THE EFFECT OF VALVE LEAKAGE ON COMPRESSOR PERFORMANCE

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Abstract. *Gas leakage that may occur in the incomplete sealing of compressor valves affects both the volumetric and isentropic efficiencies. This paper describes a numerical study of gas leakage in reed type valves of small reciprocating compressors commonly adopted in household refrigeration. The mathematical modeling approach takes into account important flow phenomena, such as acceleration and compressibility. The computations are carried out for a wide range of pressure differences that occur during a complete compression cycle. Results for the suction and discharge valves are used to analyze the influence of geometric parameters and fluid properties on the leakage process, with and without the deflection of the valves due to pressure load.*

Keywords: *Compressor, valve, leakage.*

1. INTRODUCTION

Valves are essential components for the reliability and efficiency of compressors. Usually, the lubricating oil present in compressors acts as a sealing element of valves, but gas leakage may occur due to irregularities of the manufacturing process.

Some studies in the literature on flow through reed type valves consider the simplified model of flow between parallel disks. For instance, Fleming *et al.* (1984) solved the compressible, laminar flow in a radial diffuser taking into account the variation of the cross section area. Ghila (1995) numerically solved the incompressible flow in a radial nozzle and showed that previous theories underestimate the wall shear stress in the case of high Reynolds numbers.

Sato *et al.* (2005) linearized the governing equations of the compressible flow between parallel disks by assuming that the effect of viscous friction was much smaller than that due to changes in the flow cross section area. Elhaj *et al.* (2008) simulated an air double stage reciprocating compressor with an account of the leakage through the valves following a model for isentropic compressible flow.

The present study aims to model the gas leakage through suction and discharge valves of reciprocating compressors and quantify its effect on the volumetric and isentropic efficiencies. The volumetric efficiency, η_v, is defined as the ratio between the actual mass flow rate, $\dot{m}$, and the ideal mass flow rate, $\dot{m}_{th}$:

$$\eta_v = \frac{\dot{m}}{\dot{m}_{th}} \tag{1}$$

The ideal mass flow rate is the mass flow that would be obtained under ideal conditions, i.e., absence of clearance in the cylinder, leakage in the piston-cylinder clearance, leakage through the gap between the valve and its seat, pressure loss, back flow through valves and gas superheating in the suction system.

The isentropic efficiency, η_s, is defined as the ratio between the specific work of an isentropic process, $\dot{w}_s$, and the actual compression work, $\dot{w}$, necessary to compress the same mass of refrigerant:

$$\eta_s = \frac{\dot{w}_s}{\dot{w}} \tag{2}$$

It should be noticed that any amount of work spent during the compression cycle with gas that eventually leaks through valves is not useful for the system and, therefore, the isentropic efficiency is decreased.

In the present study, a model is developed to predict the gas leakage through valves and coupled with a simulation model of the compression cycle of alternative compressors. The gas leakage through small clearances is a function of fluid properties, pressure, temperature, as well as the surface finishing and the geometry of the pair valve/seat. The model to be described herein considers fluid flow properties, valve geometry and the valve deflection due to pressure load.

2. MATHEMATICAL MODELING AND SOLUTION PROCEDURE

2.1 Compression cycle

The influence of gas leakage through valves on the compressor efficiency is evaluated by adopting a compressor simulation code (RECIP), originally developed by Ussyk (1984) and modified along the years. The code RECIP simulates the compression cycle with mathematical descriptions of the following aspects:

i) Cylinder volume as a function of the crankshaft angle;
ii) Gas properties along the compression cycle;
iii) Mass flow rate through valves and the clearance between the piston and cylinder;
iv) Valve dynamics.

A detailed description of the code RECIP can be found in Gomes (2006).

2.2 Leakage through valves

The conservation equations of mass, momentum and energy are written for an ideal gas. Moreover, the following hypotheses are assumed for the flow: laminar, compressible, adiabatic, steady state, one-dimensional. Assuming an infinitesimal element of length *dr*, width *2πr* and height *δ(r)*, as shown in Fig.1, the equations that describe the variations of flow properties along the length *dr* can be written as:

$$\frac{d\rho}{\rho} = \frac{M^2}{1-M^2}\left[\frac{dA}{A} - \frac{2\gamma C_f dr}{D_h}\right] \tag{3}$$

$$\frac{dp}{p} = \frac{\gamma M^2}{1-M^2}\left[\frac{dA}{A} - \frac{2C_f\left[1+M^2\left(\gamma-1\right)\right]dr}{D_h}\right] \tag{4}$$

$$\frac{dM}{M} = \frac{1+\frac{(\gamma-1)}{2}M^2}{1-M^2}\left[\frac{dA}{A} - \frac{2\gamma C_f M^2 dr}{D_h}\right] \tag{5}$$

where ρ, p and M represents fluid density, pressure and Mach number, respectively. Moreover, γ is the ratio of specific heats, C_f is the Fanning friction factor and D_h is the hydraulic diameter.

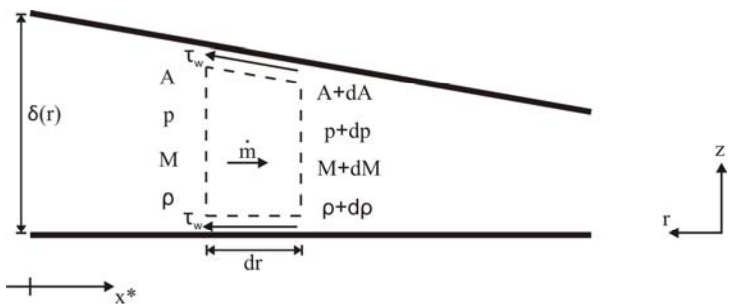

Figure 1. Infinitesimal fluid element in a convergent channel.

As shown in equations (3)-(5), flow properties vary with the cross section area and viscous friction, represented by the first and second terms between the brackets. For subsonic flow, viscous friction decreases density and pressure and increase the Mach number. The same effects are verified for density, pressure and Mach number when the flow cross section area is decreased.

The deflection of the valve due to pressure load, *w(r)*, is estimated via a model of a supported circular plate under uniform load, represented in Fig. 2.Therefore, the local gap between the valve and seat, *δ(r)*, is a function of both the valve deflection *w(r)* and the reference clearance at the edge of the valve port, δ_e.

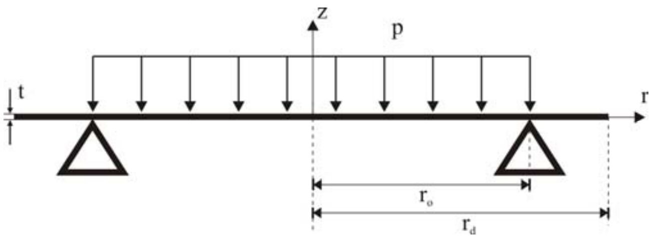

Figure 2. Circular plate model to estimate the valve deflection.

The solution of the surface deflection in the interval $r_o \le r \le r_d$, that is the region of interest to fluid flow by leakage, is given by:

$$w(r) = \frac{p r_o^{\,3}(r - r_o)}{8D(1+\nu)} \tag{6}$$

where p represents the pressure difference acting on the valve, r_o is the radius of the orifice, r_d is the radius of the disc, ν is the Poisson's ratio and D is the flexural rigidity, which was expressed as being equivalent to that for beams:

$$D = \frac{Et^3}{12\left(1-\nu^2\right)} \tag{7}$$

with E being the modulus of elasticity and t the valve thickness.

Then the transverse section geometry of the nozzle flow can be calculated as $A(r)=2\pi r[w(r)+\delta_e]$. In the case of non-deflected valve $w(r)=0$. If the flow properties are known, the mass flow rate can be calculated as follows:

$$\dot{m}(r) = \rho(r)V(r)A(r) \tag{8}$$

2.3 Solution procedure

Manipulating the term dA/A, it is possible to rewrite in Equations (1)-(3) as first order ordinary differential equations, which can be solved with the fourth-order Runge-Kutta method. The required boundary conditions are the upstream stagnation pressure p_o and temperature T_o, and downstream outlet pressure p_{out}. Naturally, the proposed model is valid for suction and discharge valves. For the discharge valve, stagnation properties are evaluated in the discharge chamber and the gas flows through the valve clearance towards the valve port. On the other hand, the stagnation condition for the flow through the suction valve is based on the properties inside the cylinder.

The first step in the solution procedure is to estimate the Mach number at the entrance of the valve clearance. Following the hypothesis of isentropic flow, the stagnation properties remain constant up to the inlet region and the flow properties can be evaluated there based on the Mach number. This initial value for Mach number allows the evaluation of other flow properties along the valve clearance via the Runge-Kutta method. The outlet pressure obtained from the numerical solution is compared with the actual value within a given tolerance. If the condition is satisfied, the iterative method is considered to be converged; otherwise, another estimate for the Mach number at the inlet is adopted and the process is repeated until convergence is achieved. If the Mach number along the duct achieves the value 1 within a specified tolerance, then the choked flow condition is present in the nozzle. Equations (1) - (8) are solved for each crank angle along the compression cycle.

3. RESULTS AND DISCUSSION

The present section show results for gas leakage in the discharge valve of a small refrigeration compressor and the effect of valve deflection. The effect of leakage on volumetric and isentropic efficiencies is analyzed for different values of valve clearance, δ_e.

The influence of the clearance size on the compressor volumetric and isentropic efficiencies is depicted in Fig. 3. When the valve deflection is not considered, the results show that the volumetric and isentropic efficiencies can be reduced by 3.7% and 4.5%, respectively, in the case of a clearance of 3μm.

Regardless the clearance size, the results also show that gas leakage is strongly increased as an outcome of the smaller flow restriction brought about by deflection. As a result, when deflection is considered, the volumetric and isentropic efficiencies are seen to be reduced by 6.8% and 8.3%, respectively, for the case of δ_e = 3μm. Hence, valve deflection must be considered in the analysis.

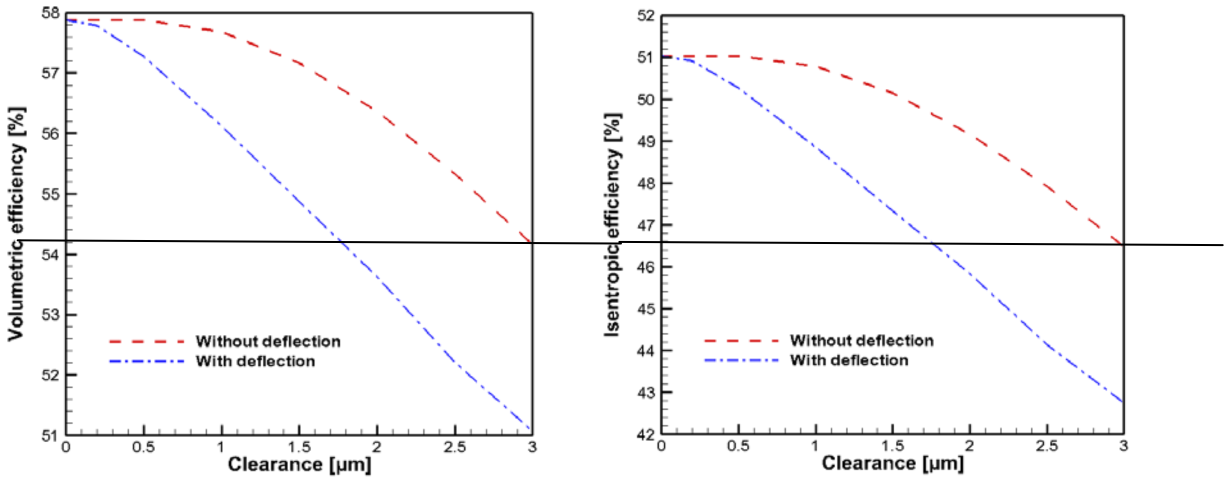

Figure 3. Decaying of (a) volumetric efficiency and (b) isentropic efficiency, obtained by deflection and non-deflection model for discharge valve.

4. CONCLUSIONS

The present paper reported a model developed to estimate gas leakage through compressor valves, with and without deflection due to pressure load. It has been observed that leakage can significantly reduce the efficiency of compressors even for very small valve clearances. In fact, the effect of gas leakage on the compressor efficiency shown in this paper is significant enough to justify a more detailed analysis of the phenomenon with the inclusion of other aspects, such as slip flow regime, surface finishing and valve misalignment.

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