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Optimized Design of a Motorcycle's Exhaust System

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Abstract. In competitions like MotoStudent organized by MEF (Moto Engineering Foundation) it is common that the organizers provide for the teams components like engine, wheels and tires that are not possible to be manufactured by them. Without knowing detailed specification for the absence of the manual and with restrictions on modifications, the team needs to project for example the motorcycle's exhaust system in an optimized way to win the competition. This system is the scope of this study, that aims to estimate internal dimensions of the engine through data of temperature collected in the exhaust tube wall. The work uses a LabView program to acquire the data and correlates two theories to make the estimative on the overlap period with the acquired data. The results obtained were of 5,89% for a 150 cc motorcycle and of 0,68% for a 250 cc in comparison with the manual's values for the exhaust tube length.

Keywords: Exhaust system, overlap period, four-stroke engine, motorcycle engine.

1. INTRODUCTION

One of the most important studies about a four-stroke engine involves the overlap valve periods (period during which both inlet and exhaust valves are open). Normally the crankshaft revolution defines the period that both valves open and close using a crank angle. During the development of an exhaust system project for a motorcycle developed by Coyotes Moto racing Team for a competition called MotoStudent organized by MEF (Moto Engineering Foundation), the team realized that there were two main difficulties in order to develop an optimized project. At first the absence of the engine's manual for the competition and then, the existence of seals that prohibit any kind of modification or internal access to the engine. It is not possible then for the team to determine the overlap period or to measure any internal dimensions of the engine.

Independently of the restrictions imposed to the engine, an efficient exhaustion system is needed in order to reduce the engine's noise and to maximize its power. The exhaustion system of a motorcycle is basically constituted by the exhaust curve and muffler. Their project and building details however directly affect the motorcycle performance, making their length, diameter and material, for example, especially important to optimize in a competition. The overlap period of an engine is the time during which both the inlet and exhaust valves are open and is directly related to the efficiency of the engine concerning the proportion of air and fuel mixture to optimize the combustion. Knowing the engine's overlap period for a defined rotation is therefore essential for optimizing the project of the exhaust system. The main goal of this work is to create another reference to determine the overlap valve periods, that will be measured in a set of time.

This study is based on two complimentary theories that will be presented in the next section. The first one is called approximate method by ROCHA (2011) and is based in a crankshaft crank angle, and the second one is based in combustion gases reflection.

2. METHODOLOGY

2.1 Crankshaft Crank Angle Theory

The valve opening point before the bottom dead center (BDC) can be used to calculate the exhaust mean tube length in SI as described by Equation 1 BELL (1980) and explained by ROCHA (2011).

$$L = \frac{21590(AVE + 180)}{N} - 76,2 \quad (1)$$

In which N is the engine's speed in rpm and AVE represents the opening of the escape valve in degrees before the

BDC.

2.2 Physical Behavior of Combustion Gases Outflow Reflection

Another theory about the exhaust operation explains the physical behavior of combustion gases outflow by the reflection mechanism that occurs inside the tube and the influence of exhaust gas in the admission of gas and fuel mixture. BLAIR (1996) and ROCHA (2011) both explain this theory and the former one shows in his thesis explicitly that the overlap period can be measured in an interval of time, which is the same as the time that the combustion gases outflow goes to the end and back due to the reflection of the gas in the end of the tube.

With an intention to increase engine power, it is possible to make modifications in the exhaust geometry to increase the combustion energy, ROCHA (2011) explains that there are two forms of pressure waves flowing through the exhaust. The first is called the overpressure wave, it occurs with the opening of the exhaust valve that pushes the gases from the burning towards the outlet to the outside, when it comes into contact with the atmosphere, dissipating, and forming a depression wave (negative pressure) that moves towards the exhaust valve, therefore, in the opposite direction to the flow of exhaust gases.

If the suction wave arrives at the cylinder at the same time as the opening of the exhaust and intake valve (overlap) the internal pressure of the combustion chamber reaches lower values, causing more air to be sucked in and consequently enriching the mixture for the explosion, allowing greater pressure to be achieved by the reaction inside the chamber, thus increasing engine power.

According to ROCHA (2011), the path of a pressure wave occurs from cylinder-atmosphere and atmosphere-cylinder modes, there are also three reflections within the exhaust, twice on the tip and once on the cylinder. When a pressure wave encounters a section change it is reflected, if it is an overpressure wave it is transformed into a depression wave and if it is a wave of depression the reflection turns it into an overpressure wave.

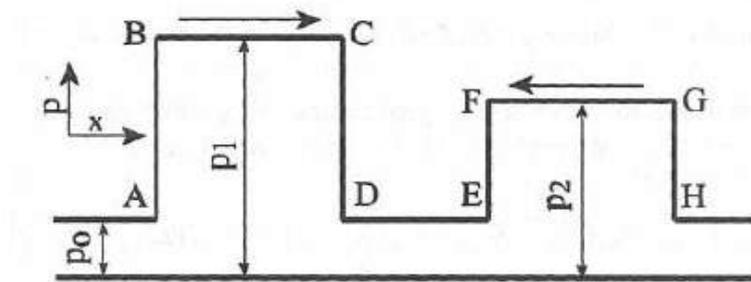


Figure 1. Two waves of pressure meeting each other, ROCHA (2011).

Figure 1 illustrates what happens when two pressure waves in opposite paths inside the exhaust intersect, it can be seen that the pressure is increased by forming an overpressure, as can be seen in the Figure 2.

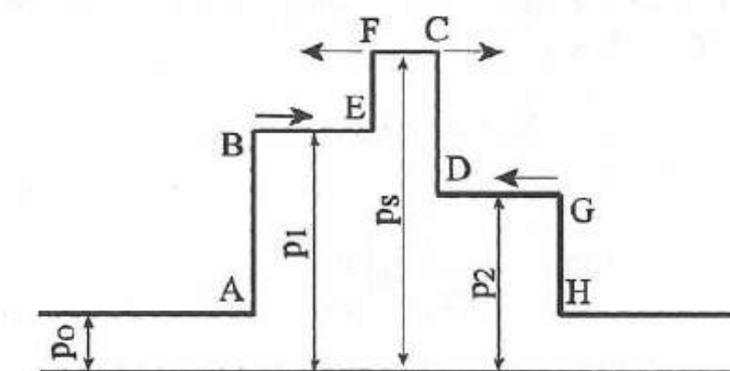


Figure 2. Two partially overlapping pressure waves, ROCHA (2011).

It is possible to differentiate the two that are reflected in the tip as in Figure 3 where the wave going into the atmosphere is called an incident "i" and the wave that is reflected "r" returns to the cylinder.

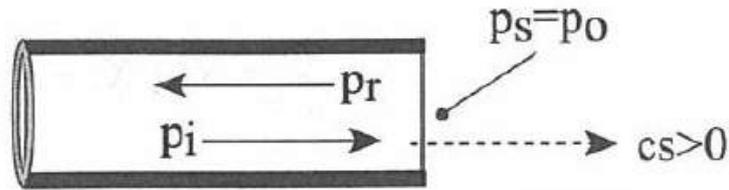


Figure 3. Two partially overlapping pressure waves, ROCHA (2011).

The characteristics of the pressure waves along the length of the exhaust pipe are not the same. The values of velocity, temperature and pressure vary due to factors such as thermal insulation and friction between the gases and the pipe wall. For these reasons it is not possible to calculate with the same parameters the loss of load and loss of heat, if these phenomena were not considered there would be a large difference between the calculated and actual wave velocity, because the speed decreases along the course.

According to ROCHA (2011), the methodology used to overcome this problem is the division of the exhaust pipe into meshes, because depending on the number of elements used, that is, the refinement of the mesh, it is possible to obtain better results in the simulation. In this way there will be different temperatures and flow velocities in each element, thus providing the calculation of the different load losses.

According to the experiments carried out by BLAIR (1996) using this same methodology it can be observed that the outlet pressure in the engine cylinder used for the tests was approximately 1.3 atm which is a typical value for Otto cycle engines, this value could be found through calculations, however, there would be a complexity due to the geometry of the exhaust valve, besides being necessary to know the exact moment of opening and closing in each cycle, for these reasons will be adopted this method for this work.

2.3 Cases Description

Firstly, it is important to determine the length of the exhaust tube and for this purpose the speed of the combustion gases outflow will be considered as 80% of the speed of the sound in the average temperature measured, since that BELL (1980) says that the pressure wave goes out with a velocity between 457 m/s and 518 m/s, but this only happens with those gases expelled initially. This consideration is also based in the results presented by HEYWOOD (1988) in Figure 4. It shows that the results obtained by tests and the model developed by himself at 1200 rpm present the speed of all gases produced by the combustion as approximately 80% of the speed of the sound in average.

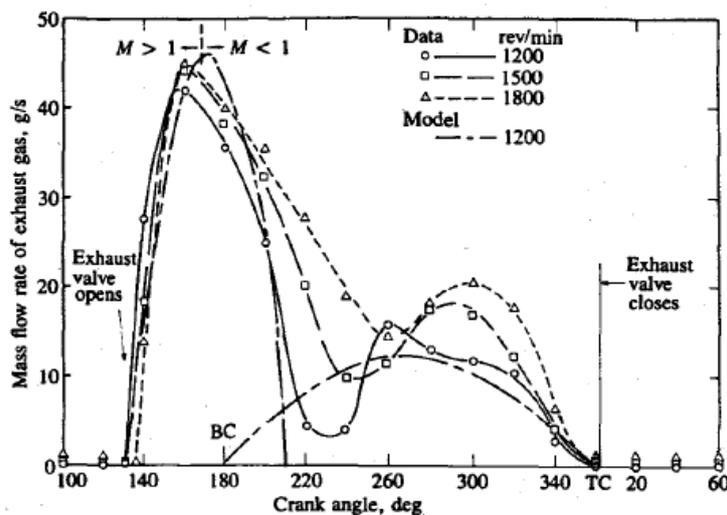


Figure 4. Mass flow rate of exhaust gas presented by HEYWOOD (1988).

It is considered that the outflow goes out of the exhaust valve to the end of the tube due to the higher pressure in the combustion chamber, compared to the pressure outside, and goes back from the end of the tube to the exhaust valve, since that the gases are reflected in the end of the tube. The interval that the gas takes in the described route represents the overlap period – interval during which both inlet and exhaust valves are open – and is the primordial basis of this work. Due to pressure difference among the combustion chamber and the exhaust valve exit, more air plus fuel goes in to combustion chamber, and this guarantee a complete combustion increasing engine efficiency. Because of this, the exhaust

tube length can be calculated by Equation 2, where L is the tube length, v_{out} is the exhaust gas velocity, and $t_{overlap}$ is the period that exhaust gas goes to end of exhaust pipe and goes back.

$$L = \frac{v_{out} t_{overlap}}{2} \quad (2)$$

The speed of sound is an important parameter in this method so that its fraction can be inserted as v_{out} and, when the gas is considered ideal, can be represented by Equation 3. It is possible to see that it depends only on the temperature of the system.

$$V_{som} = \sqrt{\gamma RT} \quad (3)$$

Where γ is the adiabatic index, R is the molar gas constant for the air and T is the temperature in Kelvin. In this work, γ was considered 1.4, R as 287 and T as the average temperature measured. This study aims to estimate the overlap period observing the temperature behavior and estimate the speed of sound in the acquired temperature so that all terms in Equation 2 are filled and the tube length can be calculated. The complete deduction of the method is available in ROCHA (2011).

2.4 Data Acquisition

According to the thesis developed by ROCHA (2011), the ideal position to measure the temperature is in the exit of the exhaust valve, but this was not possible with the available equipment. Thence the measurement occurred in the beginning of the exhaust tube. The type K thermocouple used (presented in Figure 5) was positioned touching the wall of the exhaust tube, and the temperature measured was shown simultaneously in the I304 process indicator screen produced by Contemp and presented in Figure 6.



Figure 5. Type K thermocouple utilized.



Figure 6. I304 process indicator produced by Contemp.

The data acquisition occurred using a data logger developed by National Instruments – model NI USB-6009 and presented in Figure 7. The tests were performed in two different motorcycles, a 150 cc 2004 CG150 Titan and a 250 cc 2015 Fazer Blue Flex.



Figure 7. NI USB-6009 Data Logger.

2.5 Acquisition Method

A program was developed using LabVIEW to read the information from the data logger and write the data in a spreadsheet file. This file stores the data in two columns, the first one acquires the date and time, and the second one stores the data measured. The data was transmitted in volts, and it has a relation with the temperature detected. The inferior limit measured was 0,88 V (150cc - 100°C, 250cc - 150°C) and the superior was 4,4 V (150cc - 250°C, 250cc - 300°C). Figure 8 shows the program developed in LabVIEW.

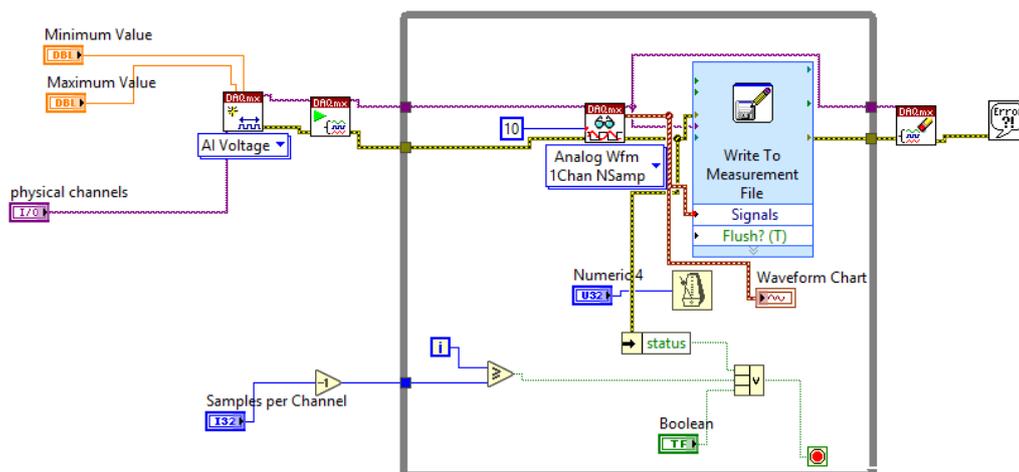


Figure 8. Program developed in LabVIEW.

2.6 Calibration

In order to calibrate the system, it was performed two experiments to compare the results obtained with the results from a previously calibrated indicator.

The experiments involved measuring the temperature in two conditions: ice and boiling water, and the results obtained can be found at Table 1. The obtained error was used for the correction in the data acquisition of the section 3.

Table 1. Calibration parameters.

	Ice	Boiling Water
Used System	2,5 °C	97,0 °C
Calibrated System	1,7 °C	100,5 °C

3. RESULTS AND DISCUSSION

3.1 Overlap Period

It is important to determine the frequency that the data logger stores the data in order to check if it is consistent with the overlap period's order of magnitude. According to the Nyquist theorem, the data logger frequency needs to be at least 2 times higher the event frequency to avoid aliasing. In this case, the overlap period was estimated using the Equations 4 and 5.

$$N = \frac{n}{60} \quad (4)$$

$$t_{360} = \frac{1}{N} \quad (5)$$

Where n is the maximum RPM (revolutions per minute), N is the RPS (revolutions per second) and t_{360} is the time to complete one complete rotation.

Table 2 shows the data for both tested motorcycles. The order of magnitude of the time to complete one rotation for the motorcycles was around 7,5 ms, so the frequency utilized for data acquisition to adequately acquire one cycle phenomenon needs to be around 270Hz. The data logger acquisition on the other hand occurs at 3Hz only, so the event to be studied represents 100 cycles (100 overlap periods). In other words, this experiment measured 100 overlap periods, and for the calculation, the time period obtained was divided by 100.

Table 2. Basic information for both motorcycles used.

	CG150 Titan 2004	Fazer Blue Flex 2015
Cylinder Capacity	150 cc	250 cc
Cylinder Capacity	9.5	9.8
Maximum Power	8000 RPM	8000 RPM
Maximum Torque	1.35 kgf.m at 6500 RPM	2.1 kgf.m at 6500 RPM
Slow Running	1400 RPM	1400 RPM

3.2 Overlap Temperature Variation

The overlap period can be recognized by a temperature variation of approximately 300 K in the exhaust port exit. This variation is presented in Figure 9 from HEYWOOD (1988), where the curve T_P shows this variation. In this situation, the temperature was measured at the valve port exit, whereas in this work, it was measured in the exhaust tube wall, so the temperature obtained was smaller than the value presented in the literature.

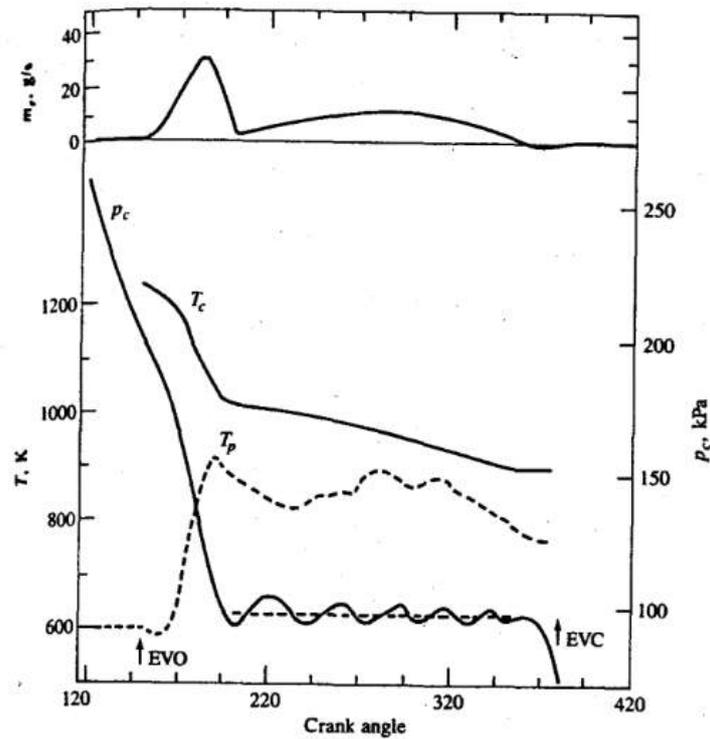


Figure 9. Curve T_P shows the measured gas temperature at exhaust port exit, HEYWOOD (1988).

3.3 Considerations about the Data Acquisition

To determine the overlap period, a graph with the temperature distribution for each motorcycle was created, and for the analysis it was considered only the regions with an increase immediately followed by a decrease in temperature variation. This behavior represents exactly an overlap period. The former and the last points were not considered so the system got some stability. After the acquisition, a mishap on the data logger was observed in ways of unreliable frequency of acquisition, so that sometimes it acquired at less than 3Hz. At some points, the temperature measured was clearly not in the extreme points of the cycles but in the middle, so these points were not considered. For the 250 cc motorcycle, the data was acquired outside so it is believed that the wind destabilized a little the temperature measurements.

3.3.1 150 cc

For the first motorcycle, 8 intervals were used, and their average time was 0.75 s. The temperature distribution and one of those intervals is represented in Figure 10.

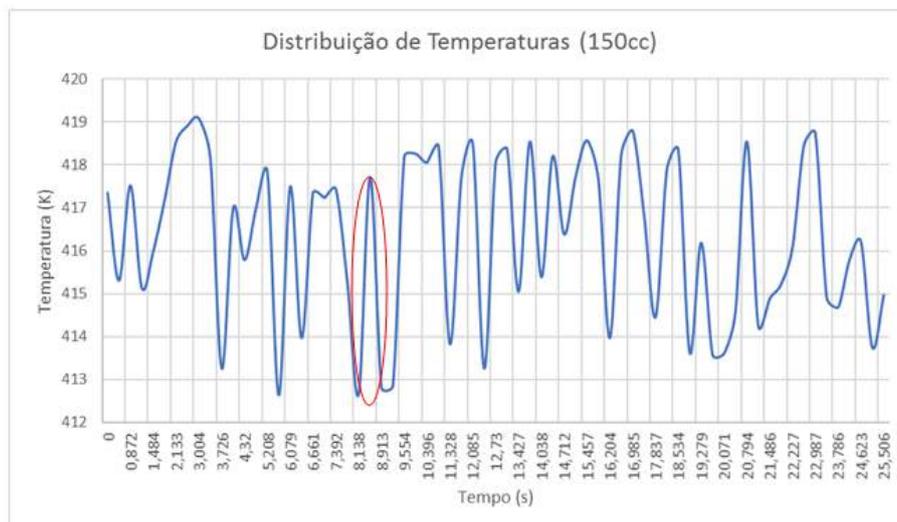


Figure 10. Temperature distribution for 150 cc motorcycle.

3.3.2 250 cc

For the second motorcycle, a similar graph with the temperature distribution in time was created, but it was necessary to split the distribution presented in Figure 11 in other two graphs (Figures 12 and 13) to facilitate the analysis.

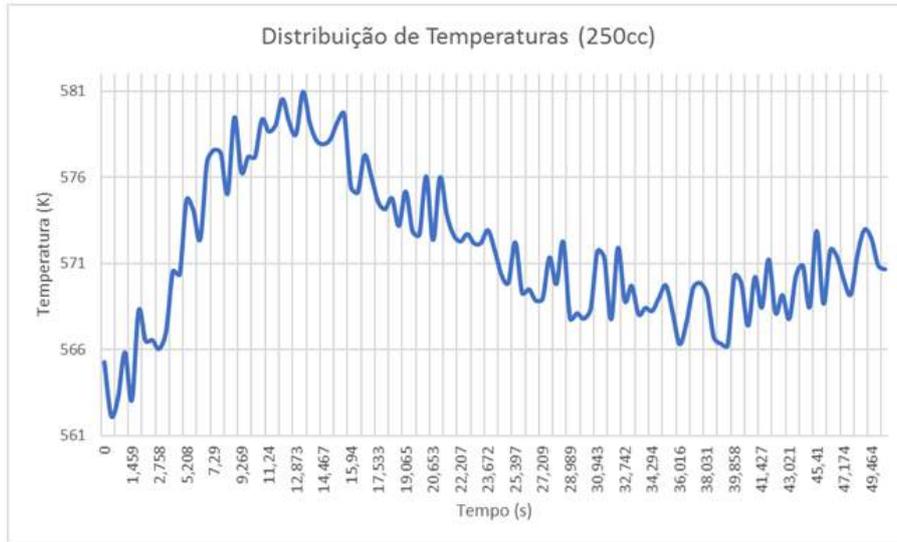


Figure 11. Temperature distribution for 250 cc motorcycle.

For the first part, 7 intervals were selected, and for the second part, there were 6, with an average time of 0.84 s. Figures 12 and 13 shows one of those intervals selected.

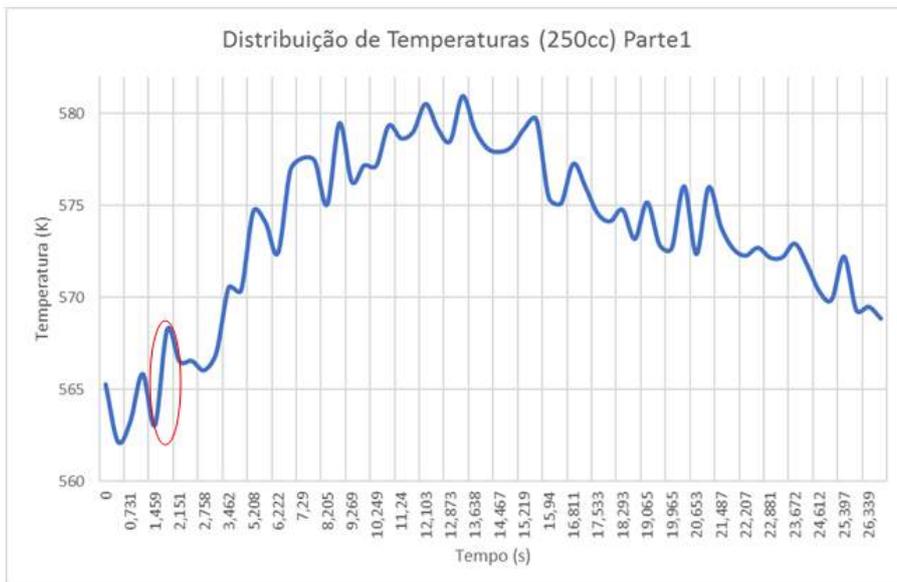


Figure 12. Temperature distribution for 250 cc motorcycle Part 1.

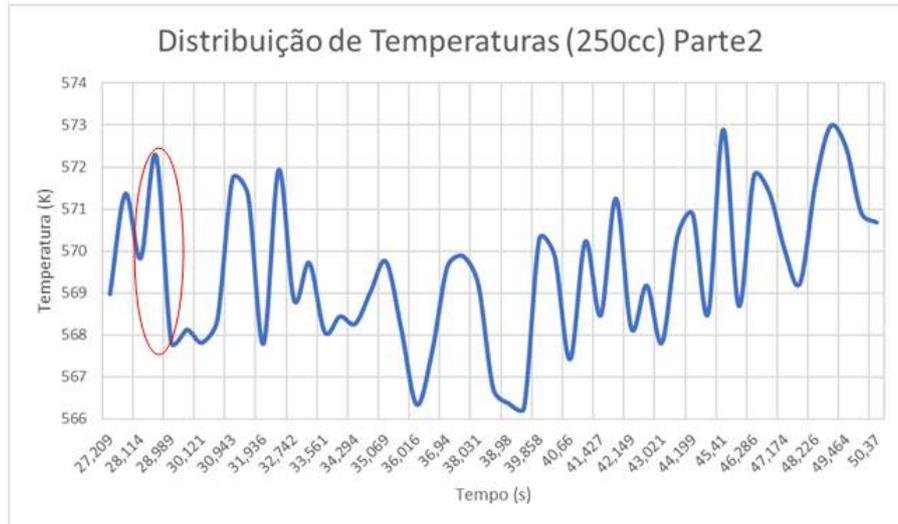


Figure 13. Temperature distribution for 250 cc motorcycle Part 2.

3.4 Results

The results obtained are shown in the Table 3 and include the average temperature measured in each case, the estimative of speed of sound on the condition, the reference value on the exhaust pipe dimension and the result obtained from this study as well as the comparative error between these values. The reference value on the pipe dimension was obtained physically measuring its size on the motorcycles.

Table 3. Summary of the results obtained.

Motorcycle	Average Temperature	Speed of Sound	Measured	Calculated	Error
150 cc	416.99 K	409.01 m/s	1300 mm	1231.33 mm	5.28 %
250 cc	571.77 K	479.31 m/s	1600 mm	1606.20 mm	0.39 %

The result for the 250 cc motorcycle can be partially attributed to the biggest number of data available in the estimation, making it more precise than for the 150 cc.

4. CONCLUSIONS

This work estimated the exhaust tube length for two different motorcycles by measuring the temperature in the exhaust tube wall. The results showed errors of 5.28% for 150 cc motorcycle and 0.39% for 250 cc motorcycle, while ROCHA (2011) presented errors between 5.7% and 10.5%. The results seem efficient however the data acquisition method used was not ideal because of the equipment available. It would be interesting to remake the data acquisition with a logger capable of acquiring the data in the adequate frequency and using a thermocouple capable of being set up at the valve port exit for more adequate comparison with literature. A complimentary experiment measuring the average speed that gases from combustion go out from exhaust valve would be interesting to compare with the estimates.

5. ACKNOWLEDGEMENTS

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