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ON EXPERIMENTAL ERRORS IN P-V DIAGRAMS

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ABSTRACT

It is common practice to fold pressure-time diagrams of compressors into pressure-volume diagrams because the latter are of special thermodynamic significance. For example, the enclosed area represents piston work. The folding is accomplished utilizing knowledge of the top dead center position and kinematic relationships of the compressor. It was found that even a small measurement error of the top dead center position may change the pressure-volume diagram significantly. Also, the influence of pressure transducer calibration error was investigated. Furthermore, errors associated with the present method of locating suction and discharge pressures with the aid of valve opening data is discussed.

INTRODUCTION

In the compressor, the area enclosed by a P-V diagram is the work per revolution performed by the piston. Therefore, a P-V diagram furnishes useful information for the diagnosis of prototype compressors. Comparing the P-V diagram of the prototype with an ideal P-V diagram allows us to identify the energy loss. If pressure pulsations of both suction and discharge side are drawn as functions of volume, thermodynamic losses due to flow restrictions in valves and gas pulsations can be separated as shown in Fig.(1). Consequently, major problems of the prototype compressor with respect to thermodynamic efficiency can be diagnosed [1,4].

To fold pressure time diagrams into pressure volume diagrams, two auxiliary informations are necessary. The one is crank position as a function of time, by which time is converted to a corresponding volume utilizing the kinematic relationship of the compressor. The other is valve motion measurement data. Because the pressure measured by piezo-electric pressure transducers is a dynamic relative pressure, a reference pressure level is necessary to set absolute pressure level. The times of valve opening or closing are used for this purpose, on the argument that pressure equalizations occur at these instances.

To achieve high accuracy of measured P-V diagrams is very difficult from a practical viewpoint, because various kinds of errors which may reinforce each other can be created during measurement or calibration.

In this paper, the influences of commonly expected errors associated with measurements, calibrations of transducers and the absolute cylinder pressure setting procedure are discussed.

BASIC EXPERIMENTS

Pressure Measurements

Pressures are measured as the function of time in the cylinder, suction and discharge cavities. For high speed type compressors (3600 rpm), piezo-electric type pressure transducers have to be used. One difficulty associated with this type of pressure transducer is that it can measure only dynamic pressures. Therefore other informations, such as valve motion data, are needed to set the absolute pressure level. Fig.(2) shows a typical installation of pressure transducers for measuring cylinder, suction and discharge pressures.

Valve Lift Measurements

Valve motion measurements are very informative experiments. Not only for valve analysis, but also because they are used as reference data to set the absolute level of the cylinder pressure. For example at the opening instant of the suction valve, the cylinder pressure can be thought to have the same pressure level as the pulsating pressure of the suction cavity [2]. Typically magnetic type proximity probes are used to measure lifts of the suction and discharge valves. Fig.(3) illustrates a typical installation. Often some modifications of the prototype are unavoidable. For example, an access hole for the discharge probe may have to be cut in the stop plate of a discharge valve which might change the height of the valve stop, or the flow passage ot the suction side is disrupted because of the suction probe.

Top Dead Center Measurement

Pressures and valve motions are measured in conjunction with the crank angle measurement so that they can be converted into functions of time or angle from the top dead center(TDC) point. The crank angle measurement can be done by using a proximity probe which measures the piston motion, or a magnetic pick up device which measures the motion of the rotor shaft, as shown in Fig.(7).

CONSTRUCTION OF P-V DIAGRAMS

Setting Absolute Pressure Levels

Suction and discharge pressures can be aligned with their absolute values because their average pressures can be thought of as being the suction and discharge line pressures which are indicated by gages measuring the average pressure. The output voltage which was recorded by oscilloscope is normalized to have zero mean value. Then, multiplying the voltages by each calibrated transducer gain and adding line pressures, absolute pulsating suction and discharge pressures can be determined. It is assumed that the drop in average pressure between the suction and discharge manifold location and the location of the average line pressure measurement is negligible.

To set absolute cylinder pressure levels, more elaborate arguments are needed. If exact pressure transducer informations and very accurate valve opening times are available, the cylinder pressure can be determined without too much difficulty by arguing that at the instant of valve opening, the cylinder pressure must be equal to the pressure in the valve manifold. This is true for either suction or discharge. However, the calibration of the pressure transducer is not expected to be that accurate. For instance, only 2 % error in the transducer gain makes about 3 psi difference in the cylinder pressure variation at the typical standard operating condition. The average pressure drop at suction is of this order of magnitude. Furthermore, this error may be additive to the valve lift and crank position measurement errors. Fig.(4) is an exaggerated illustration of what can happen if the P-V diagram is made only by using calibrated transducer gains and measured discharge valve opening time. Obviously, the suction process will not properly be described. Judgment is therefore necessary when fitting the various measurements together.

A feasible way that was found to be useful is to argue that point A at which the cylinder pressure starts its polytropic expansion can be taken as the discharge valve closing time as shown in Fig.(5). This is only possible if the valve lift curve indicates that the discharge valve shuts close to top dead center. The suction valve opening time is then chosen such that the duration of valve opening in the pressure diagram agrees with the measured duration of valve opening. The transducer gain is then calculated from the two points which are supposed to be the suction and discharge pressures. Using this gain and referencing discharge pulsation pressure, cylinder pressure was determined.

Interpretation of the Implementation Procedure

As discussed, there are many kinds of errors which can change the P-V diagram. In the experiment, for which the data is presented here, the cylinder pressure transducer gain was calculated utilizing valve motion data as described above. The ratio of calculated gain to gain from calibration measurement reflects the overall error for the P-V diagram construction. Typical ratios are within 3 % deviations from the ideal value of unity.

Calibrated gains were used for discharge and suction pressures because average values of those pressures were taken to the suction and discharge line pressures as measured by mechanical gages. Also, errors in those gains cause much smaller relative differences in the overall efficiency , as well as for each thermodynamic loss, because they affect only relative pressures about the average suction and discharge line pressures. The effect on the overall efficiencies and on each loss is listed in Table 1 for one particular operating condition. Even 20 % error makes only 1 % difference in terms of the overall efficiency, although the portions of pulsation losses to the total loss are estimated incorrectly.

Fig.(6) is a pressure-crank angle diagram which was obtained by the procedure described above. The pressure-volume diagram which is obtained from this pressure-angle diagram is shown in Fig.(1). Suction and discharge pressures which make a closed loop during one cycle were drawn only for the half cycle for which the valves are open. The thermodynamic efficiencies, valve losses and pulsation losses of the suction and discharge sides can be calculated by integrating this diagram with respect to its volume.

CONCEIVABLE EXPERIMENTAL ERRORS OTHER THAN DUE TO PRESSURE ALIGNING, AND THEIR EXPECTED INFLUENCES

Calibration Errors of Pressure Transducers

Gains of pressure transducers are calibrated by a quasi-static process, while the actual process is dynamic. Also, deviation from linearity (1% max) and temperature sensitivity (0.03% per degree Fahrenheit) may have to be considered. This can be partially eliminated by more involved calibration procedures, as was done by Murata and Fujitani [3].

In general, the error in the gain of cylinder pressure transducers will affect the overall efficiency, while errors in gains of suction and discharge pressure transducers change mainly the ratio of valve losses to gas pulsation losses. However, if the absolute pressure setting is done by the method which was previously discussed, the overall efficiencies are affected very little by gain errors, because the calibrated cylinder pressure gain is not used for the absolute pressure setting.

Errors Due to Magnetic Pick-Up

A magnetic pickup is typically installed as shown in Fig.(7). Two pins on the rotor were used in the experiment described here to produce sharp signals as they pass the pickup. One of them was installed at the TDC position and removed later in the actual experiment after the measurement of the angle between the major signal and the TDC point had been obtained.

Because the linear displacement of the piston corresponding to the rotation of the crank is very small around the TDC or BDC, even a small error in detection of the TDC point when the triggering pin is installed may lead to significant errors in terms of angle. This will cause the P-V diagram to be distorted. An example is shown in Fig.(8), where on purpose crank angle errors of TDC was introduced. For comparison a P-V diagram of presumably zero error is also shown. It is remarkable that only 2 degrees of deviation makes such a difference in the P-V diagram shape.

A negative angle error, which means the actual TDC point is reached later than actual measurement, makes the indicator diagram larger. Examining the results, the difference is larger on the high pressure side where small time differences cause large pressure deviations. Therefore, the discharge side shows more distortion due to this effect.

This causes important effect on the determination of the experimental polytropic coefficients which is an important parameter in the theoretical simulation of compressor performance and in the estimation of heat transfer. Numerical values that illustrates this effect on thermodynamic efficiencies and polytropic coefficient estimations are listed in Table 2. There is almost a 6 % deviation of the polytropic coefficient for a -2 degree of TDC location error.

Valve Opening Time Errors

A delayed response of the valve reed to the pressure changes can exist due to oil stiction or the Bernoulli effect [4]. Even in the absence of these effects and if the exact motion could be recorded, it is not easy to identify the exact starting point or end point of the valve motion because a valve reed is already in dynamic motion even while it is still on the valve stop plate or valve seat, because it flexes into the port and starts moving as pressure differential decreases or increases rapidly.

Fig.(9) shows typical measured valve motions and Fig.(10) shows expanded plottings of these valve motions around the valve opening time, as recorded on a storage oscilloscope. It is very difficult to decide on the exact instant at which a valve opens, because small dynamic responses prior to the actual opening occur. There are five or six points which can be picked as the valve opening time, each of which corresponds to about 0.4 degrees of crank angle. It is possible that typical valve opening time errors are of the order of one degree crank angle which is a large error for fitting fast rising compressor pressures to discharge plenum pressures, as it was often done in the past.

Minor Effects

Of course, small deviations of operating conditions, unanticipated effects of temperature on transducers, and pressure gage errors when average suction and discharge pressure are obtained can always exist.

CONCLUSIONS

Like all other experiments, some amount of measurement error is unavoidable for the construction of experimental pressure-volume diagrams. Common errors such as pressure transducer gain errors and errors in the detection of the valve opening instant were discussed in the view of their influences on the estimation of overall efficiencies and losses.

The effect of the top dead center position measurement error was examined also. It was found that the error distorts the experimental P-V diagram and makes a considerable error in the evaluation of the experimental polytropic coefficient.

ACKNOWLEDGMENTS

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Table 1. Typical Effect of Errors of Pressure Gain

(At operating condition of Ps = 10 psig, pd = 200 psig)

Case	Relative Changes in %				
	Overall Efficiency	Suction Valve Loss	Suction Side Pulsation Loss	Discharge Valve Loss	Discharge Pulsation Loss
Calibrated Gains	0%	0%	0%	0%	0%
Calibrated Gains × 1.1	0.6%	- 5.1%	10.8%	-6.2%	10.7%
Calibrated Gains × 1.2	1.1%	- 9.7%	21.6%	11.6%	21.6%
Calibrated Gains × 0.9	- 0.41%	3.2%	-10.6%	6.0%	10.6%
Calibrated Gains × 0.8	- 0.88%	17.1%	-21.0%	11.8%	21.0%

$$*\frac{\text{(values from gains with assumed errors)} - \text{(values from calibrated gains)}}{\text{values from calibrated gains}}$$

Table 2. Typical Effect of Errors in Top Dead Center Measurement

(At operating condition of Ps = 10 psig, pd = 200 psig)

Case	Relative Changes in %					
	Overall Efficiency	Suction Valve Loss	Suction Side Pulsation Loss	Discharge Valve Loss	Discharge Side Pulsation Loss	Polytropic Coefficients
Measured	0%	0%	0%	0%	0%	0%
+2°	-0.53	12.9%	5%	-0.9%	-7.2%	-2.6%
+4°	-1.2%	14.6%	10.8%	-1.94%	15.7%	-6.4%
-2°	- 0.45%	5.7%	-4.1%	0.73%	6.2%	5.7%
-4°	- 0.85%	10.7%	7.8%	1.34%	11.5%	10.0%

$$* \quad \frac{\text{(measured results) - (values with assumed TDC error)}}{\text{measured result}}$$

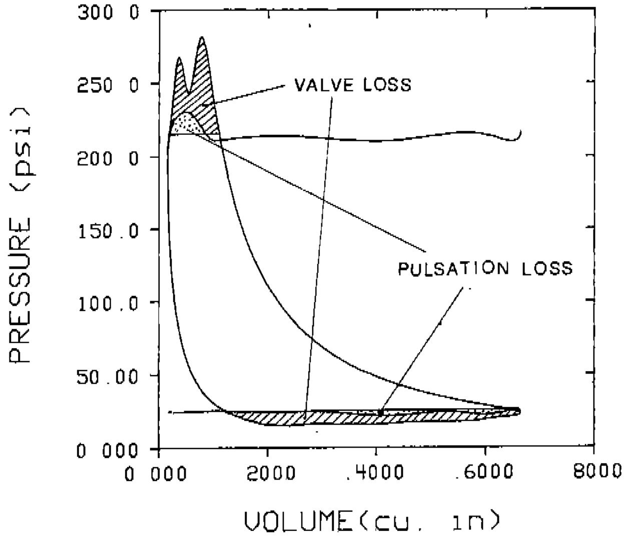


Fig.(1) Energy losses in the compressor

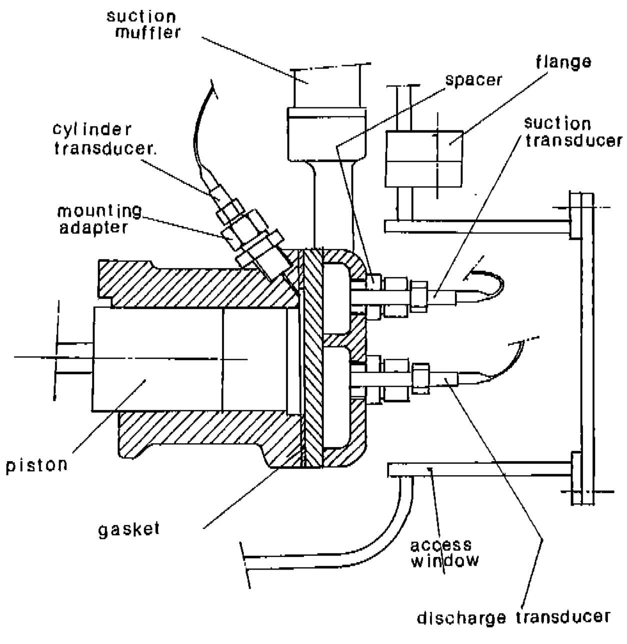


Fig.(2) Installation of pressure transducers

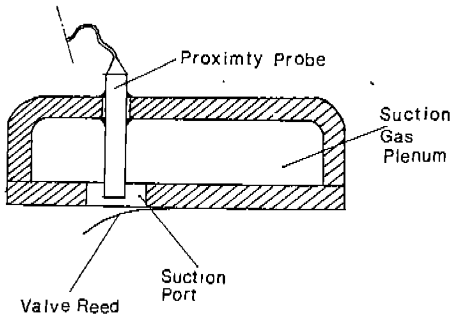


Fig. (3) Installation of the proximity probe for the suction valve

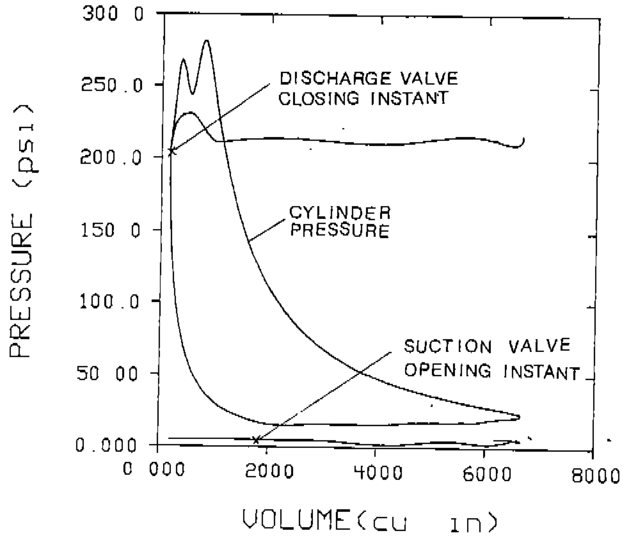


Fig. (4) An example of misfitted P-V diagrams

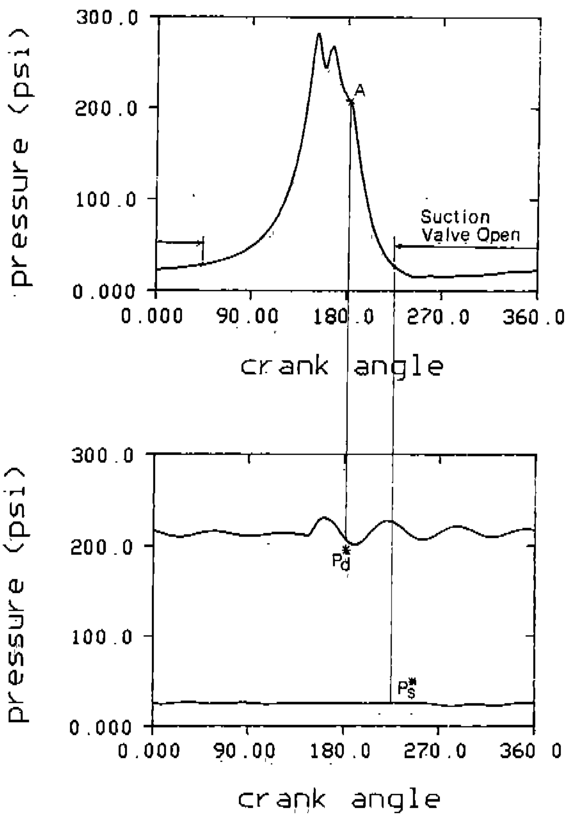


Fig.(5) Absolute pressure level setting procedure

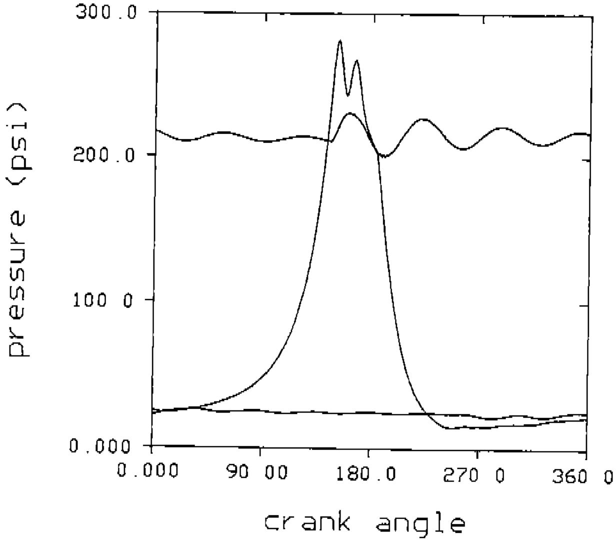


Fig.(6) Pressure-crank angle diagram

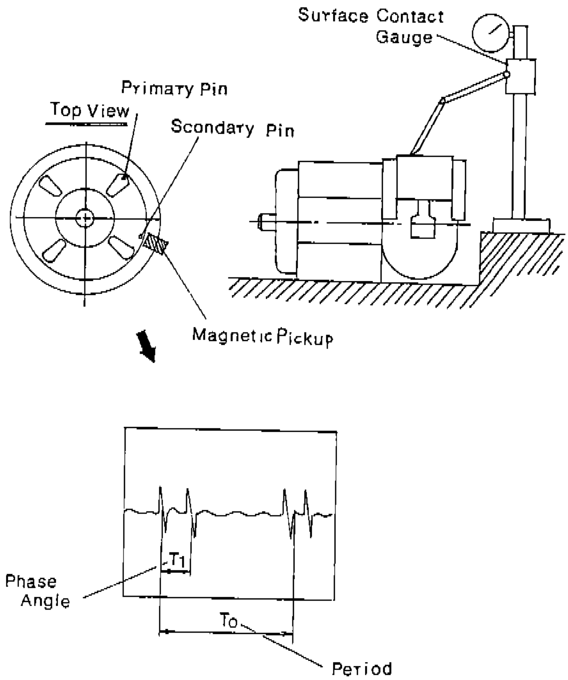
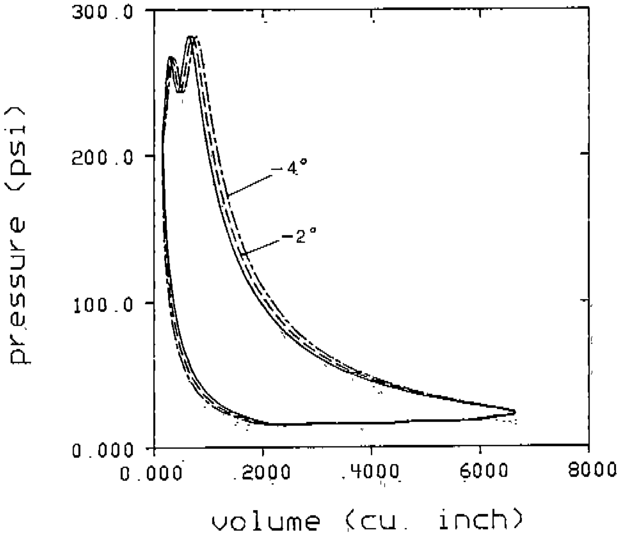


Fig.(7) Installation of magnetic pickups



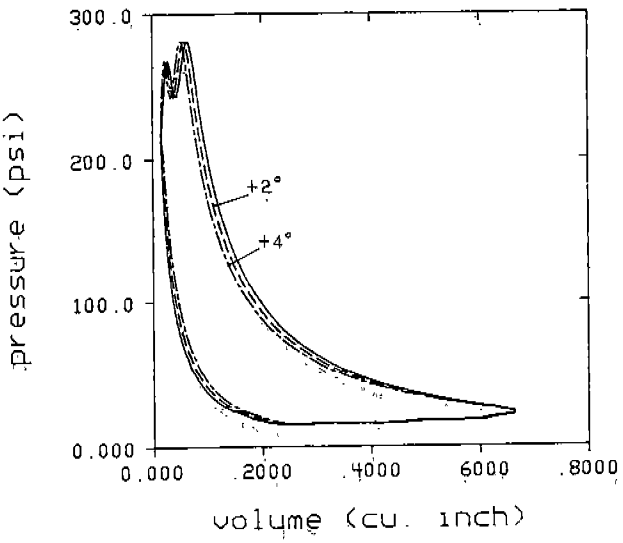
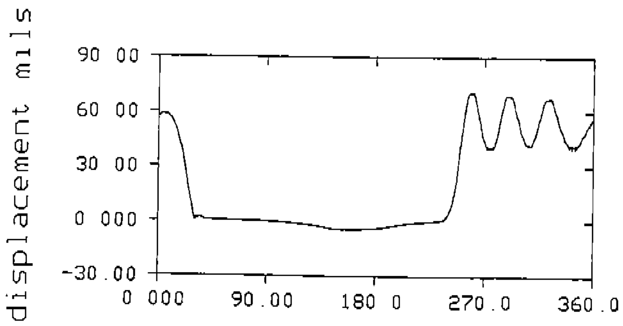
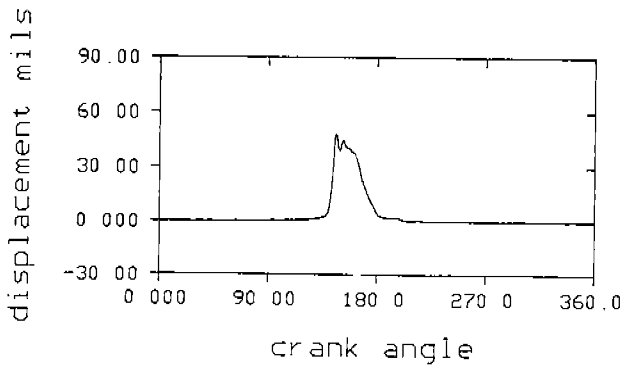


Fig.(8) Effect of the TDC measurement error on the P-V diagram

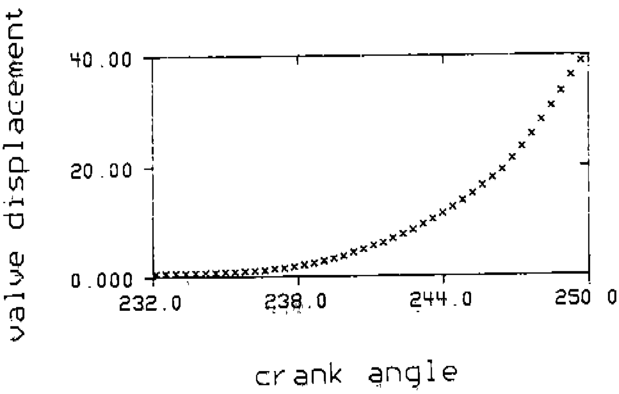


(suction valve)

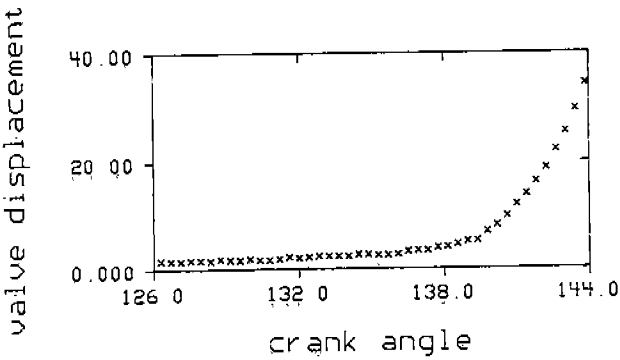


(discharge valve)

Fig. (9) Measured valve motions



(suction valve)



(discharge valve)

Fig. (10) Expanded plottings of valve motions around the opening time