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Influence of Wear on Leakage through Reed-Type Valves of Small Reciprocating Compressors

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ABSTRACT

Leakage can significantly decrease the efficiency of small reciprocating compressors adopted in household refrigeration systems. Leakage occurs in the piston-cylinder clearance and through gaps in valves formed by geometric irregularities associated with the manufacturing process. This paper presents a procedure developed to analyze experimentally gas leakage in reed-type valves taking into account the wear effect. Accordingly, leakage is measured in the valves of a small-capacity reciprocating compressor before and after the valves being subjected to wear, with the roughness of the reed and seat being measured in both conditions. Measurements of leakages in the suction and discharge valves were carried out independently in an experimental setup based on the constant volume method. Finally, a simulation model for valve leakage and an optimization algorithm were used to estimate the edge gap between the reed and seat. The edge gap was found in the range between 0.13 and 0.94 μm before wear and between 0.11 and 0.47 μm after wear. It was also found that the reed and seat roughness were reduced by approximately half after wear.

1. INTRODUCTION

Valve leakage occurs due to the pressure difference between the compression chamber and the suction/discharge chamber and can affect significantly the efficiency of small compressors. The leakage gap δ between the valve and valve seat depicted in Figure 1 is formed by geometric irregularities brought about by the manufacturing and assembly processes. This paper presents an experimental analysis of leakage in reed-type valves of reciprocating compressors, taking into account the effect of valve wear that takes places when the compressor is run for the first time.

Machu (1990) adopted an integral formulation of the energy equation to simulate a double acting cylinder compressor and estimated leakage with reference to an isentropic compressible flow through a nozzle and the concept of effective leakage area proportional to the valve passage area. The author concluded that leakage may considerably reduce the compressor efficiency even for small leakage areas. Besides the influence of leakage on the compressor performance, some authors have also studied the influence of oil. Fujiwara and Kazama (1998), for instance, analyzed the impact of leakage on the compressor efficiency experimentally considering two cases: oil-free or with oil supply. For the case without oil, the efficiency dropped drastically with the increase of the discharge pressure. However, with an oil supply as small as one drop per hour, the efficiency was greatly improved compared to the oil-free case. The authors concluded that oil has sealing effects, which reduce leakages and therefore increase the efficiency.

More recently, Silva and Deschamps (2015) developed a model to predict gas leakage through reed-type valves of small reciprocating compressors and its effect on the compressor performance, without considering the presence of oil. The authors showed that the volumetric and isentropic efficiencies can be reduced by 2.7% and 4.4%, respectively, for a gap of 1 μm between the valve and its seat. Rezende (2016) carried out measurements of leakage in reed-type valves and noticed its reduction as the tests were repeated, showing that new valve systems are subjected to an adjustment effect due to wear.

The present paper presents an experimental procedure to measure valve leakage under the effect of valve wear but without considering the presence of oil. Additionally, a method is proposed to estimate the clearance between the valve and the seat based on results from a simulation model for gas leakage coupled with an optimization algorithm.

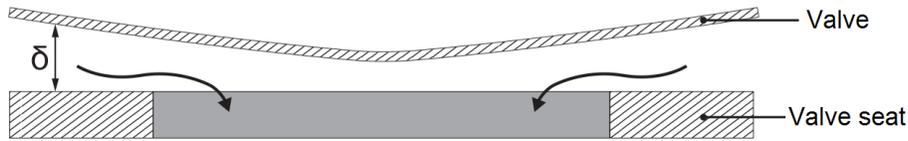


Figure 1: Leakage through the gap between the valve and its seat.

2. LEAKAGE MEASUREMENT

2.1 Experimental Procedure

Leakage through the valve was measured based on the constant volume method, which is widely employed to measure mass flow rates of gases through microchannels (Ewart, *et al.*, 2006; Graur, *et al.*, 2009; Silva *et al.*, 2018). The constant volume method consists in monitoring the pressure p_r and the temperature T_r inside a reservoir of known volume V_r . Assuming the hypothesis of ideal gas, the mass inside the reservoir can be calculated as a function of temperature and pressure:

$$m_r = \frac{p_r V_r}{R T_r}, \quad (1)$$

where R is the specific gas constant. Differentiating Equation (1) with respect to time, the mass flow rate leaving the reservoir (leakage) can be obtained from the following equation:

$$\dot{m} = \frac{dm_r}{dt} = -\frac{V_r}{R T_r} \frac{dp_r}{dt} + \frac{p_r V_r}{R T_r^2} \frac{dT_r}{dt}. \quad (2)$$

The above equation can be simplified, resulting in:

$$\dot{m} = -\frac{V_r}{R T_r} \frac{dp_r}{dt} (1 - \varepsilon), \quad (3)$$

where

$$\varepsilon = \left(p_r \frac{dT_r}{dt} \right) / \left(T_r \frac{dp_r}{dt} \right). \quad (4)$$

The parameter ε is a measure of how much the actual leakage process deviates from an isothermal process ($\varepsilon = 0$). In order to approximate the leakage to an isothermal process, the experimental setup was placed inside an insulating box and a PID controller was used to stabilize the ambient temperature during the experiments. According to Ewart *et al.* (2006), for ε smaller than 2% the non-isothermal term can be neglected in Equation (3). Then, since very small temperature variations were observed during the experiments ($\varepsilon < 2\%$), leakage was calculated as:

$$\dot{m} = -\frac{V_r}{R T_r} \frac{dp_r}{dt}. \quad (5)$$

The values of ε and \dot{m} , calculated according to Equations (4) and (5), respectively, were determined from pressure and temperature measurements performed in the leakage setup presented in Section 2.2. The pressure derivative was determined from a linear piecewise interpolation of the experimental data, while the temperature derivative was estimated as the ratio between the standard deviation of temperature and the corresponding measurement interval, as suggested by Ewart *et al.* (2006).

2.2 Experimental Setups

In some experiments, the valves were subject to wear by running them in an operating compressor before any measurement of leakage. The experimental apparatus developed for this purpose consists of a hot-cycle bench, which is illustrated in Figure 2. The operating condition of this setup is controlled by two micrometer valves (V2 and V3)

that adjust the compressor suction and discharge pressures, which are measured by pressure transmitters (P). The valve V1 is used to supply the gas to the experimental setup. A gas reservoir R1 is employed between valves V2 and V3 in order to turn the suction and discharge pressures practically independent.

The setup for measurement of leakage (Figure 3) is composed of a tank with gas, a pressure transmitter (P), a Pt100 temperature gauge (T1), five thermocouples (T2-T6) and solenoid valves (SV1-SV3). The test section is composed of three parts: the compressor compression chamber (TS1), the compressor valve plate with the valves and seats (TS2) and the suction and discharge chambers (TS3). Leakage can be measured in one of the compressor valves (suction or discharge) at a time by changing the arrangement of closed and opened solenoid valves. To measure leakage through the discharge valve, the discharge chamber is pressurized (P_c) while the compression and suction chambers are open to the environment (P_{atm}), as illustrated in Figure 4. For this case, SV1 and SV3 must be open during the experiment. Hence, there is a pressure difference applied just on the discharge valve keeping it closed and working as the leakage driving force. For the suction leakage, the discharge and compression chambers are pressurized while the suction chamber is open to the environment (Figure 5). The solenoid valves SV1 and SV2 are open, submitting the suction valve to a pressure difference and, thus, to leakage. According to Fujiwara and Kazama (1998), oil affects leakage due to its sealing effect. Hence, before the setup assembly, all the components that would get into contact with the working fluid were cleaned in an ultrasonic bath to guarantee that no oil would be present in the setup during the experiments.

A procedure was developed to establish the effect of valve wear on leakage. The valves tested were new without being subjected to wear before. First, the surface roughness of the valves and seats were measured with a profilometer. Then, the valves were clean in the ultrasonic bath removing any contaminant from their surfaces and leakage was measured using the leakage experimental setup. In the next step, the valves were installed in a compressor, which was run uninterruptedly for 12 hours. The roughness of the valves and seats was measured again. Finally, the valves were cleaned in the ultrasonic bath and leakage was measured again. Therefore, the effect of wear on the leakage could be analyzed by comparing measurements obtained for the same valves before and after being subjected to wear.

Secondary leakages through the connections of the experimental setup were measured and compared to measurements of valve leakage. The measurements indicated that secondary leakage was around two orders of magnitude smaller than those of valve leakage and of the same order of magnitude of the measurement uncertainty. Hence, secondary leakage was neglected.

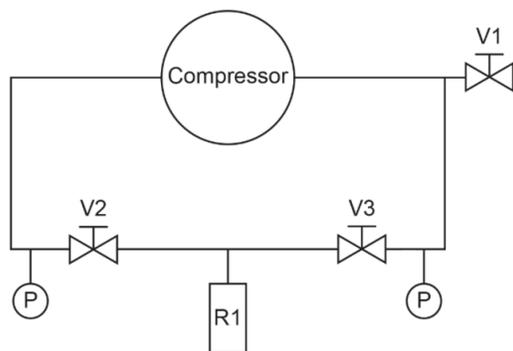


Figure 2: Circuit of the wear setup.

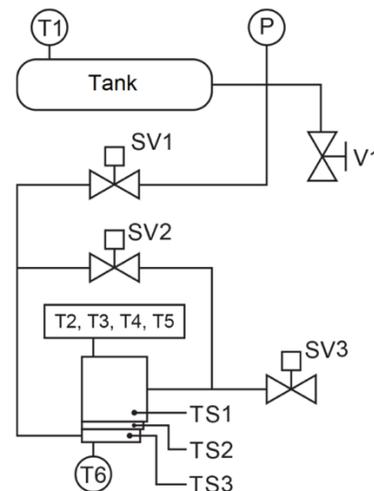


Figure 3: Circuit of the leakage setup.

3. DETERMINATION OF THE EDGE GAP

The experimental data of leakage was used to estimate the edge gap between the valve and the seat by using a simulation model developed by Silva and Deschamps (2015) to evaluate leakage as a function of valve gap. The numerical model predicts the leakage for reed-type valves, considering laminar compressible flow of an ideal gas in steady state. The model also considers the possibility of slip-flow condition. The geometry considered in the model is

illustrated in Figure 6, where the circular plate of radius r_d represents the valve, which covers an orifice of radius r_o . The model takes into account the bending of the valve, thus the local gap between the valve and seat is a function of the radius and the reference clearance at the internal edge of the orifice is δ_e , referred to as the edge gap (Rezende *et al.*, 2018).

In order to determine the edge gap that better fitted the numerical prediction to the experimental data, the genetic optimization algorithm proposed by Holland (1975) was adopted. Figure 7 shows a schematic view of how the genetic algorithm works. First, an initial population is generated randomly according to the restrictions of the problem. Next, the objective functions are computed and the solution's fitness is evaluated. In case the stopping criteria are not reached, the population is changed following the procedures of selection, crossover and mutation, resulting in a new population. Then, the objective functions are computed again and their fitness is analyzed. The procedure is repeated until the stopping criteria are satisfied. The edge gap is determined by the minimization of the difference between the numerical predictions for valve leakage and the corresponding experimental data.

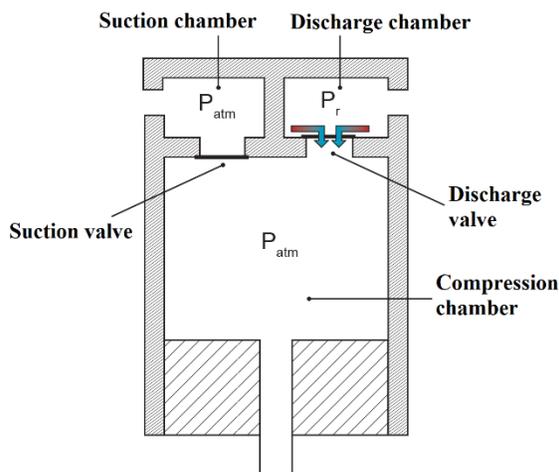


Figure 4: Discharge leakage.

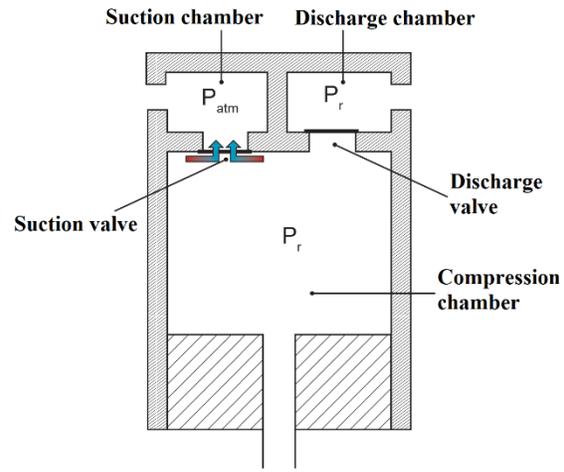


Figure 5: Suction leakage.

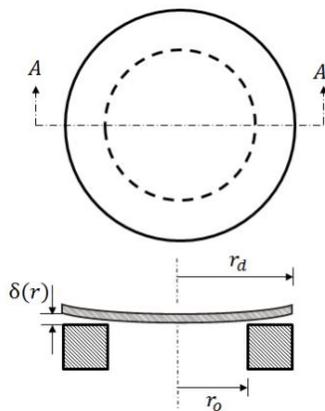


Figure 6: Geometry considered in the numerical model. Source: Silva (2012).

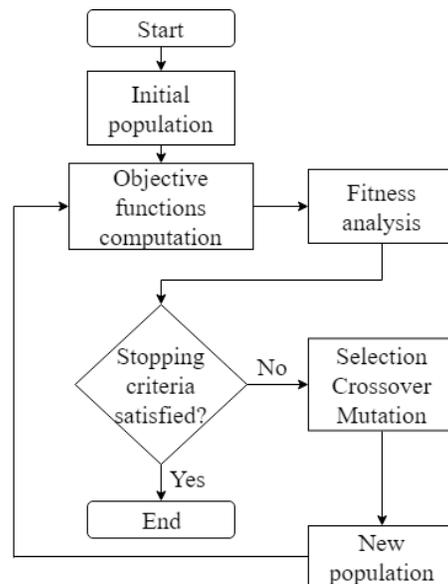


Figure 7: Flowchart for a genetic algorithm.

4. RESULTS AND DISCUSSION

In the present study, the suction and discharge valves of a refrigeration compressor were analyzed. For each valve, the experiment was repeated three times. Figure 8 shows the dimensionless leakage mass flow rate measured in three experiments for a suction valve as a function of the dimensionless pressure difference across the valve, before the valves were subjected to wear. The mass flow rate and the pressure difference were made dimensionless by dividing the measured value by the maximum values. Clearly, the leakage decreases as the tests are performed, confirming the hypothesis that wear plays an important role in the sealing performance, as suggested by Rezende (2016). Figure 9 presents the leakage for the same suction valve with (A) and without (WA) wear. Only the third experiment without wear is presented. One can clearly see that leakage is reduced by valve wear and it reaches a well-defined value after running in the compressor.

The measurements of valve leakage were repeated for the discharge valve and the edge gap for both suction and discharge valves was determined using the procedure described in Section 3. Figures 10 and 11 show the experimental data of leakage and the estimated edge gap for some pressure differences before and after the suction valve is subjected to wear. The experimental results considered are those obtained from the third experiment of each configuration. Similarly, Figures 12 and 13 present the experimental data and estimated edge gap for the discharge valve.

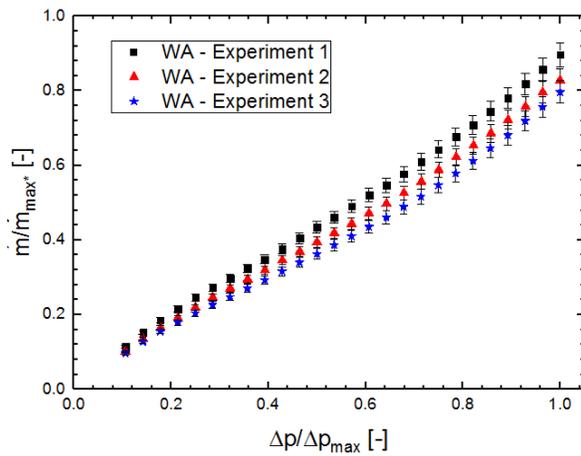


Figure 8: Leakage through the suction valve without wear.

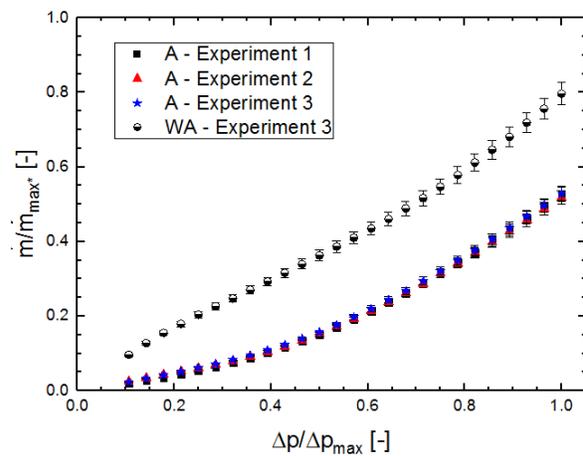


Figure 9: Leakage through the suction valve with wear

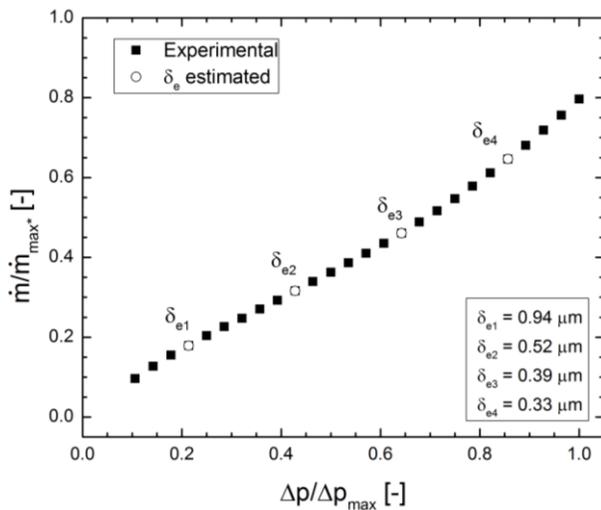


Figure 10: Edge gap for the third experiment of the suction valve without wear.

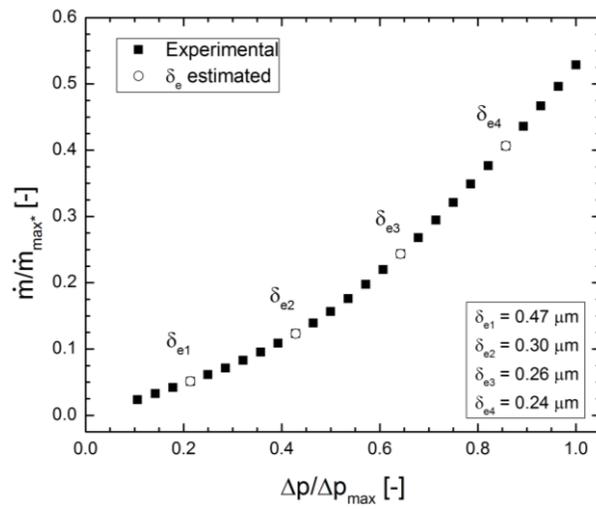


Figure 11: Edge gap for the third experiment of the suction valve with wear.

Comparing the edge gap before and after wear, one can notice that larger values are always obtained before subjecting the valve to wear, indicating that wear significantly reduces leakage. Moreover, the measurements also show that the higher the pressure difference, the smaller the gap. However, although higher pressures result in smaller gaps, leakage tends to increase with the pressure difference since it is the driving force for leakage. The size of the edge gap was found in the range between 0.13 μm and 0.94 μm before wear, and between 0.11 μm and 0.47 μm after wear. It was also found that the valve and seat roughness was reduced by approximately 50% after wear. This indicates that wear also affects the surface conditions of the valves and, consequently, its sealing capacity.

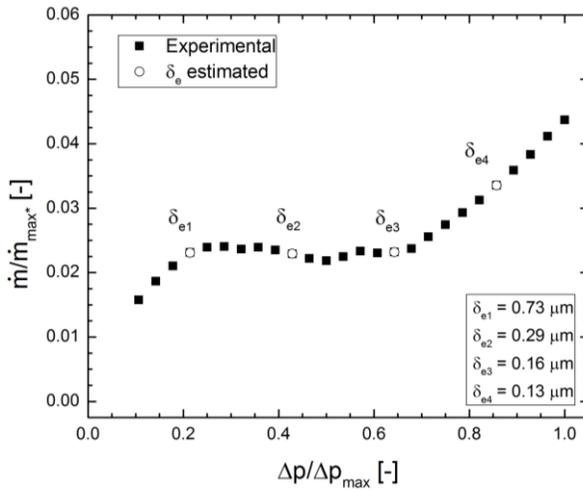


Figure 12: Edge gap for the third experiment of the discharge valve without wear.

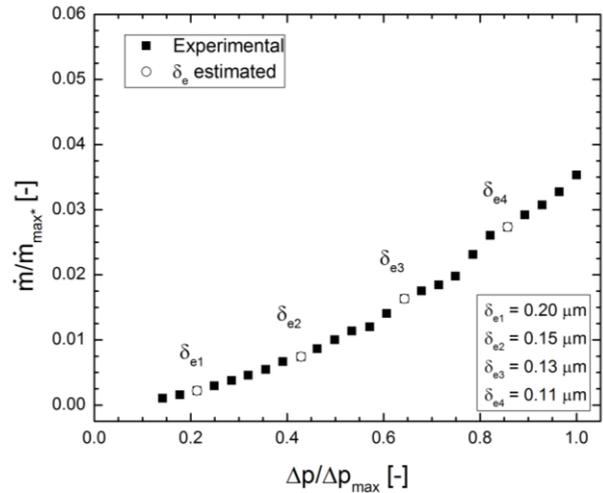


Figure 13: Edge gap for the third experiment of the discharge valve with wear.

5. CONCLUSIONS

An experimental setup was developed to measure leakage in compressor reed-type valves under the effect of wear. A numerical procedure was proposed to automatically evaluate the valve edge gap, a parameter used to characterize the sealing performance of compressor valves. The present study showed that wear affects the surface conditions of the valve and seat and must be considered in the analysis of valve leakage. Typical values of edge gap were found between 0.13 μm and 0.94 μm before wear, and between 0.11 μm and 0.47 μm after wear, reducing leakage considerably.

NOMENCLATURE

δ	gap	(μm)
$\Delta p/\Delta p_{max*}$	non-dimensional difference pressure	(-)
m	mass	(kg)
\dot{m}	leakage mass flow rate	(kg/s)
\dot{m}/\dot{m}_{max*}	non-dimensional leakage mass flow rate	(-)
p	pressure	(Pa)
r_d	circular plate (valve) radius	(m)
r_o	orifice (seat) radius	(m)
R	specific gas constant	(J/(kg.K))
T	temperature	(K)
t	time	(s)
V	reservoir volume	(m^3)

Subscript

e edge
r reservoir

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