24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0764
NUMERICAL AND EXPERIMENTAL ANALYSIS FOR PERFORMANCE IMPROVEMENT OF THE ADMISSION RESTRICTOR FOR A FORMULA-SAE VEHICLE

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Abstract. *The use of venturi restrictors in intake manifolds is an SAE requirement for all formula-type competition vehicles. The main purpose of the restrictor is to reduce the mass flow delivered to the motor, the power developed, thus increasing the competitiveness among the student teams. The objective of this research is the optimization of the geometry of a venturi type restrictor in order to allow the admission of maximum airflow to the motor. The establishment of the maximum air flow as a fixed parameter allows the elaboration of a geometry capable of providing a minimum pressure difference between the atmosphere and the pressure created in the combustion chamber for varying engine speed regimes. Through numerical analysis in a CFD environment with experimental verification, was developed a geometry capable of meeting the minimum requirements of the motor, being composed, respectively, by convergent and divergent angles of 18 degrees and 6 degrees.*

Keywords: *Admission system, Optimization, CFD analysis, Experimental analysis, Formula-SAE*

1. INTRODUCTION

Formula-SAE (FSAE) is a student competition organized by the Society of Automobile Engineers, where teams aim to design, manufacture and execute a racing vehicle prototype. The FSAE regulation makes reference to the requirement of the circular section air restrictor, installed downstream of the throttle, with throat diameter of 20 mm for gasoline engines.

According to ASME (1987), the main role of the restrictor is to limit, based on the volume displaced by the engine, the amount of energy developed by the same. According to Hanriot (2006), Heywood (1988) and Damji (2008), idealizing the internal combustion engine as a pump used in air pumping, the amount of energy it developed would be based on the efficiency with which it could move the largest volume of air from the inlet to the outlet through the exhaust gases. The restrictor would behave as a limiting component for moving air into the engine, thereby limiting the volume of air that can be displaced.

Due to the impositions of the organizing committee of the competition, the admission system becomes one of the main subsystems to prevent that the power drop developed by the motor is not significant. According to Burr (2013), this prerogative it is important that the amount of air flowing towards the combustion chamber is maximized. According to Singhal (2013) and Shami (2014), the development of a restrictor must go through the need to minimize the pressure difference between the atmosphere and the negative pressure generated in the combustion chamber, which implies in improving the volumetric efficiency. Marsico (2008) and Pulkrabek (2004) state that at based on the principle of maximizing the air flow rate at the inlet, it is necessary to make use of CFD tools to predict the minimum pressure drop through different restrictor geometries obtained by varying the convergent and divergent angles, thus minimizing the pressure drop through the flow restrictor.

Pogarevc and Kegl (2002) and Wei, *et al*. (2016) state that at low rotating speeds the required mass flow is compensated by the increase in flow velocity through its smaller area, but at high operating speeds the demand for air increases and the required mass flow becomes insufficient.

The objective of this work is to improve a FSAE restrictor geometry to provide maximum mass flow from a minimum pressure difference for all operating speeds based on experimentally proven numerical analysis.

2. METHODOLOGY

The purpose of an intake system is to allow a maximum amount of air to the combustion chamber along the intake stroke, which allows for increased fuel burn and useful work produced.

Improving the flow through an intake system increases the overall efficiency of the engine. The restrictor operates as a power output limiting device, preventing airflow at medium to high RPM, when airflow would normally be higher. Of the various design parameters that affect the overall efficiency of the restrictor the nozzle and diffuser angles are the most emblematic. The analysis of these factors allows, in a first moment, to evaluate in the CFD environment the behavior of the range of developed restrictor geometries, selecting those of better highlight for an experimental analysis.

2.1 Development of CAD geometries

The development of CAD geometries was done based on the combination of convergence and divergence angles (Fig. 1). The angles were selected according to local manufacturing limitations and technical information found in the literature. Based on this, the angles of 10 to 22 degrees for the convergent section were established due to the need to generate a fast pressure drop, and from 6 to 9 degrees for the divergent section due to the need to avoid flow separation, a phenomenon that limits the efficiency and performance of the restrictor. In addition to establishing a set of angular values for the nozzle and diffuser an inlet volume of 0.5 m³ was used as an inlet for the fluid (Fig. 2).

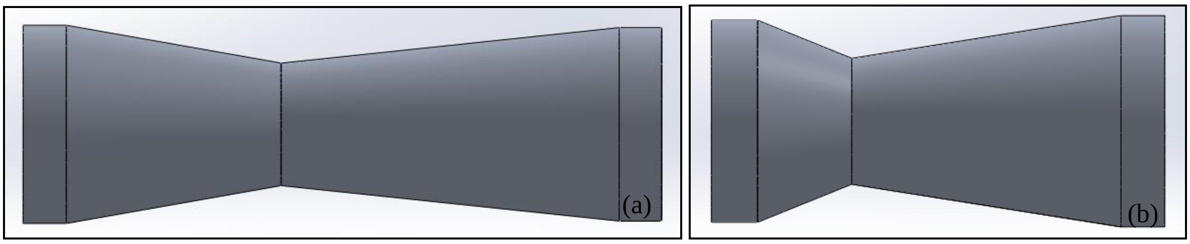

Figure 1. (a) Geometry with a convergence angle of 10º and divergence angle of 6º. (b) Geometry with a convergence angle of 22º and a divergence angle of 9º.

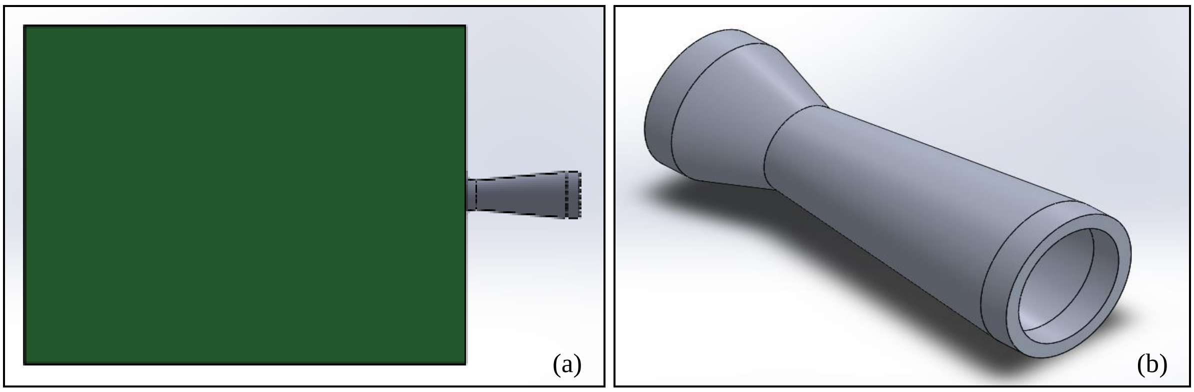

Figure 2. (a) Representation of one of the analyzed flow restrictor models with a volume inlet of 0.5 m³. (b) Representation of the isometric view of one of the restrictor models.

2.2 Numerical analysis

The computational model used to optimize the flow restrictor for a FSAE competition vehicle was performed by analyzing the fundamental equations of conservation of mass in Eq. (1), energy conservation in Eq. (2), moment conservation in Eq. (3) and isentropic mass flow in Eq. (4) were applied.

$$\frac{\partial}{\partial t}(\rho) + \nabla.\left(\rho\vec{U}\right) = 0 \tag{1}$$

$$\rho\frac{\partial u}{\partial t} + u\frac{\partial \rho}{\partial t} + \rho u\frac{\partial u}{\partial x} + u\frac{\partial \rho u}{\partial x} + \frac{\partial P}{\partial x} = 0 \tag{2}$$

$$\frac{\partial\left(\rho\vec{U}\right)}{\partial t} + \nabla.\left(\rho\vec{U}\vec{U}\right) = -\nabla P + \nabla\tau + \rho\vec{g} + \vec{B} \tag{3}$$

$$\dot{m} = \left[A.P.M.\left(1 + \frac{\gamma - 1}{2}M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}\right]\sqrt{\frac{\gamma}{RT}} \tag{4}$$

Allied to the aforementioned equations, it was necessary to use the turbulence model $\kappa - \varepsilon$ with implementation of 15 layers of prisms, with transition rate of 1.02, so that the phenomena of boundary layer could be captured. The numerical error generated during CFD analysis was monitored until the value was reduced to below 0.001%, so that digital and numerical stability were achieved for the restrictors.

In all 12 restrictors analyzed, a tetrahedron mesh was used throughout the domain. As the desired effects were in the fluid region equivalent to the restrictor where the curve mesh method was applied, allowing the region to present better defined mesh elements, minimizing errors due to distorted mesh elements in relation to geometry. Throughout the computational domain of all the restrictors were used mesh elements with different refines. While the inlet volume has 0.007 m mesh elements, the restrictor was modeled with 0.00175 m mesh elements (Fig. 3), giving for each geometry an average of 500,000 mesh elements.

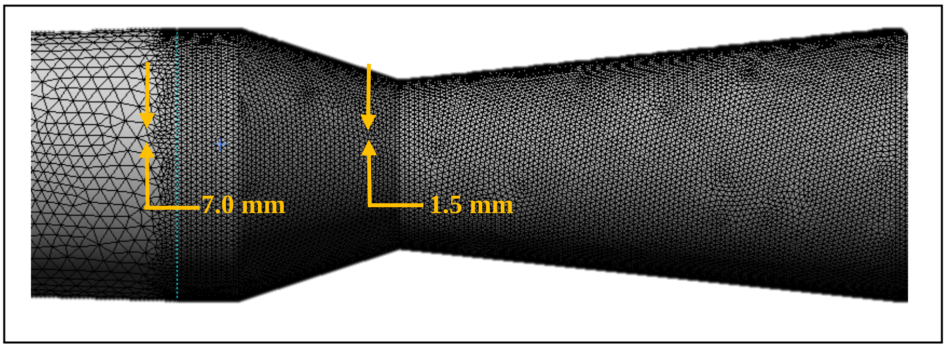

Figure 3. Details of the mesh refining used in all restrictors.

Due to the need to represent the numerical analysis of the actual physical phenomena present in the restrictor, a transient analysis with a duration of 0.0000273163 s was performed, equivalent to the development of 3 admission cycles when the vehicle is at 4500 RPM, divided into 250 time steps of 1.09265E-07 s, each with 100 loops.

The boundary condition used in the input comes from Eq. (4), which relates the mass flow rate to the flow area (A), total pressure (P_t) and flow temperature (T_t), Mach number (M), the ratio of specific gas (γ) calculations and the gas constant (R) is based on the principle that, under these ideal conditions, air can be considered as a perfect gas and, therefore, isentropic flow or the flow rate of maximum mass, called the shock condition, would occur when the Mach would appear as unitary. By the consideration of P_t = 101325 Pa, T_t = 300 K, γ = 1.4, $R_{(air)}$ = 0.286 kJ/(Kg.K), A = 0.000314159 m² and M = 1 we have that as solution of the equation is 0.0744492 kg/s.

However, the critical flow assumption is quite limited, since the calculation assumes that the flow reaches Mach unitary, which, in fact, is a complex phenomenon that uncovers the effects generated by the boundary layer thickness and surface roughness present on the surfaces of the restrictor. Even with the limitations present in this model, it presents itself as a considerable tool for the design of the restrictor in CFD environment.

The second contour condition, applied at the exit of the system, is the behavior of the static pressure related to the inlet of the intake valve, represented according to Fig. 4, obtained in advance experimentally.

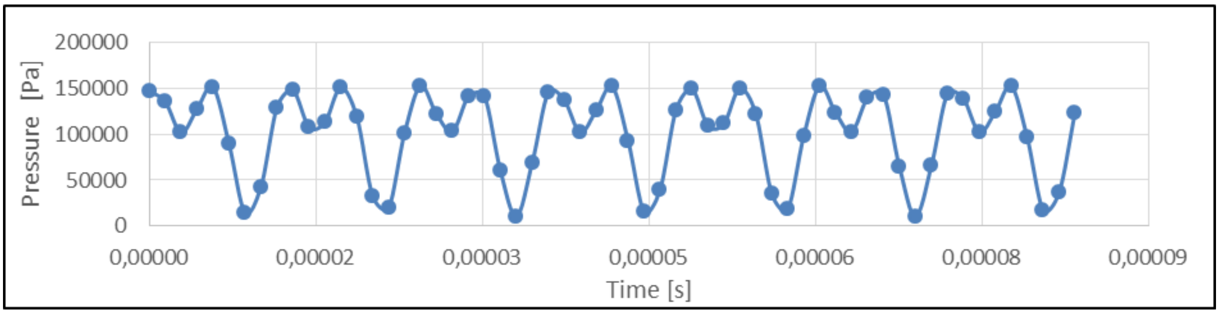

Figure 4. Static pressure behavior at the inlet of the intake valve at 4500 RPM.

2.3 Experimental analysis

The experimental analysis of the chosen restrictor after numerical analysis was performed in a flow bench, used to simulate the pressure gradient developed in the intake manifold over the operating cycles of the engine and to prove the efficiency and optimization of the new restrictor. The inlet manifold, already installed in the flow bench, was equipped with a specific set of sensors and transducers that evaluated the behavior of pressure and mass flow along the same through two capacitive pressure transducers Motorola model, being allocated at the entrance of the inlet valve and in the region between the throttle body and the new restrictor, measuring the behavior of the pressure drop.

Rotation control was performed by means of a *Bosch* KY003 rotation sensor, allowing experimental verification to be performed at fixed intervals of 1000 RPM, starting from the engine idle, set at 1500 RPM, up to 6500 RPM.

Data acquisition was performed using an *Atmel* electronic prototyping platform with a 16 MHz communication frequency aided by a *Visual Studio* programming for handling, storing and developing graphs for the data collected in the restrictor. Table 1 shows the uncertainties in experimental measurements using the instruments presented.

Table 1. Experimental uncertainty and air properties.

PARAMETERS	UNCERTAINTY
Pressure (Pa)	101,325.0 ± 4,863.6
Temperature (ºC)	± 0.48
Rotation (RPM)	±50
Density (kg/m³)	1.1544± 0.03
Dynamic Viscosity (N.s/m)	18.40 ± 0.3804

3. RESULTS AND DISCUSSION

The value of the minimum pressure variation, collected according to the numerical analysis, was marked for each row and column as shown in Tab. 2, which demonstrates the mapping of the values for the minimum pressure loss according to combinations between the angles of convergence and divergence.

Table 2. Numerical results of pressure loss in (Pa)

	Convergent Angle			
Divergent Angle	10º	14º	18º	22º
6º	7381.73	7682.11	7133.47	9151.35
8º	10117.63	7883.42	10386.25	14613.95
10º	11149.28	8828.52	13566.64	13478.16

The use of an isentropic mass flow as a first boundary condition provides a notion as to the best restrictor to be selected. However, due to its enormous simplification regarding the flow phenomenon, it does not allow to demonstrate the effective behavior of a restrictor, necessitating a second evaluation, this time based on the environmental pressures of the competition locations (Campina Grande – Paraíba/Brazil, Piracicaba – São Paulo/Brazil and Brooklyn – Michigan/USA).

To obtain this criterion, information about the pressure was collected in Campina Grande – Paraíba/Brazil, Piracicaba – São Paulo/Brazil and Brooklyn – Michigan/USA during the period from May 14, 2017 to June 15, 2017 (Tab. 3), using an average behavior of the local pressures to replace the isentropic mass flow as a boundary condition within a second numerical analysis.

Table 3. Behavior of mean atmospheric pressure at competition cities over a month. Source: INMET (Brazil) and American Meteorological Society (USA)

City/Country	Atmospheric pressure (Pa)
Campina Grande – Paraíba/Brazil	101,700 ± 321
Piracicaba – São Paulo/Brazil	94,717 ± 115
Brooklyn – Michigan/USA	98,984 ± 278

Based on this analysis it was possible to numerically re-evaluate which of them would have the capacity to provide the highest mass flow rate for the 4500 RPM rotation regime. Based on this, Tab. 4 demonstrates the mass flow associated with each restrictor in each of the competition cities.

Table 4. Numerical results of the mass flow rate, in (kg/s), for various competition scenarios.

Campina Grande – Paraíba/Brazil	Convergent Angle			
Divergent Angle	10º	14º	18º	22º
6º	0.00312540	0.00302580	0.00330700	0.00308889
8º	0.00308520	0.00312680	0.00323096	0.00300548
10º	0.00318515	0.00309875	0.00330084	0.00305875
Piracicaba – São Paulo/Brazil	Convergent Angle			
Divergent Angle	10º	14º	18º	22º
6º	0.00270060	0.00252576	0.00289754	0.00276039
8º	0.00269910	0.00263965	0.00289214	0.00279860
10º	0.00279077	0.00268799	0.00289214	0.00280021
Brooklyn – Michigan/USA	Convergent Angle			
Divergent Angle	10º	14º	18º	22º
6º	0.00304995	0.00289357	0.00316663	0.00295778
8º	0.00308520	0.00299408	0.00309382	0.00299875
10º	0.00310015	0.00293485	0.00316073	0.00301572

Based on the two numerical analyzes performed, the choice of the restrictor with 18º of convergent angle and 6º of divergent angle was made due to better performance for the minimum pressure loss and greater mass flow capacity between the tested models, taking it for experimental verification.

Figures 5, 6 and 7 show, respectively, the behavior of the pressure gradient, velocity and turbulent kinetic energy (TKE) along the selected venturi restrictor in the longitudinal plane XY.

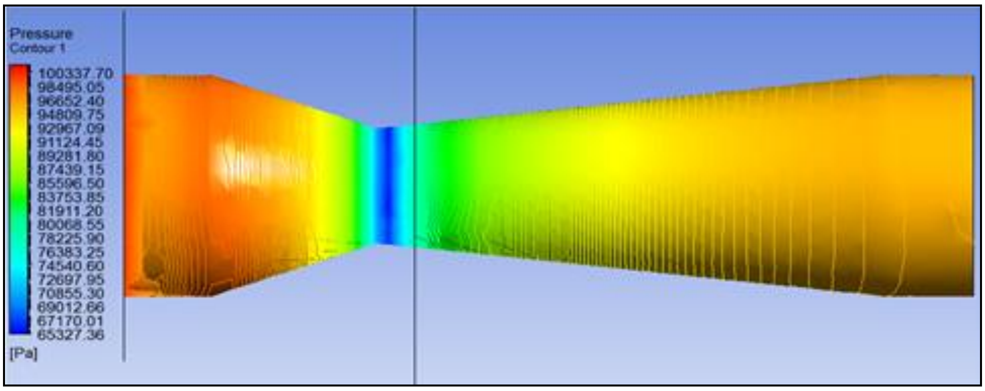

Figure 5. Pressure field in the selected restrictor.

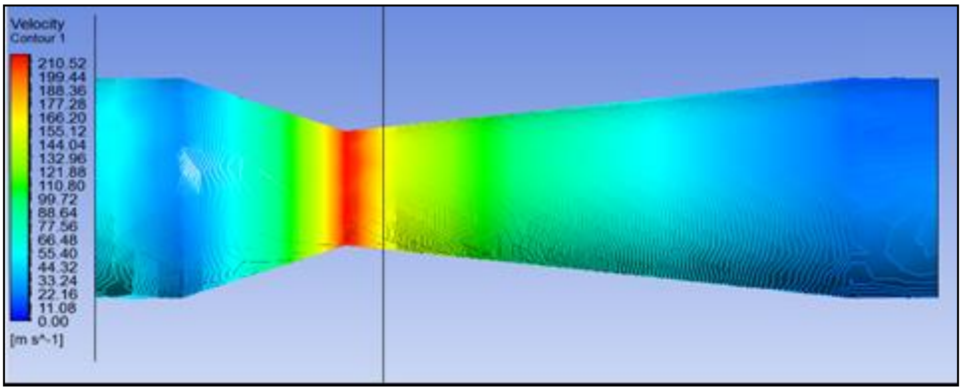

Figure 6. Velocity field in the selected restrictor.

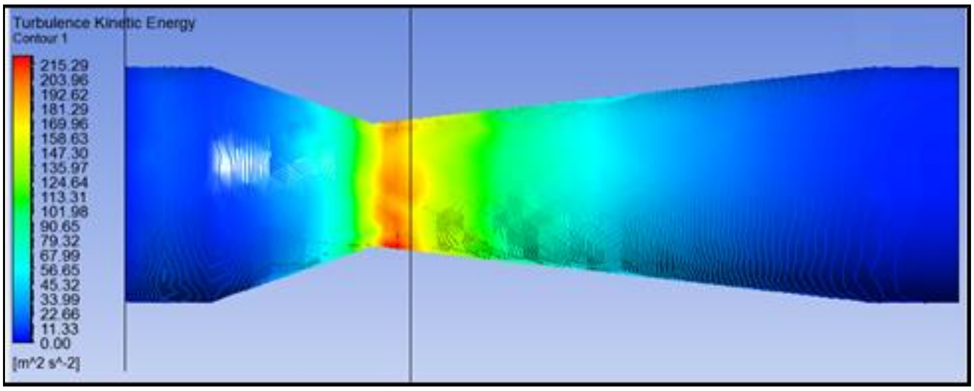

Figure 7. TKE field in the selected restrictor.

The construction of the ideal restrictor for the 2017 competition vehicle was made of lightweight material to reduce the load and stress on the throttle body, where the 6065 aluminum was considered ideal for the application.

The experimental analysis in the optimized restrictor made it possible to compare its performance to the performance of the Honda engine with the original intake system, without the presence of the restrictor, and with the intake system bearing the restrictor of the 2016 competition. The result relating to engine testing with the original intake system and with the optimized restrictor can be seen in Tab. 5.

Table 5. Experimental values for the negative pressures, in (Pa), for the original intake manifold and for the intake manifold with the optimized restrictor.

[RPM]	Original System	Optimized Restrictor	ΔP (ABS)	Δ (%)
1500	51,807.02	43,891.01	6,320.69	15.28
2500	52,789.11	46,158.1	5,004.54	12.56
3500	54,126.03	48,818.47	3,659.88	9.81
4500	54,980.75	49,933.26	2,202.74	9.18
5500	55,740.73	51,768.92	2,054.4	7.13
6500	60,578.89	56,660.92	1,594.32	6.47

The optimization of the restrictor for the 2017 competition vehicle, compared to the 2016 restrictor, promotes a 10.3% reduction in pressure loss at 1500 RPM and 7.36% for the rotation ranges between 4500 RPM and 5000 RPM (Fig. 8). This improvement is associated with the maximization and uniform distribution of air mass flow through the throttle body to the rotational speeds analyzed, showing that the admitted mass of air and the volumetric efficiency, both related to the level of pressure in the valve door, were also maximized compared to the restrictor used in the previous year.

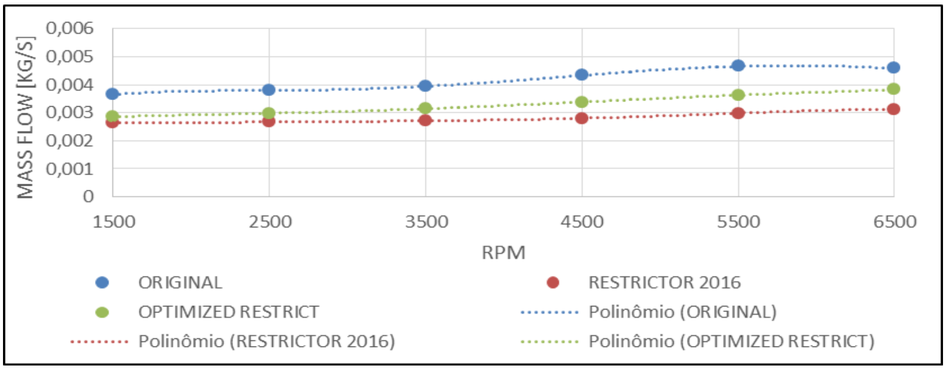

Figure 8. Comparison of the mass flow in the intake manifold with the optimized restrictor, with the original system and with the restrictor used in the 2016 competition.

The pressure increase at the port of the inlet valve generated by the optimized restrictor favored the behavior of the required mass flow to the engine during the intake cycle. The experimental analysis found that the actual mass flow rate supplied to the engine at 4500 RPM was 0.003385541 kg/s, while the intake system bearing the 2016 restrictor provided a value of 0.002804721 kg/s for the same regime of 4500 RPM, demonstrating that the optimized version allowed a 20.71% increase in the mass flow delivered. The mass flow obtained numerically and experimentally differed by 2.37%.

For the engine with the original intake system, the rate at which the volumetric efficiency increases is positive practically throughout the rotating speeds (Fig.9), however, when analyzing the behavior of the optimized restrictor with the 2016 restrictor it is possible to state that there was a significant improvement in the behavior of the volumetric efficiency between 1500 RPM and 5500 RPM in the order of 7.76%, favoring the behavior of the vehicle.

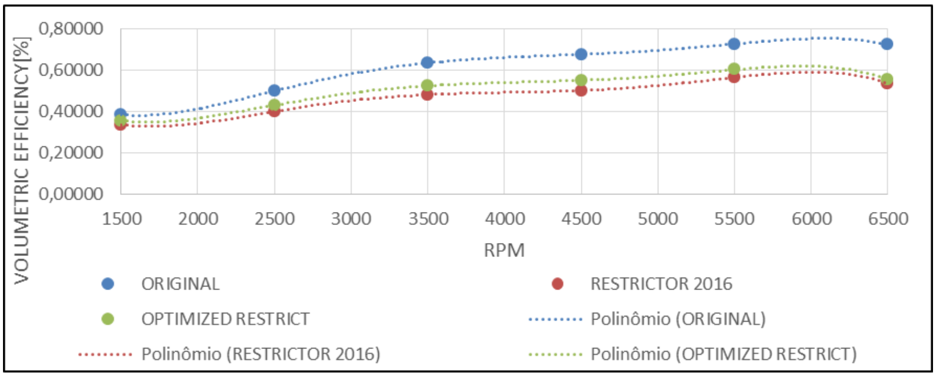

Figure 9. Comparison of the volumetric efficiency generated by the mass flow rate of the original intake system, with the optimized restrictor and with the 2016 competition restrictor.

4. CONCLUSION

From the experimental data collected and the CFD simulations, the values for the convergent and divergent venturi angles were stipulated and validated. It was observed from the analysis that the pressure loss through the 20 mm diameter throat was partially recovered through the diffuser, resulting in an improvement of the static pressure available at the valve door. This optimized restrictor concept offers an order-of-magnitude improvement in the variation of the Honda engine's volumetric efficiency with consequent improvements in ease of adjustment and acoustic noise emission control. In addition, it has the lowest total pressure drop along the diffuser of all concepts evaluated. The optimized restrictor allowed to reach the maximum air flow with less pressure loss. From the numerical and experimental data it has been proven that the developed angle restrictor allows good engine performance, allowing the vehicle to reach 100 km/h in 6 seconds.

5. ACKNOWLEDGEMENTS

This work was supported by the FSAE UFCG Scudeira Team and the Mechanical Engineering Department of UFCG and by the PET Mechanical Engineering Group (PETMEC-CG). Finally, the authors thank SESU/MEC for the financial support in the form of grants and funding for the PETMEC-CG's undergraduate researches.

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