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RATING AND DIAGNOSTIC PARAMETERS FOR HIGH-SPEED, RECIPROCATING-PISTON AIR COMPRESSORS

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ABSTRACT

This paper documents the potential of using rating parameters of reciprocating air compressors as effective service diagnostic tools.

One hundred twenty compressors were tested and the pressure ratio and capacity correlations defined for volumetric efficiency, specific effective power inputs, and overall isothermal and isentropic efficiency for groups of designs. All of these parameters have been found suitable for the diagnostics of operation and the rating of new machines.

The results of these experimental studies have been used to develop a bank of design data by analyzing and comparing the designs of over 1400 compressors worldwide. More recently, we investigated the possibility of using these results to define easily identifiable changes in operating parameters to judge the compressor state in service. Such diagnostic elements were defined based on the rating parameters and used for developing operating standards to assess air compressor oil consumption, piston ring leakages, and valve leakages. The application of this work to the diagnosis of valve leakage is discussed in this paper.

INTRODUCTION

It has been recognized that the compressor industry benefits from rating its designs before service personnel, the consumer, and the market cast their ballots. The Compressor and Refrigeration Department of the Czech Technical University in Prague, Czechoslovakia, took a fresh approach to this issue and set out to rate the interindustry progress in compressor design quality. We first studied the possibility of defining the design rating parameters and decided to test the value and practicality of our method first on groups of high-speed, piston air compressors. This experimental work of several years, based on measurements of about 120 compressors manufactured in Czechoslovakia, yielded sets of parameters pertaining mainly to energy consumption and capacity and allowed relative rating of similar designs.

As an added benefit, these parameters were found to be useful as diagnostic operating parameters in judging the condition of a machine. This paper describes the results obtained when the developed rating parameters were used for diagnostic purposes.

DEVELOPMENT AND USE OF PARAMETERS

In the following sections, the rating and diagnostic parameters that were identified as applicable are defined, their development summarized, and an example of their use described. Although this is only an abbreviated summary of practical applications yielded by the overall work, it documents the value of developing generalized data for the compressor industry. For example, our experimentally generated data allowed assessment of design trends when we compared about 1400 varied compressors manufactured worldwide. In that context, it would be appropriate to develop and use similar techniques for assessing the progress of the more recent trend of developing rotary, positive-displacement concepts. Also, the diagnostic value of the parameters should not be overlooked; they offer the operators a simple means for watching over the operating cost savings.

Developing Rating Parameters

Manufacturers can experiment with various parameters to judge the quality of their compressor designs. Often, these parameters are difficult to define analytically, particularly when they depend heavily on the manufacturer's compromise between its design/technological tradition and production capabilities and the given machine operating parameters. To avoid this difficulty in defining the parameters theoretically, we decided to select, define, and develop only those for which data could be developed experimentally. The three parameters used for the purposes of this presentation, coincide conveniently with those used as individual machine design characteristics: the total volumetric efficiency (capacity factor) λ_d, specific effective input P'_e, and total isothermal efficiency η_{cit}. The mean piston speed c_s is also used, as a reference parameter.

We analyzed the designs of and tested 120 single- and two-stage air compressors of current Czechoslovak production. Most of the compressors were lubricated and air-cooled; however, the tested group included several non-lubricated and water-cooled designs.

The general testing conditions were maintained as follows:

- Ambient air temperature (and that of the air inlet in the suction filter), 20° to 25°C
- Steady crankcase oil temperature (depending on compressor type), 60° to 80°C
- Cooling water inlet temperature (for water-cooled compressors), 15° to 20°C.

Individual parameters were reduced as functions of the theoretical capacity Q_t, characteristic to the individual compressor group, and as functions of the pressure ratio. Graphically represented parameters of total volumetric efficiency include reference to the range of respective mean piston speed c_s as well.

A linear regression technique was used to reduce the results of evaluation for the practical range of pressure ratios, and the final results were correlated by the least-squares method.

Examples of the functional results of developed rating parameters are presented graphically in Figures 1 through 3.

The individual rating parameters are defined as follows:

Total volumetric efficiency is given as:

$$\lambda_d = \frac{Q}{Q_t} \cdot 100 \ [\%]$$

where:

$Q = [m^3/h]$ = the real compressor capacity, measured by an orifice or bobbin flow meter

$Q_t = 360\ S_1 L\ n\ [m^3/h]$ = the theoretical compressor capacity

$S_1\ [m^2]$ = the total area of first-stage pistons

$L\ [m]$ = the piston stroke

$n\ [rps]$ = the compressor speed.

Specific power input is given as:

$$P'_e = \frac{P_e}{Q} \ [W/(m^3h^{-1})]$$

where P_e is the effective power input given by:

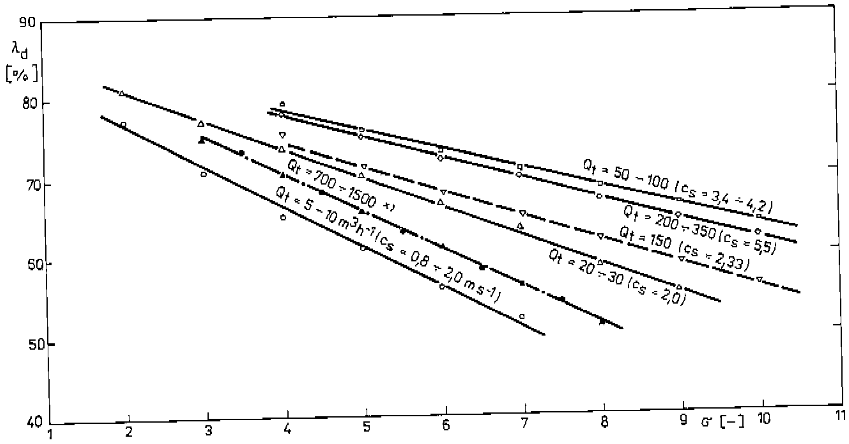
$P_e = M_t \cdot \omega\ [W]$, or calculated indirectly by using the input of electric motor as:

$P_e = P_{mot} \cdot \eta_{mot} \cdot \eta_p\ [W]$

where:

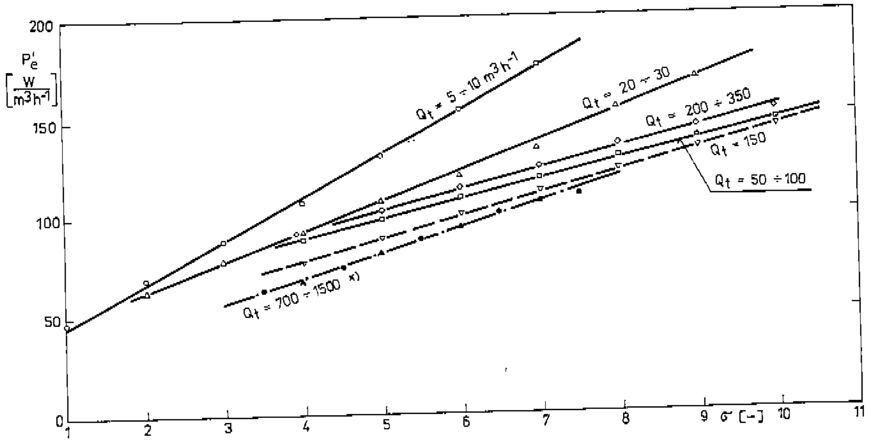
$M_t\ [Nm]$ = compressor shaft torque

$\omega = 2\pi\, n\ [rad/s]$ = the angular compressor shaft speed



x Non-lubricated, water-cooled.

Figure 1. Capacity Factor Correlation for Single-Stage Compressors



x Non-lubricated, water-cooled.

Figure 2. Specific Power Input Factor Correlation for Single-Stage Compressors

P_{mot} [W] = the electric motor input

η_{mot} = the electric motor efficiency defined by measurement or by motor characteristics

η_p = the transmission efficiency; for V-belt-driven compressors considered to have been in the range of 96% to 98%.

Total isothermal efficiency is given as:

$$\eta_{cit} = \frac{P_{it}}{P_e} \cdot 100 \; [\%]$$

where P_{it} [W] is the isothermal input for an ideal compressor.

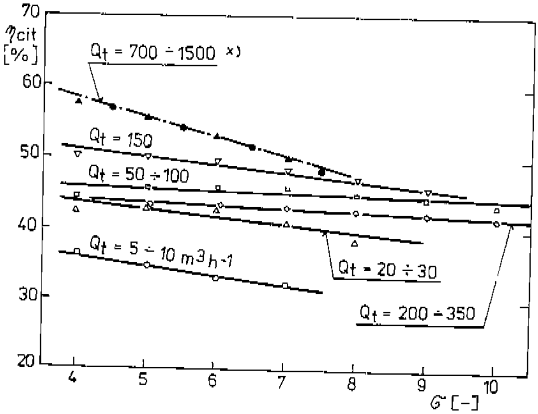


Figure 3.

Isothermal Efficiency Factor Correlation for Single-Stage Compressors

x Non-lubricated, water-cooled.

Mean piston speed is given as:

$$c_s = 2\,L\,n \; [m/s]$$

Also defined are:

σ = the pressure ratio

σ_c = the overall pressure ratio for two-stage compressors

p_{s1} = the inlet pressure of the first stage

p_{v2} = the discharge pressure of the second stage.

The results of our studies can be used either to compare the quality of similar compressors by a particular manufacturer or those of various manufacturers or as a guide for designing new and better compressors. However, in this paper we wish to highlight the diagnostic value of the defined parameters. Our experience with this application, particularly for analyzing the status of valve operation, is summarized below.

The Effect of Valve Performance on Rating Parameters

A malfunction of a compressor valve (leakage, broken valve plate, etc.) could significantly influence the energy effectiveness of a process. Therefore, we set out to identify whether a simple technique to trace a failure or malfunction as an automatic check of the component status can be formulated. We found that the method described below, which would capitalize on the predetermined knowledge of the relationship between the rating parameters and the status of the valve performance, can accomplish this task.

To investigate the relationship between the compressor rating parameters and the quality of valve sealing, we conducted experiments simulating leaking valves on a two-stage, air-cooled air compressor with a nominal capacity of 250 m^3/h at a discharge gauge pressure of 1.0 MPa and a speed of 1250 rpm. An "artificial" leakage was created by milling grooves progressively in a compressor valve seat plate in incremental sizes. For all of the experiments, only one set of valves (such as the intake valves of the first stage, etc.) was modified while the others retained their original shape.

The compressor was driven by a dynamometer so that the input was directly measured. The corresponding capacity was measured by an orifice meter. Pressures were measured by tensometric pressure transducers and temperatures by thermocouples.

The results, (or the relative changes of the rating parameters as functions of valve leakages) are presented in Figures 4 through 7. The values used in these figures are defined as:

$\Delta S/S$ [-] = relative groove size

ΔS [mm^2] = groove area ($\Delta S = \Sigma$ ab).

S [mm^2] = overall free-flow area for the valve. For the first-stage inlet and discharge valves S = 2,200 mm^2; for the second-stage, S = 1,200 mm^2.

Q, P_e, P'_e [-] = relative change in capacity, effective (shaft) input, and specific effective input, respectively

t_s, t_V [°C/°C] = relative temperature change in the inlet/discharge valve chambers, respectively

t_{SF}, t_{S4} [°C/°C] = relative temperature change in the suction filter and suction manifold, respectively

σ [-] = relative change in the pressure ratio

Index 1,2 = first and second stage, respectively.

From the presented relationships, the influence of valve leakage on the rating compressor parameters is readily visible. For example, the findings corroborate experience which advocates that it is of greater relative importance to maintain properly operating, higher stage valves to support high energy economy and first-stage valves to sustain compressor capacity.

More importantly, however, the relationships suggest the possibility of determining the physical state of the valves through easily obtainable diagnostic signals — specifically the operating pressures and temperatures. For example, a decrease in a particular-stage pressure ratio indicates a leaking valve of that stage. Also, a reheating of gas (air) between the inlet manifold and the inlet valve chamber could be used to determine whether or not the inlet valve is the one that leaks.

In addition, the developed relationships allow for formulating simple correlation functions, such as:

$$Q,\ P_e,\ P'_e = f\ (t_s - t_{sU})$$

or

$$Q,\ P_e,\ P'_e = f\ (\sigma_{1,2})$$

This can be derived using either linear or nonlinear regression (such as regression polynomial). These functions then allow one to assess changes in capacity, shaft input, or specific shaft input based on easily measurable diagnostic signals.

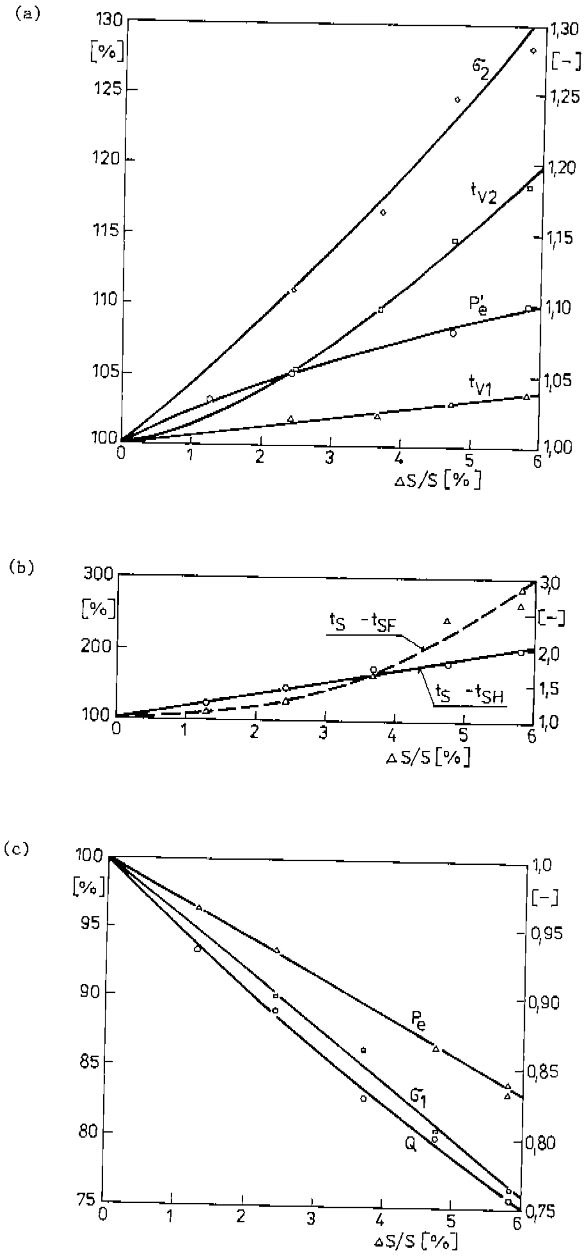


Figure 4 (a, b, c). Relative Changes in Compressor-Rating and Other Operating Parameters as Functions of Relative Groove Size (Leakage) in the Inlet Valve of the First Stage

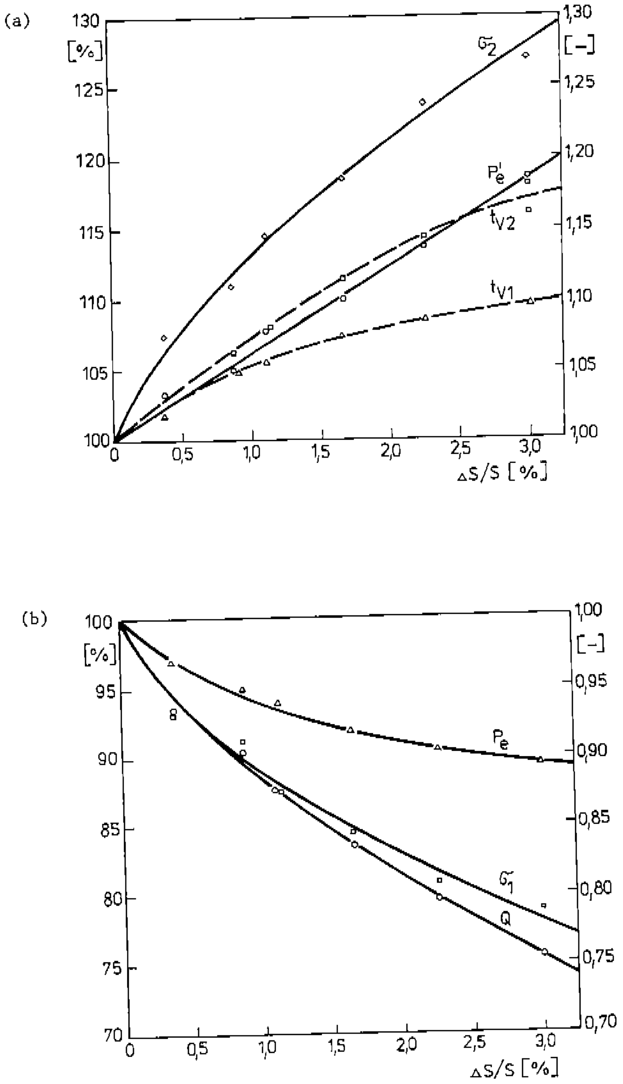


Figure 5 (a, b). Relative Changes in Compressor-Rating and Other Operating Parameters as Functions of Relative Groove Size (Leakage) in the Discharge Valve of the First Stage

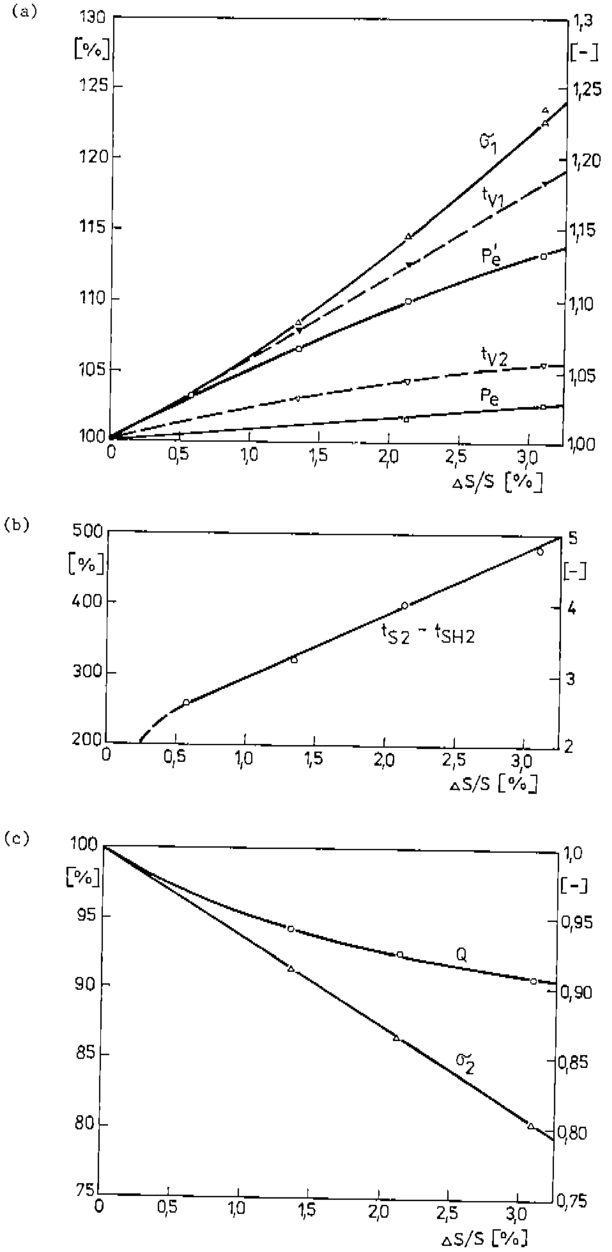


Figure 6 (a, b, c). Relative Changes in Compressor-Rating and Other Operating Parameters as Functions of Relative Groove Size (Leakage) in the Inlet Valve of the Second Stage

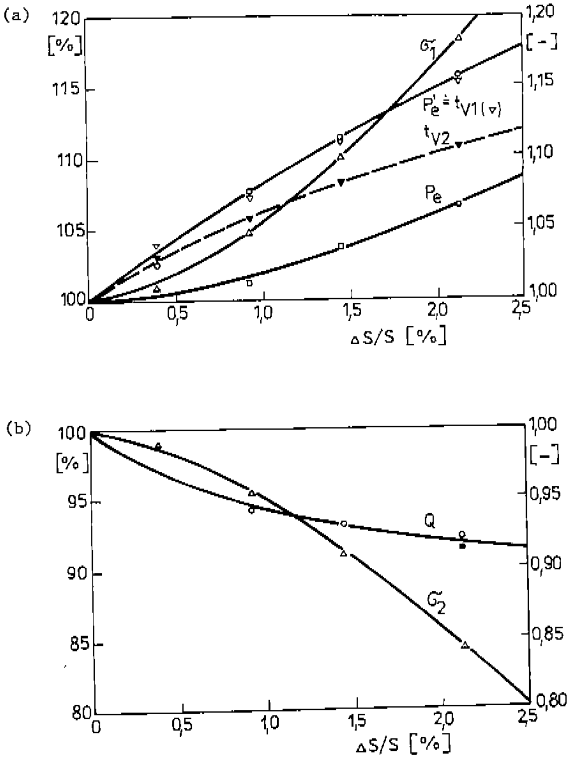


Figure 7 (a, b). Relative Changes in Compressor-Rating and Other Operating Parameters as Functions of Relative Groove Size (Leakage) in the Discharge Valve of the Second Stage

CONCLUSIONS

On the basis of our measurements of 120 air compressors of manufactured in Czechoslovakia, we have developed rating parameters specific to the design groups that can be used for rating the quality of machines of similar design and for routine operating diagnostics.

As a specific variant of this work, combined with the additional experimental measurements and simulation of valve leakage, new relationships were generated among the valve leakage, easily obtainable diagnostic signals, and the rating parameters. These can provide a simple means of determining the condition of valves in their operating environment.