# APPLICATION OF CATENARY CURVES IN HERMETIC COMPRESSOR BASED ON COMPUTATIONAL SIMULATIONS

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**Abstract.** *The techniques used in old buildings, as in suspension bridges, improved in the course of time, generating curved structures that minimize materials and maximize strength. Among the curves used there is the catenary curve, which is an excellent way of building with arches that are supported by the weight and provide stability, flexibility and strength to the structures. The curves catenaries offer better distribution of forces and tensions and its main advantage is that the forces applied in any curve point are divided equally by all her. As a result, structures built in this way have the maximum strength with the least possible use of material. In this work we studied an alternative use in hermetic compressors used in domestic refrigeration, with the objective of reducing material and better thermal efficiency and structural. The catenary curves are applied to the geometry of the cylinder block, keeping the other parts, piston, shaft and connecting rods in their original format. A preliminary study allowed the selection of a viable set of values for the two parameters that determine each catenary. A compressor model was created in the software Claim Space and several simulations were performed in Ansys software for catenary different selected. As criteria for the selection of alternatives sought to maximize the area of heat transfer and minimize the structural tensions. Another important criterion is the minimum thickness of the cylinder to prevent the gas permeability of gray cast iron. Computer simulations showed that the catenary curves produce an efficient temperature distribution, caused by the significant increase in the area. As a result, we obtained an excellent improvement in the rate of heat transfer, so as to minimize the gas temperature at the compressor outlet. Thus the fluid arrives at the condenser with a lower temperature, improving the efficiency of the cooling system. In evaluating the stress simulations showed small variations in the structures, showing the applicability of the catenary in thermomechanical equipment. In addition, there was a noticeable reduction in volume and mass in the compressor cylinder block, to ensure the sustainable use of raw materials. The changes suggested in this work may represent savings in the industry compressors that can be reversed to consumers of household coolers and also industrial.*

**Keywords:** *Catenary, Compressor, Simulations.*

## 1. INTRODUCTION

The curves catenaries have applications in projects of analysis of structures in engineering. They are present in different types of structures, such as the suspension bridges, architectural projects, in electric networks or even in the nature. The use of catenary has two important implications that they must be considered in a project: resistance and deformation of the material. When a structure is exposed to an extreme load, as an explosion, the catenary can help to support the load or even resist a collapse [14].

Figure 1. Hercílio Luz Bridge

Figure 2. Spider Web

Although the idea of application of catenaries is not new, it has been rarely used in the thermomechanical industry. Because of increased consumption of devices as conditional air and coolers by part of the population, there has been a great effort from both the industry and research centers to improve the energy efficiency of compressors, in order to make them more sustainable. Prasad indicates that the temperature must be a decisive parameter in the operation of compressors, it affects the dimensional stability and the integrity of the components, and therefore, the impact of the heat transference must be boarded of the point of view of the reliability [12].

When considering the thermal analysis, other secondary analyses must be made to evaluate the effect of the catenary. A very important factor is the stress provoked in the material, because the compressor is exposed to it during its entire operating. Moreover, the compression process can affect the closing of the cylinder, therefore the stresses caused in the screws will be able to imply in one consequent coolant leaking, it can lead to a reduction in the efficiency of the system. Literature deals with some methods to improve the energy efficiency of hermetic reciprocating compressors; however, few refer to changes in the geometry of the compressor cylinder block. According to recent studies, the consumption of electric energy of a residence is strongly stimulated by the coolants, in which the compressors are the responsible ones for this consumption. On the other hand, some technologies are being implemented to reduce further the energy consumption. Therefore, this work has the objective to propose an alteration in the geometry of a hermetic reciprocating compressor using a catenary curve, which will be applied in all the surfaces of the compressor cylinder block.

A preliminary study allowed the election of a set of viable values for parameters ‘b’ and ‘c’ that determine each catenary. A model of the compressor was built in Space Claim® software and some simulations were performed in Ansys® software for several catenaries.

Thus respecting some criteria of selection, a new geometry of the compressor is presented in this work.

## 2. MATERIALS AND METHODS

### 2.1 Equation of the catenary

The first mathematical approach of the catenary was given in 1690, this year Jacob Bernoulli proposed a challenge to discover the curve that describes a perfectly flexible inextensible chain of uniform density hanging from two supports not in the same vertical line. In the next year Leibniz, Huygens and Johann Bernoulli found the following equation for the curve that soon later was called as catenary. The equation of the catenary is described in the equation (1):

$$y = b\cosh\left(\frac{x-a}{b}\right), \tag{1}$$

where ‘b’ is the width of the catenary and ‘a’ the parameter that translates it in the horizontal axis. However, due to symmetry of the compressor relative to axis y, there are interest in vertical translations and not horizontal ones, thus the equation (1) transforms into the equation (2), which describes the catenaries on the compressor cylinder block:

$$y = b\cosh\left(\frac{x}{b}\right) + c, \tag{2}$$

where ‘c’ determines the vertical translations.

### 2.2 Selection of the numerical values for parameters ‘b’ and ‘c’

The main objective of the use of curves in the cylinder block is to increase the area of the thermal exchange surface, in other words, the biggest interest is in the catenaries that can remove the biggest possible amount of material, obeying the constraints of the compressor geometry. Therefore the useful catenaries are those that extend much as possible in the vertical and horizontal direction. In the vertical direction there is a conditioning of the gray cast iron, which for being porous needs at least 5 mm thickness to prevent leakage of the coolant. In the horizontal, the maximum extension of the catenaries is reached in the points, B, C, D, and, F, but only can be reached in the catenaries of the top region, since there is another restriction in the lateral regions, which is given by the ends of the screw holes G and H.

The coordinate system is selected such that its Y-axis is perpendicular to each surface of the cylinder block and its origin is located 5 mm from the cylinder. Therefore there are three coordinated systems whose origins are the O1 points, O2, O3, they allow to find the coordinates of the points (Table 1) that will define the parameters ‘b’ and ‘c’.

Table 1. Coordinates of the points that define the parameters ‘b’ e ‘c’

| Point | Coordinate system | Coordinate |
|---|---|---|
| A, B | x1, y1 | (±22,15 ; 6) |
| C, D | x2, y2 | (±18,74 ; 7,27) |
| G | x2, y2 | (10,26 ; 3,81) |
| C1, D1 | x2, y2 | (±13,93 ; 7,27) |
| E, F | x3, y3 | (±18,74 ; 7,27) |
| H | x3, y3 | (-10,26 ; 3,81) |
| E1, F1 | x3, y3 | (±13,93 ; 7,27) |

The pairs of points C1-D1 and E1-F1, located on the lateral surfaces of the cylinder block are found by extrapolation of the catenaries with origin in O2 and O3 respectively, which also pass for the ends of screws G and H. On the basis of the points A, B, C1, D1, E1 and F1 can be obtained the subgroups of $\mathbb{R}^2$ where be located the future catenaries.

Top Region: $S = \{(x,y) \in \mathbb{R}^2 \mid x \in [-22.15 ; 22,15] \wedge y \in [0 ; 6]\}$
Lateral Regions: $L = \{(x,y) \in \mathbb{R}^2 \mid x \in [-13.93 ; 13.93] \wedge y \in [0 ; 7.27]\}$

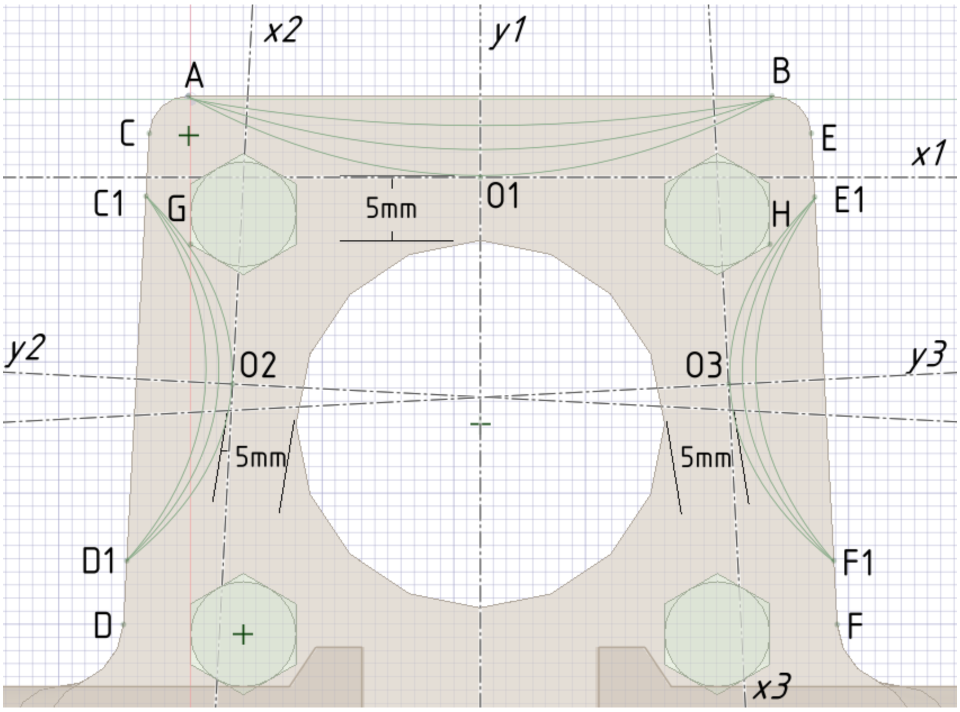


Figure 3. Frontal view of the compressor cylinder block with points and catenaries.

By analyzing the symmetry of the cylinder block and subsequent machining, it is assumed that the catenaries will have as extremities the same pairs of points shown in Figure 3, A-B, C1-D1 and E1-F1. Three catenaries are selected in each region. The separations between them chosen in the central part are, of 2,0 mm in top region and 1,0 mm in the lateral regions. The lateral catenaries have a lesser width (C1D1<AB), in order to guarantee a bigger area, they need to penetrate as much as possible in the lateral region of the cylinder block.

This choice was made because a greater number of catenaries or a shortest spacing between them, the curves would respectively have areas close to the original or similar areas between them.

Therefore when substituting the coordinate of the superior extremity and the vertex one of each catenary in the equation (2), it is obtained a system of two nonlinear equations that can be resolved numerically to get the values of ‘b’ and ‘c’ as shows Table 2.

Table 2. Catenary Parameters

| Catenary | b | c |
|---|---|---|
| TC1 | 14,4107 | -14,4107 |
| TC2 | 16,4148 | -15,4148 |
| TC3 | 19,2162 | -17,2162 |
| LL1 | 41,8061 | -41,8061 |
| LL2 | 49,8877 | -48,8877 |
| LL3 | 62,0004 | -60,0004 |
| RL1 | 41,8061 | -41,8061 |
| RL2 | 49,8877 | -48,8877 |
| RL3 | 62,0004 | -60,0004 |

The nine catenaries in the cylinder block are represented in Figure 3, three at the top and the other six divided into three for each side. The curves are applied only in the compressor cylinder block, the other parts remain its original format. A catenary applied in a region that is not the block can interfere in the valve geometry, thus would be necessary a modification in the geometry of the parts inside the cylinder head, which can be object of study of a future work.

**2.3. Thermal and Structural Simulations**

One of the heat transmission paths that influences the performance of alternative compressors is the transport of heat of compression to external media, since the thermodynamics establishes that removal of heat during the compression process results in a decrease of the work of compression [4]. Thus the application of catenaries in the compressor cylinder block of coolers has as objective to increase such transference. The way to evaluate the efficiency of the heat transmission in this work is to calculate temperatures on the external surfaces of the cylinder block for each new geometry, which is expected to have lower temperatures when comparative with standard geometry.

The temperature of the coolant inside the cylinder is not constant but it varies periodically with time, therefore, an average temperature can be used during the cycle in order to perform a thermal analysis in steady state. The temperatures of the components within the cylinder head are found in literature. Heat transfer from cylinder to the recirculated gas by natural convection is assumed, despising the radiation [5].

The structural analysis has as objective to determine the feasibility of the application of catenaries in the cylinder block. Considering the small geometrical modifications performed is sufficient to compare the new stress distribution to the distribution in standard geometry, which is structurally reliable for being produced in industrial scale. In order to evaluate the stress, the Von Mises Stress is calculated, criterion of resistance of materials containing the security coefficient that will indicate a possible fracture of the compressor.

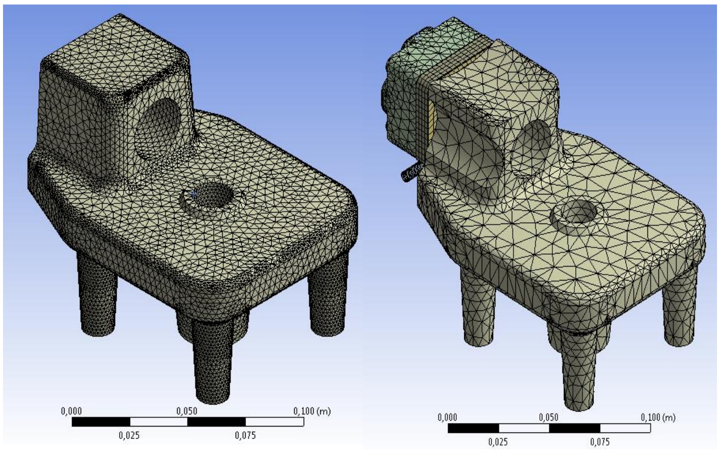

Figure 4. Thermal and structural mesh

The thermal and the structural simulation are performed in Ansys® software, Figure 4 show the components of the compressor with its respective meshes used in each simulation. The mesh of structural simulations does not need to be very refined, except in the corners of each component to prevent that these elements will flattened.

## 3. RESULTS AND DISCUSSION

The efficiency of the refrigeration process depends on the performance of each one of its components: evaporator, condenser, devices of expansion and the compressor. Amongst them, the compressor is considered the “heart” of the system, therefore it creates the flow of the cooling one throughout the components of the system. When considering a new geometry for the block, must be evaluated the requirements that determine the performance of the compressor. For this, literature considers the thermal analysis and the structural one. For both analyses will be used the geometry suggested in this work and a standard geometry.

The thermal behavior of the compressor for the diverse catenaries revealed trustworth as it shows figure 4.1. The profile of temperature for the catenary with the lesser parameter `b' was the one that presented with one better distribution in the surfaces superior how much in the laterals. In figure 4.2 the profile of temperature for a standard geometry is presented, in order to do comparative analysis.

The best catenary (`TC1', 'RL11' and `LL1') presented a bigger area of thermal exchange compared with geometry standard, therefore, better it will be the transference of heat between cooling and the external environment (compressor shell). The conditions of contour for the axis, connecting rods and the piston had been kept same for both the simulated compressors. Of this form, the influence of the temperature caused for new geometry will only imply in the block of the compressor. In order to get a quantitative profile of temperatures, an imaginary line was traced that encloses the extremities in points 1 and 2, as shows figure 4.2, where it will be taken as reference point for all simulations.

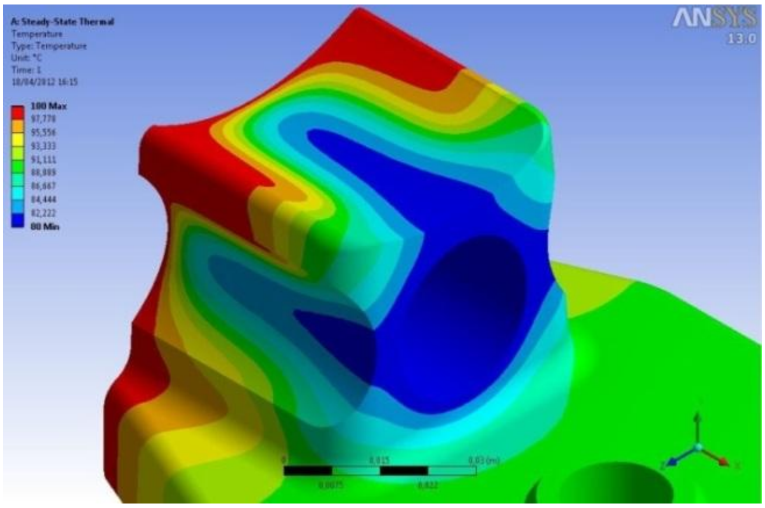


Figure 4.1. Temperature in the new geometry

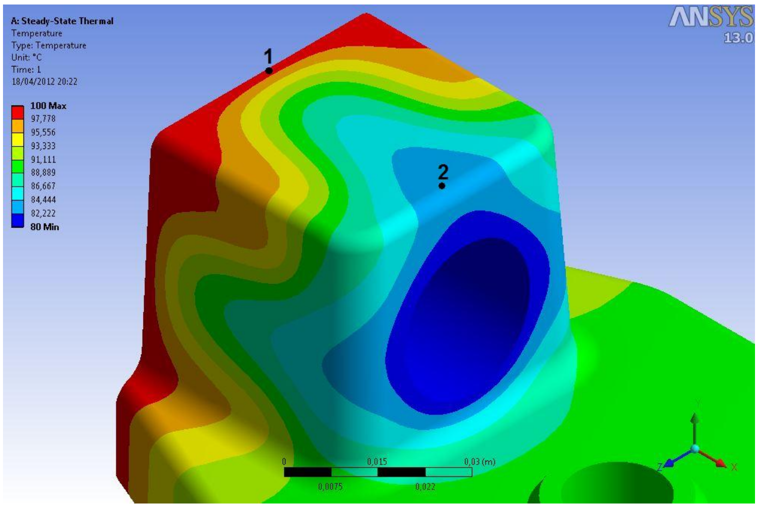


Figure 4.2. Temperature in the standard geometry

For the other selected catenaries, the temperature profile revealed superior to standard geometry, but below of the best catenary (`TC1', `LL1' and `RL1'). In figure 4.3 the profile of temperature for the top catenaries in relation the standard is presented. The decline of the temperature for standard geometry revealed inferior, evidencing that how much lesser the area of heat transference it leads to a flow of lesser heat and the temperatures biggest. Thus, top catenaries 1, 2 and 3 had gotten an excellent performance, being the catenary 1 the one that presented a more surplus decline of temperatures between all.

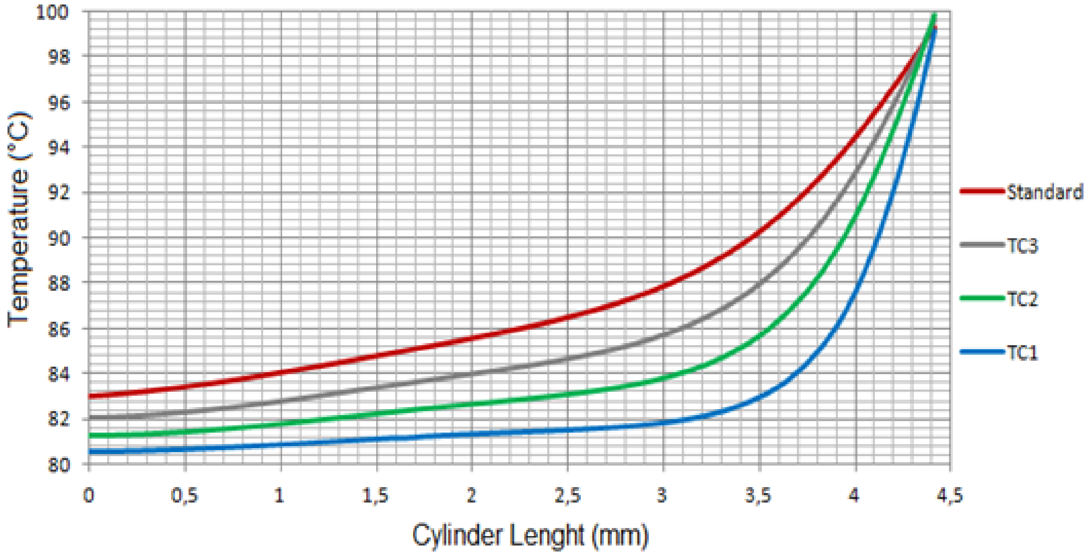


Figure 4.3. Temperature profile on the block top region

In the laterals, the difference of temperatures between geometry proposal and the standard is too great. Whereas the surfaces with the catenaries present an abrupt profile, geometry standard decreases moderately until reaching the final temperature, as it is presented in figure 4.4.

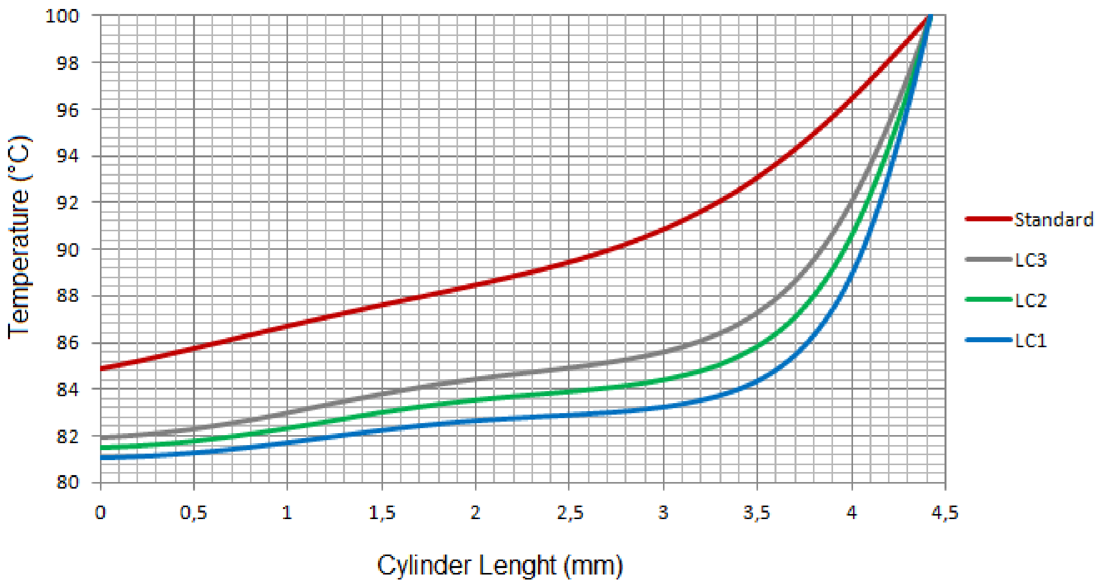


Figure 4.4. Temperature profile on the block lateral regions

Beyond the thermal analysis, the structural behavior of the block of the compressor must be evaluated, in order to validate geometry proposal in this work. In such a way, the analysis of tensions was defined equivalents.

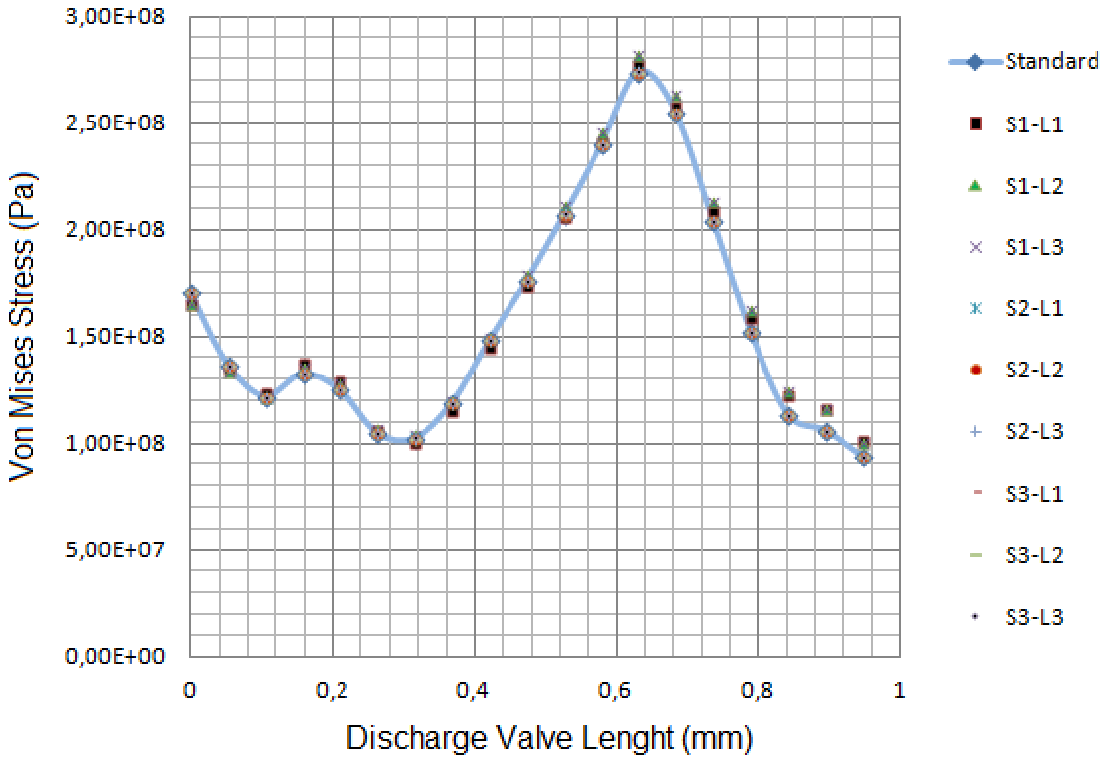


Figure 4.5. Tensions on the discharge valve

Another important factor that the importance of the use of catenaries in compressors standard out is the economic factor, in what if it says respect to the sustainable use of raw materials such the cast iron and other materials. When applying an arched surface in material with a rectilinear surface, remarkably reduces the necessary amount of material for the manufacture of one determined part. In table 3 it can verify the variation of mass, volume and area for the set of the best catenaries \`TC1', \`LL1' and \`RL1' comparatively rectilinear geometry, applied to the block of the compressor.

Table 3. Comparison of the properties between geometries

| Properties | Standard geometry | Proposed geometry | Variation |
|---|---|---|---|
| Massa | 2767,8 g | 2625,0 g | - 142,8 g |
| Volume | 387,1 $cm^3$ | 367,1 $cm^3$ | - 20,0 $cm^3$ |
| Área | 53,6 $cm^2$ | 47,1 $cm^2$ | + 6,4 $cm^2$ |

The variation of mass between the standard geometry standard and the proposal in this work was very significant (11,9 %). Beyond what, this variation will be considered in a production of compressors that it will be multiplied by thousands of units, throughout one year of production. The material economy becomes evident, moreover, the reduction of the temperatures in the block and without structural disturbances.

## 4. CONCLUSION

The methodology adopted to study the closing of the hermetic compressor cylinder was adequate to the considerations made in this study. The results we obtained, show the changes in geometry allow for a better distribution of temperature in relation to the initial geometry while not compromise the structure of the compressor block. Another form would to put fins for dissipate heat the surface of the cylinder block, in other words, how much bigger the area of transference of heat, more efficient will be transfer for the external environment (compressor shell).

The reduction of the material gotten in this work aims at beyond the economy to the use most sustainable of the mineral resources beyond reducing the weight of the compressor, becoming lighter and facilitating its transport.


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PRAE – Pró - Reitoria de Assuntos Estudantis - Universidade Federal de Santa Catarina
ESSS – Engineering Simulation Scientific Software


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