the volumetric efficiency at CT/ET=35°/-15°C is higher than at CT/ET=40°/-15°C. However, the γs of type B at CT/ET=40°/-15°C is higher than at CT/ET=35°/-15°C.

**CONCLUSION**

1) We made it clear that the characteristics of the four different kinds of pressure transducers affected the accuracy of P-V diagram measurements using a single cylinder reciprocating compressor in which they were mounted.

2) A was the most accurate of the transducers. This was judged by the results that the variation in sensitivity was the smallest in the calibration test, the difference of the indicated gas work calculated by the (a) and (b) methods was the smallest and the relation between Wo, Wa, Wd, and the compressor running conditions had no discrepancy.
3) The B type transducer had the poorest low frequency response, so that it was difficult to indicate the pressure precisely at the suction stroke. Therefore, it showed the discrepant result that the mechanical efficiency increased as the compressor speed increased.

4) The C type transducer was the smallest, but was apt to be affected by its mounting torque. Therefore, if C type is used, the pressure curve must be checked by recording it during the calibration test.

5) The D type transducer showed satisfactory accuracy, but was inferior in noise and high frequency response to A.

6) By using the B.P.V., it was possible to indicate the absolute pressure level with the accuracy of ±3.0 kPa. If the valve delay time is taken into account, the B.P.V. will be useful for a compressor speed of 3000-3600 rpm.

REFERENCES


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