2022

A Low-cost Photoelectric Based Displacement Measurement System To Quantify Valve Lift Motion In Reciprocating Type Compressors

Anjum Naeem Malik

Pooya Pashak

İsmail Lazoğlu

Çağlar Şahin

A low-cost photoelectric system to measure valve displacement in reciprocating type compressors

Anjum Naeem MALIK [1*], Pouya PASHAK [1], Ismail LAZOGLU [1], Çağlar ŞAHİN [2]

[1] Manufacturing and Automation Research Center, Koç University, Sarıyer, Istanbul 34450, Turkey

[2] Arçelik A.Ş. R&D Directorate, Tuzla, Istanbul 34950, Turkey

* Corresponding Author

ABSTRACT

This paper presents a development of a system based on the photoelectric technique to measure the displacement of the reed valve in reciprocating type hermetic compressors. The motivation for that is mainly related to developing a cost-effective, non-invasive, and adaptable system to monitor valve dynamics in real-time. The proposed system is comprised of an infrared type of transmitter and receiver pair installed inside the cylinder head, targeting the face of reed valve. The system is calibrated to quantify the displacement of the suction valve. The results are compared with a mathematical model for the valve's dynamic behavior.

The valve is assumed as one-degree of freedom mass and spring system. The fourth-order Runge-Kutta method is adopted to solve the coupled first-order differential equations system in MATLAB. The experimental results and the mathematical model are in good agreement at high rotating speeds of the compressor as compared to the low speeds.

1. INTRODUCTION

The refrigerator is an essential need of every household nowadays and is considered one of the primary energy consumers among other domestic appliances. Improving the energy efficiency of refrigerators can significantly reduce worldwide energy consumption and the carbon footprint (Malik et al. 2021). A household refrigerator is equipped with a hermetic reciprocating compressor, which comprises an electric motor coupled with a crankshaft to drive the piston inside the cylinder and perform the necessary compression operation on the refrigerant. Reed-type valves are used on the suction and the discharge sides to control the refrigerant flow in the cylinder head. The dynamics of the reed valves are directly related to the compressor's efficiency and the overall performance of the refrigerator. Therefore, analyzing the valve dynamics is of key importance in improving domestic refrigerators' performance and energy efficiency.

Several analytical and experimental approaches to understand the dynamics of the reed valves have been presented in the literature. The analytical techniques were mostly targeted to capture the dynamic performance of the reed valves under different conditions. A reed valve can be modeled as a single degree of freedom mass and spring system. Costagliola (1950) introduced this kind of modeling, but his model could not predict the valve's flutter phenomenon. Habing (2005) studied the flow through the valve and valve motion in compressors and validated the theory with experiments. A 0-D model, also called the thermodynamic model, is a computationally efficient method to simulate the valve motion. This method identifies the mass, pressure, and temperature of the gas by implementing mass and energy balance equations in each control volume (Longo & Gasparella, 2003). Touber (1976), in a more detailed way, explained the mathematical formulation of the valve flow, dynamics, and unsteady thermodynamic processes by taking the compressor cylinder, suction chamber, and discharge chamber as control volumes. Taranović *et al.* (2017) implemented a valve's dynamic model to simulate the valve motions in the reciprocating compressor for motor vehicles and verified by thermodynamic properties measured experimentally in the cylinder. Jin & Hong (2012) deduced a new valve dynamic model by assuming the refrigerant as a real gas based on the L-K state equation. The model was verified by a step-less capacity regulation compressor. Farzaneh-Gord & Khoshnazar (2016) used the same valve model along with the thermodynamic model by considering three control volumes i.e., cylinder, suction chamber, and discharge chamber. In their study they used these models as a tool for valve fault detection.

The experimental approaches were usually comprised of measuring the valve lift motion, the frequency, the number of flutters, and the opening/closing time of the valve using different kinds of transducers under real operating conditions. For example, Prasad and Woollatt (2000) used a fiberoptic sensor to measure the valve motion in the VIP-type compressor accurately. Ludu *et al.* (2000) employed an endoscopic video system to visualize the motion of the suction and discharge valves. Buligan *et al.* (2002) and Nagy *et al.* (2008) utilized the laser doppler vibrometer (LDV) with the help of transparent windows to quantify the suction and discharge valve lift. Mayer *et al.* (2014) analyzed the valve dynamics using different numerical models and laser displacement sensor-based experimental validation. Nagata *et al.* (2010) and Zhang *et al.* (2018) applied strain gauge sensors to quantify the dynamic behavior of the suction and discharge valves. The experimental studies to understand the valve's dynamics were either comprised of sophisticated and expensive equipment or invasive sensors that disturb the dynamics of the valve and have high installation complexity. The manufacturers of domestic refrigerators prefer measuring systems having low installation complexity and less operating cost. The non-invasive and low-cost optical type sensors comprised of a transmitter and receiver pair have been proposed for different applications in the literature, for example, displacement measurements, object detection, force measurements, frost detection, and home automation (Malik et al. 2020). Considering the size, ease of retrofitting, low cost, accuracy, reliability, non-invasive measuring principle, and low power consumption, the optical sensing technique seems suitable for the valve lift measurements in reciprocating compressors.
In this study, a low-cost photoelectric-based measurement system is developed to quantify the dynamics of the suction valve in a reciprocating compressor, and the results are compared with a mathematical model.

2. EXPERIMENTAL SETUP

The experimental setup was comprised of a hermetic reciprocating compressor, a photoelectric sensor, a function generator, and a data acquisition system.

2.1 Photoelectric sensor development

The photoelectric sensor was comprised of an infrared (IR) based transmitter and receiver. The transmitter emits light at a wavelength of 850 nm in a dispersive manner at a certain viewing angle rather than being point focused. The receiver was a photodiode type that receives the reflected light from the target object. The sensor works on the principle of change in the intensity of the light at the receiver end consequent to an interruption and reflection of the emitted light by the target object. The schematic illustrating the working principle of the photoelectric sensor is shown in Figure 1. The current flowing through the receiver circuit (I_r) is directly proportional to any change in the intensity of the light reaching the receiver end. In the case of a static target object, the distance between the sensor and the target object (ΔX) remains unchanged. As a result, the difference between the emitted and the received light stays minimum, which results in no change in the I_r. However, when the target object displaces, the intensity of the light decreases at the receiver end, which reduces the I_r. The output current can be translated into an equivalent voltage signal (V_r) using Kirchhoff's voltage rule, as shown in Equation (1). The output voltage signal V_r was related to the valve's displacement through the calibration procedure.

$$V_r = V_{cc} - I_r R_r \tag{1}$$

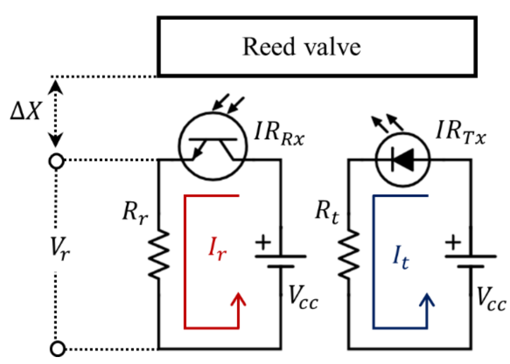


Figure 1: The schematics illustrating the working principle of the photoelectric sensor targeted for valve's dynamics measurements.

2.2 Installation of the photoelectric sensor

The developed photoelectric sensor (IR sensor) was installed inside the neck region of the suction muffler of the hermetic reciprocating compressor, targeted to measure the displacement of the suction valve as illustrated in Figure 2. The connecting wires of the photoelectric sensor were carefully routed through the suction muffler without disturbing the body of the muffler.

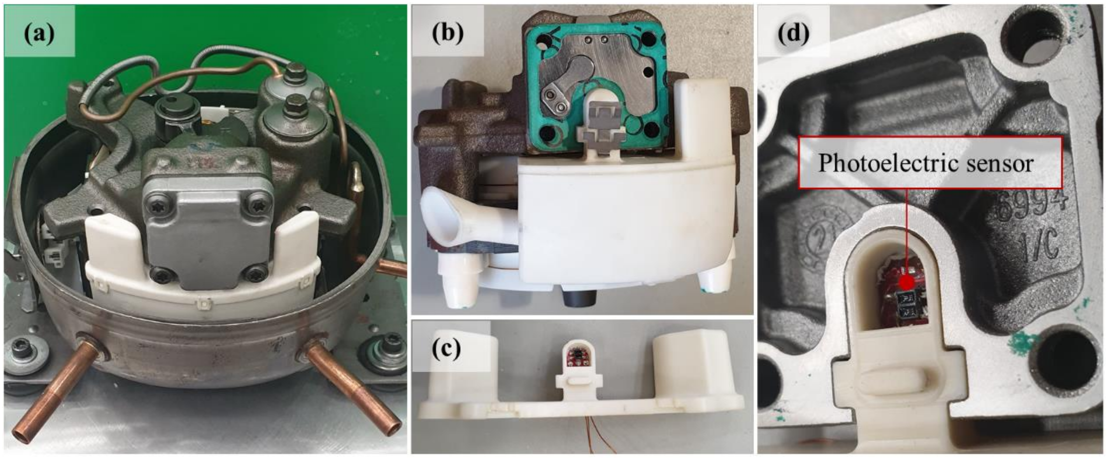
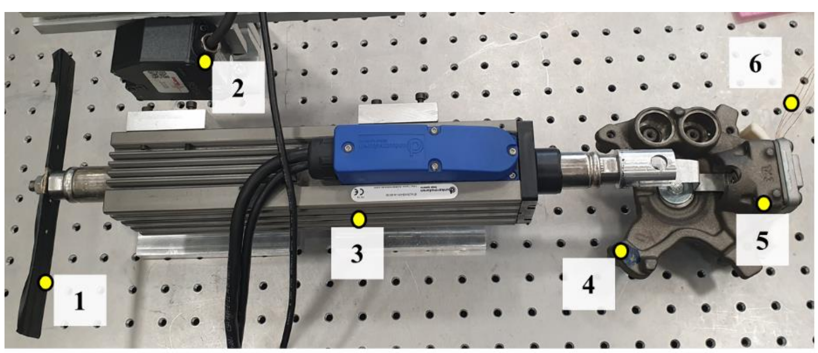


Figure 2: The installation of the photoelectric sensor in the suction muffler of the compressor (a) the hermetic reciprocating compressor used in the experiment, (b) the compressor's main body, (c) the disassembled suction muffler with the photoelectric sensor placement, (d) the cylinder head illustrating the neck of the suction muffler with the installed photoelectric sensor.

2.3 Calibration of the photoelectric sensor

The calibration setup comprised an electromechanical-based linear actuator (Dunkermotoren STB-1105), a laser displacement sensor (Keyence HK-052), the compressor body, and the data acquisition system, as shown in Figure 3. The calibration of the photoelectric sensor was performed by manually displacing the suction valve using the moveable shaft of the linear actuator in pre-determined steps, whereas the corresponding output voltage signal (V_r) of the photoelectric sensor was recorded through a data acquisition system at a sampling frequency of 10 kHz.



1. Laser reflector
2. Laser sensor
3. Linear actuator
4. Compressor body
5. Cylinder region
6. Photoelectric sensor wires

Figure 3: The calibration setup for the photoelectric sensor

The correlation between the output voltage of the photoelectric sensor and the suction valve's displacement was generated using linear regression, as shown in Figure 4 and Equation (2). The displacement of the suction valve varies linearly with the photoelectric sensor's output voltage.

$$X_s = 5.63(\Delta V_r) + 0.158 \quad (2)$$

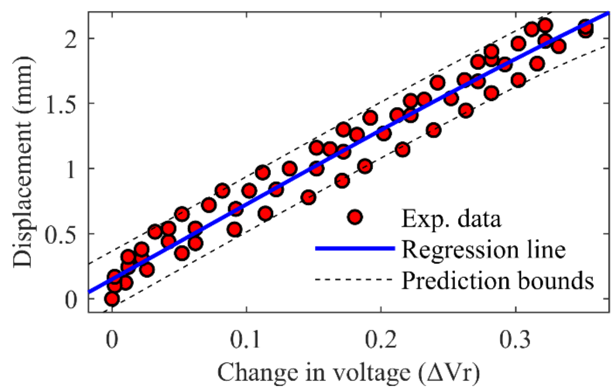


Figure 4: The correlation between the displacement of the suction valve versus the change in the output voltage of the photoelectric sensor

3. MATHEMATICAL MODEL

The fourth-order Runge-Kutta method is adopted to solve the coupled first-order differential equations system in MATLAB. Figure 5 shows the schematic diagram of the reciprocating compressor. It consists of a slider-crank mechanism, a cylinder and two chambers with reed-type valves for suction and discharge. To study the valve motion considering the cylinder as the only control volume is sufficient. Unsteady mass and energy balance equations are written in the control volume to calculate the in-cylinder gas properties during the compression cycle.

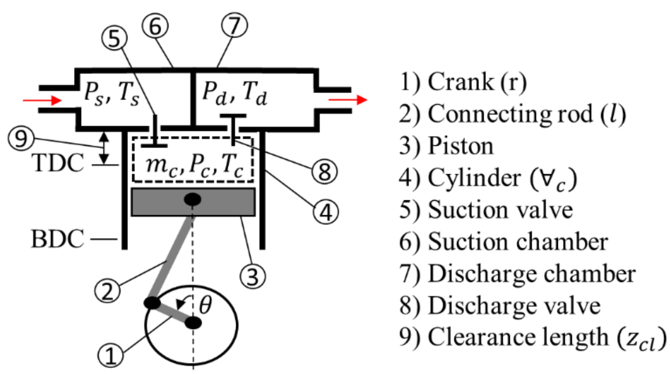


Figure 5: Schematic diagram of reciprocating compressor

3.1 Piston movement

A slider-crank mechanism is used in the compressor, which converts the crank's rotational movement to a linear reciprocating movement in the piston. The piston's distance from the cylinder head and its velocity are given by: (Touber, 1976)

$$z = z_{cl} + l + \mathrm{r} - \sqrt{l^2 - r^2 sin^2\theta} - \mathrm{r}cos\theta \quad (3)$$

$$\frac{dz}{dt} = \mathrm{r}\,\omega\, sin\theta\ (1 + \frac{rcos\theta}{\sqrt{l^2 - r^2 sin^2\theta}}) \quad (4)$$

3.2 Mass and energy balance

A mass balance equation with no valve leakage is given in Equation (5). The energy balance equation (first law of thermodynamics) in the cylinder by considering the gas as an ideal gas is given in Equation (6). The work term in the energy equation was replaced by $dW = Pd\forall$, and finally, the instantaneous temperature of the gas inside the cylinder can be deduced as shown in Equation (4). (Farzaneh-Gord & Khoshnazar, 2016)

$$\frac{dm_c}{dt} = \frac{dm_s}{dt} - \frac{dm_d}{dt} \tag{5}$$

$$\frac{dT_c}{dt} = \frac{1}{m_c\, c_v}\left(\frac{dQ_c}{dt} - P_c A_c \frac{dz}{dt} + \frac{dm_s}{dt} c_p T_s - \frac{dm_c}{dt} c_p T_c - c_v T_c \frac{dm_c}{dt}\right) \tag{6}$$

$\frac{dQ_c}{dt}$ is the heat transfer between gas inside the cylinder and the cylinder wall. In this study, since the aim is modeling the valve dynamics, therefore, this term was assumed to be zero.

3.3 Valve flow and dynamics

The well-known Saint-Venant-Wantzel Equation (7) was adopted to calculate the mass flow passing through the valve. This equation is valid under these assumptions: one-dimensional quasi-steady-state, isentropic flow in a converging nozzle, and ideal gas (Taranović *et al.*, 2017; Touber, 1976).

$$\frac{dm}{dt} = \alpha A_0 \sqrt{\frac{2k}{k-1} P_{up}\rho_{up}\left(\left(\frac{P_{do}}{P_{up}}\right)^{\frac{2}{k}} - \left(\frac{P_{d0}}{P_{up}}\right)^{\frac{k+1}{k}}\right)} \tag{7}$$

α is the semi-empirical flow coefficient which accounts for the effect of the viscosity, flow expansion after separation, and non-uniform state of gas in the cross-section. The reed valve is assumed as a one-dimensional mass-spring system, and Newton's second law is applied as shown in Equation (8).

$$m_v \frac{d^2 X_s}{dt^2} + c_f \frac{dX_s}{dt} + k_s(X_s + X_0) = C_g A_v \Delta P \tag{8}$$

On the left-hand side, the terms from left to right are inertia force, damping force, and spring force, respectively. The only term on the right-hand side corresponds to the gas force. C_g is called the gas force coefficient or the drag coefficient and ΔP is the pressure difference between the upstream and downstream sides of the valve.

To model valve rebound, a simple concept is applied. The valve's velocity after collision equals the velocity before the collision multiplied by a constant coefficient called rebound or restitution factor C_r (Habing, 2005).

$$\frac{dX_s}{dt}\Big|_{ah} = -C_r \frac{dX_s}{dt}\Big|_{bh} \tag{9}$$

3.4 Operating conditions

The experiments were performed in the laboratory environment with air as a working fluid under controlled ambient conditions where the temperature and relative humidity was 25±2°C and 60±3%, respectively. To analyze the performance of the photoelectric sensor in quantifying the dynamics of the suction valve, the compressor was driven at different rotating speeds (1150-4150 RPM) using a function generator. The compressor was detached from the refrigeration loop, and the discharge line was connected to the suction line to avoid the spillage of lubrication oil during the experiments. Therefore, the suction and the discharge pressures varied in the range of 1 bar to 1.5 bar at different rotating speeds.

The suction valve was made up of steel with a modulus of elasticity of 210 GPa, a natural frequency of 220 Hz, and a thickness of 0.2 mm.

4. PERFORMANCE ANALYSIS

The presence of lubrication oil inside the compressor casing directly affects the performance of the optical type sensors targeted to quantify the dynamics of the reed type valves. Therefore, a near-infrared (NIR) spectroscopy technique was adapted to analyze the transmission spectra of IR radiations through the lubrication oil presence in the test compressor. The NIR spectroscopy scan of the lubrication oil sample at a wavelength range of 0-3000 nm is illustrated in Figure 6.

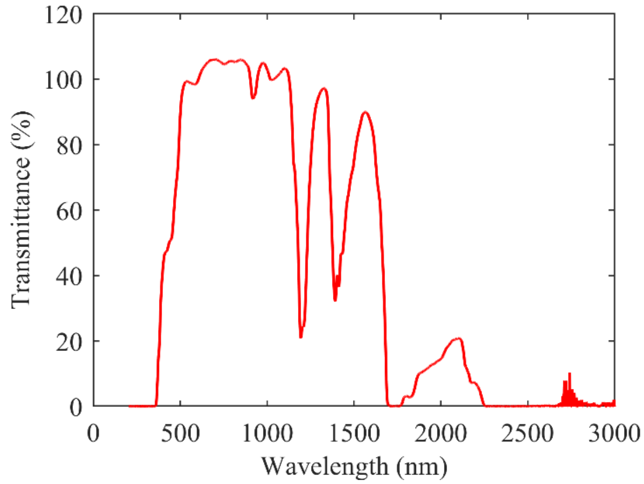


Figure 6: The near-infrared (NIR) spectroscopic scan illustrates the transmittance of IR radiations through the lubrication oil sample.

The results of the NIR scan depicted that the transmission of the IR radiations through the lubrication oil was maximum between 400-1150 nm wavelength. Therefore, the effect of the lubrication oil on the results of the developed photoelectric sensor (operating at 850 nm) stayed at a minimum level.

4.1 Valve displacement measurements

The simulated and the experimental results of the dynamic motion of the suction valve at rotating speeds of 1150 RPM, 2350 RPM, 3550 RPM, and 4150 RPM are shown in Figure 7. The horizontal axis represents the time scale in milliseconds, and the vertical axis represents the normalized displacement of the suction valve. The movement of the piston for one complete cycle was considered for comparison between the experimental and the mathematical model.

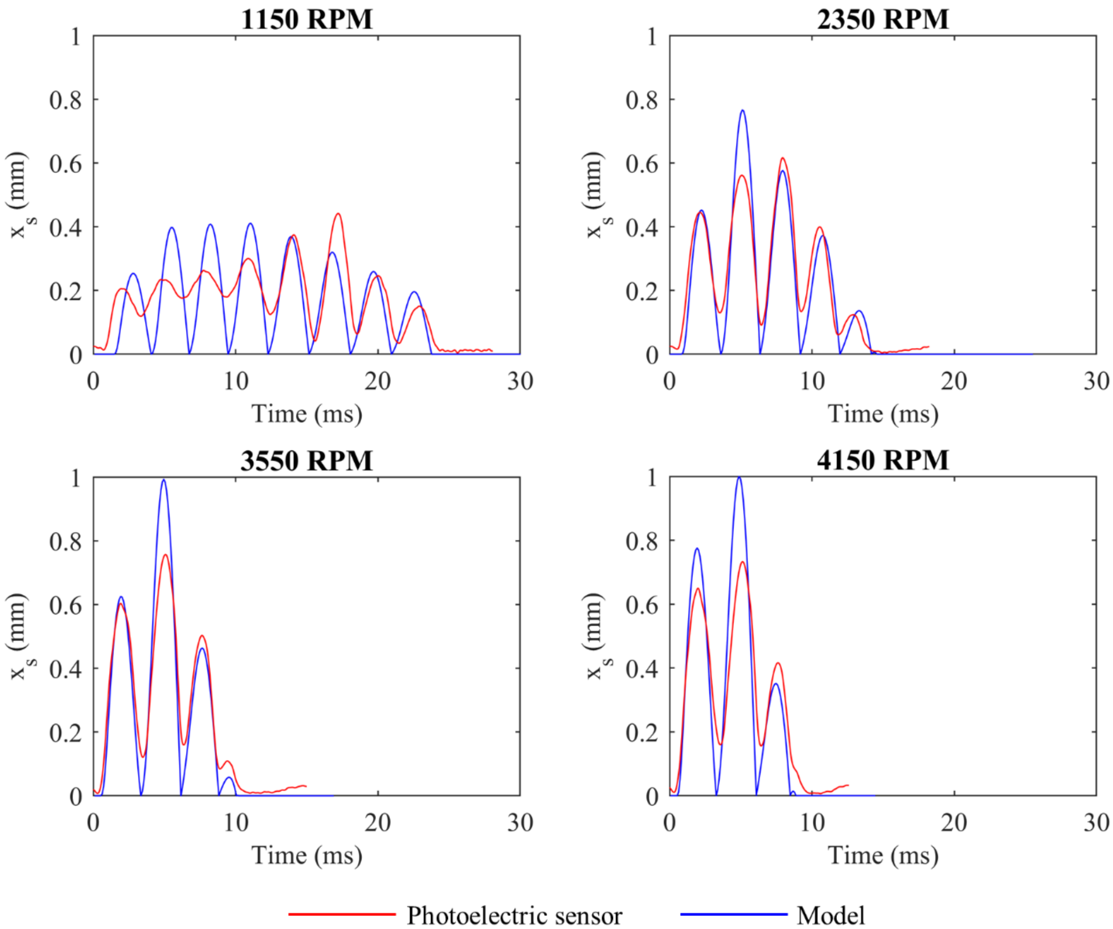


Figure 7: The normalized simulated and the experimental results of the dynamic motion of the suction valve at rotating speeds of 1150 RPM, 2350 RPM, 3550 RPM, and 4150 RPM

As illustrated in Figure 7, the simulated and the experimental results are in good agreement with each other regarding the number of flutters at all the rotating speeds of the compressor. In terms of the amplitude of the displacement (X_s) of the valve, the error margin between the simulated and the experimental results is high at low speeds (1150 RPM) in comparison to high speeds (from 2350 RPM to 4150 RPM). Furthermore, the maximum displacement of the suction valve increases in direct proportion to the compressor's rotation speed. This increase in the valve's displacement was attributed to the rate of change of cylinder pressure, consequent to the movement of the piston from TDC to BDC. The pressure difference between the cylinder and the suction muffler increases with the increasing speed of the compressor; consequently, the displacement of the suction valve also increases. The suction valve's vibration frequency remained almost constant with the compressor's rotation speed.

The maximum displacement and the total number of flutters of the suction valve at different rotation speeds of the compressor for all the experiments are illustrated in Figure 8.

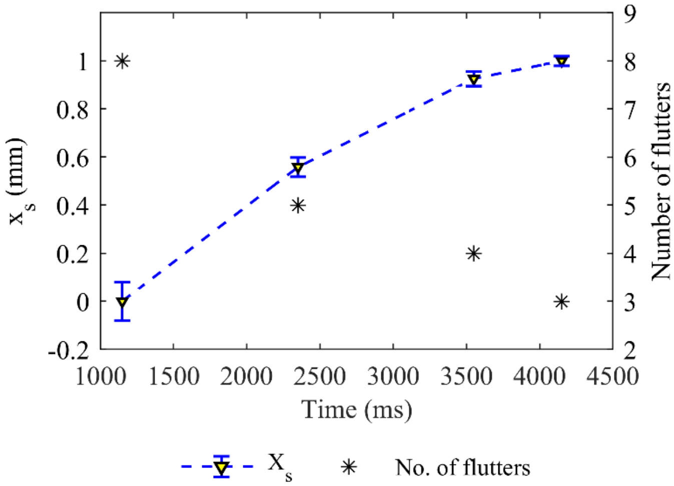


Figure 8: The maximum displacement and the total number of flutters of the suction valve at different rotation speeds of the compressor for all the experiments

The number of flutters of the suction valve decreases as the rotating speed of the compressor increases. The decrease in the flutter number of the suction valve was attributed to the decreased suction stroke time because of the increased rotating speed of the compressor.

Future studies will be targeted for validating the performance of the proposed photoelectric senor inside the refrigeration cycle under real operating conditions. In addition to that, the results of the newly developed photoelectric sensor can be compared with the commercially available sensors such as fiber optic and strain gauges. Furthermore, the developed photoelectric sensor was able to successfully quantify the dynamics of the reed valve at high rotating speeds of the compressor compared to low speeds. Therefore, at low speeds, more experimental investigations are required to improve the performance of the photoelectric sensor.

4.2 Cost comparison

The commercially available sensors that various experimental studies have employed are significantly expensive in terms of initial and operating costs. For example, a typical fiber optic sensor, as reported by Prasad and Woollatt (2000), a laser doppler vibrometer employed by Nagy *et al.* (2008), and a laser displacement sensor utilized by Mayer *et al.* (2014) have estimated costs, respectively ten times, hundred times, and thousand times higher than the approximated cost of the proposed photoelectric sensor in this study.

5. CONCLUSION

In summary, the development of a low-cost photoelectric sensor to quantify the dynamics of the suction valve in the hermetic reciprocating type compressor was presented. The photoelectric sensor was installed inside the neck of the suction muffler of a reciprocating compressor. The sensor was calibrated and validated to measure the motion of the suction valve with a 5% error margin. The results of the suction valve's dynamic behavior using a photoelectric sensor were compared with the mathematical model. The results indicated that the photoelectric sensor comprised of a transmitter/receiver pair successfully captured the dynamics of the reed valve inside the reciprocating compressor at higher rotating speeds compared to low speeds. The results further revealed that the maximum displacement of the suction valve increases with the compressor's rotation speed. Furthermore, the suction valve's vibration frequency stays almost constant, whereas the total number of flutters decreases with the increasing speed of the compressor.

NOMENCLATURE

Symbol

A_0	Valve flow area	(m^2)	r	Crank radius	(m)
A_v	Valve plate area	(m^2)	T	Temperature	(K)
ah	After hit	(-)	t	Time	(s)
bh	Before hit	(-)	V	Voltage	(v)
C_g	Gas force coefficient	(-)	X	Valve displacement	(m)
C_r	Rebound factor	(-)	X_0	Spring preload displacement	(m)
c_f	Damping coefficient	$N\ s\ m^{-1}$	z	Piston displacement	(m)
c_p	Specific heat at constant pressure	$(J\ kg^{-1}\ K^{-1})$	α	Flow coefficient	(-)
c_v	Specific heat at constant volume	$(J\ kg^{-1}\ K^{-1})$	R	Resistance	(Ω)
I	Current	(A)	RPM	Revolutions per minute	(rpm)
k	Specific heat ratio	(-)	∀	Volume	(m^3)
k_s	Spring stiffness	$(N\ m^{-1})$	Δ	Change quality	(-)
l	Connecting rod length	(m)	BDC	Bottom dead center	(-)
m	Gas mass	(kg)	IR	Infrared	(-)
m_v	Valve mass	(kg)	LDV	Laser doppler vibrometer	(-)
P	Pressure	(Pa)	TDC	Top dead center	(-)
Q	Heat transfer	(J)	VIP	Valve-In-Piston	(-)

Subscript

c	Cylinder	r	Receiver
cc	Common collector	Rx	Receiver
cl	Clearance	s	Suction
d	Discharge	Tx	Transmitter
do	Downstream	up	Upstream

REFERENCES

Malik, A.N., Khan, S.A., & Lazoglu, I., (2020). A novel hybrid frost detection and defrosting system for domestic refrigerators. *Int. J. Refrig. 117,* 256–268.

Buligan, G., Paone, N., Revel, G. M., & Tomasini, E. P. (2002). Valve lift measurement by optical techniques in compressors. *Proceedings of the International Compressor Engineering Conference at Purdue*. West Lafayette, USA.

Ludu, A., Betto, A., & Regner, G. (2000). Endoscope video of compressor valve motion and pressure measurement assist simulations for design improvements. *Proceedings of the International Compressor Engineering Conference at Purdue.* West Lafayette, USA.

Mayer, J., Bjerre, P., & Brune, F. (2014). A comparative study of different numerical models for flapper valve motion. *Proceedings of the International Compressor Engineering Conference at Purdue.* West Lafayette, USA.

Nagata, S., Nozaki, T., & Akizawa, T. (2010). Analysis of dynamic behavior of suction valve using strain gauge in reciprocating compressor. *Proceedings of the International Compressor Engineering Conference at Purdue.* West Lafayette, USA.

Nagy, D., Almbauer, R. A., Lang, W., & Burgstaller, A. (2008). Valve lift measurement for the validation of a compressor simulation model. *Proceedings of the International Compressor Engineering Conference at Purdue.* West Lafayette, USA.

Prasad, B. G., & Woollatt, D. (2000). Valve dynamic measurements in a VIP compressor. *Proceedings of the International Compressor Engineering Conference at Purdue.* West Lafayette, USA.

Zhang, W., Ji, L., Xing, Z., & Peng, X. (2018). Investigation on the suction reed valve motion with sticky force in a refrigerator compressor. *Energies*, *11*(11), 2897.

Costagliola, M. (1950). The theory of spring-loaded valves for reciprocating compressors. ASME. *J. Appl. Mech*. 17(4), 415–420

Farzaneh-Gord, M., & Khoshnazar, H. (2016). Valve fault detection for single-stage reciprocating compressors. *Journal of Natural Gas Science and Engineering*, *35*, 1239-1248.

Habing, R. A. (2005). Flow and plate motion in compressor valves. (Doctoral thesis, Twente University, Netherlands).
Jin, J., & Hong, W. (2012). Valve dynamic and thermal cycle model in stepless capacity regulation for reciprocating compressor. *Chinese journal of mechanical engineering, 25*(6), 1151-1160.

Longo, G. A., & Gasparella, A. (2003). Unsteady state analysis of the compression cycle of a hermetic reciprocating compressor. *international journal of refrigeration*, *26*(6), 681-689.

Taranović, D., Ninković, D., Davinić, A., Pešić, R., Glišović, J., & Milojević, S. (2017). Valve dynamics in reciprocating compressors for motor vehicles. *Tehnički vjesnik, 24*(Supplement 2), 313-319.

Touber, S. (1976). A contribution to the improvement of compressor valve design. (Doctoral thesis, Delft University of Technology, Netherlands).

Malik, A.N., Khan, S.A., & Lazoglu, I., (2021). A novel demand-actuated defrost approach based on the real-time thickness of frost for the energy conservation of a refrigerator. *Int. J. Refrig. 131,* 168–177.

ACKNOWLEDGEMENT

This research was supported by manufacturing and automation research center, mechanical engineering department, Koc university, Istanbul, Turkey and the Arcelik A.S. R&D Directorate 34950 Tuzla, Istanbul, Turkey.