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In Situ Performance Evaluation of Industrial Reciprocating Air Compressors

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INSITU PERFORMANCE EVALUATION OF INDUSTRIAL RECIPROCATING AIR COMPRESSORS

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ABSTRACT

This paper discusses the need for insitu performance evaluation of reciprocating air compressors. Defines and groups the performance indicating parameters that are to be monitored for evaluation of performance of compressors as vital and diagnostic parameters. Measuring methods that are suitable for offline measurement on insitu basis are evaluated. As compressors are energy intensive devices, their performance needs to be monitored periodically. In large reciprocating compressors, performance monitoring devices are installed permanently for continuous online monitoring. In lower capacity reciprocating compressors performance is monitored periodically offline on insitu basis. Parameters that indicate the performance of the compressors are divided in to two groups as vital parameter and diagnostic parameters. Vital parameter namely specific power consumption needs to be monitored regularly and it is compared with bench mark values. If the value of the vital parameter decreases below the bench mark diagnostic parameters that cause the loss in performance of the compressor are measured. The diagnostic parameters are electrical losses, mechanical losses, thermodynamic losses and air capacity loss. Measuring methods that are suitable for measuring these parameters offline on insitu basis is discussed in this paper.

1. INTRODUCTION

Compressed air is an energy form combining speed, power and safety. Compressed air is used widely throughout the industry and is often considered as 'fourth utility' at many facilities. Compressors are used for production of compressed air. Compressors can be classified based on the principle of operation as positive displacement compressors and roto-dynamic compressors. Positive displacement compressors are further grouped as reciprocating compressors and rotary compressors. Reciprocating compressors have advantage of broad capacity control; inter stage cooling, flexibility to compress any gas regardless of its gas constant. Reciprocating compressors are available in sizes from less than 1 HP to more than 600 HP. Continuous monitoring systems are installed in reciprocating compressors having capacity >350kW and especially those used in hydrocarbon processing. As large number of reciprocating air compressor systems ranging from 30 to 350 kW are installed in various industries, performance monitoring of these compressors needs to be done periodically and using off-line methods on insitu basis to conserve energy.

2. NEED FOR INSITU PERFORMANCE EVALUATION

Compressors are energy intensive devices. The purchase of a compressor should be decided by their life cycle costs rather than by taking the capital costs alone in to consideration. Radgen and Blaustein (2000) give details on the life cycle cost of the compressor taking average life of a compressor between 13 to 16 years, the proportion of various costs associated is given in Table 1.

Table 1 Life Cycle Cost of Compressors

Investment costs	15 to 20%
Maintenance costs	6 to 8%
Energy costs	79 to 71%

Since the operating energy cost of compressors is quite significant proportion in their life cycle costs, the performance of the compressors should be monitored regularly and kept at its best levels.

2.1 The role of monitoring

Monitoring and tracking system performance itself does not improve energy efficiency (Radgen and Blaustein, 2000). Nevertheless it is often the first step in improving energy efficiency for two basic reasons. Measuring air use and energy consumption is essential in determining whether actions proposed in improving energy efficiency is cost effective. Tracking of system performance is a valuable tool to detect performance degradation, or change in the nature or quantity of air use.

2.2 Present state of the art of monitoring reciprocating compressors

Products available commercially for monitoring of reciprocating compressors provide functions for machine protection, condition monitoring and performance monitoring. For condition monitoring of the compressor the mechanical condition of the compressor is assessed by measuring parameters such as frame vibration, piston rod drop, suction and discharge valve temperature, main bearing temperature cross head acceleration, multi event Key-Phaser signal and cylinder pressure. These systems have alarm and interlocking feature to protect machines in the event of occurrence of abnormal conditions.

The reciprocating compressor monitoring products available in the market are expensive. Moreover the practices of continuous monitoring of reciprocating machines have not gained the same level of acceptance as compared to centrifugal compressors It is observed that in general continuous monitoring systems are installed in reciprocating compressors having capacity >350kW and especially in those used in hydrocarbon processing. Reciprocating air compressor systems ranging from 30 to 350 kW installed in various industries are far too many and the performance monitoring needs to be done periodically and using off-line methods which are reliable quick and cost effective.

3. PERFORMANCE INDICATING PARAMETERS OF RECIPROCATING AIR COMPRESSORS

The parameters to be monitored to asses the performance of the reciprocating compressors is grouped in to two categories. A parameter which indicates the overall performance of the compressor is called vital parameter. The categories of parameters that are used to identify the reasons for degradation of performance are called diagnostic parameters. In practice vital parameter should be measured periodically and its value is compared with bench mark values. If the value of the vital parameter deviates from the bench mark value then the diagnostic parameters needs to be measured to identify problem in the compressor.

Vital parameter:
- Specific Power Consumption

Diagnostic parameters:

Power losses:
- Electrical losses: Electrical power - Mechanical Power
- Mechanical Losses: Mechanical power - Indicated Power
- Thermodynamic losses: Actual indicated power - Ideal Power

Air flow capacity losses:
- Volumetric efficiency
- Leakage from the system

3.1 Specific power consumption

Specific Power Consumption is the vital parameter for assessing the overall performance of reciprocating air compressors. Specific power consumption is defined as power consumed by the compressor to deliver one cubic meter of free air per minute at rated pressure, which is expressed in units kW/(m^3/min.). In imperial units it is expressed as kW/100cfm. FAD of the compressor and electrical power consumption are measured for calculating specific power consumption.

3.2 Power Losses

Power losses are the indicators of how the power is lost in various parts of the compressor system. It can pinpoint the cause for degradation of compressor's overall performance.

3.2.1 Electrical losses: It is the difference between the electrical power supplied to the electric motor and mechanical power supplied to the compressor crank shaft. The electrical losses indicate the energy conversion efficiency of the drive motor and energy transmission efficiency of the belts and couplings.
3.2.2 Mechanical Losses: It is the difference between the mechanical power input to the compressor and indicated power of compression. The mechanical losses account for the frictional losses in the compressor system and power required to drive accessories like lubrication pump and journal bearing oil pump.
3.2.3 Thermodynamic losses: It is the difference between actual indicated power and ideal or theoretical power required for compression. The thermodynamic losses indicate the losses due to valve resistances offered to the flow and loss due to the deviation of compression and expansion processes from ideal process.

To calculate the power loss parameters Electrical power consumption, Mechanical power consumption, In-cylinder pressure and Instantaneous swept volume measurements are required.

3.3 Air flow capacity losses

Air flow capacity losses are components that reduce the FAD of compressors. Capacity loss occurs due to re-expansion of high pressure air left in the clearance volume at the end of discharge process. The assessment is made by measuring the volumetric efficiency of the compressor, which is the ratio of actual volume of air delivered and swept volume of the compressor. The capacity losses also occur due to leakages in the compressor and in the flanges and piping systems. FAD of the compressor and leakage rate measurements required for estimation of airflow capacity losses.

4. MEASUREMENTS

For performance monitoring of compressors FAD of air compressor, Electrical power consumption, Mechanical Power consumption, Indicated Power consumption, and leakage rate are to be measured. There are number of techniques available for measurement these parameters. However, only the techniques that are suitable for offline insitu measurements are presented in following sections

4.1 FAD Measurement

Air flow in reciprocating compressor is pulsating in nature. The FAD of a reciprocating compressor is the time average of the pulsating flow. In conventional differential pressure measuring devices like orifice meters and venturimeters, the pressure drop across the flow element Δp is proportional to the square of the flow rate. If these devices where subjected to pulsating flow measurement, the time average of pressure drop Δp indicated will be higher than the true value. Therefore in pulsating flow measurements the average flow rate indicated by these devices will be higher than the actual flow. Additionally if the response time of the manometer used to measure the pressure drop Δp is more than the pulsation period of the flow, square root error arises. In laboratories these devices are being used to measure the FAD of reciprocating compressors by damping the pulsations of the air flow using acoustic filters. Plint and Martyr (1995) give a formula to calculate the volume of single chamber acoustic filter. It is found that the volume of the single chamber pulsation filter required for a double acting reciprocating compressor with swept volume of 3.15 liters is 460 liters, which is 145 times the compressor swept volume. Because of its large size, acoustic filters are not suitable for industries. In a compressor installation where in number of compressors are to be tested, a bulky acoustic filter cannot be moved from one compressor to other during air flow measurement. Therefore conventional differential pressure producing flowmeters are not suitable for insitu FAD measurement.

Laminar flow meters are used measuring pulsating flows. In viscous (laminar) pipe flow the pressure drop varies as first power of the velocity; hence the time average of the pressure drop is equal to the pressure drop corresponding to the mean flow rate. This characteristic makes it quite suitable for measuring pulsating flows. Laminar flow meters are expensive and bulky.

The compressed air flow meter shown in Figure 2, is a device wherein array of various size critical flow nozzles are used. The specifications of the compressed air flow meter is given in Table 2. The flow through a sonic nozzle is constant for a particular upstream pressure as long as the pressure ratio across the nozzle is maintained below the critical pressure ratio of air. During the conduct of the test the compressor system is isolated from the industrial distribution network by closing outlet valve of the receiver. Then compressed air flow meter is installed in the air receiver. Compressor under test is started; nozzles in the compressed air flow meter are opened in a particular combination till rated pressure is maintained in the receiver. At this condition the flow rate of the compressor is equal to the flow through the compressed air flow meter. By comparing the compressed air flow meter readings with laminar flowmeter it is found that the error is with in 2% of FSR. Compressed air flow meter is suitable for measurement of FAD of a reciprocating compressor.

Table 0 Specifications of compressed Air flowmeter

Make	M/s Compessed Air Management Impact RM Inc., Canada
Model	LP150
Range	800cfm

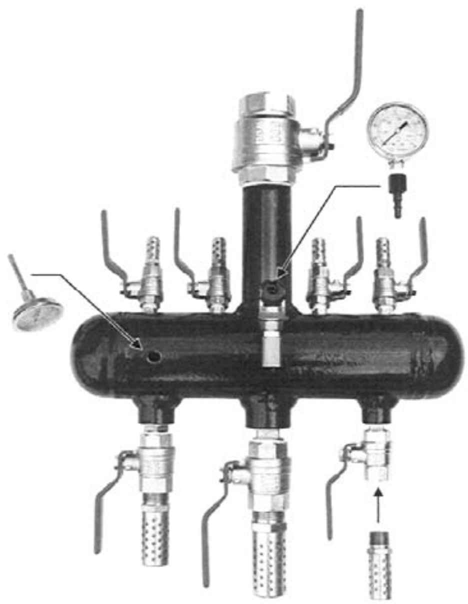

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Figure 1 Compressed air flow meter

4.2 Electrical power Measurements
Electrical power consumption of a motor can be measured insitu using portable power meters. However when motors are driven by variable speed drives, the wave forms of voltage / current are distorted. In these installations power measuring instruments which are capable of measuring power harmonics are to be used.

4.3 Mechanical Power Measurement
Mechanical power is computed from torque and speed measurements. Measuring torque of reciprocating compressors installed in industries for offline monitoring is very difficult. Standard torque transducer models that are readily available require substantial modifications to fix them on already installed compressors. An innovative installation design, shown in Figure 2, developed by the authors facilitates the mounting of torque transducer in the existing machines with little modifications. The design significantly reduces the complexities involved in mounting and removing the torque transducer in the industrial compressors. The torque transducer used for the research work is inductively powered and transmit data using telemetry.

4.4 Indicated Power Measurement
Indicated power of a compressor is computed from the p-V diagram of the compressor. In-cylinder pressure and instantaneous swept volume measurements are required for drawing p-V diagram. Dynamic pressure transducers are used for measuring in-cylinder pressure. Medium and small capacity reciprocating compressors do not have ports to mount pressure transducers. It is recommended that compressor manufacturers provide ports for installing pressure transducers in the compressors at suitable locations. These pressure transducer ports can be used for mounting pressure transducers during measurements and plugged when not needed. If the pressure transducer ports

are not readily provided in the compressor indicated port assembly as shown in Figure 3 can be used or ports can be drilled at suitable locations. A piezoresistive transducer is suitable for measurement of in-cylinder pressure. Piezoresistive transducers are preferable to piezoelectric transducers as they measure the absolute pressure directly and therefore pegging is not necessary. Moreover the temperature involved in compressors is within the operating range of standard piezoresistive transducers.

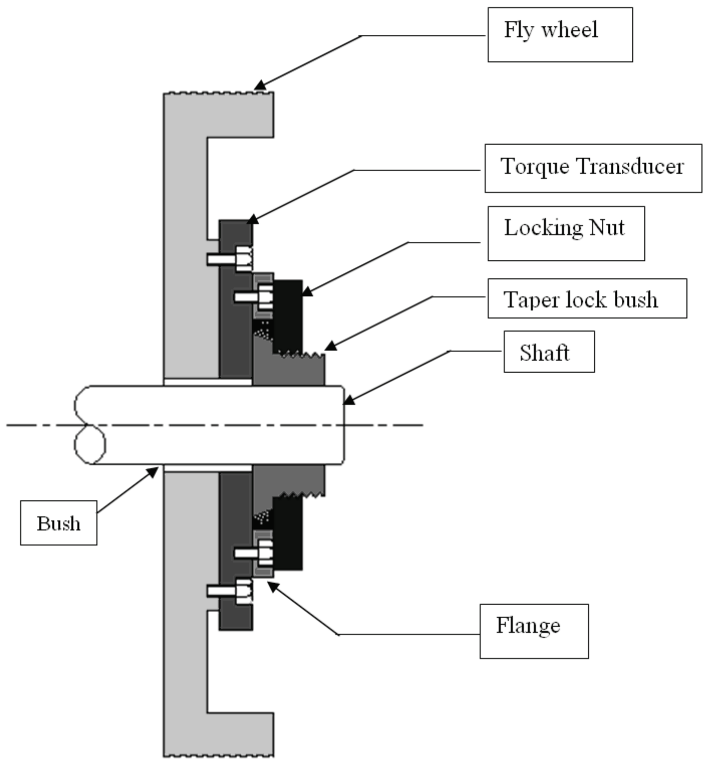

Figure 2 Mounting of Torque Transducer on the Compressor Flywheel

Figure 3 Indicator port assembly with Keine Valve

Crank angle encoders are used presently for measurement of instantaneous swept volume of reciprocating machines. The crank angle encoders are delicate devices that require special care in installation. Construction of some of the compressors does not provide access to fix crank angle encoders, some times necessitates significant modifications also. These problems render crank angle encoders unsuitable for offline monitoring of industrial compressors. Moreover the output signals from the crank angle devices are to be post processed to convert crank angle to instantaneous volume by computing kinematic relation of the slider crank mechanism used in the reciprocating compressor.

To facilitate insitu measurement of instantaneous swept volume of reciprocating compressors a new device is developed (pannir selvam *et al.,* 2004). This device shown in Figure 4 consists of a template cam and a non contact laser displacement sensor. The template cam has profile cut according to relationship between crank angle and swept volume. The cam is permanently fitted on the compressor crank shaft suitably and rotates in unison with the compressor shaft. The non contact laser displacement sensor measures the profile of the cam dynamically and provides voltage output proportional to the cam profile and therefore to instantaneous swept volume.

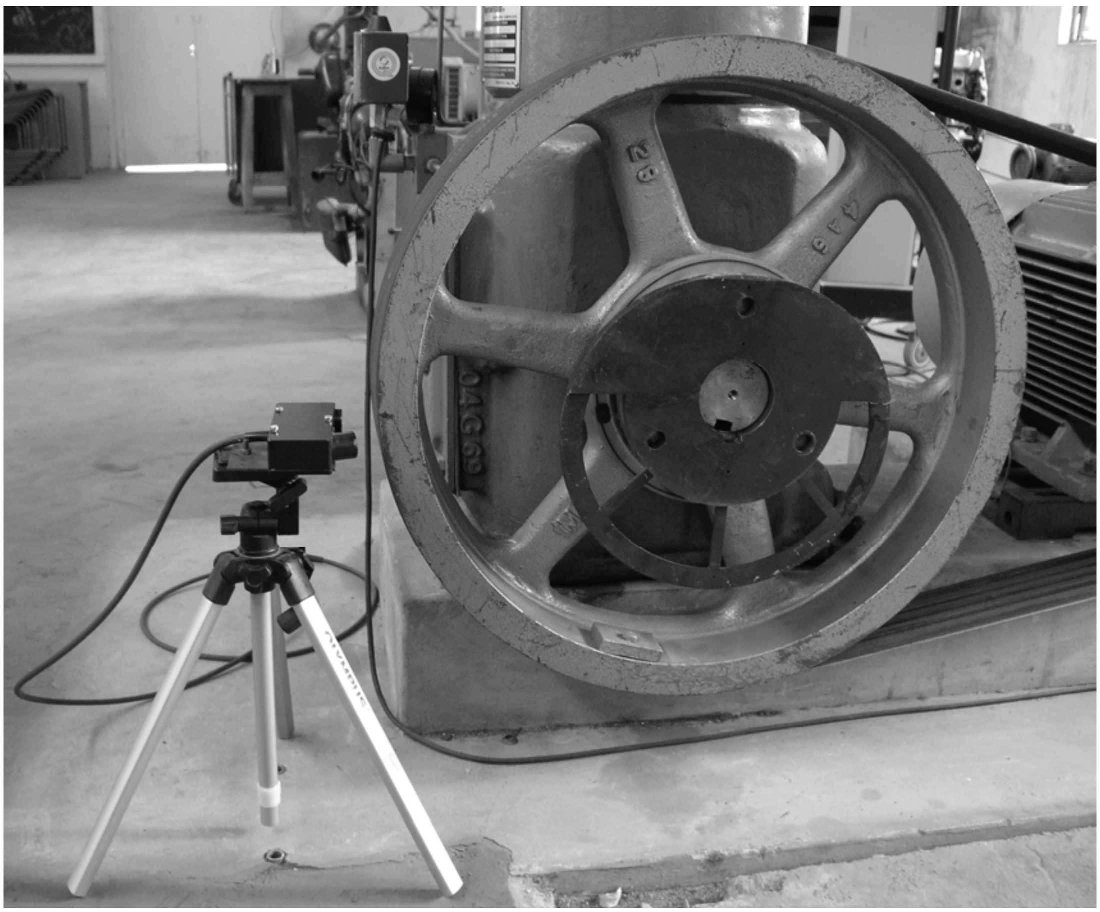

Figure 4 Instantaneous swept volume sensor installation

In industrial compressors, inexpensive template cam is permanently fitted on the compressor. When the measurement of instantaneous swept volume is needed, the laser displacement sensor is targeted on the cam. Therefore complicated installation is done away with. The device directly provides voltage analogous to the swept volume therefore post processing electronics is not necessary. An oscilloscope operated in X-Y mode gives p-V plot. In installations having multiple compressors, a single laser displacement sensor is enough to acquire the p-V diagram of all the compressors offline.
Actual and theoretical indicated power are calculated from p-V diagram by numerical integration.

4.5 Measurement of leakage rate

Leakages from a compressor system are a cause for capacity loss. For quantifying leakage rate from a compressed air system two methods are found suitable. They are pump down test method and ON-OFF time method. During leakage tests, compressor is isolated from distribution system suitably. Pump down test method quantifies the leakage by measuring time required for pressure to drop from a high level to lower level. ON-OFF time method is suitable for reciprocating compressors fitted with constant speed control. After isolating the compressor and receiver from the distribution, compressor is started and the period during which the compressor runs at loaded condition (ON time) and unloaded condition (OFF time) is noted. Since the compressor is isolated from the distribution, it runs in loaded condition only to meet the leakages in the system. The leakage rate is given as the ratio of ON time and total time. The leakage is expressed in percentage of rated capacity of compressor.

5. CONCLUSIONS

Energy cost of a compressor is approximately 75% of its life cycle costs. Performance monitoring is a valuable tool to detect performance degradation of compressor during operation. It helps to keep the energy cost in check. Even though in large reciprocating compressors online performance monitoring systems have been installed, in medium and small capacity industrial compressors installation of on line systems is not economical. In medium and small capacity compressors, performance should be monitored periodically using off-line monitoring methods. Various parameters that are indicators of the performance of air compressors are defined. It is not necessary to monitor all these parameters at regular intervals; instead it is enough to monitor vital parameter called specific power consumption periodically. If the specific power consumption valve decreases below the bench mark limit diagnostic parameters needs to be measured. Diagnostic parameters help to identify the power loss making components and airflow capacity loss making components. Various measuring techniques that are suitable for offline measurement of FAD of a reciprocating compressor, Electrical power consumption, Mechanical power consumption, Indicated power consumption and leakage rate are discussed.

NOMENCLATURE

Cfm	Cubic feet per minute	
FSR	Full Scale Reading	
FAD	Free Air Delivery	(m^3)

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