Development of a Reconfigurable Prototype Peristaltic Compressor

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Abstract. Traditional positive displacement compressors require valves, internal volume ratios or both to operate. These two features generate the majority of the losses in compressors. The peristaltic compressor is a novel compressor architecture that feature valve-less compression with variable volume ratios, which provides the potential for highly efficient compression. This paper will present a design of a reconfigurable prototype peristaltic compressor and illustrate how the structure of the compression chamber and actuation pattern affect the compressor efficiency. The prototype utilizes a flexible diaphragm constrained and sealed against a female die to make a compression chamber. Linear actuators with male dies press the diaphragm sequentially against the female die to move and compress the fluid. Preliminary experiments were performed using air as the working fluid for volume ratios ranging from 1.143 to 8 and operational frequencies ranging from 1.28 to 2.31 Hz. These results suggest that the actuation pattern has an impact on the major parameters such as mass flow, displacement volume, and pressure ratio which influence the overall efficiency of the compressor.

1. Introduction
Refrigeration and air-conditioning systems are applications of the vapor compression cycle, which are widely used in various fields such as residential buildings, industry, aviation and transportation. Increasing demand for a more efficient vapor compression cycle has created the necessity for more innovative equipment, particularly for compressors. The compressor experiences significantly more losses than other components in a vapor compression cycle [1]. The main factors to these losses in positive displacement compressors are valves which cause leakage, port losses in the case of rotary and reciprocating compressors, and fixed volume ratios which cause over/under compression in the case of scroll and screw compressor [2].

A peristaltic compressor has the potential to operate at variable volume ratios without valves and is therefore an interesting candidate for efficient compression, particularly for the HVAC&R industry. The compressor consists of a linear cylindrical chamber. The chamber is formed by using a flexible material that serves as a diaphragm. The chamber can be compressed via electromechanical actuation methods to form a series of segmented compression pockets. Once adjacent electromechanical devices are actuated, a pocket is formed and is separated from the rest of the chamber. This compression is accomplished without the use of fixed volume ratios or valves. The ultimate goal is to evaluate this technology for HVAC&R purposes and understand its full potential in various applications.
A preliminary thermodynamic model of the peristaltic compressor has been developed, presented in a companion work by Islam & Bradshaw [3] using various diaphragm shapes, materials, actuation speeds and volume ratios which was leveraged to generate the design of a reconfigurable prototype by allowing the estimation of the required physical dimensions of the compressor. The prototype allows for a feasibility evaluation of this compression technology, providing an easy way to vary the volume ratio and diaphragm shape/materials to achieve the optimum capacity and volumetric efficiency. While the ultimate goal is refrigerant compression, air is currently being used as a working fluid, for experimental simplicity.

2. Literature Review

In recent years, diaphragms have been examined as a mechanism to be used as a compressor in vapor compression cycles. Previous work showed that the diaphragm offered the potential of a less leaky mechanism and ability to generate higher pressures [4]. The peristaltic actuation mechanism first introduced in a miniature compressor where a cylindrical elastic tube used to compress synchronously and discharge gas by using electrostrictive ceramic blocks. The efficiency of the system is very low due to energy consumption by the circuit and bigger size of the capacitors [5]. Saif et al. [6] developed an analytical model to predict the deformation and internal stress of the diaphragm. The model was studied under a circular cavity and a parabolic cavity condition. When the actuation occurred, in the first condition, a two-sided membrane coming towards to contact on a floor and for the second case, the upper membrane went down to the bottom layer of the cavity to compress the area. The result of the experiment indicated that the parabolic condition gives higher pressure. That implies, mass flow rate will be better when the compression chamber has a fixed gap area and the diaphragm actuation fills the area.

A computational analysis of a mesoscopic peristaltic compressor introduced a new actuation design where an electric field actuated a diaphragm to make a sinusoidal wave which moved the fluid through a channel. The compression ratio can be controlled by changing the depth of the cavity. The authors derived a geometric model, energy balance and diaphragm dynamics of the system. The theoretical analysis of the paper showed that the peristaltic compressor can perform the required work for a compressor. The analysis of physical testing is missing to evaluate the result and the author did not examine the heat transfer of the system [7].

Sathe et al. [8] developed a similar concept using progressive actuation of a single circular diaphragm in a compressor. An electrostatic actuation force was applied on the diaphragm in order to pull it down by using a DC voltage. In this segment, the inlet valve opens and refrigerant enters the chamber. After the suction stroke, a reversed applied voltage pulls off the diaphragm and opens the discharge valve to complete the compression stroke. A prototype was used to test the actuation of the diaphragm. The highest pressure rise of the prototype is 1.5 kPa, but the predicted pressure from the simulation was 30 kPa for R134a. The main limitation of this method is the sustainable pressure of the diaphragm [9].

Pressure and discharge volume rely on the actuation pattern of the diaphragm. Pressure rise to its maximum capacity when compression and discharge happen simultaneously. Performance of the compressor also increases when the forward stroke of the diaphragm occurs because the flow rate of the fluid is maximized at that point [10]. The main drawback of using electrostatic actuation is that, it may not be suitable for liquid because the electrostatic process may ionize the liquid. The displacement of the electrostatic actuation is also comparatively smaller than other actuation techniques. Chen et al. [11] proposed a rhombic micro displacement amplifier for a piezoelectric actuator which can improve the displacement by no more than 100 μm.

All the research for electrostatically actuated peristaltic compressors that use a diaphragm have some limitations and they are the theoretical model of microscale compressors. The efficiency of a compressor can be increased by reducing the irreversibility. The peristaltic compressor shows promise, as it can compress without an internal volume ratios and valves which leads the system to reduce the
irreversibility [1]. Previous work in this area developed only rudimentary prototypes for feasibility purposes and did not highlight these features. This work will present a more comprehensive prototype design that allows the ability to study the influence of variable volume ratios, valve-less operation, and easily reconfigurable geometry.

3. Reconfigurable Peristaltic Compressor Mechanism
The actuation of the diaphragm occurs sequentially along a linear axis by using 10 linear actuators. The flexibility of the diaphragm allows the process to perform the compression without any discharge and suction valves. The internal volume ratio of the compression chamber can also be modified by changing the actuation sequence. Preliminary testing is performed using air as the working fluid in the compression chamber. Figure 1 presents a schematic of the proposed re-configurable peristaltic compressor prototype. The diaphragm is constrained and sealed against a female die which creates a cylindrical compression chamber. A male die (piston) is attached to a linear actuator and presses the diaphragm against the female die to provide compression by sealing the chamber synchronously.

Figure 1: Reconfigurable prototype platform of a peristaltic compressor that has been designed for this study [12].

The actuators, which play a key role in the operation of the Peristaltic Compressor, are controlled by a programmable logic controller (PLC). These actuators are programmed using Rockwell Automation’s Studio 5000 programming language. The program was designed to provide a straightforward and intuitive way to operate the compressor. As such, there are only three operations the user needs to perform: turning on the servos, selecting the appropriate motion pattern, and starting and stopping the compression cycle.

The user can control the compression ratio of the current test by selecting an actuator as a pivotal piston which indicates when the fluid from the compression chamber will begin to discharge or by selecting an actuator as valve which will create several compression pockets. In order to achieve different volume ratios, we present two different actuation modes: Mode 1 and Mode 2. Each mode has several patterns that can be used to operate the compression process.
3.1. **Mode 1 Actuation**

For the first mode, the 1st and 10th piston will operate as the suction and discharge valves of the compressor. For example, consider a selection of the 7th piston as the pivotal piston, which is illustrated in Figure 2. Initially, all the pistons are up and the working fluid fills the diaphragm. Then, at step 2, the 1st and 10th pistons isolate the fluid within the compression chamber. At the start of compression in step 3, the 2nd to 6th piston will press the diaphragm sequentially and compress the fluid to a significantly smaller volume. Then in steps 4 and 5, when the system hits the 7th piston, simultaneously 7th to 9th piston will press the diaphragm in a sequence and the 10th piston will rise to allow fluid to discharge from the system.

![Figure 2: Schematic diagram of the operation with pivotal piston 7 selected for Mode 1.](image)

3.2. **Mode 2 Actuation**

For the second mode, a new compression pocket will be formed by using an actuator to separate two pockets of adjacent compression, this actuator is referred to as the valve. For example, suppose piston 4 is the valve and piston 7 is the pivotal piston, as illustrated in Figure 3.

![Figure 3: Schematic diagram of the operation with pivotal piston 7 and valve 4 selected for Mode 2.](image)
At the start of the process, the 4th piston presses the diaphragm. Then at step 2, the 1st and 10th pistons descend and creates two different compression pockets. The First pocket between the 1st and 4th pistons isolate the fluid, and compression starts at step 3 with the descension of the next piston. In step 4, the 3rd piston presses the diaphragm, and the valve piston starts to rise to move the compressed fluid into the next compression pocket. The actuation of the second pocket will act as in Mode 1. In the second pocket, 5th and 10th piston isolate the fluid and sequentially start to compress the fluid. In step 6-7, when the system hits the pivotal piston 7, simultaneously 7th to 9th pistons completely descend while the 10th piston ascends to discharge the fluid. In the meantime, 1st and 4th piston create another pocket to start the next cycle. This pattern will continue until the compressor is stopped.

These two modes can be controlled to achieve a large variety of volume ratios by choosing different pivotal pistons and valves. The volume ratios of the compression chamber that can be achieved vary from 1.143 to 8. The results from this large variety of volume ratios will allow for an efficient study of the influence of the volume ratio on relevant compressor metrics such as the volumetric efficiency.

4. Reconfigurable Prototype Design
The detailed design and manufacture of the prototype is presented in this section. The working platform for the compressor prototype is a movable cart. Atop this cart, the compressor frame was mounted. The frame contains the list of components shown in the SOLIDWORKS render of the final compressor design.

![Prototype Compressor Design](image)

This design contains the following: A steel frame, a machined aluminium channel and sealing components, and linear actuators. Male dies (Pistons) are connected to the actuators, and the diaphragm is attached and sealed with the female die. Understanding the seal paths of a component that would eventually be used with a flexible diaphragm while being “modular” in terms of component redesign or replacement was challenging. The advantage to making the compression chamber modular will be clearer in the future, as the research group will have the ability to change chamber profiles/dimensions with the replacement of one component rather than completely redesigning and manufacturing all parts. The chamber dimensions for the parts were taken from the thermodynamic model, and the remaining
work focused on diaphragm sealing. This was accomplished by the use of O-ring seals at each end of the compression chamber, with the seal bars running the length of the chamber to seal the diaphragm along the edges. A cross-sectional diagram of these components is shown below in Figure 5. The O-ring gland was designed with Marco gland design documentation for an outside diameter seal type based on a fixed bore diameter of 0.0254 [m] using a -020-size ring.

![Figure 5: Part design highlighting seal paths.](image)

All the parts installed on the steel frame as designed. At the inlet and outlet of the peristaltic compression chamber, both a pressure transducer and a resistance temperature detector (RTD) are mounted in a pipe network and used to measure pressure and temperature on either side of the compressor. An Omega mass flowmeter with analog output is used at the inlet of the compressor to measure the mass flow rate. Each of these sensors are integrated into the analog I/O module, which reads the data to be processed and displays it in the Studio 5000 software. A Recovery tank is used to collect the compressed fluid allow a continuous discharge pressure from the system through a metering valve. The metering valve is mounted at the outlet of the compressor to manage fluid flow and backpressure. By regulating the metering valve, the pressure ratio of the compressor can be controlled. Following Figure 6 shows the schematic of the prototype with the measuring sensors.

![Figure 6: Schematic of the compressor setup with the sensors.](image)

A 40-Durometer neoprene rubber sheet of 0.125" thickness is used as the diaphragm, and it is constrained against the female die with the seal bars and seal caps. Figure 7 (a) shows the construction of the diaphragm in the experimental setup. When the compressor is operational, the linear actuators sequentially press the diaphragm against female die and create a vacuum pocket. The process pulls air into the compression chamber from the inlet, which is open to the atmosphere. Figure 7 (b) demonstrates how the sensors are placed at the inlet to measure the flow rate, pressure and temperature of the suction fluid. During operation, the actuators compress the air and discharge it through the recovery tank. The pressure and temperature of the discharge fluid is measured by the outlet sensors, as illustrated in Figure 7 (c).
5. Preliminary Test Results

In the reconfigurable prototype compressor, various diaphragm shapes have been used which are also considered in the computational model. After an analysis, it was determined that the circular shape of the compression chamber has limitation to rebound the diaphragm properly during the linear actuation. When the diaphragm stayed flat on the female die, the mass flowrate and pressure ratio of the system increased, and the sealing pattern created a semi-circular compression chamber. An investigation also shows that the diaphragm gets stretch because of its elasticity due to linear actuation which keeps changing the displacement volume of the compression chamber. It takes around one hour of the actuation process on the diaphragm to become stable and after that, the displacement volume is measured to do the performance test of the prototype. Two different test matrices for Mode1 and Mode2 have been introduced where actuation speed, pivotal piston, valve and metering valve position (which controls the pressure ratio of the compressor) are considered.

The discharge pressure of the system is adjusted using the metering valve. The compressor is tested in a variety of metering valve positions including fully closed to test the pumping limit of the compressor prototype. The 1st and 10th pistons are acting as an inlet and discharge valve. 2nd to 9th pistons area is considered to calculate the displacement volume. The volumetric efficiency of the compressor is calculated by using the displacement volume, mass flow rate ($\dot{m}$) and compressor speed ($f [Hz]$) by using the following equation:

$$\eta_{vol} = \frac{\dot{m}}{\rho \dot{n} f V_{disp}}$$
Here, $\rho_{in}$ is the density at inlet and displacement volume of the compressor is $V_{disp}$. Figure 8 shows how the mass flow and volumetric efficiency of the system change for different pressure ratios. Both mass flowrate and volumetric efficiency decrease by increasing the pressure ratio. When operating the system with a higher pivotal piston the fluid is compressed over a larger area and when using a smaller pivotal piston, fluid is discharged earlier than higher pivotal pistons. For that reason, the mass flowrate improves when a higher pivotal piston is used for the actuation.

![Figure 8: Variation of the Mass flow rate and Volumetric efficiency with pressure ratio for Mode 1.](image)

For Mode 2, a different actuator (3-6) is used as the valve to change the actuation pattern and displacement volume of the compression chamber. The analysis shows that the area of the first compression pocket for valves 3 and 4 is relatively small. As a result, the system could not bring in enough fluid to be compressed in the second compression pocket, which impacts the overall efficiency and mass flow rate. Valve 5 for pivotal piston 6, 7, 8 & 9 and valve 6 for pivotal 7, 8 & 9 were chosen to analyse Mode 2, which is illustrated in the following figures.

![Figure 9: Variation of the Mass flow rate for Mode 2: a) When actuator 5 is used as a valve, b) When actuator 6 is used as a valve.](image)
As the analysis of Mode 2 indicates, the actuation mechanism pulls less mass, and during the compression on the second pocket, a certain amount of mass leaks backwards into the first compression pocket. In Mode 1, the fluid does not get enough space to leak backwards because of its pattern, which is described in the third section. Therefore, in the Mode 2 results, typically the pressure ratio of the system decreases by increasing the pivotal piston.

6. Conclusions

This paper presents the design and development of a reconfigurable prototype peristaltic compressor in order to help the reader understand its operation. The prototype design highlights the flexibility to modify the dies or compression chamber’s dimensions to find the most appropriate piston actuation pattern with results presented for two modes of operation. Preliminary test results from both modes suggest the peristaltic compressor can achieve higher volumetric efficiency by regulating the volume and pressure ratios. The design is also able to produce significant mass flow rate at relatively high volumetric efficiencies. The main drawback of the system is the material and shape of the diaphragm, which limits the pressure at the pumping limit. The material of the diaphragm needs to be soft as the elasticity of the material influences the ability to move fluid. Consequently, the diaphragm becomes worn over time and requires replacement. The flexible nature of the diaphragm results in each diaphragm having slightly different displaced volume, which may affect the displacement volume of the compression chamber. The analysis also showed that the more the fluid is compressed, the better the resulting volumetric efficiency.

The prototype compressor, and work captured in the above sections, serve as the starting point for future opportunities to advance the understanding of the novel design. The prototype will be used to validate a comprehensive mechanistic thermodynamic model. When validation has been completed by using air as a working fluid, the compressor model and prototype will be modified to process refrigerants. The compressor may then be connected to a small compressor hot-gas-bypass load stand which will allow for a more detailed understanding of the novel compressor’s performance in the context of a complete vapor compression cycle.

Figure 10: Variation of the Volumetric Efficiency for Mode 2: a) When actuator 5 is used as a valve, b) When actuator 6 is used as a valve.
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References

[1] Ahamed JU, Saidur R, Masjuki HH. A review on exergy analysis of vapor compression refrigeration system. Renew Sustain Energy Rev [Internet]. 2011;15(3):1593–600. Available from: http://dx.doi.org/10.1016/j.rser.2010.11.039

[2] Pearson A. What does the future hold for compressor manufacturers? Proc Inst Mech Eng Part E J Process Mech Eng. 2015;229(2):88–95.

[3] Islam M, Bradshaw C. Development of a Mechanistic Chamber Model of a Novel Peristaltic Compressor for Air-conditioning and Refrigeration Applications. In Purdue Conference, 2021; 2021.

[4] Bradshaw C, Islam M, Tubbs C. Peristaltic Mechanism for Compression of Compressible Fluids. US Provisional Patent Application 63/019,707, 2020.

[5] Lawless WN, Arenz RW, Cross LE, Lawless WN, Arenz RW. Miniature, solid-state gas compressor. Miniature, solid-state gas compressor. 1987;1487.

[6] Saif MTA, Alaca BE, Sehitoglu H. Analytical modeling of electrostatic membrane actuator for micro pumps. J Microelectromechanical Syst. 1999;8(3):335–45.

[7] Sulfridge MA, Miller NR. The Mesoscopic Peristaltic Compressor. 2001;61801(January).

[8] Sathe AA, Groll EA, Garimella S V. Analytical model for an electrostatically actuated miniature diaphragm compressor. J Micromechanics Microengineering. 2008;18(3).

[9] Sathe AA, Groll EA, Garimella S V. Optimization of electrostatically actuated miniature compressors for electronics cooling. Int J Refrig. 2009;32(7):1517–25.

[10] Mathew B, Hegab H. Analytical modeling of microscale diaphragm compressors. Appl Therm Eng.2013;51(1–2):130–6. http://dx.doi.org/10.1016/j.applthermaleng.2012.08.052

[11] Chen J, Zhang C, Xu M, Zi Y, Zhang X. Rhombic micro-displacement amplifier for piezoelectric actuator and its linear and hybrid model. Mech Syst Signal Process [Internet]. 2015;50–51:580–93. Available from: http://dx.doi.org/10.1016/j.ymssp.2014.05.047

[12] Bradshaw C. Development of a Novel Peristaltic Compressor for Air Conditioning Applications. ASHRAE 019-1819. Funding Source: ASHRAE Innovative Research Grant. Project Dates: S. 2019-present. 2017.