1978

Some Aspects of Laboratory Testing of Two-Stage Reciprocating Compressors

K. Hanjalic

N. Stosic

Hanjalic, K. and Stosic, N., "Some Aspects of Laboratory Testing of Two-Stage Reciprocating Compressors" (1978). *International Compressor Engineering Conference.* Paper 282.
https://docs.lib.purdue.edu/icec/282

SOME ASPECTS OF LABORATORY TESTING OF TWO-STAGE RECIPROCATING COMPRESSORS

Kemal Hanjalić and Nikola Stošić
Mašinski fakultet
and
Institute of Thermal Engineering ITEN-Energoinvest
Sarajevo, Yugoslavia

ABSTRACT

The dynamic testing of a two stage reciprocating air compressor with inter- and after-cooling during the steady and transient state operation is reported and the encountered problems discussed. Measurements and recordings of the instantaneous temperature and pressure in cylinders, suction and discharge chambers and in the associated pipework and air-coolers were carried out together with the instantaneous torque on the compressor shaft. Specific account is given to the selection and calibration of adequate types of measuring transducers that would possess the desired dynamic characteristics, but also meet the mounting and strength limitations encountered in particular in case of testing of small compressors.

INTRODUCTION

The measurements of the instantaneous thermodynamic and dynamic variables in reciprocating compressors impose specific requirements upon the types and characteristics of the measuring transducer in spite of the fact that the basic frequency of the cyclic thermodynamic process occurring in the compressor is in the range of only several ten's of Hz. High frequency oscillation of the self-actuated reed valves, commonly used in small compressors together with the pressure wave propagation and the associated sharp crests in temperature- and pressure-time profiles require instruments that possess broad frequency response and small signal distortion. In case of small compressors, mounting the transducers within the available space poses additional difficulties as well as limitations upon the choice of the adequate instruments.

TEMPERATURE MEASUREMENTS

Thin wire based transducers such as the resistance thermometers and thermocouples seem to be most frequently used for measurements in reciprocating compressor installations although their dynamic performances are generally inferior to those of optical or sonic temperature sensing devices. The convenience of direct application to the measurements in real compressors in spite of limited space avaiable for mounting seems to be the guiding advantage of the wire transducers in comparison with optical and sonic methods which often require the use of specially designed model engines. The required dynamic response could be achieved if the wire thickness is sufficiently small. However, the periodic changes of the mechanical stresses in the wire, resulting from the intermittent nature of the basic thermodynamic process as well as the practical difficulties in connecting the sensing wire with the extension or compensating leads of considerably larger diameter enforces the lower limit on the wire thickness. Measurements reported here were performed by means of Cr-Al micro-thermocouples. The thermocouples were chosen in preference to the resistance thermometers because the later require larger wire to achieve the same sensitivity in order to eliminate the ends influence. Among various wire diameters tested 12.5 microns was finally selected as the compromise between the required mechanical durability and the acceptable dynamic sensitivity.

The thermocouple response can be estimated from the standard equation which defines the instantaneous energy balance of the thermocouple heads (with the radiation heat exchange between the thermocouple and the surrounding gas neglected):

$$\frac{\partial T_w}{\partial t} = \frac{4\ \alpha}{\rho c D}\left(Tg - \beta\frac{v^2}{c_p} - T_w\right) - \frac{4\sigma\varepsilon}{\rho c D}\left(T_w^4 - T_s^4\right) + \frac{\lambda}{\rho c}\frac{\partial^2 T_w}{\partial x^2} \tag{1}$$

The above equation can be solved numerically to yield the required gas temperature Tg sensed by the wire, if the heat transfer coefficient $\alpha(x,t)$ and the wire temperature $T_w(x,t)$ distributions along the wire are known, together with the temperature of the surrounding wall T_s and other coefficients appearing in the equation.

In order to obtain some indications about the actual response of the thermocouple in unsteady conditions and the influence of various effects upon it such as different heating and cooling rates and times, here the opposite task was undertaken; that is to calculate the wire temperature T_w while the gas temperature Tg was simulated to represent closely a typical temperature-time record in a compressor cylinder.

For this purpose the equation (1) was simplified by neglecting the kinetic heating term as well as terms representing the heat exchange due to radiation and conduction. Thus only the convective heat transfer term was retained, in addition to the rate of change of internal energy of the thermocouple, the equation (1) being reduced to the ordinary time dependent differential equation. The neglected effects were accounted for through static errors, evaluated for each effect separately.

Heat transfer coefficient was evaluated from the standard relationship of the form $Nu = C\ Re^m$, where constant C and the exponent m were assigned values of 0.89 and 0.33 respectively as recommended by Hilpert for the Re number ranging from 0.63 to 3.4. Because of uncertainty in evaluating the gas velocity in the cylinder around the thermocouple head, the values between 2 and 10 m/s were tested, but due to the small values of the exponent m, the influence of gas velocity in the considered cases appeared to be small.

The gas temperature simulation was based upon the experimental results: expansion and compression processes were represented by polytropic curves obtained from pressure records and cylinder volume calculated from the kinematic relationships, while the suction and discharge processes were represented by linear temperature changes. With these assumptions, the actual thermodynamic process was highly simplified, but the temperature profile obtained served as a good qualitative representation of the actual process for the purpose of evaluating the thermocouple response to the periodic signal which is generated in a compressor cylinder. Results are given in Fig. 1, where the modelled gas temperature is shown together with the calculated thermocouple temperature for two values of the gas velocity, 2 and 10 m/s, and for two wires, 12.5μ and 100μ in diameter.

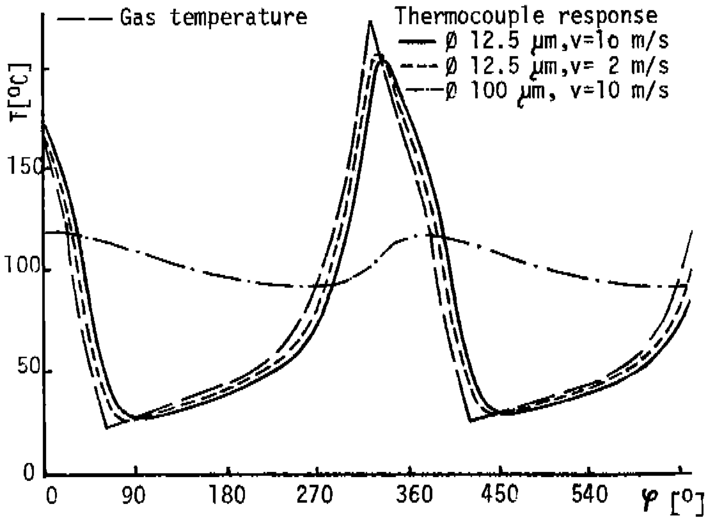

Fig. 1 Modeled gas temperature and thermocouple response

The results show that the 12.5μ diameter thermocouple follows the gas temperature closely and could be accepted for practical use, particularly at higher gas velocities. The largest discrepancy occurred at the peak temperature, where the thermocouple shows a temperature 12°C lower than the actual gas temperature. These results confirm the earlier conclusion that the influence of the wire diameter is predominant. The thermocouple with wire diameter 100μ showed a very poor response: the difference between the maximum and minimum temperature was only 25°C whereas the actual difference was more than 200°C. An experimental temperature-time record in the cylinder of the compressor used, showed reasonably good agreement with the modelled temperature, as shown in Fig. 2.

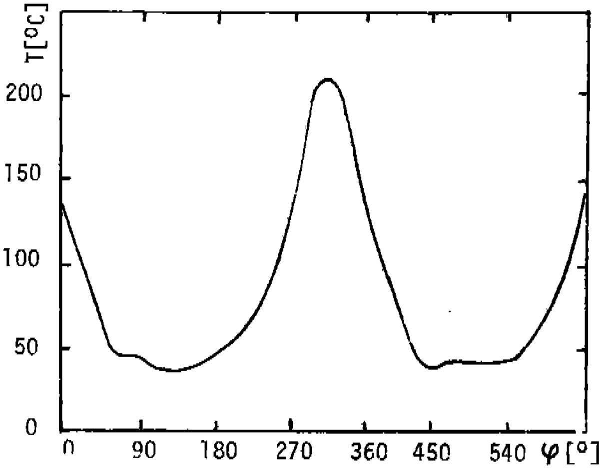

Fig. 2 Thermocouple record of the gas temperature in cylinder (12.5 μm)

In order to verify the thermocouple time constant and evaluate experimentally its frequency response, the dynamic calibration of the thermocouple was performed using the method suggested in reference [10]. A strong light source with a system of mirrors and lenses and an orifice, served as a radiation heat source. Between the light source and the thermocouple a rotating perforated disc was placed. The rotational speed of the disc was recorded firstly with a photo-cell and later with an inductive type transducer. The ratio of the thermocouple signal amplitudes at a certain disc speed to the steady signal gave directly the amplitude-frequency characteristics of the thermocouple, Fig. 3.

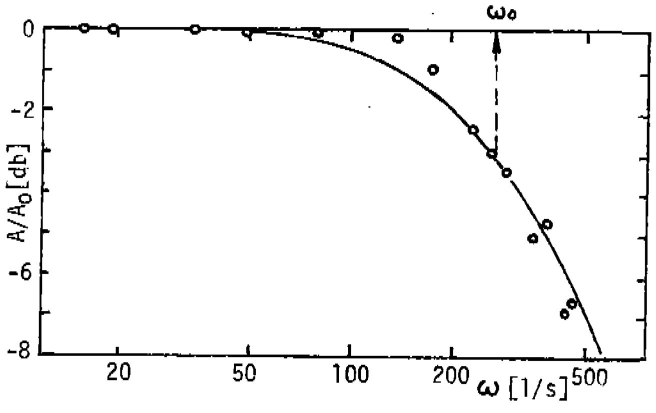

Fig. 3 Thermocouple amplitude response

Experimental results, presented in the form of the logarithmic amplitude response, followed qualitatively the form of the first order characteristics so confirming the assumption implicit in equation (1). The intersection of the asymptotes corresponds to an amplitude fall of about 3 db, and this value gives the angular frequency of ω_0=250 rad/s (f=40Hz). This frequency corresponds to a time constant value of τ=4 ms. The direct evaluation of the time constant derived from the simplified form of the equation (1) as $\tau=\rho cD/4\alpha$ yields values of 4.88 and 2.85 ms for gas velocities of 2 and 10 m/s respectively, showing a good agreement with the above evaluated value of 4 ms, which corresponds roughly to the gas velocity of 6 m/s.

The above analysis and the results obtained indicate that the thermocouples used can follow only about the first 3 to 6 harmonics of the temperature fluctuations in a typical reciprocating compressor, considering that at 1000 rev/min the basic frequency is 16.7 Hz. Higher harmonics would require the use of smaller diameter wire and would pose substantial practical problems.

PRESSURE MEASUREMENTS

The pressure records in cylinders and interconnecting elements supply usually the fundamental information needed for the estimatation of the compressor overall performances as well as the details of the valve functioning and pressure wave propagation. Various types of pressure transducers have been used for measuring the instantaneous pressure. Because of high frequencies and low amplitudes, the measurements of pressure pulsations in suction and discharge chambers is frequently accomplished with the transducers whose dynamic characteristics differ from those which are generally used for the recording of the cylinder pressure.

Diaphragm transducers have the widest application for measuring unsteady pressures, both absolute and differential, but their use in reciprocating compressors is somewhat limited by their large dimensions, which prevent mounting them directly at the place where the pressure is to be measured. External mounting with a connecting channel, with its own dynamic characteristics, may result in serious errors. Piezoelectric transducers have been frequently used for pressure measurements in I.C. engines, being suited for measurements of high frequency and high amplitude pressure pulsations. Their attractive feature is the high mechanical impedance resulting in a low energy consumption, as well as high natural frequency. This latter feature is of particular use in the present application where even fortieth and higher harmonics may contribute to the final form of the pressure diagram. Furthermore, because of the high inlet impedance there is no need for external feedback elements, enabling the manufacture of compact transducers of miniature dimensions. The main shortcoming of the piezoelectric transducers is the high output impedance and the lack of response to a steady signal. The lack of response to a steady signal poses difficulties if the absolute pressure, e.g. the intermediate pressure in a two-stage compressor, is to be measured. This difficulty can be overcome by use of special adapters with fast-acting valves which permit rapid connection with the atmosphere or some other known reference pressure [9].

In the present work two types of pressure transducers have been used: the "Kistler" piezoelectric, and the "Disa" capacitive diaphragm-type transducer. Because of the small gas velocities and fairly uniform pressure distribution within the cylinder, the pressure measurements could be performed anywhere in the cylinder, but the transducer mounting is restricted by the compressor geometry. The cylinder head and the valve body usually serve best for this purpose. In spite of small compressor dimensions, a piezoelectric transducer was successfully mounted within the valve body enabling direct contact of the transducer with the space concerned. However, the capacitive transducer was mounted externally, its diaphragm being connected with the cylinder via a connecting passage drilled through the valve body and the connection lead through the cylinder head. This channel must affect the dynamic characteristics of the transducer. In order to evaluate the effect of the connecting passage, an approximate analysis was performed and the results compared with the measurements obtained by the piezoelectric transducer with no such passage. Assuming the pressure changes to be small, and regarding the system as being of the lumped parameter type (justified if the channel length is short compared with the wave length of fluctuating pressure) the channel behaviour may be represented by a second order linear dynamic system. The analysis showed that a large volume of connecting passage improves its dynamic characteristics, introducing smaller measuring error. However, the presence of the connecting passage necessarily increases the compressor clearance, which has several well known undesirable effects. In order not to increase excessively the compressor clearance, the pressure channel should be kept as small as possible, which is contrary to the earlier defined requirements for better dynamic characteristics. The pressure channel was selected to have the shortest possible length. Its maximum natural frequency was evaluated and the pressure measurements compared with those obtained by the piezoelectric transducer.

Pressure recording was performed with both piezoelectric and capacitive transducers in the cylinders, suction and discharge chambers and pipe systems of several types of reciprocating compressor. Fig. 4 shows the comparison of the pressure record in the first and second stage cylinder of a two-stage compressor, obtained by piezoelectric and capacitive transducers. To obtain at least an approximate level of the absolute pressure with the piezoelectric transducer, only the first record, obtained immediately after starting the transducer from rest (before the electric charge had drifted) was used. Results indicate noticable, although not excessive differences between the two records. Some small differences could be expected due to the variation of the ambient and working conditions, since the measurements had not been taken simultaneously. However, even if the differences in the expansion and compression lines could be regarded as acceptable, the suction and discharge periods differ considerably. Both transducers record some pressure oscillations during these periods (generated by the valve movement) but the record obtained with the capacitive transducer shows in all cases considerably higher amplitudes. Since the basic frequency of the pressure oscillations is about 0.5 kHz, they should be recorded equally well by both transducers, considering that their frequency response span up to 20 kHz. Perhaps the excessive amplitudes of the pressure oscillations recorded by the capacitive transducer could be ascribed to the effect of the connecting passage. The calculated natural frequency of the passage was about 800 Hz which is close to the fundamental frequency of the pulsating pressure, yielding near resonant conditions. With a value of damping factor $\xi = 0.03$ there may have been considerable amplitude amplification as well as phase shift. Substantial changes in the connecting passage dimensions were not possible considering the dimensions of the compressor and the transducer, and the records obtained with the piezoelectric transducer were taken as the more reliable. However, the capacitive transducer records served to determine the reference pressure, repairing this deficiency of the piezoelectric transducers.

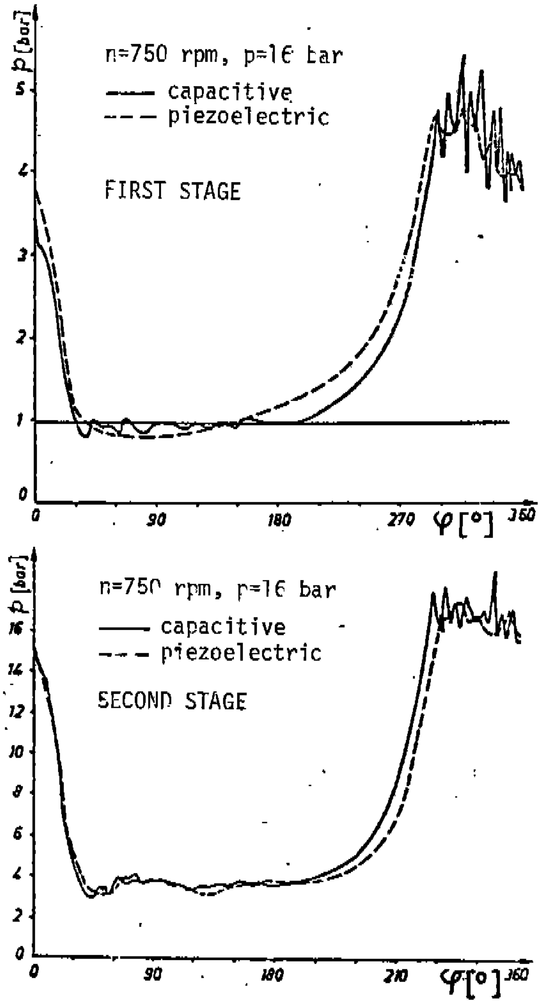

Fig. 4 Pressure-crank angle records in cylinders

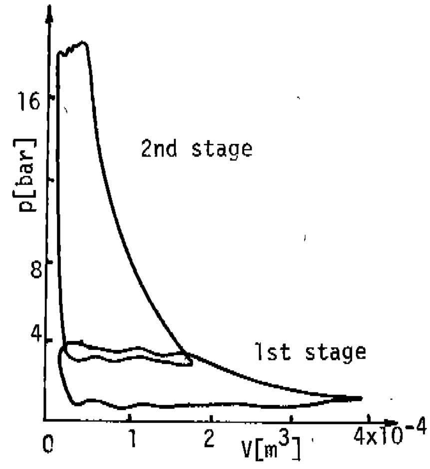

Fig. 5 Pressure-volume diagram

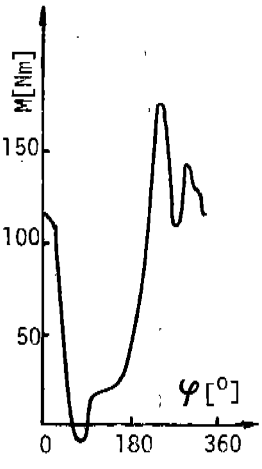

Fig. 6 Torque-crank angle diagram

TORQUE MEASUREMENTS

In order to evaluate the compressor shaft power and gain some further insight into the dynamics of the moving components of the compressor, torque measurements were made. Several types of torque transducers were used including a self made strain gauge transducer with sliding copper rings for signal transmission. The most satisfactory results were obtained with the commercially available inductive contactless transducer "Vibrometer", which enabled the instantaneous torque to be measured with good accuracy. The recording of the instantaneous torque proved to be especially useful for the investigation of the transient dynamic behaviour of the compressor, in particular during the initial starting period, when the shaft torque reached a value several times higher than that at steady conditions. Some difficulties with respect to the signal repeatability were experienced initially, when variable speed transmission was used to vary the compressor speed at the constant speed of the driving electrical A.C. motor. It was found later that the flexible belt-type transmission gear variator "Flender" was the source of the torque oscillations, the frequency of which was different from that due to the compressor speed. Consequently the measured signal was gradually changing from one cycle to another. When the compressor was connected directly to the A.C. motor, the recorded signals were repeatable. A typical record of the torque variation as a function of crank angle during a single cycle of a two-stage two-cylinder reciprocating compressor with cranks of the LP and HP cylinders displaced by 90°, is shown in Fig. 6 for the steady state operation. The integral under the curve yielded the average torque and shaft power that differed only by 3% from the shaft power evaluated by measurement of the driving motor electrical power consumption and the available data for the motor efficiency.

CONCLUSIONS

Some experience of laboratory measurements and computer simulation of reciprocating compressors has been reported. The application of the microthermocouples for measuring the instant temperatures in cylinders and other elements of the compressors yielded satisfactory results, but also indicated the limitations of the use of wire-based thermometers of transient measurements in reciprocating compressors. For pressure measurement in small compressors the piezoelectric transducers appeared to be most suitable because their small and compact dimensions enable flush mounting. Some experience with the externally mounted capacitive transducers and the influence of the interconnecting channels upon the transducers dynamic response has also been discussed.

REFERENCES

1. Benson, R. S. and Brundrett, G. W., "Development of a Resistance Wire Thermometer for Measuring Transient Temperatures in Exhaust Systems of Internal Combustion Engines", Temperature, its Measurements and Control in Science and Industry, Vol. 3 (1962) 631-653.
2. Boiten, R. G., The Mechanics of Instrumentation", Proc. Instn. Mech. Engrs. London, 177 (62-69), 1963.
3. Böswirth, L., "Messungen an einem Schellaufenden Kolbenverdichter", Konstruktion, 26, (143-151), 1974.
4. Davies, P.O.A.L., "Measurement and Recording of Transient Pressures in Unsteady Flow", Proc Inst. Mech. Eng., 1966.
5. Doebelin, E. O., "Measurement Systems: Application and Design", McGraw-Hill, 1966.
6. Hanjalić, K. and Stošić, N., "On the Measurements of the High Frequency Pressure Oscillations in Reciprocating Engines", (in Serbocroat), Symp. JUREMA, Zagreb (1975).
7. Hanjalić, K. and Stošić, N., "Application of Microthermocouples to the Measurements of the Instant Temperature in Reciprocating Engines", (in Serbocroat), Symp. JUREMA, Zagreb (1975).
8. Leah, A. S., Booth, E. P., and Rounthwaite, C., "Double Wire Method of Resistance Thermometry in Gaseous Explosions", Fuel, Supl. (1955), 59-70.
9. Martini, K. H., "Messung van Geswechselvorgangen an Brennkraftmaschinen", Technische Rundschau Sulzer, 1963.
10. Pišlar, V., et al., "Determination of Microthermocouple Dynamic Characteristics", Int. Seminar on Heat and Mass Transfer, Hercegnovi, (1969).
11. Stankewitch, L., "Messung Schnellveranderlidhen Gastemperaturen und Gasgeschwindigeiten an einem Zweitakt Dieselmotor", VDI-Forschungsheft 521, (1968).