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A Combined Practical Approach to Condition Monitoring of Reciprocating Compressors using IAS and Dynamic Pressure

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***Abstract*—**A Comparison and evaluation of the different condition monitoring (CM) techniques was applied experimentally on RC e.g. Dynamic cylinder pressure and crankshaft Instantaneous Angular Speed (IAS), for the detection and diagnosis of valve faults in a two - stage reciprocating compressor for a programme of condition monitoring which can successfully detect and diagnose a fault in machine. Leakage in the valve plate was introduced experimentally into a two-stage reciprocating compressor. The effect of the faults on compressor performance was monitored and the differences with the normal, healthy performance noted as a fault signature been used for the detection and diagnosis of faults.

The paper concludes with what is considered to be a unique approach to condition monitoring. First, each of the two most useful techniques is used to produce a Truth Table which details the circumstances in which each method can be used to detect and diagnose a fault. The two Truth Tables are then combined into a single Decision Table to provide a unique and reliable method of detection and diagnosis of each of the individual faults introduced into the compressor. This gives accurate diagnosis of compressor faults.

***Keywords*—**Condition Monitoring, Dynamic Pressure, Instantaneous Angular Speed, Reciprocating Compressor.

I. Introduction

RECIPROCATING compressors are one of the most popular machines in use in industry. The timely detection of faults, which may influence the performance, is expected to help in both reducing maintenance costs and increasing the plant efficiency.

Compressor valves can be the largest single cause of unscheduled reciprocating compressor shutdowns. The aim of this research is to develop more accurate and sensitive fault detection and diagnosis tools that can be used with two-stage reciprocating compressors. The paper uses, in order to compare them, CM techniques (dynamic cylinder pressure and IAS) for the study of predictive maintenance of a reciprocating compressor. It also introduces the measurement of IAS in order to assess its suitability for CM and predictive maintenance.

Much attention has been paid to monitoring and diagnosing faults in reciprocating compressors. Liang [1] has developed a procedure for the detection and diagnosis of valve faults using vibration time domain, frequency domain and smoothed-pseudo-Wigner-Ville-distribution (SPWVD).

Gu and Ball [2] have studied automating the diagnosis of valve faults in reciprocating compressors. In 1984 Imaichi [3] studied vibration sources in reciprocating compressors and how to minimize vibration generation.

Daniel [4] focused his attention on vibration and dynamic pressure methods, including the P-V diagram, for fault diagnosis and condition monitoring of reciprocating compressors. Elhaj *et al.* [5] developed a new method for monitoring and diagnosis of valve faults in reciprocating compressors by using time domain, frequency domain and continuous wavelet transform (CWT) of the airborne sound signals.[6] Ishll, et al. Studied the vibration of a small reciprocating compressor. These have been developed into a CM system for investigating the condition of valves in reciprocating compressors using conventional vibration analysis of the valve impact signature combined with the timing of events such as valve closure and opening times.

More recently, Liu [7] used neural networks and fuzzy logic to process IAS signals from diesel engines for the purpose of CM. Sweeney [8] has used IAS to analyse gearbox transmission errors. Ben Sasi used the variation in IAS for the monitoring of electric motors [9] Liang [10] demonstrated the capability of IAS from a transient motor to detect faults in the asymmetric power supply and the rotor bar.

The other aim of this study is to investigate and compare the practical use of two different CM techniques; dynamic cylinder pressure and IAS, using both conventional transducers for machine monitoring and less well established types. To apply signal processing methods and techniques such of time domain to extract fault features for early fault detection and to compare their performance. This project introduces a new monitoring technique for the reciprocating compressor. The ultimate aim is to produce a 'Decision Table' which will allow, from the CM signals, the unique identification of any one of the given valve faults.

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II. Experimental Set-up

A reciprocating air compressor was adopted for the experimental study. In order to perform the experimental study, an optical encoder, pressure transducers and other necessary instrumentation was attached to the compressor as shown in Fig. 1. The pressure transducers were installed on the heads of the first and second stage cylinders by drilling a small hole in the cylinder head, where the pressure sensor was installed. The optical encoder was mounted to the end of crankshaft on the flywheel at the compressor crankshaft side. A marker was used to give a trigger on every complete revolution of the flywheel. The data acquisition software is an updated Windows based interface, able to perform online data sampling and monitor compressor parameters such as IAS and dynamic pressure.

Fig. 2(a) shows the measured of IAS over a compressor cycle for three values of the discharge pressure, 0.27, 0.54 and 0.82 MPa. The measured of the IAS was fluctuated over the cycle and varied with discharge pressure. Variation of IAS with variation of discharge pressure was encountered; variation was minor, 453 to 455 rpm. For 0.82 MPa the minimum IAS was 423 rpm, for 0.54 MPa - 428 rpm and 0.27MPa - 434 rpm.

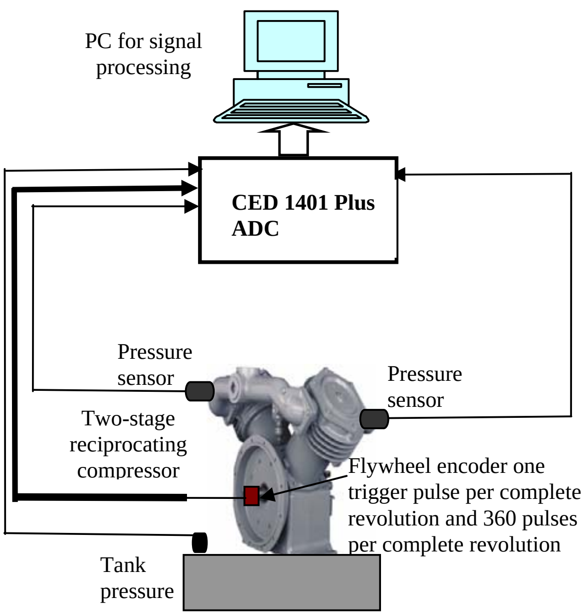

Fig. 1 Schematic diagram of reciprocating compressor test system

III. Suction Valve Leakage in Both 1st and 2nd Stages

Time Domain Analysis of Leakage in the 1st Stage Suction Valve

In this research the high pressure cylinder discharges into a tank in which the pressure was measured as 816kPa (120psi), while the low pressure cylinder discharges direct to the 2nd stage with a back pressure of about 260kPa (38psi). Clearly the effects of leakage in the suction or discharge valves of 1st and 2nd stages are likely to be quite different from each other.

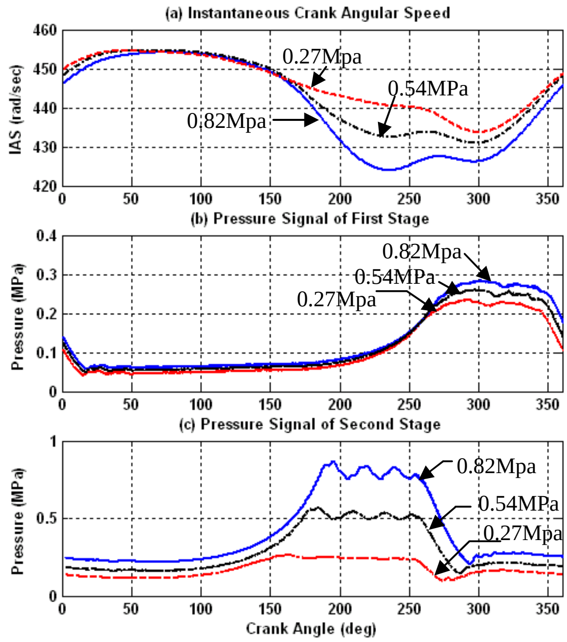

Fig. 2 Measured results; (a) IAS with different discharge pressures, (b) low pressure cylinder waveform, and (c) high pressure cylinder waveform

Fig. 3(b), (c) shows the experimentally measured dynamic pressure in the 1st and 2nd stage cylinders for a healthy suction valve, a valve with 0.2% leakage in the valve plate and a valve with 0.8% leakage.

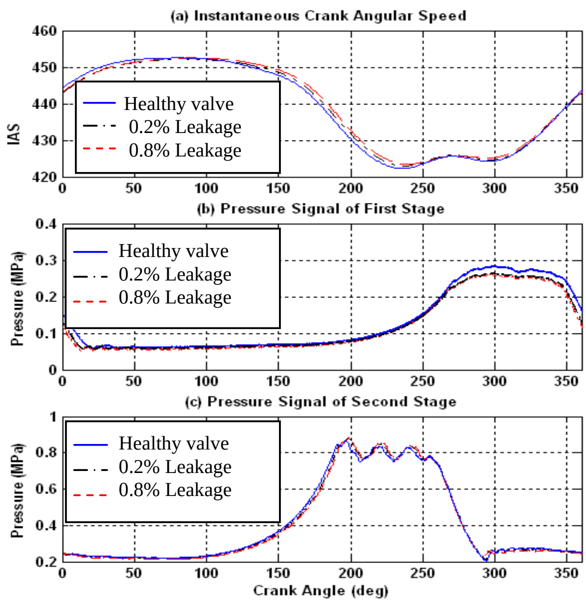

Fig. 3 Measured crankshaft IAS as a function of 1st stage suction valve leakage; a) IAS waveform, b) cylinder pressure of 1st stage and c) cylinder pressure signal of 2nd Stage

The deviation of the pressure signal from normal due to valve leakage can be seen clearly, during discharge and expansion, particularly of the 1st stage. The suction valve of the 1st stage opens earlier the greater the leakage, due to the lower clearance pressure in the cylinder caused by the leakage itself. Leakage through the 1st stage suction valve also causes the 1st stage discharge valve to open later and close earlier.

A leaky suction valve in the 1st stage can affect the pressure in the 2nd stage and hence valve movement, as seen in Fig. 3(c) where both the suction valve and the discharge valve open slightly later, both due to the lower than normal pressure feed from 1st stage.

Fig. 3(a) shows that leakage in the 1st stage suction valve causes a deviation of the measured IAS signal from its baseline. Both measured results show an increase in IAS between about 120° and about 230° due to the reduction in the cylinder pressure of both 1st and 2nd stages caused by the leaky suction valve, this lead to reduction in load acting on the crankshaft. The small peak in IAS value of 428rpm, which occurs at crankshaft angle of about 280°, is related to the 1st stage compression stroke and discharge cylinder pressure as show in Fig. 3(a).

Leakage of 2nd Stage Suction Valve

The effect of a leaky 2nd stage suction valve on the measured dynamic cylinder pressure can be seen in Fig. 4(c). The effect of the leaky suction valve in the 2nd stage is to increase the measured pressure in the 1st stage as seen in Fig. 4(b). The 1st stage suction valve opens later due to increase of the clearance cylinder pressure, and the discharge valve opens later because the leakage through the 2nd stage suction valve increases the pressure in the pipe between the cylinders, requiring a greater pressure difference to open the discharge valve of the 1st stage.

There is a slight decrease in the maximum pressure reached in the 2nd stage cylinder, the discharge valve closes slightly earlier so re-expansion occurs slightly earlier, the suction valve open earlier and there is a small upward shift in the suction line.

A leaky 2nd stage suction valve causes lower pressure in the 2nd stage and, simultaneously, a higher pressure in the 1st stage. Fig. 4(a) are the measured IAS, respectively, with leakage in the 2nd stage suction valve, and show that the peak level between about 30° and 120° increases with leakage due to lower pressure in the 1st and 2nd stage cylinders. The IAS waveform moves down (decrease in IAS) at around 300° due to higher pressure in the 1st stage cylinder caused by the high pressure leakage back through the suction valve of the 2nd stage and this increases the load acting on the crank shaft.

IV. Discharge Valve Leakage in both 1st and 2nd Stages

Discharge valve leakage will result in higher pressure air returning to the cylinder when the discharge pressure is greater than the cylinder pressure.

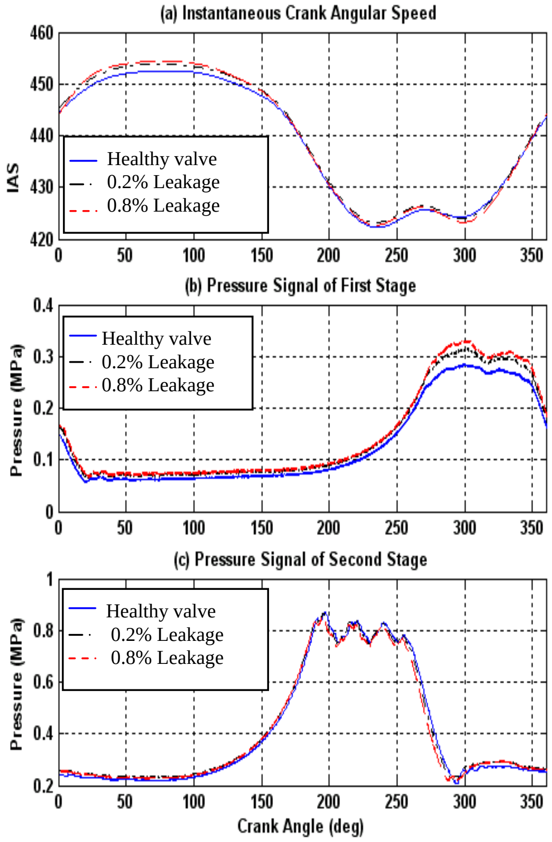

Fig. 4 Measured crankshaft IAS as a function of 2nd stage suction valve leakage; a) IAS waveform, b) cylinder pressure of 1st stage and c) cylinder pressure signal of 2nd stage

This will occur during re-expansion, suction and part of the compression stroke, for both 1st and 2nd stages. However, the effect of discharge leakage of the 1st stage will be different from the 2nd stage. If there is leakage through the discharge valve the cylinder pressure will always be above normal during expansion, suction and compression. Since the leakage is proportional to the pressure differential across the valve, the mass flow rate through the leak is greater at the end of expansion and beginning of compression when the cylinder pressure is close to the suction pressure.

Time Domain Analysis of Leakage of 1st Stage Discharge Valve

Fig. 5 (b), (c) shows the experimentally measured dynamic pressure in the 1st and 2nd stage cylinders for a 1st stage discharge valve, which is healthy, with a 0.2% leakage in the valve plate and with a 0.8% leakage.

As result of the leakage the cylinder pressure needed to open the 1st stage discharge valve is reached sooner, see Fig. 5(b). The reason for this is that high pressure air flowing through the discharge leak raises the compression pressure above that which normally exists. As result the pressure needed to open the valve is reached sooner. Suction valve motion is also altered because the higher cylinder pressure slightly delays the time at which the pressure becomes low enough to open the suction valve. The 1st stage discharge valve leakage also affects the 2nd stage cylinder pressure and the consequent valve movements. Fig. 5(c) shows the 2nd stage discharge valve opens and closes slightly later. The reason for this is that the pressure from the 1st stage is lower than for reference (healthy) condition and this causes low feed pressure to the 2nd stage. The effect increases when the leakage severity increases.

Fig. 5(a) shows the measured and predicted values, respectively, of IAS for leaky 1st stage discharge valves, and significant deviation of the IAS from its baseline can be seen for the measured values. Between crank angles of about 130° to about 230° the IAS waveform is shifted upwards (increasing IAS). This is due to the lower pressure in the 2nd stage cylinder during its compression stroke and consequent lower load acting on the crankshaft, see Fig. 5(a). Between crank angles of about 240° to about 280° the IAS is shifted downwards (decreasing IAS).

This is due to the higher pressure in the 1st stage cylinder during its compression time caused by the high pressure leakage back through discharge valve during suction and consequent higher load acting on the crankshaft.

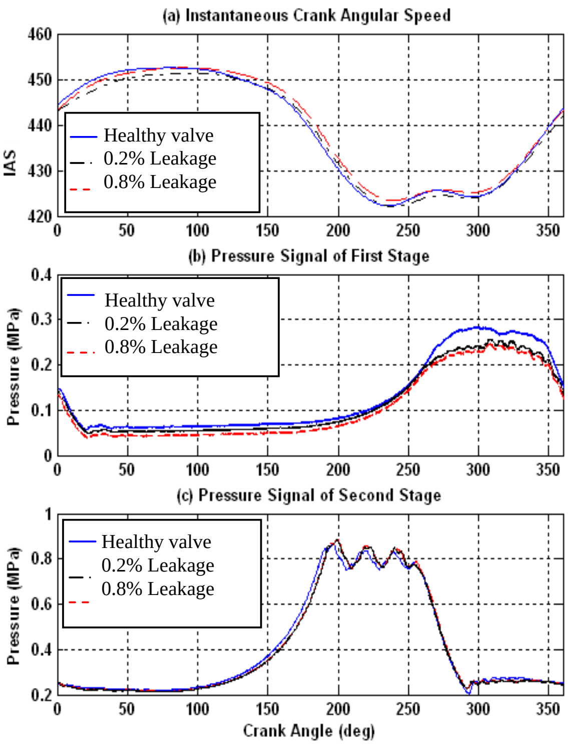

Fig. 5 Measured crankshaft IAS as a function of 1st stage discharge valve leakage; a) IAS waveform, b) cylinder pressure of 1st stage and c) cylinder pressure signal of 2nd stage

Time Domain Analysis of Leakage of 2nd Stage Discharge Valve

The measured variation in cylinder pressure in both 1st and 2nd stage cylinders, due to a 2nd stage leaky discharge valve, is shown in Fig. 6(b),(c). The most obvious observation is; the 2nd stage discharge valve opens earlier the greater the leakage, because high pressure air flowing back from the storage tank through the discharge leak raises the pressure in the cylinder above that which normally exists. As result the pressure needed to open the valve is reached sooner.

The 2nd stage suction valve opens later the greater the leakage, for the same reasons the discharge valve opens earlier. The maximum pressure reached in the 1st stage cylinder increases with leakage. The 1st stage suction valve opens later the greater the leakage because the higher cylinder pressure delays the time at which the pressure is low enough to open the valve.

The discharge valve of the 1st stage closes later because the higher pressure observed during the suction time of 2nd stage leads to higher pressure in the cooling system which, in turn, leads to the discharge valve of 1st stage opening later.

Fig. 6(a) shows the measured values, respectively, of IAS for leaky 2nd stage discharge valves, and substantial deviation of the IAS from its baseline can be seen. Between crank angles of about 30° to about 130° the IAS waveform is changed and shifted upwards (increasing IAS) during the suction time of both 1st and 2nd stages which result from higher pressure leaking back and acting to force the piston

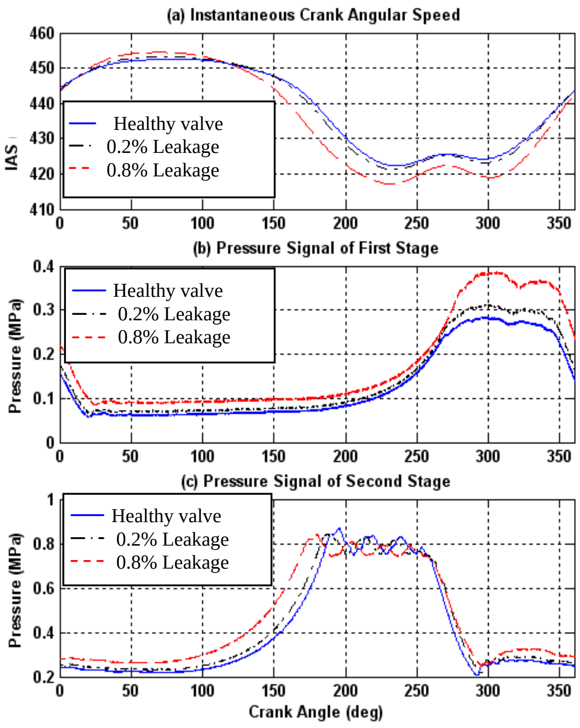

Fig. 6 Measured crankshaft IAS as a function of 2nd stage discharge valve leakage; a) IAS waveform, b) cylinder pressure of 1st stage and c) cylinder pressure signal of 2nd stage

down the cylinder, lowering the load acting on the crank shaft. However, between crank angles of about 140° to about 350° the IAS waveform is changed and shifted downwards (decreasing IAS) substantially.

This is the result of higher than normal pressures during compression in both 1st and 2nd stages. The former is due to back pressure from 2nd stage cylinder causing higher discharge pressure for the 1st stage, and the latter is due to high pressure leakage back into the 2nd stage cylinder, see Fig. 7 (b), (c).

V. Dynamic Pressure Analysis

Table I and IA shows the Truth Table for the dynamic cylinder pressure signal for the four common valve faults. Here a time domain analysis only was performed and information about the valve fault is contained in the amplitude of the pressure signal and its time of occurrence within the cycle.

TABLE I
DYNAMIC PRESSURE TRUTH TABLE FOR VALVE FAULTS IN RECIPROCATING COMPRESSOR

Signatures / Faults	1st stage Suction valve				1st stage Discharge valve				1st stage CP		2nd stage Suction valve				2nd stage Discharge valve				2nd stage CP	
	Valve open		*Valve close*		*Valve open*		*Valve close*				*Valve open*		*Valve close*		*Valve open*		*Valve close*			
	-	+	-	+	-	+	-	+	L	H	-	+	-	+	-	+	-	+	L	H
1st stage leaky SV	♦					♦	♦		♦							♦				
2nd stage leaky SV		♦			♦			♦		♦	♦				♦		♦		♦	
1st stage leaky DV		♦				♦	♦		♦			♦				♦				
2nd stage leaky DV		♦				♦		♦		♦	♦				♦					

TABLE IA
KEY TO SYMBOLS

1st stage CP	Cylinder Pressure of 1st stage
2nd stage CP	Cylinder Pressure of 2nd stage
L	Low pressure
H	High pressure
–	Valve open earlier
+	Valve open later

VI. IAS Analysis

TABLE II
IAS TRUTH TABLE FOR VALVE FAULTS IN RECIPROCATING COMPRESSOR

1st stage leaky SV	Decrease 0° – 100°, increase 120° – 250°, and 270°-340°
2nd stage leaky SV	Increase 0° – 160°, slight increase 200° – 280°, decrease 280° – 320°
1st stage leaky DV	Decrease 0° – 120° , and 240°-300° , increase 130° – 250°
2nd stage leaky DV	Increase 0° – 120° substantial decrease 130° – 360°

Table II shows the Truth Table for the IAS signal for the four common valve faults. Here a time domain analysis only was performed and information about the valve fault is contained in the amplitude of the angular speed and its time of occurrence within the cycle. This leads to increase the load acting on the crank shaft.

From the Truth Table II, a number of identification markers for the different valve faults may be seen. For example, lower than normal IAS over the range of crank angles 0 to about 100° indicates a leaky 1st stage valve. A substantial decrease in IAS from about 130° to about 360° should be taken as a strong indication of a leaky 2nd stage discharge valve.

VII. Synthesis of Results - Decision Table

Examination of the two Truth Tables shows that each of the four faults introduced into the compressor causes a number of changes to the normal signals. By judicious examination of each individual fault in each of the two Truth Tables a Decision Table can be compiled which lists the defining and unique characteristics for each fault. For example, a leaky 1st stage suction valve is indicated by at least the following changes to the normal signal:

(a) the pressure in the 1st stage cylinder is lower than for normal operation, and (b) a slight increase in IAS during the 2nd stage compression and discharge (crank angle about 120° to 250°).

Unfortunately while (a) and (b) eliminate a number of possible faults they do not identify a leaky 1st stage suction valve, (a) and (b) on their own could also equally well indicate a leaky 1st stage discharge valve.

The Decision Table III, shown below, lists the major signatures corresponding to each of the four faults. Strictly, only three signatures are required to identify which of four faults is occurring providing there is a unique correspondence and, as can be seen from the Decision Table, it is possible to identify each of the four faults.

Some faults have similar signatures when comparing only the details present in the main body of the table. In these circumstances reference to the IAS adds sufficient information to distinguish the faults.

It is considered that the use of the Decision Table could be a significant development in CM techniques. There are two reasons for this. In an industrial situation the Plant Manager or Controller will be provided with more information concerning any particular machine and its possible faults, and this will allow better decision making.

The different monitoring processes will provide different and separate information about the same fault which can be cross-checked automatically and, where a fault is not confirmed, eliminate false alarms. Of course, where the fault is confirmed then the alarm will be given. Such an approach has been adopted in industrial fire fighting systems to great benefit in the petrochemical plants where, in the author's, experience the introduction of such a system greatly reduced false alarms**.**

VIII. Conclusion

Dynamic cylinder pressure and IAS are directly related and both proved useful information for fault detection and diagnosis.

A comprehensive assessment of a range of different transducers was performed, facilitated by simultaneous data collection using a multi-channel data acquisition system.

The less-than-conventional parameter measurement transducer was an optical shaft encoder to measure IAS. Data from these transducers confirmed that useful information can be extracted from dynamic pressure and IAS data.

Dynamic pressure is an extremely powerful CM tool, the deviation of the pressure signal from the normal can be seen clearly. The valves' opening and closing for both 1st and 2nd stages may be clearly observed and show the difference between healthy and faulty valves (valve leakage). Also the increase of cylinder pressures due to leaky valves can be clearly observed.

The experimental work have both demonstrated that IAS analysis is capable of characterizing compressor operation at different discharge pressures, and successful detection of valve faults (e.g. leakage valves) can be made from deviation of the IAS waveform from its baseline.

IAS measurement of a reciprocating compressor flywheel is a very convenient, economic, reliable and non-invasive technique. Because the IAS is closely related to the air pressure in the cylinder and the power torque acting on the crankshaft, it is expected to provide information useful for fault detection and fault diagnosis. Variation in IAS is more obvious with faults in the 2nd stage valves than in the 1st stage, and with leaky valves.

TABLE III
Decision Table

Faults	1st stage Suction valve				1st stage Discharge valve				2nd stage Suction valve				2nd stage Discharge valve					Change in IAS
	VO		*V C*		*VO*		*V C*		*V O*		*VC*		*V O*			*V C*		
Signatures	-	+	-	+	-	+	-	+	-	-+		-	+	-	+	-	+	
1st stage leaky SV	♦					♦	♦								♦			Decrease 0 – 100°, increase 120 – 250° and 270° - 340°
2nd stage leaky SV		♦			♦			♦	♦					♦		♦		Increase 0 – 160°, slight increase 200 – 280°, decrease 280 – 320°
1st stage leaky DV		♦				♦	♦			♦					♦			Decrease 0 – 120°and 240°-300°, increase 130 – 250°,
2nd stage leaky DV		♦				♦		♦	♦					♦				Increase 0 - 20° substantial decrease 130 – 360°

TABLE IIIA
KEY TO SYMBOLS

Cylinder Pressure (L)	Low pressure
Cylinder Pressure (H)	High pressure
_	Valve open and close earlier
+	Valve open and close later
O	Open
C	Close
SV	Suction Valve
DV	Discharge Valve

Truth Tables which combine and synthesize the information on fault signatures show the capabilities of the technique used and presents this in such a way that allows easy comparison of the fault signatures of each individual fault. Comparison of the Tables shows the relative merits of the different techniques in determining any given fault – that is the relative capabilities of the various techniques.

Truth Table I shows how variation in cylinder pressure may be combined with changes in the angles at which the valves open and close to diagnose specific valve faults. Comparison of these Tables confirms the data regarding valve opening and closing times, and additional information is gained on either impact levels or cylinder pressure.

The information shown in Truth Table II is totally different from that shown in the other Truth Tables, and shows how variation in IAS can be used for specific fault identification, a novel method used here for detection and diagnosis of valve faults for the first time.

The Decision Table, Table III, lists the major signatures detected by each method, corresponding to each of the four valve faults. The author's experience in the petrochemical industry is that even the best of present systems can fail to detect a fault or, even more often, will raise the alarm when no fault is present. The author has compiled the Decision Table based on his working experience with fire fighting and plant control systems, that the use of two parallel, complementary systems can largely resolve this problem. When the two systems agree on, say, raising a fire alarm the danger of false alarms is largely eliminated, the same could be done for CM.

The author is proposing a similar approach to machine CM. That is, at least two systems in parallel to provide a nearly 100% reliable system. Given the cost of breakdown in chemical plants this is economically most reasonable.

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