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ABSTRACT

Instrumentation and data acquisition/analysis techniques that are similar to those used for reciprocating compressors were developed and used for testing and development of a laboratory scroll compressor. The techniques feature the measurement of shaft speed and instantaneous pressures within the scroll elements in conjunction with the use of digital oscilloscopes and analysis methods for extracting detailed information regarding the compressor operating characteristics. These techniques provide knowledge regarding the type and magnitude of energy losses within the compressor that are not otherwise obvious using only traditional measurements such as EER and volumetric efficiency. As a result, the real effects of scroll compressor design variables can be unambiguously identified and used to guide testing and development activities in a timely manner.

NOMENCLATURE

d	diameter of pressure passage
l	length of pressure passage
n	polytropic exponent, data point number
s	length of transducer clearance space
w	distance of pressure passage from scroll wall
CA	crank angle
P	pressure
V	volume
W_A	available shaft work
W_C	over-compression work
W_I	indicated work
W_N	net work
W_S	under-suction work
η	efficiency

Subscripts:

0-4	transducer locations
a	condition at min. volume in compression process
b	condition at max. displacement volume
c	condition at start of discharge
D	discharge line
E	electrical
M	mechanical
S	suction line

INTRODUCTION

Compared with reciprocating compressors, the scroll compressor has a relatively short history of development. However, many of the development techniques used for reciprocating compressors and engines can be adapted to the scroll compressor. In particular, measurement of instantaneous shaft speed and pressures within the scroll elements are useful in understanding the details of the scroll compression process and its controlling parameters, and to identify problem areas. A laboratory scroll compressor has been instrumented with several dynamic pressure transducers strategically located in the compression pockets so that a fluid element can be tracked continuously from suction to discharge. The resulting measured pressure-crank angle and pressure-volume diagrams are analyzed to determine the indicated work, details of the suction-compression-discharge processes, losses during the suction and discharge processes, and regions of excessive leakage within the scroll wraps. Further analyses of this information reveals the extent to which the polytropic compression approaches an isentropic process.

These methods have been used extensively in the development of a scroll compressor that operates over a wide speed and load range. This paper describes the techniques used in proper location of the instrumentation, data acquisition and reduction procedures featuring the use of digital oscilloscopes, and analysis methods useful in extracting information to guide research and development activities. Typical data and results are presented to show the energy loss contributions due to electrical, mechanical, and gas dynamic processes.

LABORATORY PROTOTYPE COMPRESSOR

A laboratory prototype scroll compressor shown schematically in Fig. 1 was designed as a test bed for scroll compressor component development. The low-side compressor is designed with a great deal of flexibility to facilitate investigation of important design parameters such as rotational speed, suction manifold configuration, drive shaft support bearing types, orbiting scroll anti-rotation devices, and compliance techniques. In addition, many scroll element design parameters such as the wrap details, tip seals, discharge port size and shape, etc., can easily be evaluated using interchangeable parts.

Instrumentation is strategically located in the compressor to measure and monitor temperatures and pressures in critical locations. Temperature measurements include refrigerant suction and discharge, oil, bearing housings, motor stator, and temperature rise of refrigerant due to heat rejection from the drive motor. Pressure measurements include refrigerant suction and discharge, and instantaneous pressures within the scroll elements. Provisions are included to measure both instantaneous and average shaft speed using magnetic sensors. Further discussion of the pressure measurements in the scroll elements is given below.

DYNAMIC DATA ACQUISITION/REDUCTION SYSTEM

The principal components of the dynamic data acquisition/reduction system are shown schematically in Fig. 2. The system features the use of four hermetically sealed piezoelectric pressure transducers and a four-channel digital oscilloscope that is interfaced with a laboratory computer and peripheral equipment. A magnetic position sensor is used in conjunction with a shaft-mounted single-tooth gear to provide an angular reference position and to trigger the oscilloscope. A second sensor is used in conjunction with a multi-tooth gear to provide instantaneous angular position information.

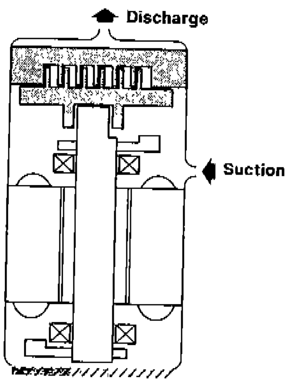

Fig. 1 Laboratory Scroll Compressor

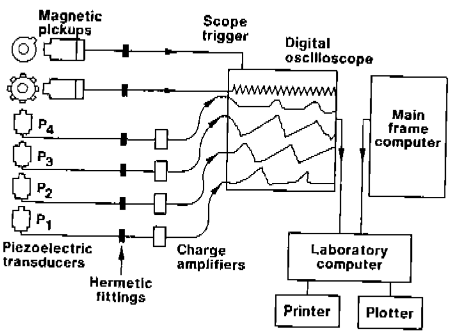

Fig. 2 Instrumentation/Data Acquisition System

The four piezoelectric pressure transducers are located in the fixed scroll such that the compression process associated with a given fluid element can be followed from suction to discharge. These transducer locations are labeled 1-4 in Fig. 3. Unlike a reciprocating compressor, several transducers are required because a given transducer location will be exposed to the compression process associated with a given fluid element for only a portion of the compression cycle. A reference pressure for the transducer closest to the suction plenum (no. 1 transducer) is established by an independent measurement of the suction plenum pressure (location 0 in Fig. 3) during a period of time in the suction process when both locations are exposed to the same pressure. The relative position of the fixed and orbiting scrolls at this time is shown in Fig. 4-a. Subsequently, a reference pressure is established for the no. 2 transducer during the period of time when both the no. 1 and no. 2 transducers are exposed to the same pressure (Fig. 4-b). This process is continued in a similar manner for the no. 3 and no. 4 transducers as shown in Figs. 4-c and 4-d respectively.

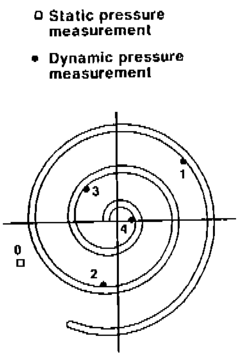

Fig. 3 Pressure Measurement Locations in Fixed Scroll

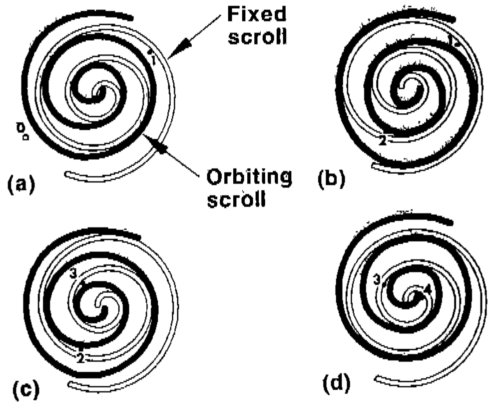

Fig. 4 Scroll Position for Transducer Reference Pressures

A typical piezoelectric pressure transducer installation in the fixed scroll element is shown in Fig. 5. In order to locate a small pressure port at a precise location in the scroll, the transducers were slightly recessed from the compression surface as shown. A short passage of length (l) and diameter (d) was used to sense the scroll pressure and a very small volume was present below the transducer diaphragm by virtue of the small clearance distance, (s). These are critical dimensions for such an installation since they determine the natural frequency of the passage. In general, it is desirable to minimize (l) and (s) and to maximize (d) to increase the passage natural frequency to values well above the expected frequency spectrum of the measured pressures. Conversely, the passage natural frequency should be kept well below the resonant frequency of the transducer. Organ pipe and/or classical Helmholtz theory can be used to design an acceptable passage as discussed in detail in Refs. 1, 2, and 3. Another transducer location parameter is the distance of the sensing passage from the scroll wall (distance (w) in Fig. 5). This distance must be small to maximize the crank angle over which the transducer is active, but must not be so close to the scroll wall as to introduce wall interference effects.

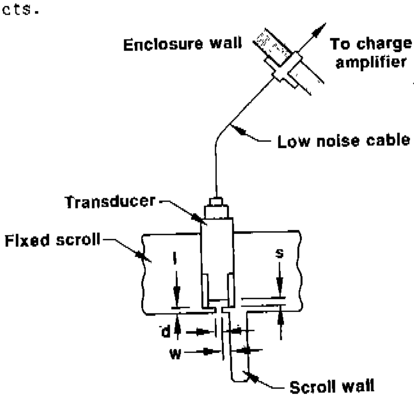

Fig. 5 Typical Transducer Installation

Typical oscilloscope pressure vs. time waveforms measured with this system are shown in Fig. 6. Note that the transducers have been positioned such that an adequate overlap period exists between the time when a transducer signal becomes active (ex: no. 2 transducer) and the time when the signal from the previous transducer (ex: no. 1 transducer) is lost because of the scroll wall interference. This time interval prevents transient errors in referencing due to the rapidly changing pressures when a transducer port is covered and uncovered by the scroll wall. The repetitive, overlapping nature of the scroll compression process is clearly shown; two complete compression cycles and portions of two others are shown in Fig. 6. The oscilloscope time base can be changed over a wide range so that more digitized data points are concentrated during a single compression cycle. Conversely, numerous cycles can be captured to monitor cycle repeatability. The measured waveforms (voltage vs. time) are stored in the oscilloscope memory and on floppy disks in digital format. This information is subsequently transferred to the laboratory computer for data reduction and analysis.

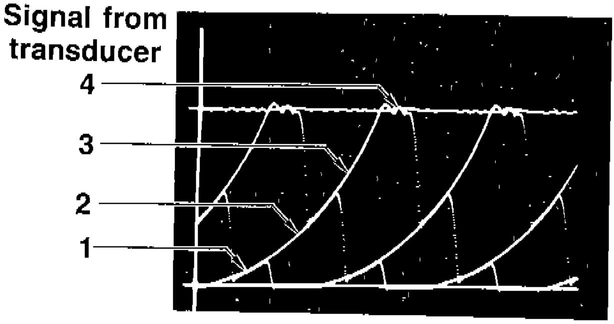

Fig. 6 Typical Pressure Waveforms

The signals from the magnetic position sensors are also stored and transferred in a similar manner. Knowing the reference crank angle from the single tooth signal and the angular increment from the multi-tooth signal, a relationship is established between each digitized data point and the crank shaft position. Subsequently, analytical expressions describing the general relationship between crank angle and volume within the scroll compression chambers are used to relate the measured pressures to the local compression volume. Thus, data files are created for subsequent data analyses and for storage on hard disk.

DATA ANALYSIS

Knowledge of pressure versus volume characteristics in scroll compressors can be an extremely useful tool in analyzing the compression process. Many of the techniques that have been developed for other displacement type machines such as reciprocating compressors and Otto cycle engines can be utilized. A typical pressure-volume diagram for a scroll compressor is shown schematically in Fig. 7. The cycle is initiated as the refrigerant enters the compression pockets during the suction process as the volume of the pockets increases from the minimum volume (V_a) to the maximum displacement volume, (V_b). For scroll compressors, the mimimum volume is approximately zero. Typically, the pressure in the compression pockets during the suction process is slightly lower than the suction line pressure, P_s, as shown in Fig. 7. This suction under-pressure characteristic is an energy loss since additional work must be done to re-compress the refrigerant to the suction line pressure. The under-suction work is calculated from:

$$W_S = \int_{V_a}^{V_b} (P_S - P) \, dV \qquad (1)$$

Additional details regarding the suction process are contained in Ref. 4.

At this point, the pockets are sealed and the cycle proceeds as the refrigerant is compressed to the volume V_c. Discharge of the compressed refrigerant starts to occur at V_c and continues until the final residual volume, V_a, is attained. Under certain conditions compression continues to occur during the discharge process as shown in Fig. 7. This represents an over-pressure situation (relative to the discharge line pressure P_D) and is considered an energy loss, since work is done on the gas that must be "given back" during the discharge process. This over-compression work is calculated from:

$$W_C = \int_{V_a}^{V_c} (P - P_D) \, dV \qquad (2)$$

The net useful work on the refrigerant is then:

$$W_N = \int_{V_c}^{V_b} (P - P_S) \, dV + \int_{V_a}^{V_c} (P_D - P_S) \, dV \qquad (3)$$

and the total or indicated work is:

$$W_I = W_S + W_C + W_N \qquad (4)$$

Thus integration of various portions of the indicator diagram reveals how much of the total available shaft work is actually imparted to the refrigerant, i.e., indicated work, and how much of that work is of net use, i.e., net work.

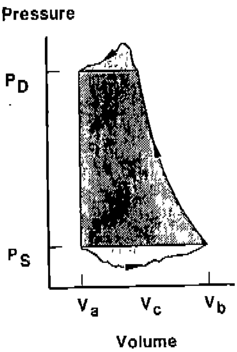

Fig. 7 Pressure/Volume Diagram

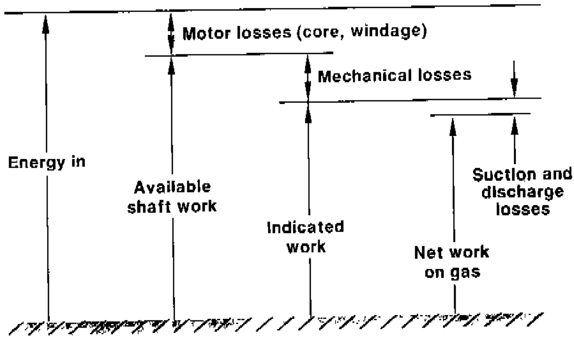

Fig. 8 Energy Accounting

Furthermore, if one has knowledge of the drive motor efficiency, η_E, at the actual test conditions, an energy accounting system can be constructed as shown in Fig. 8. In this accounting system, the electrical energy supplied to the compressor (Energy In) is measured directly with an independent meter. The available shaft work, W_A, is then:

$$W_A = \eta_E \cdot \text{Energy In} \qquad (5)$$

The total or indicated work actually imparted to the refrigerant is taken from Eq. (4) and thus the compressor mechanical efficiency can be calculated as:

$$\eta_M = \frac{W_I}{W_A} \qquad (6)$$

and the indicated efficiency is:

$$\eta_I = \frac{W_N}{W_I} \qquad (7)$$

TYPICAL DATA

The data acquisition/reduction/analyses methods discussed above have been used successfully to identify and correct problems during compressor testing and development activities. Examples of typical data generated with the laboratory scroll compressor are presented in Figs. 9-11.

A typical pressure-crank angle relationship generated from experimental measurements is shown in Fig. 9. Also shown for comparison is the predicted relationship obtained from a computer simulation of the scroll cycle. In general, the agreement between predicted and measured pressures is very good and lends credence to both the measurement techniques and the computer simulation, Ref. 5.

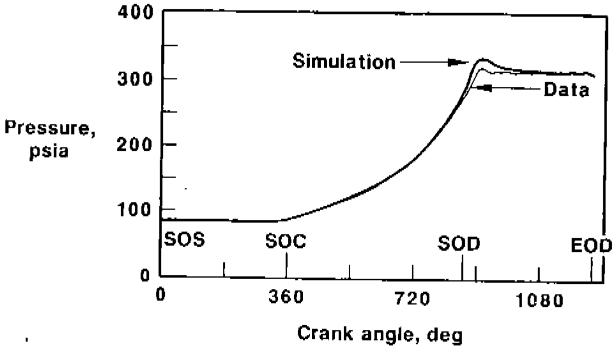

Fig. 9 Pressure/Crank Angle Diagram

A typical pressure-volume diagram constructed from experimental data is shown in Fig. 10a. These data are also plotted using logarithmic coordinates in Fig. 10b. If the scroll compression process is assumed to be polytropic, i.e.

$$\frac{P_c}{P_b} = \left(\frac{V_b}{V_c}\right)^n \tag{8}$$

Then

$$\log\left(\frac{P_c}{P_b}\right) = n \log\left(\frac{V_b}{V_c}\right) \tag{9}$$

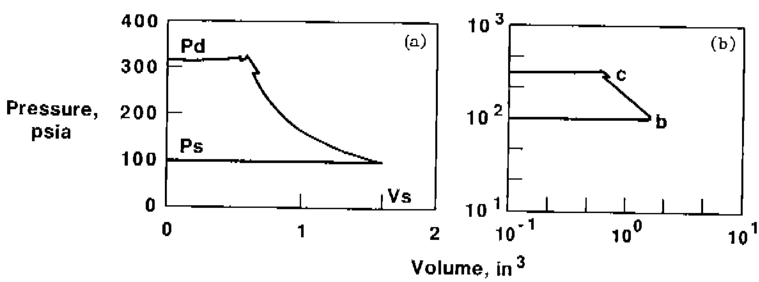

Fig. 10 Pressure/Volume Data

Thus, the polytropic exponent, n, is numerically equal to the slope of the line c-b in Fig. 10b. This is a very useful method of data analysis since it can reveal certain problems in the scroll compression process that would not otherwise be obvious. For instance, a compression line that is not straight could be an indication of excessive internal leakage in certain regions of the process. Likewise, a line that is straight but has a very high slope (n) could be an indication of excessive leakage throughout the process, i.e., heating of the refrigerant due to re-circulation pumping. If problems are apparent, a more detailed view of the process can be taken by calculating local polytropic exponents in certain regions of the cycle rather than the overall value alluded to above.

Presented in Fig. 11 are power distribution data in accordance with the accounting system shown in Fig. 8. Note that in Fig. 11 power is used in the accounting system rather than energy. Fig. 11a shows this distribution for a scroll compressor operating at a constant input drive frequency of 90 Hz and 45 deg. F saturated suction conditions for various saturated condensing temperatures. Likewise, the distributions shown in Fig. 11b are for a scroll compressor operating at the ARI condition over a range of drive frequencies. Other parameters such as various efficiencies and polytropic exponents can be presented in a similar manner. The real effect of many compressor design parameters previously alluded to can be determined unambiguously when data are analyzed in this manner.

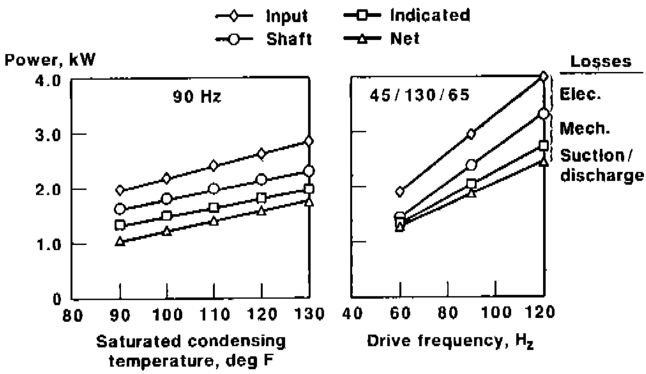

Fig. 11 Power Distribution Data

CONCLUSIONS

An on-line data acquisition/reduction system that is similar to those used for reciprocating compressors has been developed and used very effectively for scroll compressor testing and development.

Knowledge of the type and magnitude of energy losses (i.e., electrical, mechanical, gas dynamic, etc.) that can be acquired using these methods is extremely valuable when used in conjunction with traditional independent measurements of EER and volumetric efficiency.

Using the instrumentation and data acquisition/analyses techniques described, the effects of important design variables can be evaluated in detail and used to guide further development activities in a timely manner.

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