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ABSTRACT

The Design approach of hermetic compressors for household refrigeration usually follows a sequence that considers an initial concept, normally based on existing families (goal here is incremental optimization or design itself). Those designs are then upgraded with new features aiming improvements in efficiency, sound quality or even cost reduction. Compressors usually have a cylinder head that fits discharge and suction valve. In a new and compact design for linear compressor, the suction valve is placed on the top of the piston, requiring new shapes in order to make it possible to comply with gas flow, fatigue and dynamic requirements. This article aims to present the use of an optimization procedure to develop the suction valve design for this type of compressor. The results obtained in terms of performance and reliability with the optimization process and final results in compressor are presented.

1. INTRODUCTION

In recent years, industry has been challenged to develop more efficient machines and equipments, in order to reduce consumption and save energy. This demand has been promoted by governments and other institutes with the final objective of reducing investments in energy generation and protect the planet. Governments have been placing restrictions to the commercialization of household electric machines with lower energetic efficiency, compelling the industries in this sector to invest more and more efforts to take care of these new requirements. In the household refrigeration industry for example, the efficiency targets for the next years are very compelling. Another positive effect of this increase in equipment's efficiency trend, is that it represents money saving for the end user, once the energy cost is becoming higher year over year.

Another significant factor in the design of machines and equipments is related to the size. Final user is increasingly concerned with the space optimization, and harmony with the environment in which the equipments are fit. The same trend can be observed in the household refrigeration industry, and particularly in the hermetic compressor industry. New technologies are constantly being developed with higher efficiency, lower size and weight, and that can offer more options for the installation in the systems.

As an attempt to comply with this rising demand, a technology of reciprocating compressor driven by a linear motor was developed. This type of compressor has its stroke controlled by an electronic central board called inverter, once it does not have a fixed stroke. This compressor is presented in Figure 1, which illustrates the machine in a cut view, as well as its main components.

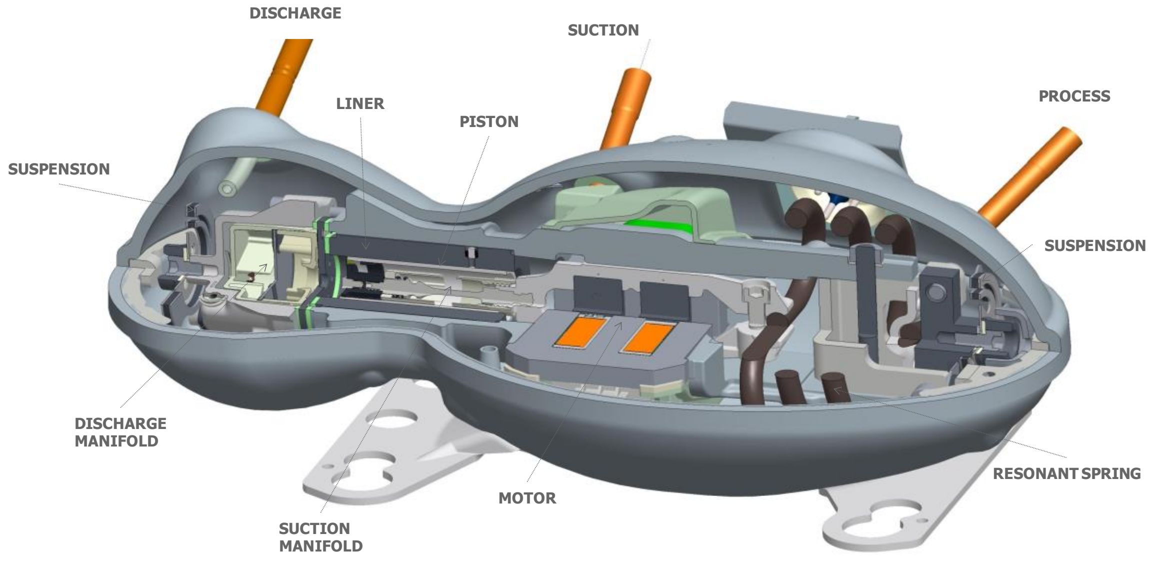


Figure 1: Linear compressor technology.

This technology also presents other innovative characteristics, which are listed below:

- A low height, that allows internal refrigerator space saving;
- It does not require lubricating oil, that allows a unique and total friendly characteristic related to the environment, as well as flexibility for installation;
- A larger capacity range, allowing lower temperature variation, and better food preservation;
- A better sound quality due to lower vibration and lower sound variation in-between starting, running and stopping,

The development of the new technology requires the use of new knowledge and methods, as well as new tests and approval criteria. One of the fundamental systems in this kind of compressor is the suction manifold. In this technology, this process is done through the piston, and the suction valve is placed at its top, as illustrated in Figure 2. This article aims to present the methodology used to develop the valve geometry, considering efficiency and reliability criteria necessary for this type of component. Final efficiency results are also presented in comparison with another valve geometry evaluated.

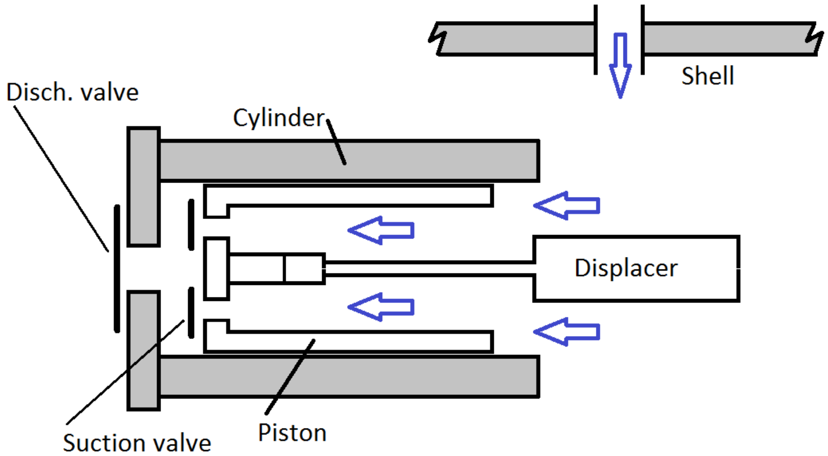


Figure 2: Schematic view of the linear compressor suction manifold

2. SUCTION VALVE OPTIMIZATION

According to Bortoli and Puff (1998), the use of design optimization together with FEM – Finite Element Method – is a powerful tool to improve the compressor components' design. It is not a magic box and depends a lot on the problem formulation quality. The optimum is just a function of the design variables, and the problem must be as simple as possible to reduce computer run time.

The main objective of this article is to perform the suction valve optimization, considering that it is assembled on the piston top. The main design variables were considered, although defining only one reduced thickness. The optimization software ModeFrontier was used together with the FEM software ANSYS to perform the optimization. The design variables are described in Table 1, and illustrated in Figure 3.

Table 1: Design Variables

Variable	Description
NP	Number of valve legs
E1	Width at the first leg region
E2	Width in the middle of the leg
E3	Width at the final portion of the leg
RR1	Fillet radius at the beginning of the leg
RR2	Fillet radius at the end of the leg

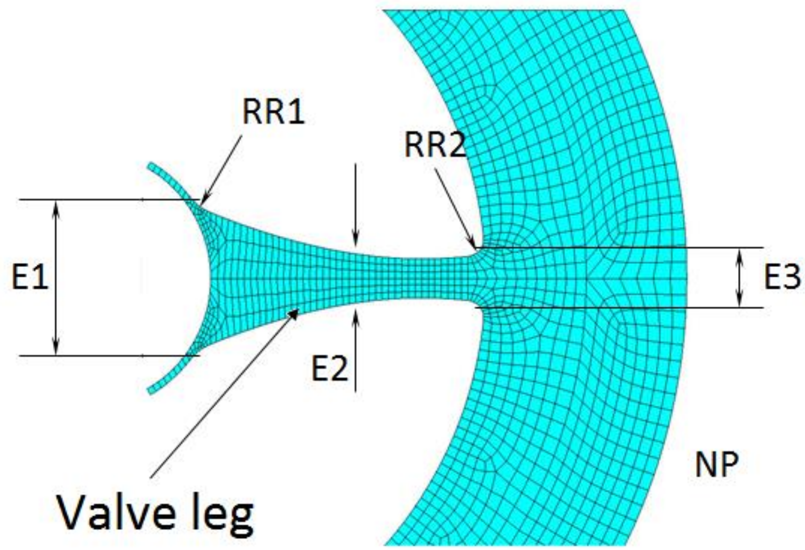


Figure 3: Illustration of the design variables

Once the design variables were defined, the optimization strategy was assembled, aiming to minimize the objective function, defined as the ratio between the maximum stress S_{max} and the valve stiffness K, as defined in Equation (1).

$$F_{obj} = \frac{S_{\max}}{K} \tag{1}$$

An APDL (2) – Ansys Parametric Design Language – was developed in order to have an automatic way to generate the designs according to the design variables. This application takes the design variables, builds the models and runs the FEM analysis. At the end, response variables are extracted. Figure 4 illustrates the optimization scheme assembled to perform the process.

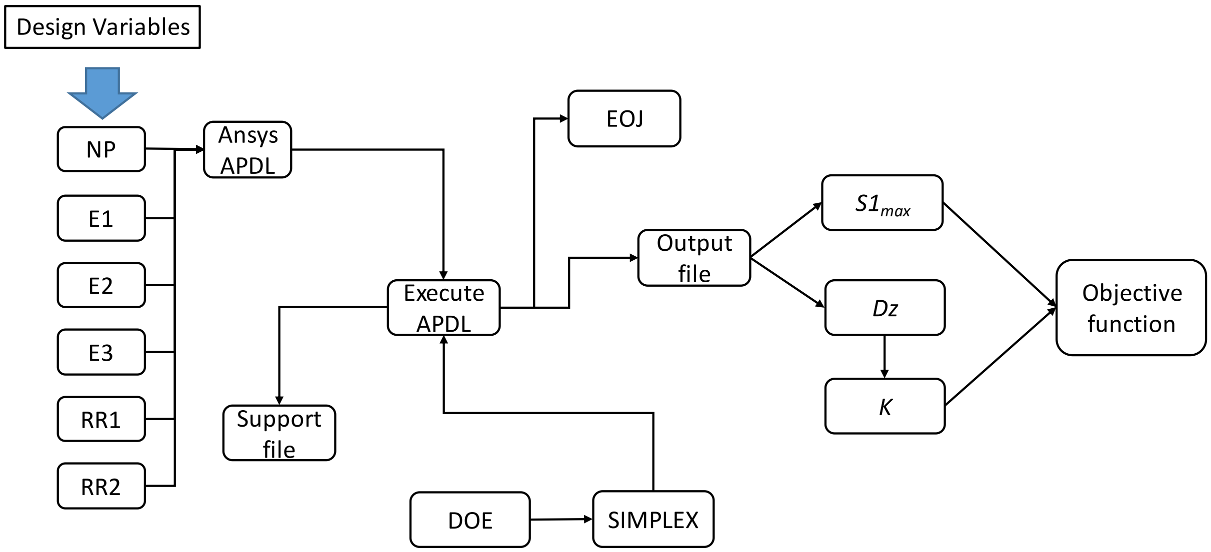


Figure 4: Optimization Scheme used in this analysis

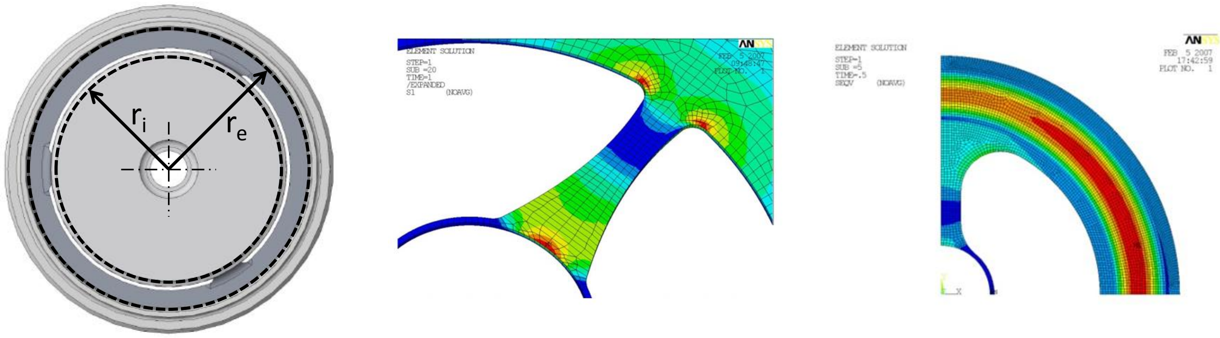
3. STRESS AND FATIGUE ANALYSIS

After performing the optimization steps, one of the verifications needed to initiate the component certification is related to the reliability. Hermetic compressors for household refrigeration need by nature components that can support dynamic loads at the level of giga-cycles, as described by Berger and Kaiser (3) for mechanical springs. This is because compressor valves work in the VHCF – Very High Cycle Fatigue regime. To accomplish this requirement, a criterions evaluation must be performed, considering three king of loads to which valves are commonly submitted.

- Bending over the suction port due to the gas pressure;
- Bending due to valve opening;
- Impact velocity of the valve against the valve seat.

To evaluate bending stress due to valve opening at each cycle, a pressure is applied on the valve surface corresponding to the main pressure difference. Figure 5a represents the annular suction port on the piston top, and Figure 5b a typical stress result due to the valve opening.

The evaluation of the stresses resulting from the compression pressure over the valve orifice is done using FEM as well. The pressure load corresponding to the maximum compression pressure is applied on the annular area of the orifice. A typical result of this kind of load is presented in Figure 5c.



a) Piston top layout   b) Bending stress distribution   c) Orifice stress distribution

Figure 5: Models for stress evaluation

It is very important to emphasize that for both cases the load is cyclic and dynamic. Considering this, adequate fatigue criteria must be used to evaluate the probability of failure due to the real loads and real life.

The third type of load that is experienced by the valve is related to the collision velocity against the valve seat in each cycle. The determination of this velocity is extremely dependent on the application condition, and was not evaluated in this work using FEM. In substitution, an experimental approach was used by constructing a compressor with a glass cylinder and get images of the piston in movement. The valve movement was then evaluated with relation to the piston movement, using the treatment of the images. Figure 6 illustrates the experiment performed, which was only possible because the compressor does not use oil.

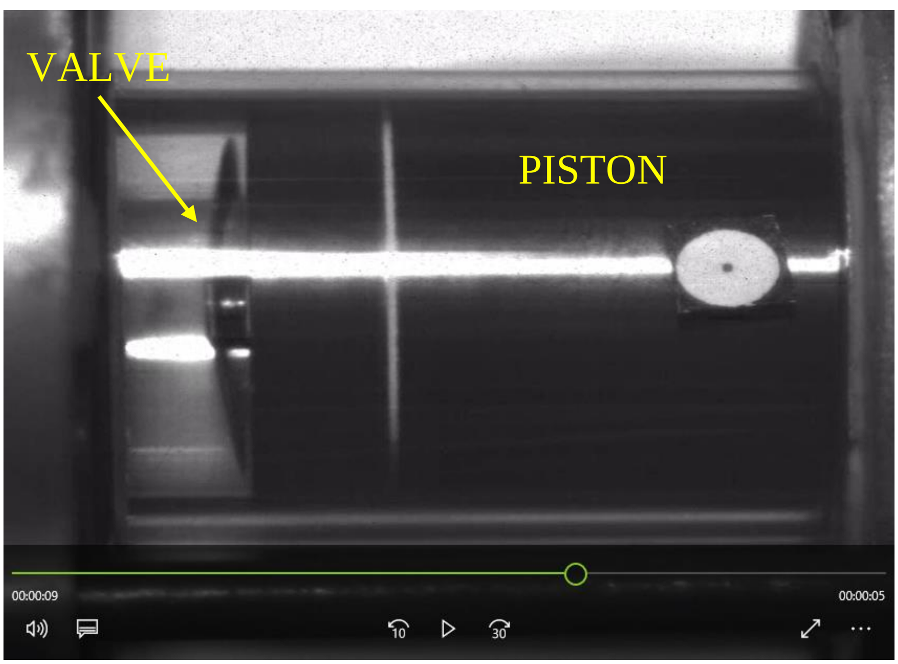


Figure 6: Illustration of the experimental approach used to evaluate the valve movement.

After all fatigue evaluations were performed, some compressors were assembled using different valve models, and based on them the performance was evaluated.

4. RESULTS

The application of this method resulted in the evaluation of different geometries for the suction valve. Two of the geometries evaluated are illustrated in Figure 7 and Figure 8 presents the optimization process result showing the objective function decrement as function of the use of the methodology.

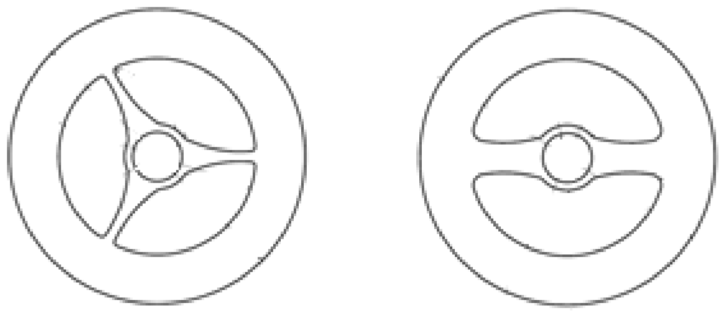


Figure 7: Two valve models obtained from the method usage.

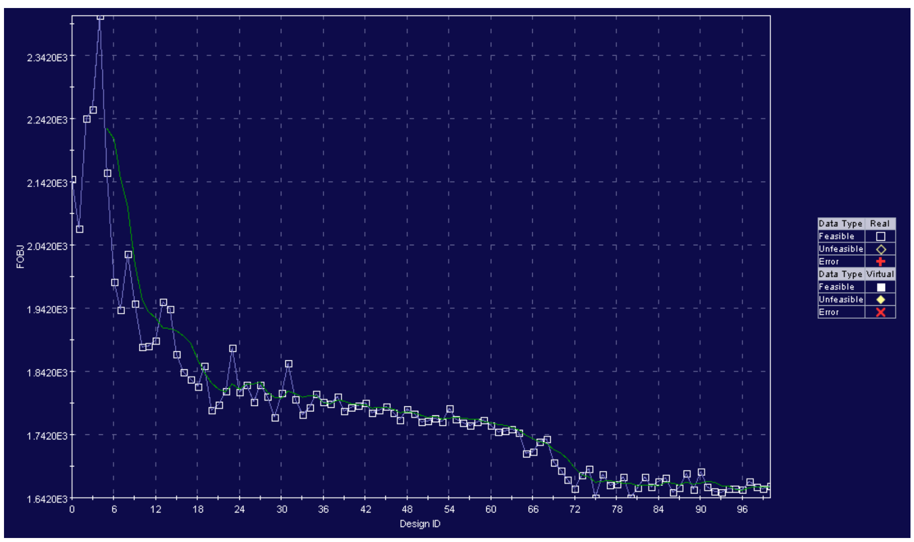


Figure 8: Path of the optimization process, showing the objective function minimization.

After performing the optimization process, a stress analysis was performed as per described in the previous section. The stress analysis was done considering two confidence levels according to Shigley and Mischke (4). These two levels consider the statistical confidence levels used as criteria for the valve orifice definition.

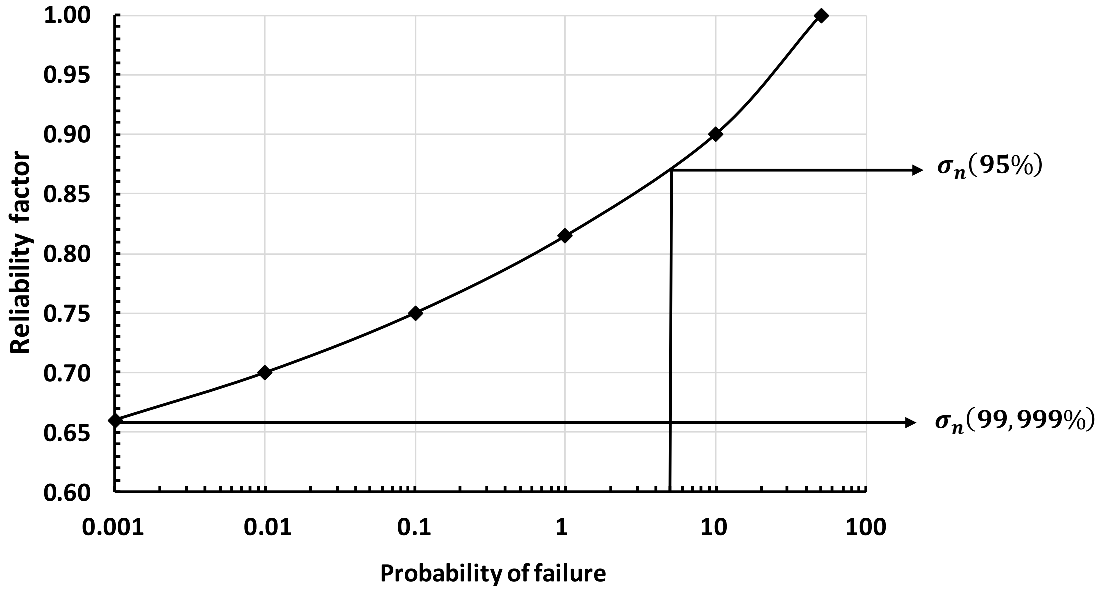


Figure 9: Reliability factor and confidence levels considered for the fatigue evaluation.

Figure 10 shows the results obtained for the valve movement.

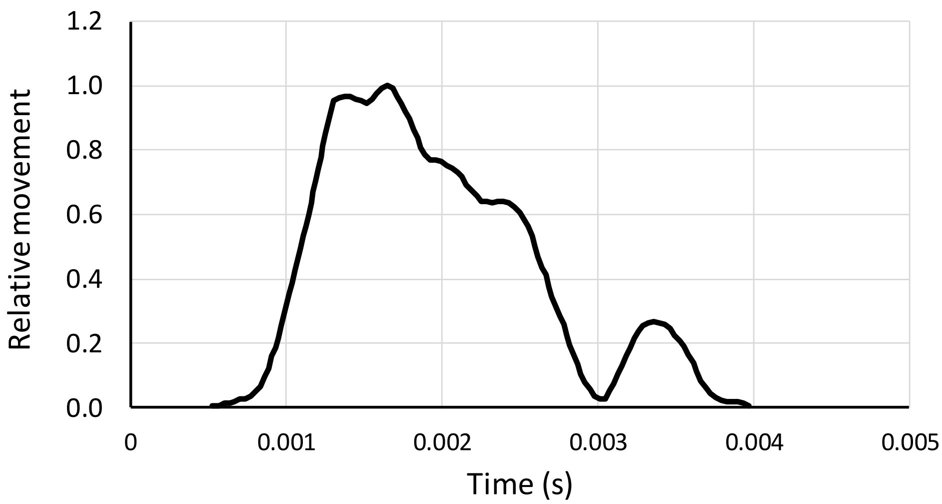


Figure 10: Suction valve movement measured using optical technique.

To close the analysis, resultant geometries were prototyped, some less optimized and other with the best theoretical responses. The prototypes were assembled in compressors, and those were tested in performance. The graphic of Figure 11 shows the comparison of efficiency (COP – Coefficient of Performance) obtained with the geometries tested. In this graphic one can observe the COP result for the options prototypes, taking as reference the one with lower performance. The result for the best one is 5.3% better than the worst one. In terms of compressor performance, it is a huge increase.

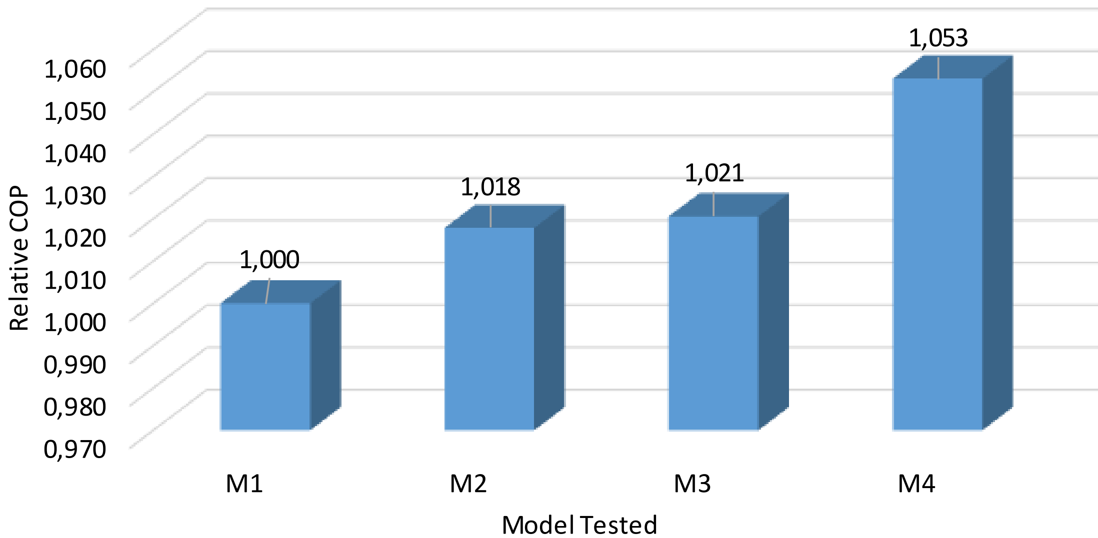


Figure 11: Relative COP measured for four models tested in the optimization process

5. CONCLUSION

The results obtained at the end of the optimization process show its efficacy. It is certainly a tool of major importance during the development of products with high degree of innovation. The combination of an optimization model with other numerical tools like FEM can reduce in a large degree the computational effort because through the optimization logic a larger number of possibilities can be evaluated in the search for the global optimum, within the boundaries stablished. The final result for COP, about 5.3% better than the reference.

For sure, an important check after the optimization process must be performed, taking into account reliability criteria, not considered during the objective function minimization. In this case, FEM tool is used together with an innovative experimental approach, on evaluating the valve movement using captured images. Combined, the methodologies were used to evaluate fatigue stresses and valve impact velocity, characteristics that are fundamental for the approval of the chosen model.

To finalize, it is important to observe that this new compressor technology, without the use of lubricating oil, adds new possibilities to the development of new approval criteria, and evaluation methodologies.

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