Ultra-thin reed valves for higher energy efficiency in compressors

Muhammad Waqas TOFIQUE[1]*, Alexander LÖF[1], Dipankar SARKAR[1], Chris MILLWARD[1]

[1]voestalpine Precision Strip AB, Research & Development,
Munkfors, Sweden
Contact Information (+46761429713, Waqas.Tofique@voestalpine.com)

* Corresponding Author

ABSTRACT

Inside a reciprocating compressor, a reed valve is a critical component that contributes to a compressor's structural reliability, efficiency, and noise emission. Theoretically, the thinner the reed valve, the higher the efficiency and the lower the noise emission. Thinner reed valves are, however, more susceptible to premature failure at compressor load levels because for a given power output level of the compressor the stresses on thinner valves will be higher. Moreover, from a metallurgical point of view, the size (area) of potential crack initiating inclusions/defects makes major fraction of the reed valve cross-section.
Flap-X is a high strength martensitic stainless steel grade that is developed as a reed valve steel whose higher impact fatigue and bending fatigue strength, in general, allow using thinner gauges for reed valves. By testing reed valves of this steel grade in the ultra-thin gauge of 0.076 mm, we are looking to give the compressor manufacturers advantages like higher compressor efficiency and reduced noise while ensuring reliability of valve operation. Tests were conducted in a custom-built impact fatigue test system that uses compressed air pulses to induce reed valve movement and striking against the valve plate. Reliability tests were conducted by testing multiple reed valve samples to millions of load cycles that helped estimate their impact fatigue strength/life.
From our tests, the ultra-thin reed valves demonstrated efficiency gains. Moreover, the reed valves showed reasonable impact fatigue life at compressor load levels. This is believed to be due to the higher strength and smaller size of potentially crack initiating inclusions in the tested valve steel grade.

1. INTRODUCTION

Keeping in view the challenges posed by the climate change, there are various policy regulations adopted by the governmental and other regulatory bodies around the world that prescribe energy efficient systems. Compressors are widely used in household, automotive, commercial buildings and industrial applications for various purposes ranging from refrigeration and air conditioning/cooling to provision of compressed air for other purposes.
In compressor systems, the reed valve is a crucial component as its smooth operation allows the reliable operation of a compressor and, hence, the operation of any appliance that the compressor is installed in. In order to improve the efficiency of the compressor systems, weight reduction and noise reduction, thinner gauges of reed valves are being favored by compressor manufacturers. However, by reducing the thickness there are other unknowns like valve reliability as well as the effect of this gauge reduction on valve movement parameters like valve lift and impact velocity that become ever more important to analyse.
This study aims to fill this gap by conducting impact fatigue testing on the ultra-thin gauge of 0.076 mm thick reed valves manufactured from the best-in-class reed valve steel grade. The focus of this paper is to study the impact fatigue life of reed valves as well as their loading parameters like impact velocity and valve lift.
The problem of impact fatigue of reed valves has been studied by several researchers using various experimental as well as numerical modelling techniques. Svenzon *et al.* (1976) and Futakawa *et al.* (1982) conducted the impact fatigue experiments using their custom-built impact fatigue equipment and analysed the fractured valve surfaces. Altunlu *et al.* (2012) have also studied the effect of different tumbling times as well as the different impact velocity levels on the life length of the tested reed valves in their own custom-built impact fatigue test system. Tofique *et al.* (2018) have studied the impact fatigue phenomenon of reed valves when tested against impact plates of different materials. Their study focussed on understanding the influence of the material properties on the impact fatigue life

of reed valves. In other contributions by Tofique *et al.* (2021_a, 2021_b), the reed valve movement for different operating parameters was studied experimentally and valve stresses were simulated numerically. Some other researchers have contributed towards understanding of the impact fatigue phenomenon using different numerical modelling techniques. For instance, Böswirth (1996), Soedel (2007) and Rigola *et al.* (2015) have proposed different numerical models to deepen the understanding of the reed valve movement behaviour incorporating both the fluid flow parameters as well as the structural properties of the reed valve. Other researchers have carried out validation of the numerical modelling techniques with their experiments. For instance, Mayer *et al.* [10] carried out a validation of Fluid-Structure Interaction (FSI) computational methods by reproducing experimental results of reed valves. There have also been numerous theoretical studies in the past such as by Böswirth (1980), Pandeya *et al.* (1978) and more recently by Yu *et al.* (2017) that discussed the dynamic behavior of a generic geometry of reed valves and the impact fatigue stress state generated due to their impact against the impact seat during compressor operation.

2. EXPERIMENTAL

Reed valve movement experiments were conducted on a custom-built impact fatigue test rig that, in normal operation, uses air pulses to produce movement of the valves at a range of frequencies (Hz) and pulse widths (milliseconds). The frequency, and pulse-width, is provided as input to the control software on the connected computer.

A schematic sketch of this custom-built impact fatigue test rig is shown in Figure 1. A dedicated compressor provides compressed air at up to 13 bars pressure. This compressed air gets stored in a storage tank. The compressed air is transferred through tubes of 4 mm inner diameter and passes through a flow meter that measures the airflow rate in liters per minute. The air pressure regulator regulates the magnitude of the compressed air pressure before it passes through a high frequency solenoid valve. There is a possibility to increase or decrease the magnitude of pressure supplied to the solenoid valve, and hence the airflow rate, through the pressure regulator. The compressed air pressure reported in this paper is measured at the solenoid valve opening.

The reed valve was made to strike the valve plate repeatedly inducing impact fatigue stresses in them, hence, mimicking the movement of a reed valve in an actual compressor. A laser sensor measures the reed valve's displacement, and thus velocity, and its operating frequency at a sampling rate of 10000 per second. This data is displayed and stored on the control software.

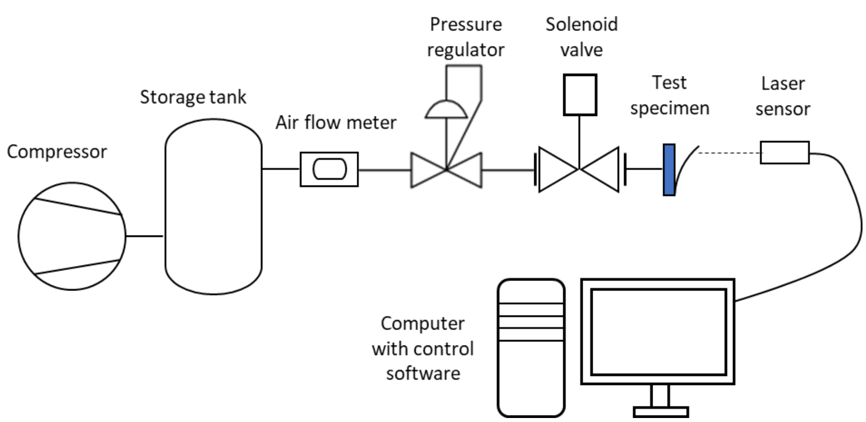
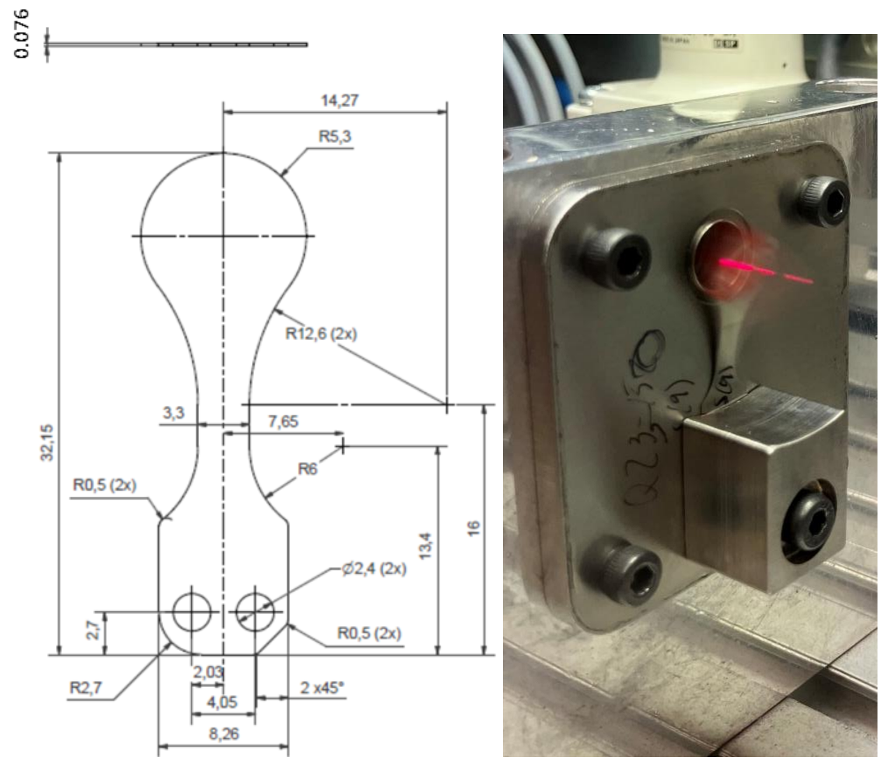


Figure 1: Schematic drawing of the working of the custom-built impact fatigue test system available at voestalpine Precision Strip AB, Sweden, that was used to test the ultra-thin reed valves (test specimens) in this study.

In the custom-built impact fatigue test system, one crucial component that influences the reed valve movement is the high frequency solenoid valve. It is a two-way, in-line valve that is electrically actuated with moulded-in cable. Installed in the impact fatigue test system, it receives compressed air after the pressure regulator and through its fast-switching action coverts it into pressurized air pulses of fixed frequency and pulse-width. These pressurized air pulses are then supplied to a reed valve/test specimen that moves in response.

2.1 Test specimen design

The geometry of the reed valves tested in this work is presented in Figure 2. This reed valve design was chosen as it is a simple and efficient design that is quite common in the compressor industry. In the impact fatigue test system, the reed valves were mounted using a steel dice that covered a part of its length. The measuring point of the laser detecting valve movement data was 7.5 mm from the top edge of the valve head along the centerline.



(a) (b)

Figure 2: a) The geometry and dimensions of the ultra-thin reed valve specimens tested in this study, (b) an ultra-thin reed valve tested without a retainer against a steel valve plate in the impact fatigue test system at voestalpine Precision Strip AB.

The reed valves were manufactured from 0.076 mm ultra-thin strip of a high strength valve steel grade whose nominal chemical composition and mechanical properties are shown in Table 1 and Table 2, respectively. The tested valve steel grade is a martensitic stainless steel that is hardened and tempered and designed specifically for long-life valve components, where toughness and impact fatigue strength are essential.

Table 1. Nominal chemical composition (wt. %) of the tested steel grade used for the reed valves.

Steel grade	**C**	**Si**	**Mn**	**Cr**	**Mo**	**P**	**S**
Flap-X	0.38	0.45	0.55	13.5	1.00	≤0.025	≤0.015

Table 2. Nominal mechanical properties of the tested valve steel grade.

Steel grade	**Proof strength, $Rp_{0.2\%}$ (MPa)**	**Tensile Strength, Rm (MPa)**	**Elongation (%)**	**$Rp_{0.2\%}$/Rm**	**HV_1**
Flap-X	1580	2100±60	≥6	0.8	613-643

The tested material was cold rolled to 0.076 mm thickness followed by hardening and tempering treatments. The surface of the material was brushed. The reed valves were manufactured using photochemical etching along the rolling direction of the material. The reed valves were tested in both tumbled and untumbled conditions in two different configurations, explained later in the results section.

For the impact fatigue tests, ten valve plates were machined from each of the austenitic stainless steel grade “EN 1.4301” and Polyether Ether Ketone (PEEK) material, whose material properties are listed in Table 3. The hardness of the plates was measured using the standard ISO 6507-1: 2005. The damping measurements were conducted using impulse excitation apparatus (IEA) to measure the internal friction ($Q^{-1} = k/(\pi * f_r)$) as defined in the work by Roebben *et al.* (1997). The PEEK material possesses higher damping capacity and is softer compared to the austenitic stainless steel grade.

Table 3. Hardness and damping (Q^{-1}) of the valve plate materials used in this study.

Steel grade	Referred to as	Condition	Hardness (HV)	Damping ($Q^{-1} = k/\pi f_r$)
EN 1.4301	Steel valve plate	Annealed	180	$5.4*10^{-4}$
Polyether Ether Ketone	PEEK valve plate	-	36	$6.3*10^{-3}$

A previous study by Tofique *et al.* (2018) showed the effect of using PEEK valve plates in significantly improving the impact fatigue life of 0.203 mm thick reed valves of the same valve steel grade. This served as a motivation for testing the ultra-thin reed valves in tumbled condition against the PEEK valve plates in a much more challenging configuration without a retainer in this study.

3. RESULTS

In the impact fatigue test system, a frequency of 50 Hz and pulse-width of 10 ms was specified in the control software. This meant that compressed air pulses of 50 Hz frequency were created by the solenoid valve.

3.1. Impact velocity versus number of cycles

The impact fatigue test data is shown in Figure 3 by plotting the impact velocity of the reed valves against the number of cycles endured by them. The runout samples are indicated by the data points located at or to the right of the vertical black line at 15 million cycles. All the data points plotted to the left of the vertical dashed line at 15 million cycles represent the reed valves that failed during the impact fatigue testing.

The reed valves tested using retainer against steel valve plate endured greater number of cycles, albeit at lower impact velocities than those tested without a retainer. It must be noted that all the other test parameters such as input frequency (50 Hz) of compressed air pulses, pulse width (10 ms), pressure (3.4 bars) and air flow rate (86 litres/minute) were kept same for all the tested samples. The only difference is that the reed valves tested against PEEK valve plates are in tumbled condition whereas those tested against the steel valve plates were in untumbled condition.

The impact fatigue results show that the impact velocity of the reed valves tested without using a retainer was on average 1.6 times higher than those tested using a retainer. The higher impact velocity of the reed valves tested without retainer resulted in premature failure of the reed valves before the 15 million cycles cut-off limit. On the contrary, only one out of eleven reed valves tested using a retainer failed before the 15 million cycles limit. This result shows that even the beneficial effects of higher compressive stresses in the tumbled ultra-thin valves and the higher damping capacity of the PEEK valve plates were not enough to counteract the high impact velocities experienced by the reed valves tested without a retainer.

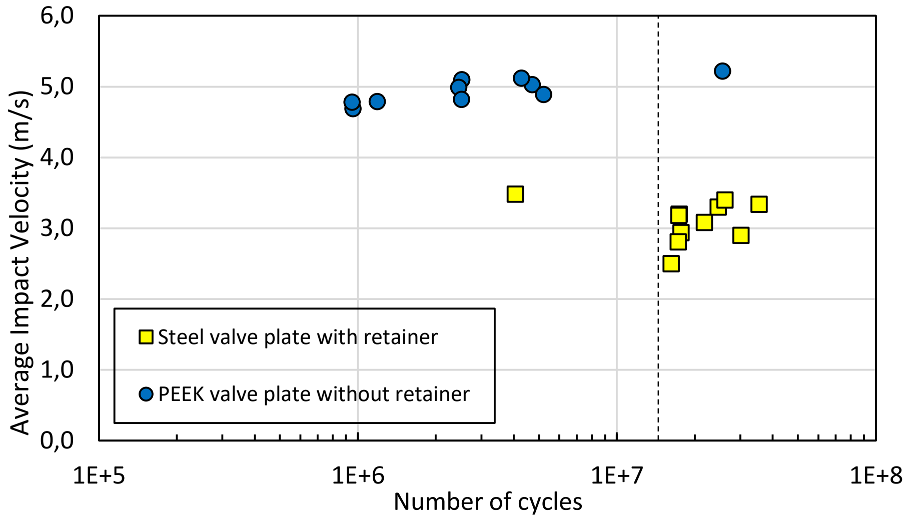


Figure 3. Impact fatigue test results of two different 0.076 mm thick reed valve and valve plate configurations with average impact velocity of each tested sample plotted against the number of cycles endured by them.

To illustrate the effect of the difference in energy transfer between the reed valves tested without a retainer and those with a retainer, the square of impact velocity is plotted in Figure 4. The square of impact velocity represents the kinetic energy ($0.5*m*v_{impact}$^2) transfer from the reed valve to the valve plate. The greater the energy of impacts the higher the induced impact stresses in the reed valve as a consequence of the impacts and the higher the probability of reed valve failure. Figure 4 shows that the reed valves tested without retainers impacted with 2-3 times higher energy against the PEEK valve plates than those tested with retainers.

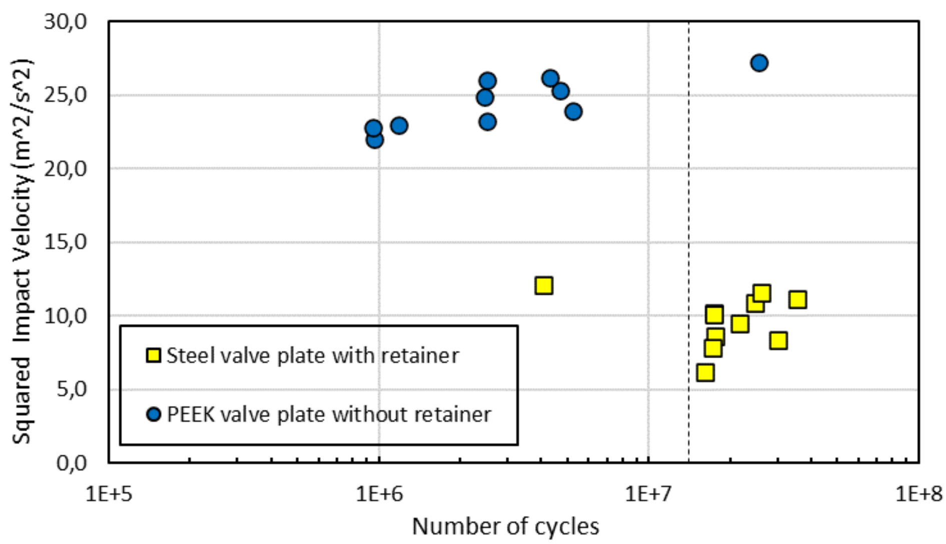


Figure 4. Impact fatigue test results of two different 0.076 mm thick reed valve and valve plate configurations with square of average impact velocity of each tested sample plotted against the number of cycles endured by them.

3.2. Displacement curve of 0.076 mm thick reed valves with retainer

The ultra-thin reed valves using a retainer was registered using a laser sensor that measures its displacement at a point approx. 7.5 mm from the valve head tip. The positioning of the laser sensor below the valve tip means only a conservative estimate of the valve displacement was achieved in this study as the maximum displacement is experienced by the valve tip.

The displacement curve of 0.076 mm thick reed valves with retainer is shown in Figure 5, where the valve plate/seat position is illustrated at approx. -4 mm by the dashed line. The reed displacement response is plotted for input frequency of 50 Hz and pulse-width of 10 ms. It can be observed that the reed valve opens with a slight delay after the trigger voltage is applied to the high frequency solenoid valve. After the valve is pushed open to the maximum amplitude, the valve flutters without striking against the valve plate. The reed valve then closed due to elastic spring force as it acted against the compressed air, since the solenoid valve was still open. As the reed valve struck against the valve seat, it bounced up twice partly under the action of the compressed air. As another compressed air pulse arrived at the reed valve, this movement cycle was repeated again.

However, it can be seen in Figure 5 that there are slight differences in the magnitude of the reed valve amplitude that occur due to local differences in air pressure, airflow rate and obliqueness of the reed valve during its movement – especially after it bounces back from the impact seat.

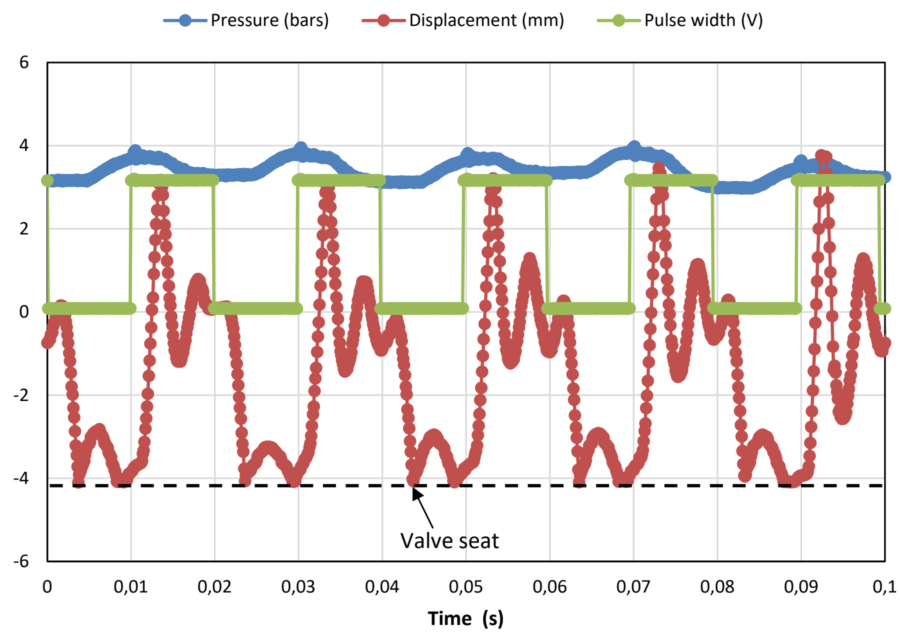


Figure 5. Reed valve displacement, pressure and pulse width (10 milliseconds) plotted against time for a 0.076 mm thick reed valve tested against the steel valve plate using a retainer.

3.3. Displacement curve of 0.076 mm reed valve without retainer

The displacement of the 0.076 mm thick reed valves tested without retainer is shown in Figure 6. The displacement curve shows much higher valve lift so much so that it exceeds the range of the used laser sensor's detection range. Hence, curve fitting was used to predict the missing valve displacement and highest peaks of movement. After curve fitting, the obtained valve lift of the reed valves tested without a retainer was on average approx. 1.7 times that of those tested with a retainer. Moreover, there is only one impact/bounce against the valve plate.

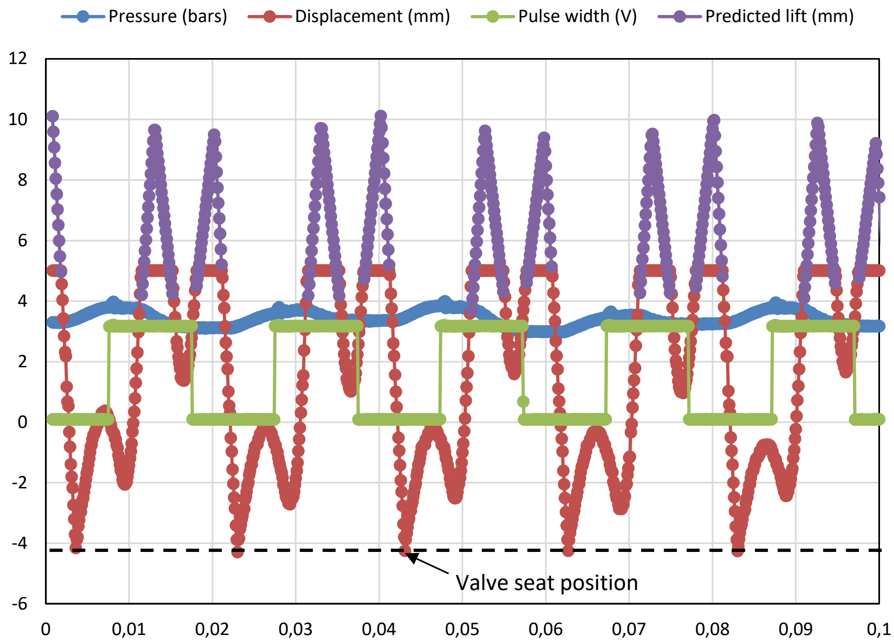


Figure 6. Reed valve displacement, pressure and pulse width (10 milliseconds) plotted against time for a 0.076 mm thick reed valve tested against the PEEK valve plate without using any retainer.

3.4. Impact velocity of reed valves

The velocity of reed valves is a critical parameter that helps determine the intensity of impact against the valve plates. In this study, it is determined by subtracting the successive points of displacement, say x_1 and x_2, recorded by the laser sensor at successive time points, say t_1 and t_2, as shown in the following formula:

$$v_1 = \frac{x_2 - x_1}{t_2 - t_1} \tag{1}$$

The intensity of the impact is determined by the kinetic energy transferred by the valve to the valve plate. This kinetic energy depends on the velocity of the valve, thus termed the impact velocity of the valve, just before it strikes against the impact plate, see the negative portion of the reed velocity curve in Figure 7. Thus, the impact velocity of the reed valves is reported as the load parameter in this study.

The impact velocity of the reed valves is calculated by averaging the velocity of approach (at least 5-10 data points of multiple pulses) of the reed valve before striking the valve plate. There is some scatter in the velocities of the reed valves that is corresponding to the scatter in the reed valve displacement. This scatter is in turn translated to the impact velocity but averaging over multiple data points minimizes this scatter.

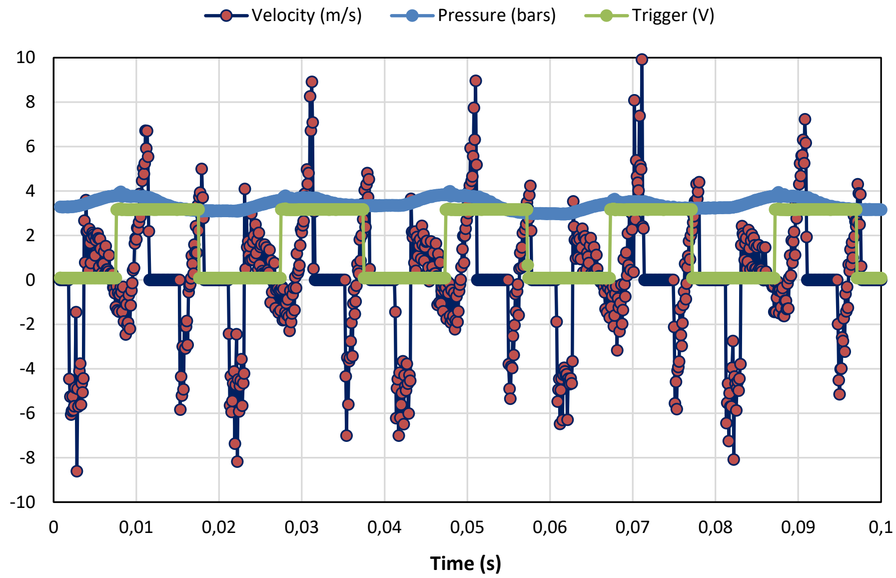


Figure 7. Reed valve velocity, pressure and pulse width (10 milliseconds) plotted against time for a 0.076 mm thick reed valve tested against the PEEK valve plate without using any retainer.

3.5. Relationship between impact velocity and valve lift

The average valve lift of all the tested reed valves was plotted against their impact velocities in Figure 8. There seems to be a linear relationship between the valve lift and the impact velocity of the reed valves. The higher the valve lift the higher impact velocity of the reed valves.

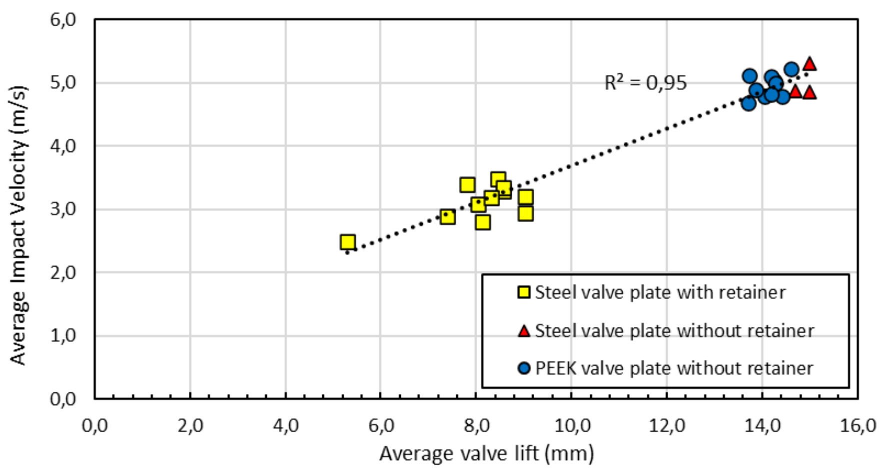


Figure 8. Relationship between the average valve lift and the average impact velocity of the tested reed valves.

4. DISCUSSION

In today's world, there is an ever-increasing demand on improving efficiency of compressors, weight reduction, miniaturization and noise reduction. In order to meet these requirements, there is interest in using thinner gauges of reed valves. From metallurgical point of view, we are approaching the lower limits of thickness when employing 0.076 mm for reed valves as the non-metallic inclusions that can initiate fracture in these high strength steels constitute a major fraction of their cross-section. Therefore, only valve steels with high degree of material cleanness along with other material properties, can sustain the harsh operating conditions inside compressors. The tested material is a patented valve steel grade specifically designed to meet requirements of cleanness, high bending fatigue strength and impact fatigue strength that enables usage of thin gauges of reed valves in compressor applications.

In this study, the impact fatigue test results of 0.076 mm thick reed valves are presented. The lower stiffness of the ultra-thin reed valves allows greater flexion or valve lift. As shown in Figure 8, the higher the valve lift the higher impact velocity of a reed valve for a given thickness and other operating parameters. It has been discussed by various authors such as Pandeya *et al.* (1978) in the past that higher impact velocity of reed valves leads to higher magnitude of impact fatigue stresses upon impact against the valve plate. In order to reduce the impact fatigue stresses in the ultra-thin reed valves, it was decided in this study to use PEEK valve plates that have proven in the past to give significantly higher impact fatigue life as shown by Tofique *et al.* (2018). Moreover, tumbled reed valves are more resistant to impact fatigue cracking due to higher levels of compressive stresses induced on their surface along with removal of edge and surface defects left by the valve cutting/production processes. However, the impact fatigue test result in this study showed that when the reed valves are tested without using a retainer, the average valve lift (approx. 14 mm) and impact velocity (approx. 5 m/s) is quite high. This, in turn, results in high impact fatigue stresses in the reed valves because the kinetic energy transferred to the valve plates is approx. 2.5 times higher causing impact fatigue failure of nine out of ten tested specimens before the 15 million cycles cut-off limit. On the other hand, by using a retainer, the valve lift and impact velocity of the reed valves is reduced by 1.6 – 1.7 times. Consequently, this results in reduction of number of failures to only one out of eleven tested specimens.

The testing of ultra-thin reed valves shows that with higher valve lift the reed valves are also prone to fluttering. Valve flutter can be a factor that lowers the energy efficiency of a compressor. Therefore, suitably designed valve retainers for discharge valve that reduce the flutter movement are recommended.

5. CONCLUSIONS

Based on the test results obtained in this study, the following conclusions are drawn:

- The use of ultra-thin gauge of 0.076 mm Flap-X reed valves in harsh conditions of impact fatigue testing shows some promise.
- The ultra-thin reed valves are likely to have higher valve lift resulting in higher impact fatigue stresses which means higher probability of failure if not designed properly to reap the benefits of higher valve lift.
- The ultra-thin reed valves demonstrated high valve lift that can translate into significant improvement in COP of compressors.
- A suitably designed valve retainer will help control the valve lift to the required level as well as reduce the valve flutter during compressor’s operation.
- If a suitably designed valve retainer is used, the tested valve steel material, with superior cleanness, is likely to give acceptable valve life at thinner gauges, releasing the potential gains for the compressor manufacturer.

REFERENCES

Altunlu, A. C., Lazoglu, I., Oguz, E., Kara, S., “An investigation on the impact fatigue characteristics of valve leaves for small hermetic reciprocating compressors in a new automated test system”, Fatigue & Fracture of Engineering Materials & Structures, pp. 826-841, 2012.

Böswirth, L., “Hypothesis on the failure of spring-loaded compressor valve plates” in Proceedings of the International compressor engineering conference at Purdue, Purdue University (198-206), Paper 332., Indiana, USA, 1980.

Böswirth, L., “A new valve simulation program and its use for the design of valves” in International Compressor Engineering Conference, Lafayette, India, USA, 1996.

Futakawa, A., Namura, K., “Impact fatigue behaviour of flapper valve steel” in International Compressor Engineering Conference, Lafayette, Indiana, USA, 1982.

Mayer, J., Bjerre, P., Brune, F., “A comparative study of different numerical model for flapper valve motion” in International Compressor Engineering Conference, Lafayette, Indiana, USA, 2014.

Pandeya, P. N. S. W., “Analysis of the influence of seat-plating or cushioning on valve impact stresses in high speed compressors” in Proceedings of the International compressor engineering conference at Purdue, Purdue University, Indiana, USA, 1978.

Rigola, J., Aljure, D., Lehmkuhl, O., Perez-Segarra, C.D., Oliva, A., “Numerical analysis of the turbulent fluid flow through valves. Geometrical aspects influence at different positions” in 9th International Conference on Compressors and their Systems, London, 2015.

Roebben, G., Bollen, B., Brebels, A., Van Humbeeck, J., & Van der Beist, O., “Impulse excitation apparatus to measure resonant frequencies, elastic moduli, and internal material friction at room and high temperature”, Review of Scientific Instruments (1997) 68 (12), 4511-4515.

Soedel, W., Sound and vibration of positive displacement compressors, ISBN: 0-8493-7094-3, Taylor & Francis Group, 1st Ed., 2007.

Svenzon, M., “Impact fatigue of valve steel” in International Compressor Engineering Conference, Lafayette, Indiana, USA, 1976.

Tofique, M. W., Millward, C., Löf, A., Nawaz,A., “Investigation of valve reed-impact plate interaction with respect to their impact fatigue properties” in 24th International Compressor Engineering Conference, Lafayette, Indiana, USA, 2018.

Tofique, M. W., Löf, A., Millward, C., “Experimental analysis of reed valve movement for different reed valve designs tested in an impact fatigue test system” in IOP Conference Series: Materials Science and Engineering, Volume 1180, 12th International Conference on Compressors and their Systems (Compressors 2021) 6th-8th September 2021, London, United Kingdom.

Tofique, M. W., Löf, A., Schillaci, E., Castrillo, P., Rigola, J., “Experimental and numerical analysis of reed valve movement in an impact fatigue test system and reciprocating compressors” in 25th International Compressor Engineering Conference at Purdue, May 24-28, 2021.

Yu, X., Tan, Q., Ren, Y., Jia, X., Jin, L., “Numerical study of the reed valve impact in the rotary compressor by FSI model”, Energy Procedia 105, pp. 4890-4897, 2017.

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