

ENC-2022-0723

MODELING, OPTIMIZATION AND PROTOTYPING OF A CENTRIFUGAL AIR COMPRESSOR FOR PORTABLE ARTIFICIAL RESPIRATORS

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Abstract. Centrifugal air compressors are used in artificial respiration applications due to their constructive simplicity, robustness and reduced size. This type of compressor is suitable in situations where high output pressures are not required, such as artificial lungs. In this sense, this project tested a physical-mathematical model that allowed us to evaluate, with a great level of detail, the performance of a centrifugal compressor used in artificial respiration applications. The model was validated with experimental data from commercial manufacturers of air compressors. Then, this model was used in the optimization of geometry and operational conditions and artificial breathing applications, where it aimed to reduce energy wear and portable battery-powered applications, for this purpose, eleven losses were implemented following the theoretical model from the Euler equation. After the optimization step, a prototype of the compressor was built on a 3D printer making it possible to obtain a performance curve through the use of pressure, flow, rotation and electric power sensors. The compressor in its optimized form was tested on an artificial lung, using a filling balloon in its simulation, allowing data to be obtained that proved the efficiency of its performance.

Keywords: *Centrifugal compressor, artificial respirators, loss correlation set, optimization, performance.*

1. INTRODUCTION

An air compressor is a positive displacement flow machine, that is, energy transfer is effected by volume variations that occur due to the movement of the boundary on which the fluid is confined. Compressors used in artificial respirators are usually centrifugal, which are characterized by having radial discharge flow (Fox, Mcdonald's, 2011). The growing need for centrifugal air compressors for applications in the use of artificial respiration already existed and was intensified after the occurrence of the global pandemic caused by the Covid-19 virus. In this context, the choice of centrifugal compressor is due to its constructive simplicity, robustness and reduced size, which makes it a reference technology. The structure of a centrifugal compressor used is exemplified by Fig. 1.

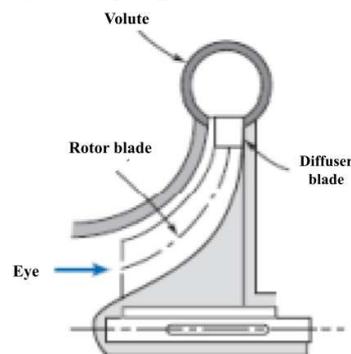


Figure 1. Schematic diagram of centrifugal compressor. (Fox, Mcdonald's, 2011)

These types of compressors are designed so that they can provide a relatively small discharge with a high value load. According to the rotary movement of the rotor, the fluid is suctioned to the rotor eye through the feed section of the compressor and flows radially out of the rotor, developing a rotary movement. The air enters through the center of the moving rotor, and is directed to the vanes, where it is driven to the periphery of the rotor out of its discharge openings, entering the volute, that is, the volute (Chaowei et al.2019).

In view of the model presented and its relevance, it was understood the need for improvement work aimed at reducing energy expenditure in portable battery-powered applications. This work will therefore present the physico-mathematical model with a great level of detail of compressor performance through the loss ratio in the compressor with the Euler equation; a DC motor model was also used, which is a direct current motor. It is worth noting that centrifugal fans are widely used by industries in the most diverse applications. In addition to the improvements mentioned, compressor optimization included prototyping on a 3D printer of a centrifugal compressor and obtaining a performance modeling curve.

2. THEORETICAL FRAMEWORK

2.1 Calculation of losses

This work was based on the loss ratio in the compressor with the Euler equation. The detailing of these losses provides the parameters that make it possible to measure and improve the model studied. Extracted from the article (Xuezhi *et. al* 2019). These losses are listed below:

Losses and authors

- 1 Input guide vane diffuser. (Galvas)
- 2 Loss of friction of the skin. (Jansen)
- 3 Loss of blade load. (Coppage,Aungier)
- 4 Loss of mixing. (Johnston and Dean, Aungier)
- 5 Cutting-edge slack loss. (Rodgers et al.)
- 6 Loss of incidence. (Conrad, Aungier, Galvas)
- 7 Loss of input diffusion. (Aungier)
- 8 Loss of strangulation. (Aungier)
- 9 Loss of shock. (Aungier, Whitfield and Baines)
- 10 Loss of friction of the disc. (Daily et al.)
- 11 Loss of recirculation. (Coppage, Oh)
- 12 Loss due to leakage. (Aungier, Jansen)
- 13 Loss of diffuser without van. (Stanitz)
- 14 Loss of the radial diffuser with fins. (Aungier)
- 15 Loss of curvature of 90 degrees. (Aungier)
- 16 Loss of the diffuser with axial fin. (Galvas)

2.2 Euler's equation

Coming from the conservation of the amount of angular movement, the Euler equation is used as a basic theory in the modeling of the centrifugal compressor, assuming the following format:

$$\Delta H_{Euler} = U_3 C_{3u} - U_2 C_{2u} \quad (1)$$

Where H_{Euler} is the specific enthalpy, U is the peripheral speed of the rotor and C is the tangential velocity of the fluid at the rotor outlet and inlet, respectively. This equation allows the determination of the maximum enthalpy gain of an ideal compressor. (Fang et al. 2014)

Given the Euler equation, the isentropic efficiency of the compressor can be calculated from the inclusion of losses that occur between the inlet and outlet of the compressor. (Xuezhi et al. 2014). These losses include: i) losses in the inlet nozzle; losses in the rotor (shear losses on the surface, blade losses, losses due to mixing, losses at the tip of the blades, losses at the rotor inlet, blocking losses, friction losses in the rotor, recirculation losses, leakage losses) and losses in the diffuser (loss of the outlet nozzles, losses of the axial outlet nozzles, loss of 90° curve). All these losses can be seen in Eq. (2):

$$\eta_s = \frac{\Delta H_{Euler} - \Delta H_{int} - \Delta H_{IGV} - \Delta H_D}{\Delta H_{Euler} + \Delta H_{par}} \quad (2)$$

Where η_s is the isentropic efficiency, ΔH_{Euler} the specific enthalpy gain given by the Euler equation, ΔH_{int} rotor losses, ΔH_{IGV} inlet nozzle losses, ΔH_D diffuser losses and ΔH_{par} is parasitic enthalpy due to recirculation, leaks, and rotor. The specific work made available by the compressor for flow is:

$$w_{disp} = \eta_s \Delta H_{Euler} + \Delta H_{par} \quad (3)$$

Where w is the specific work and η_s is the efficiency defined in the Eq. (2).

2.3 DC motor model

For this experiment, a DC motor model was used, which is a direct current motor, and this will have the following configuration:

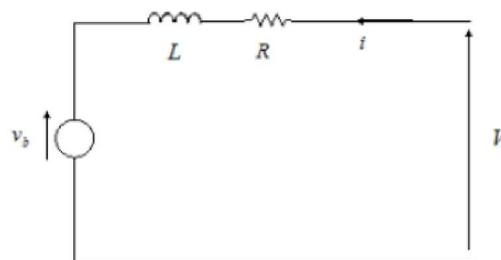


Figure 2. DC motor model.

From the electrical circuit model and the mechanical model of the electric motor, the following equations are obtained for a DC motor operating in permanent regime.

$$I_{electric} = \frac{V_{electric} - (K_{motor} \times \Omega)}{R_{arm}} \quad (4)$$

$$P_{initial\ electrical} = V_{electric} \times I_{electric}^2 \quad (5)$$

$$P_{mec} = P_{init\ ele.} - [I_{electric}^2 \times R_{arm} - B_{motor} \times \Omega^2] \quad (6)$$

In Eq. (4) $I_{electric}$ represents the electric current, which is given in ampere, $V_{electric}$ is the electrical voltage, given in volts, K_{motor} is the constant of engine motor torque, Ω represents the angular velocity and finally, R_{arm} is the armature resistance, this is given in Ohm. As for Eq. (5) we have $P_{initial\ electrical}$ which is the initial electrical power, given in watts. The voltage and current given by Eq. (5) has already been explained by Eq. (4). Finally, in Eq. (6) we have the mechanical power, also given in watt and B_{motor} which is the constant of friction of the engine. The values of the variables K_{motor} , R_{arm} and B_{motor} are obtained through measurements.

2.3 Simulation of spontaneous breathing of the human lung

To support the experiment, we used the article (Liming et al., 2019) with spontaneous breathing. In this study, a pneumatic model was created and a mathematical relationship was proposed, an experimental device was built and used in the prototype: pressure and flow sensors, a data acquisition card, a data analysis computer that were added to the mechanical ventilation system to collect pressure and flow data and analyze the curves that would be generated. (Liming et al., 2019) The experimental prototype of this citation used an active lung ASL5000 to simulate spontaneous breathing of the human lung with high precision. For such a simulation, the lung simulator is separated from the ventilator and works independently. The principle of the pulmonary phantom says that the difference in muscle pressure provides the power for spontaneous breathing, because when inhaling the respiratory muscle it works by changing the volume of the abdominal cavity and thoracic cavity. A respiratory cycle is defined has a duration of 4s, 1s for the inspiratory time and

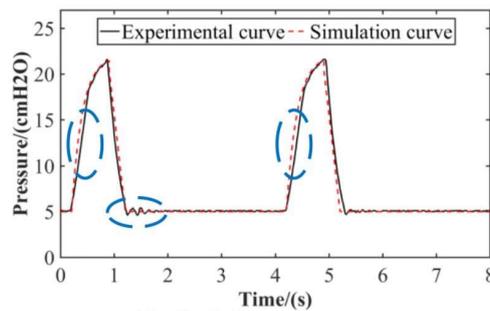
3s for the expiratory period and the curvature of change produced by the respiratory muscles approximately satisfies the sinusoidal curvature. It is assumed that the change in pressure generated by the respiratory muscles acts only during inhalation, and the work is carried out mainly by the elastic recoil force of the lungs and chest wall during expiration. (Liming H.et al. 2019)

Based on these data, an experiment and mathematical simulation of mechanical ventilation in pressure support ventilation (PSV) mode was carried out, varying the degrees of spontaneous breathing; this pressure support is used to facilitate spontaneous breathing during mechanical ventilation. The treatment of mechanical ventilation in patients with chronic obstructive pulmonary disease (COPD) was taken as an example. The type of function and the shape of the curve of the muscle pressure difference are the same as in the mathematical simulation of healthy people. However, the Pmus is adjusted to 5 cmH₂O, indicating a significant reduction in the patient's ability to perform spontaneous breathing. (Liming H.et al. 2019)

In pressure support ventilation mode (PSV), the operating pressure of the fan works as a function by Parts. When a respiratory flow is detected, the ventilator is triggered and the firing time is expressed. (Liming H.et al. 2019)

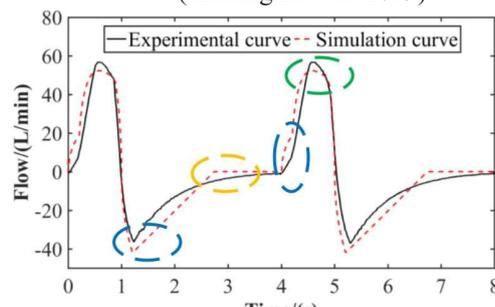
The results obtained through the experiments provided data graphically, they are ventilation pressure curves, flow, tidal volume and pressure of the mechanical ventilation system in PSV mode. These were the curves with the results that guided the experiment and are shown in sequence. (Liming H.et al. 2019)

Figure 3. shows that the experimental values lag behind the simulated values, and the experimental absolute values of expiratory flow and inspiratory pressure are lower than the simulated values. These phenomena are surrounded by blue dotted lines in the figure. The reasons can be attributed to the piston resistance in the active lung simulator, the canal resistance in the flow sensor and other additional dissipations. For the same reasons, the pressure value shows a short-term oscillation in the corner of Fig 3. (a). (Liming H.et al. 2019)



(a) Ventilation pressure curve

Figure 3. (a). Ventilation pressure curve with experimental curve and simulation curve. (Liming H.et al. 2019)



(b) Flow curve

Figure 3. (b). Flow curve with experimental curve and simulation curve.(Liming H.et al. 2019)

3. METHOD

3.1. Modeling and optimization

To perform the modeling of the centrifugal compressor, the Euler Eq. (1) was used as a reference to determine the maximum enthalpy gain for the compressor. After determining the enthalpy gain, the next step was to define the isentropic efficiency given by calculating the losses in the input nozzle, rotor and diffuser, demonstrated by Eq. (2). The specific work made available by the compressor at flow was also important for the modeling construction of the prototype, it was found through Eq. (3).

One of the main objectives of the prototype is to carry out three important conversions, these being the generation of electric power through the electric motor, similarly, the electric energy will be converted into mechanical energy and finally, the transformation of mechanical energy into hydraulic flow energy occurred. For such transformations, the DC motor was used for the conversion of electric energy through its mathematical modeling, made through the equations of electric current (4), initial electric power given by Eq. (5) and the mechanical power Eq. (6). In this way, we model the centrifugal compressor.

Through the study of the characteristics of human respiration, it was possible to understand what the main application needs were. Graphs a and b in Fig. 2 were used as a basis to define the parameters to be optimized, since they provided the values of the experimental data of the simulated values. Through the ventilation pressure, flow, tidal volume and pulmonary pressure curves, we used these observed values and generated a graphic map that defined the main parameters for our compressor, thus allowing us to define what was the desired maximum pressure and flow rate for better consumption, reaching the ideal values of 2 kPa and a flow rate of 60 L/min. Fig. 4.

The next step was to carry out its optimization, therefore, it was attempted to reduce as much as possible the number of losses, losses that will be subtracted from the Euler equation.

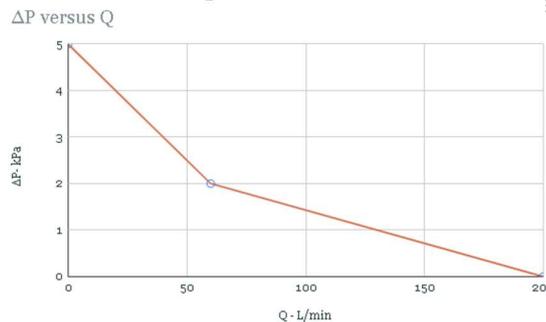


Figure 4. Maximum pressure chart and ideal flow rate.

3.2 Method of calculating the parameters

The calculation of losses was carried out in an EES (Engry Equation Solver) software program, in this program, the main losses were implemented so that it was possible to find a partial result and proceed with the validation of the model. In the program it was possible, through the code implemented and data entered, to generate a curve that compares the values of a compressor from a manufacturer with the ones from this work. This was the case with each new loss implemented, enriching the level of detail so that the optimization of the compressor can be carried out.

3.3 Experimental assembly

To carry out the experiments, a bench was set up that was improved according to the development of the research. This bench had a tested compressor, pressure sensors to determine the increase in enthalpy given by the compressor, valve for flow regulation, nozzle plate for air flow measurement, compressor rotor rotation sensor and the compressor that had been optimized and installed.

3.4 Experimental procedure

After using the compressor model built in the first test version, the final prototype model was created and printed. After the printing, this compressor was installed on a bench.



Figure 5. Final prototype.

To do the experiment and perform the measurements, the valve was left open at a fixed voltage of 2.6 volts, the data was saved and the pressure of the compressor was measured, as well as its flow rate, these measurements will generate

points in the graph. As the valve opened, the flow rate was gradually reduced, causing an increase in pressure until the flow reached zero. To observe such variations, the software LabVIEW was used, which is a systems engineering software created specifically for test, measurement and control applications, with easy access to hardware. On the display of this software it was possible to follow the variations in pressure, rotation, temperature and flow values.

3.5 Prototype Construction

The prototype of the compressor was initially designed in the software called FreeCAD, a 3D parametric CAD modeler. This software is aimed directly at use in mechanical engineering and product design. The measures that allowed the improvement of its efficiency and performance were adjusted. Fig. 6.

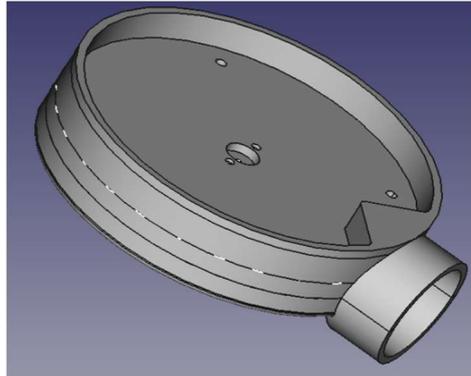


Figure 6. Compressor model modeled in FreeCAD.

After printing the prototype on a 3D printer, this is the final result achieved for our compressor.



Figure 7. Printed final prototype with separation of the rotor and carapace.



Figure 8. Final prototype printed and closed.

4. RESULTS AND DISCUSSIONS

4.1 Optimization curves and compressor choice

From the curve in Fig. 4 it was possible to establish the values we would like to achieve for the creation of the compressor. The value obtained was a pressure of 2 kPa and a flow rate of 60L/min. From this graph, a limit curve for the solution of the compressor model was generated, and we chose a solution for the model that was above this 2 kPa curve. Although there are infinite solutions, the ideal solution was the one that used the least amount of energy for the application.

The following graphs are the results obtained through the model generated, thus, when analyzing the electric power curve, a point was selected on the curve that indicated that the lower the electrical voltage, the lower the voltage used by our rotor, respecting the pressure limit of 2 kPa. In this way, we were directed to the lowest points, which indicate higher measurement values for the creation of the rotor. the model was simulated several times by varying the outer diameter of the rotor and the voltage, these values allowed the creation of the maps that are graphically expressed in Fig. 9, Fig. 10, Fig. 11, Fig. 12 and from this, the radius and voltage were chosen for analysis of the efficiency of the system, with values of 34 mm for the radius of the rotor and 2.3 volts for the voltage.

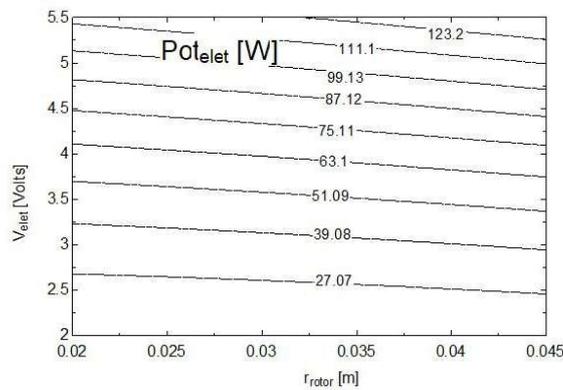


Figure 9. Electric power graph.

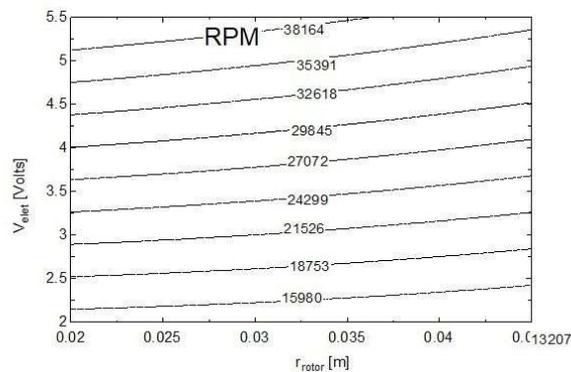


Figure 10. Rotations per minute graph.

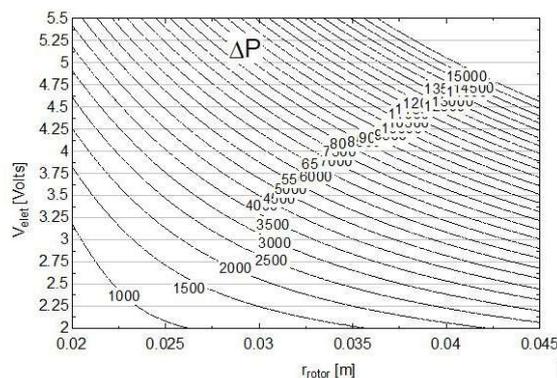


Figure 11. Pressure variation graph.

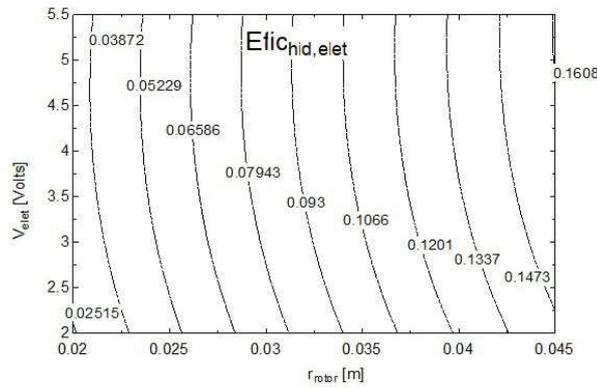


Figure 12. Hydraulic and electrical efficiency graph.

4.2 Tests and comparison with model

After the initial test have finished, inserted the losses and optimized the compressor, new tests were carried out and the new result obtained can be seen in Fig. 13. The graph proves through the depression variation curve that the optimization has achieved the objectives stipulated by this project, that is, the model and the experiment are complying with the pressure requirements of 2 kPa at a flow rate of 60L/min.

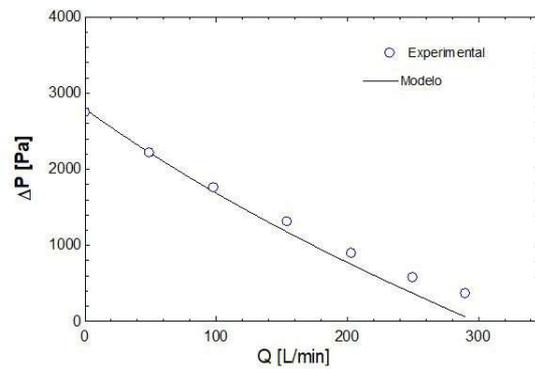


Figure 13. Final result Model vs Experiment.

Figure 14 shows the modified losses for the geometry of the built rotor. It is noted that losses due to contraction and expansion affects along the compressor have a great effect on performance. Losses due to surface friction also have a relevant effect, along with the 90° curvature of the flow. The loss due to recirculation proved to be important mainly for low flows.

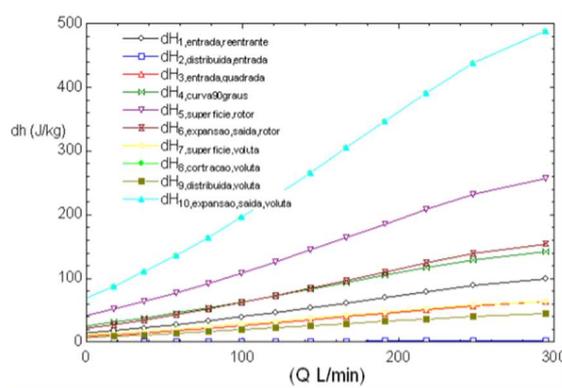


Figure 14. Losses calculated for the built compressor.

4.3 Simulation test

After completion of the tests and comparison with the model, a balloon was used to perform the transient test for filling and emptying test lung. In this way, it was possible to analyze what will be the effect of our rotor on human breathing after its optimization. Good results were achieved, indicating once again the efficiency of the centrifugal compressor. Such results can be seen in Fig. 15. Positive flow rates indicate lung filling (inspiration) and negative expiration flows.

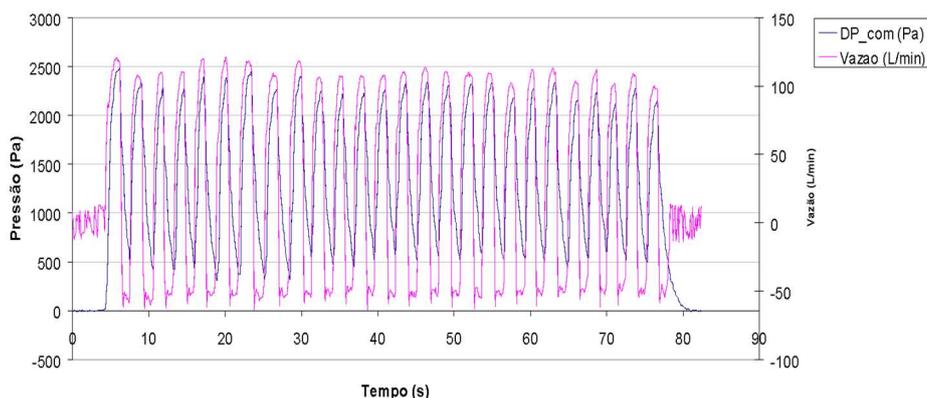


Figure 15. Lung inflation and emptying test with pressure, time and flow values.

5. CONCLUSION

Through this work, 11 losses were added to the theoretical model from the Euler equation, allowing its optimization in order to meet the demands generated by the difficulty in the respiratory tract, whether caused by the Covid-19 virus or any other disease that prevents a natural functioning of human breathing. The model was also validated, from comparisons with data from manufacturers' catalogs, generating graphic experimental data that allowed us to assimilate and analyze the proposed results. The compressor in its optimized form was tested on an artificial lung, using a filling balloon in its simulation, allowing the obtaining of data that prove the efficiency of its performance. The prototype of the centrifugal compressor printed on a 3D printer and applied to the mechanical ventilation system was tested, allowing the obtaining of a performance curve in which it shows that the objectives proposed by this research have been achieved, in order to reduce its energy consumption for the application of artificial respiration.

6. ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian Association of Mechanical Sciences (ABCM) for the financial support throughout the research period.

7. REFERENCES

- Aires, Margarida. Fisiologia. 5^oed, 2018. Guanabara Koogan-RJ
- Araújo, A. M. Ventilação Aplicada à Engenharia de Segurança do Trabalho. Recife, 2009.
- Dixon, S.L. Fluid Mechanics, *Thermodynamics of Turbomachinery*. Butterworth-Heinemann, (1998).
- Fang, X. Chen, W. Zhou, Z., Xu, Y. Empirical models for efficiency and mass flow rate of centrifugal compressors, *Int. Journal of refrigeration* 41 (2014) 190-199.
- Finco, Felipe. Projeto e validação experimental de um ventilador pulmonar. Universidade de São Paulo. São Carlos, 2021.
- Guyton, Arthur C.; HALL, John E. Tratado de Fisiologia Médica. 13^o ed. Rio de Janeiro: Editora Elsevier Ltda, 2017.

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Liming H., Yan S., Maolin C., Shuai R., Yixuan W., Hao Z., Qihui Y. Dynamic Characteristics of a mechanical ventilation system whit spontaneous breathing, IEEE Access DOI : 10.1109/ACCESS.2019.2955075 (2019).

Pritchard P. J. Fox, Mcdonald's. Introduction to Fluidynamics. 8ed. (2011). Dixon, S.L.

Xuezhi, D. Xiyang, L. Zhigang, S. Shixun, W., Qing, G. Chunqing, T. A method to select loss correlations for centrifugal compressor performance prediction, Aerospace Science and Technology 93 (2019) 105335

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