MATHEMATICAL MODELLING OF REED VALVE LIFT WITH CRANK ANGLE IN PISTON COMPRESSORS

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Abstract: Compressors are the primary part of any air handling mechanical system and also consume the highest amount of energy in a system e.g. in refrigerating systems. As per reports published 40% of the compressor failures are caused due to compressor valves. Valve lift is one of the most important parameters in Reed valves. Valve lift is affected by the forces acting on the valve, material and dimensional properties of the reed, compressor parameters, and flow properties of the gas used. This project aims at formulating a mathematical model of valve lift for the reed valves. The results will help in understanding the flow losses during strokes leading to optimization of the capacity and working power of the compressor. It will also provide a general idea about the stresses acting on the valve, the space requirement, and the life of the valve. The various parameters affecting the valve lift can then be adjusted to get a desirable valve lift and most importantly in designing the valves. The mathematical models of pressure drop, power loss, valve lift, etc. were compared with the standard datasheets and found to be in good agreement.

***Index Terms* – Reed Valve, Valve lift, Compressor Valves, Mathematical Model.**

I. INTRODUCTION

The increasing demand to reduce energy consumption and to optimize the performance of reciprocating compressors poses a great challenge to the researchers. The reed valves are the key component of the reciprocating compressors and are responsible for 40% of the total failures [1, 2]. Hence, valve optimization must be a top concern for potential savings. Reed valves are commonly used in small piston compressors in the medium RPM range of 960-1500 RPM. They are used due to their simplicity, low cost, and high efficiency. Reed type valves are a type of non-return valves. Formulation of mathematical models of reed type compressor valves started in 1950 with M. Costagliola [3], who modelled reed valves considering it as a single degree of freedom system. H.E. Khalifa [4] analyzed the Stiction effect in reed valves. Feng Wang [6] carried the work of H.E.Khalifa forward and formulated a single DOF model based on actual motion characteristics of the valve. Rodrigo A. [9] simulated the dynamic behaviour of the ring-shaped oil film between the discharge valve and seat. H.Bukac [5] established the relation between various valve parameters and plotted them against each other. Amit Jomde [7] modelled and simulated the performance in linear compressors (patented by LG Electronics Inc.), which are quite similar to piston compressors. Yuan ma [8] studied the behaviour of reed valves by keeping the valve lift to be constant. Venkatesan [10] established models for suction and discharge valves and validated it experimentally using a piezoelectric pressure transducer. Shillian. Z [11] theoretically compared the differences between the suction and discharge valves. Prakash R.[12] established models for heat transfer in the valves, mass transfer within the valves, valve simulation, formulation of the thermodynamic processes in the cylinder working space, and kinematics of the compressor. Analyzing the above studies, 1D beam-type modelling is most used. Though different methodologies will fetch different results, it is important to approach the physical model with these assumptions.

Most of the present studies focus on modelling the hinged type of reed valve by considering it to be a cantilever beam. The present study focuses on modelling the unhinged type of reed valves. The unhinged type of reed valve is shown in figure 1 (right) below. This unhinged type has a without limiter and with limiter variant. The limiter/ stopper /retainer/ valve guard introduces various other valve parameters like rebound and impact stresses. Modelling a valve is a multi-parameter consideration process. If the relationship between every valve parameter is identified, an optimal valve system can be designed and the failure conditions can be predicted.

II. VALVE DYNAMICS

Compressor valve dynamics influence valve life and compression efficiency. A compressor valve opens and closes with every compression cycle. Interaction of the flow of the compressible system and the dynamics of the mechanical system i.e. the valve makes the mathematical modelling rather complex to understand.

Reed Valve

A reed valve usually consists of a valve reed, valve seat, limiter, gasket, and a spring. It is actuated due to the pressure difference acting across the valve. The variants of the reed valves are shown below. The hinged type reed valve resembles a cantilever beam whereas the unhinged type resembles a simply supported type of beam. The unhinged type of valve reed in practical situations displaces from its central portion during its actuation, whereas the shorter sides of the reed remain un-displaced or moderately displaced. During maximum actuation, the unhinged valve reed makes an inverted ‘U’ shape. Hence, it is modelled considering it to be a simply supported beam.

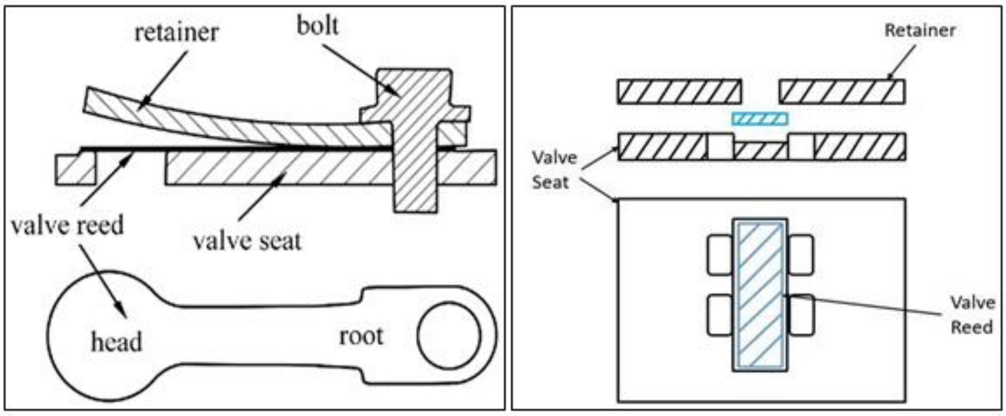

Figure 1 Variants of Reed Valve - Hinged (Left) and Unhinged (Right)

Valve Lift

Valve lift is one of the primary factors deciding the efficiency and reliability of the compressors. Since the suction process is longer than the discharge process. The valve lift on the suction side must be greater than the discharge side, for the same mass flow rate conditions. Reliability is usually achieved by the lowest practicable lift and valve efficiency is achieved by using the highest available lift. A higher valve lift is associated with higher efficiency of compressors. On the other hand, higher valve lift tends to result in higher impact velocities and subsequently higher impact fatigue stresses in reed valves. Factors such as rotating speed, operating pressure and molecular weight of the gas determine the limits of allowable valve lift. The impact resilience of various materials used for valve plates (steel, polymers, etc.) also influences the maximum acceptable valve lift. Excessive valve lift can have very detrimental effects on valve life, due to high-velocity impact forces, valve flutter, late closing, and other life deteriorating developments.

Dynamic model

Assumptions:

I. The vortex formation of gases across the reed valves has not been considered.

II. The average velocity of the air has been considered.

Nomenclature

m	Mass of the reed (kg)	h	Valve lift (m)
t	Time (seconds)	θ	Crank Angle (rad)
ω	Angular Velocity (rad/s)	A	Area of Valve Slot (m^2)
ΔP	Pressure Difference (Pa)	V	Velocity of the gas through the slot (m/s)
k	Stiffness (N/m)	x	Increment in Valve lift (m)
E	Young's Modulus (Pa)	I	Area Moment of Inertia (m^4)
L	Length of the Reed (m)	ρ	Density of the gas (kg/m^3)
f	Friction Factor	L_s	Length of the seat
d	Slot diameter (m)	K_c	Contraction Coefficient
K_b	Bend Coefficient	V_e	Velocity in Exhaust Pipe (m/s)

The various forces acting on the reed valve due to pressure difference on suction and discharge side were balanced using Newton's second law of motion. The equation was then integrated twice to get the result of valve lift vs. time and subsequently to get a valve lift vs. crank angle. The forces acting on hinged and unhinged type of reed valve are the same. The forces acting on the hinged type valve is shown below.

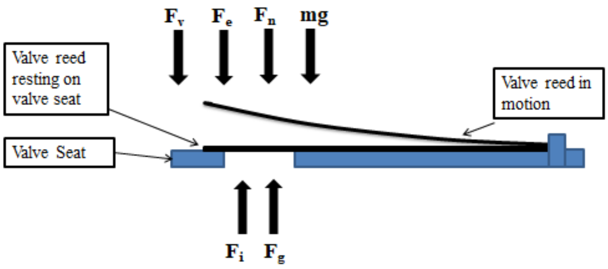

Figure 2 Forces acting on the Hinged type Reed Valve

According to Newton's second law of motion:

$$m.\frac{d^2h}{dt^2} = \mathbf{\Sigma.}F$$

$$m.\frac{d^2h}{dt^2} = (F_g + F_i) - (F_v + F_n + F_e + mg)$$

To convert this expression into a valve lift against a crank angle,

$$\theta = \omega.\ t$$

$$d\,\theta = \omega.\, dt$$

$$m.\omega^2.\frac{d^2h}{d\theta^2} = (F_g + F_i) - (F_v + F_n + F_e + mg)$$

The gas force (Fg) is responsible for the opening of the valve due to pressure difference. Impact force (Fi) takes into account the sudden impact due to the velocity of gas on the valve reed. The gas force and the impact force support the motion of reed in the direction of flow. Whereas, the viscous force (Fv), gas dampening force (Fn), spring force (Fe), and reed weight (mg) opposes the motion of reed. The viscous force takes into account the effect of viscosity due to oil in between the reed and the valve seat. The gas dampening force accounts for the dampening caused due to the backflow of the gas. The spring force accounts for the stiffness of the reed. However, the gas dampening force and the weight of the reed were neglected due to smaller magnitudes. The viscous force was dropped as the compressor with which the results were to be compared was oil-free.

$$F_g = A\times (\Delta P)$$

$$F_i = \rho \times A \times V^2$$

$$F_e = k\times x$$

Stiffness and frequency are the parameters directly affecting the valve lift. Higher the stiffness, the lower is the lift. On the other hand, higher frequency causes the valve reed to fluctuate more and hence, reduces the valve lift. To calculate the stiffness in a hinged type reed valve, use,

$$k = \frac{3\times E\times I}{L^3}$$

To calculate the stiffness in an unhinged type reed valve, use,

$$k = \frac{48\times E\times I}{L^3}$$

The pressure drop across the valve was calculated as a result of losses occurring due to friction, contraction, expansion, and bending of gas. The friction factor and Reynolds number were calculated from the characteristic dimension.

$$\text{Pressure drop due to friction} = \rho\times g\times \frac{f\times L_s\times V^2}{2\times d}$$

$$\text{Pressure drop due to contraction} = 0.5 \times \rho\times k_c \times V^2$$

$$\text{Pressure drop due to expansion} = 0.5 \times \rho \times (V_e - V)^2$$

$$\text{Pressure drop due to bending} = 0.5 \times \rho \times k_b \times V^2$$

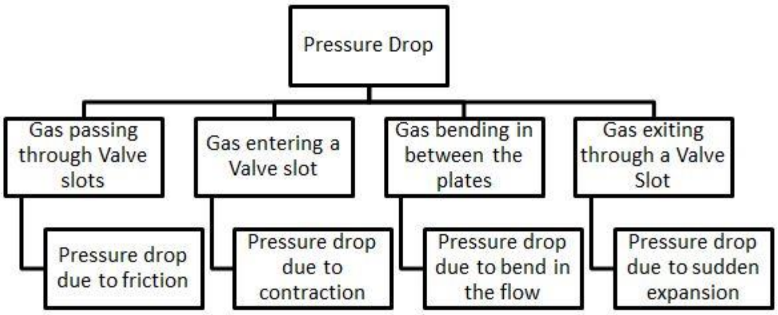

Figure 3 Pressure Drop Calculation

The methodology for finding pressure drop in hinged and unhinged valves is different. The flow of gas through the valve needs to be visualized to determine the equations to be used while calculating pressure drop.

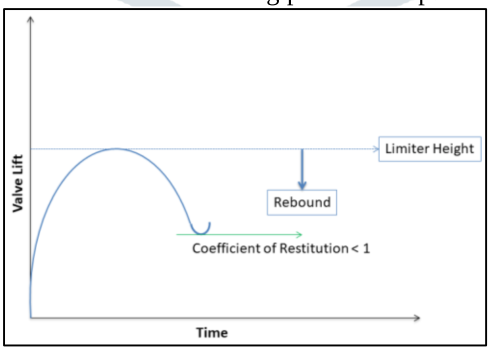

Figure 4 Calculating Valve Lift in Rebound Conditions

The valve lift during rebound conditions was more complex to model as compared to free conditions. Since the valve reed has an impact against the limiter, the after rebound height depends upon the coefficient of restitution of limiter material, forces acting, the velocity of the gas, and the reed material. The known parameter, in this case, was the velocity. It is known that the velocity of the reed when it is resting on the seat is zero. Also, the velocity, when reed reaches the lowest position after the rebound is zero. Framing this in mind the valve lift for the rebound conditions was given and the results are shown below.

To determine the opening and closing angles of the valves, the pressure equation with crank angle was established, the following result was plotted using MATLAB. In the figure below, the opening angle for the discharge valve was approximately 102 degrees, and the closing angle at TDC i.e. at 180 degrees. Similarly, suction valve opening and closing angles are 220 degrees and at BDC i.e. at 360 degrees.

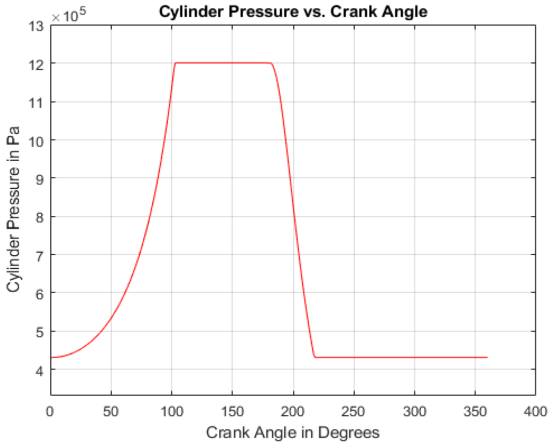

Figure 5 Cylinder Pressure vs. Crank Angle Plot

MATLAB Coding

The formulated equations were coded using MATLAB for free lift and with limiter conditions. The derived equations from equations were solved using MATLAB. The models of stiffness, frequency, pressure drop, valve lift with and without limiter conditions, and for the unhinged type of reed valve were given.

III. Results and Discussion

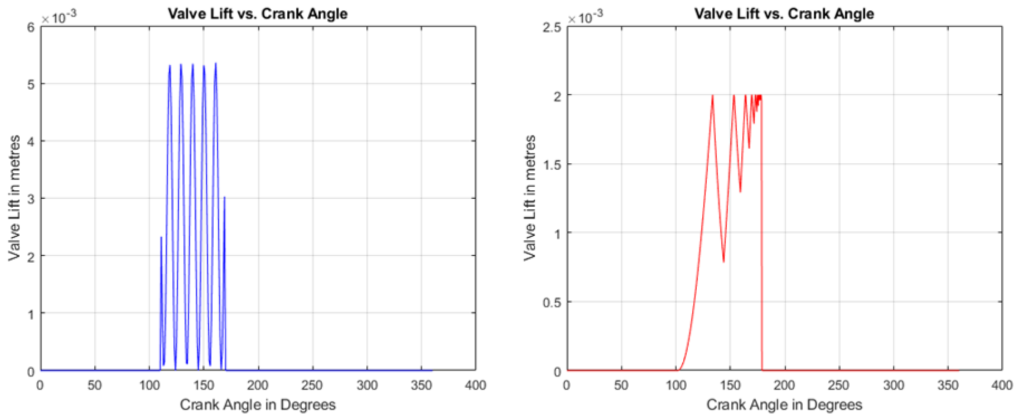

Figure 6 Valve Lift vs. Crank Angle in Unhinged Valve without Limiter (left) and with Limiter (Right)

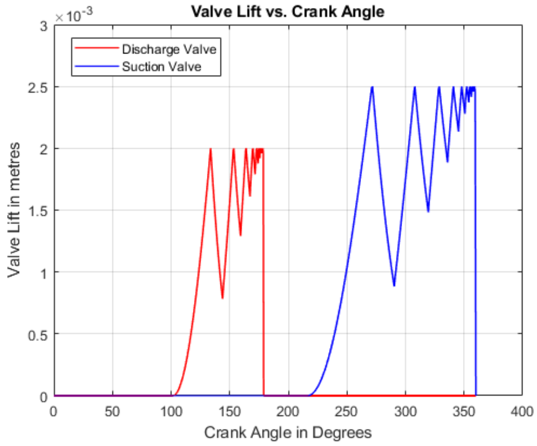

Figure 7 Valve Lift vs. Crank Angle in Unhinged Valve for Suction and Discharge Valves

Inferences from the above plots: The valve opens up as the pressure inside the compression chamber exceeds the surplus pressure over the delivery line pressure. As the valve moves up, it collides with the limiter, which limits its motion. With this collision, there is an energy loss during the rebound. Since the limiter height is fixed, this poses a restriction to the movement of valves. The pressure drop and power loss due to this restriction height were compared for validation purposes.

This opening and closing of the valve due to the forces discussed in the report, along with the stiffness of the valve and the energy lost during rebound – leads to valve fluttering. At the same time, the allowable time available for the valve to be opened depends upon the polytropic index of compression, the pressure ratios that the compression chamber is working under, and the flow losses which occur due to the valve.

The mathematical models were validated using standard datasheets from reed valve manufacturers and were found to be in good agreement.

IV. CONCLUSION

Since, reed valves are the most used valves in small compressors, Valve lift vs. Crank angle curves can help deduce important conclusion regarding reed valve design. These plots can be used to understand the flow losses during delivery – leading to optimization of the capacity and working power of the compressor.

It also provides a general idea about the stresses acting on the valve, the space requirement, and the life of the valve. The various parameters affecting the valve lift can then be adjusted to get a desirable valve lift and most importantly in designing the valves.

The mathematical models of pressure drop, power loss, valve lift, etc. were compared with the manufacturer standard datasheets and found to be in good agreement.

V. ACKNOWLEDGEMENT

This work was supported by Atlas Copco India Ltd.

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