FCTUC FACULDADE DE CIÊNCIAS E TECNOLOGIA
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# Cooling systems analysis

Dissertation submitted for the degree of Master of Industrial Engineering and Management.

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"The award for a thing well done is to have it done."

*Ralph Waldo Emerson*

To our parents.

# ACKNOWLEDGEMENTS

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# ABSTRACT

This master thesis report describes the behavior of a cooling system based on the power consumption and power losses during the velocity range. The thesis is a report of the behavior of the cooling system to understand were we having more needs to cold down the system. It was used a excel sheet to describe the values of power, losses and efficiencies of the various components of the cooling. With the excel sheets built we studied various cases in the system to show the points more important to take care with the cooling system.

Continuing the study, it was showed the power consumptions of the cooling system and also the heat dissipation capacity. The objective included in this thesis is to show that in the regular cooling systems the use of the engine's velocity to move the fan and the coolant pump is not the best choice. Could be currently the less expensive one,but not the best one.

This thesis didn’t have the objective to find a solution for a perfect cooling system, but a good report of the problems of the actual cooling systems and where we should spend more time to improve them. This is just a preparatory work for a new work.

**Keywords** Engine, cooling systems, efficiencies in engines, losses, hydraulic system, pump, fan, heat dissipation, power consumption, cooling system, pressure drop.

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# LIST OF SYMBOLS AND ABBREVIATIONS

| Abbreviation | Description | Unit |
|---|---|---|
| $\eta$ | Global efficiency | % |
| $\eta_{max}$ | Maximum Efficiency | % |
| $\omega^*$ | Dimensionless parameter to calculate the efficiency | No units |
| T | Torque | N/m |
| $\omega$ | Velocity | Rpm |
| P | Power | W |
| $\pi$ | Pi | No units |
| $P_{fan}$ | Power of the fan | W |
| $\omega_{fan}$ | Velocity of the fan | rps |
| $T_{fan}$ | Torque of the fan | N/m |
| HD | Heat dissipation | W |
| q | Fluid Flow | $m^3/s$ |
| $\Delta P$ | Pressure drop | $N/m^2$ |
| $P_{losses}$ | Power losses | W |
| $R^2$ | Coefficient of determination | %/100 |
| $P_{in}$ | Input of power in the system | W |
| $\eta_p$ | Speed of the pump | Rpm |
| $q_p$ | Flow output by the pump | $M^3/s$ |
| $q_L$ | Flow without losses | $M^3/s$ |
| $P_L$ | Power without losses | W |
| $P_{out}$ | Output power | W |
| $\eta_m$ | Speed of the motor | Rpm |
| $M_m$ | Torque of the motor | N/m |

# 1 INTRODUCTION

## 1.1 Background

Since the beginning of the engine's history, the control of the temperature was one of the items that always received a lot of attention from the engineers.

As the engines were evolving and increasing the power, there was a need for improvement of the cooling systems, because the range of temperature became on account of higher power, ever closer.

The engine needs to maintain a constant temperature and ideal, even when subjected to great efforts because it is composed of parts of different materials with different coefficients of expansion, which work on friction constant and millimetric adjustment.

Internal combustion engines are heat engines that can reach very high temperatures. From all of this thermal energy generated, only a small part, around 30% are processed effectively as work, another 35% are lost by the exhaust system and the rest is up to the cooling system that receives help from the lubrication system. Excess heat energy produced by an engine should be directed so as not to become detrimental to their operation.

A coolant system is used for removing excess heat from, engines, electric motors, hydraulic systems and mechanical units. There are several ways in which coolant systems can be designed. Coolant systems can be used to cool just one machine or equipment or a centralized cooling system can be used. A coolant system can be developed according to the specification provided by customers and equipments used. Some of the specifications that should be considered for the design of a cooling system are cooling capacity, power consumption, power source etc.

### 1.1.1 Project definition

The goal of this project is to find in the cooling systems where exist more and less efficiency, more and less losses and what can be due to increase the efficiency and reduce the losses.

As known, the cooling system has a very important work in the operation of the engine. The engine has some different stages, but the objective is to study what happen with engine's efficiency and losses when we are have a high torque and low speed and also when we have low torque and high speed.

The main aim of this work is to specify the requirements of a coolant system for different kind of energy transformers, such as: engines, electric motors, hydraulic systems and mechanical units. For all energy transformers the power losses/excess heat varies according to its operation point (speed and torque). The coolant system must be able to handle the power losses in full operation range of the energy transformers.

From this specification of a coolant system, different system concepts have to be analyzed like the case high torque-low speed and also low torque-high speed. Finally the control of coolant systems has to be studied. The control target is to maximize cooling capacity at minimum power consumption for the coolant system. A typical coolant system for an engine is shown in Figure 1.1.

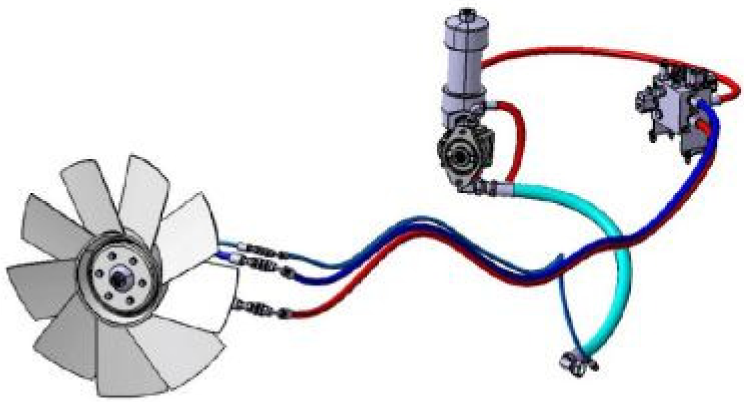

**Figure 1.1 - Typical coolant system for an engine [1]**

# 2 METHODOLOGY

## 2.1 Literature study

In order to improve the knowledge of cooling systems efficiencies, to investigate if (or how) this problem has been solved in the past and to find possible models the literature is carried. The literature used for this project is based in master thesis, PHD thesis, courses documents and internet documents. The main topics are cooling systems, hydraulic systems, efficiencies models and how to implement a model that can show the behavior of the losses in different examples.

## 2.2 Physical background

This project is based on efficiencies in cooling systems. So the maximum base is in the efficiencies calculations for the first part of the thesis.

For the second part is the study of the heat dissipation and the power consumption of the cooling system. This system is divided in the two. The part of the hydraulic system, and the part of the air system.

### 2.2.1 Efficiencies of engines, pumps and motors

To calculate the efficiency of an engine, pump or motor the following equation 2.1 is the method should be used.

$$\eta = 1 - (1 - \eta_{max}) \frac{(\omega^{*} + 1)^2 + \eta_{max}(\omega^{*} - 1)^2}{(\omega^{*} + 1)^2 - {\eta_{max}}^2(\omega^{*} - 1)^2}$$

**Equation 2.1**

With η is the efficiency of the motor, $\eta_{max}$ is the maximum efficiency of the motor. And $\omega^*$ is the dimensionless parameter represented in the equation 2.2.

$$\omega^* = \frac{\omega/_T}{(\omega/_T)_{n_{max}}}$$

**Equation 2.2**

The $\omega/_T$ represents the velocity ($\omega$) and torque $T$ at the moment and $(\omega/_T)_{n_{max}}$ the velocity and torque in the maximum efficiency point.

$$P = T * \ \omega * 2 * \pi/60$$

**Equation 2.3**

The P represents the Power, T is the torque and $\omega$ is the velocity, and this equation is used to calculate one of the parameters knowing the other two. The equation is divided by 60 because we are using rpm and we need to convert to rps.

## 2.2.2 Scheme of the system

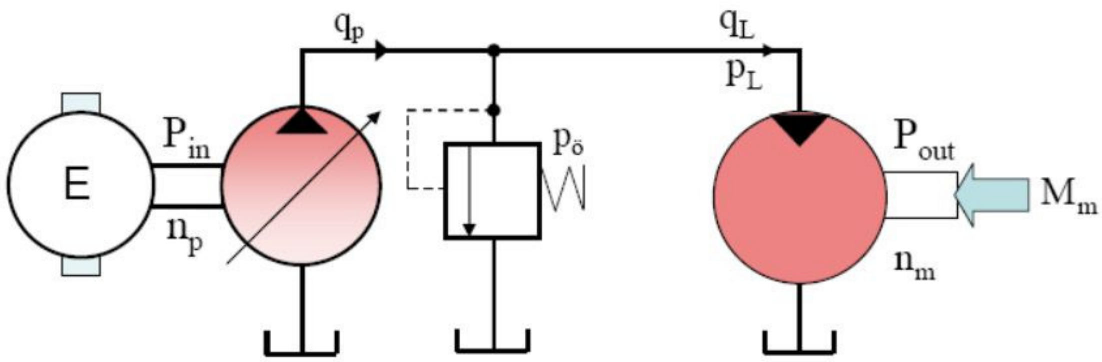


**Figure 2.1 - Scheme of the system**

This figure shows the base of the system that was used to study the efficiency.

There's an Engine (E) connected to a pump that moves the fluid in the hydraulic system, at the end, in the right there's the load side where the fluid makes the load side move (motor).

In this system are four components to give an individual study: the engine, the pump, the hydraulic system and the motor /load side.

#### 2.2.2.1 Engine

To calculate the efficiency of the engine is used the equation 2.1 represented in the last sub chapter. Using the velocity and torque of the engine changing with time.

#### 2.2.2.2 Pump

To the efficiency of the pump is used a constant value. After the search in the catalogues of pumps is discovered that the efficiency of a pump can varies between 85 – 97%. After discuss this value with the coordinator is decided that is a reliable value.

#### 2.2.2.3 Hydraulic system

To the hydraulic system is more complicated. Knowing that the efficiency depends of the structure on the circuit; corners, pressure drops, size; we made a research [2] that say that the efficiency of the hydraulic system varies between 60-90%.

#### 2.2.2.4 Load side (motor)

The method used in the load side use the same equation as the motor. The input power is equal to the input power in the motor without the losses in all the system (motor + pump + hydraulic system). With that power and changing the velocity can be calculated the torque or changing the torque can be calculated the velocity. For that velocity /torque calculations are used the equation 2.3.

### 2.2.3 Heat dissipation and power consumption

This part is divided in two. The part of the hydraulic system and the part of Air system.


**Figure 2.2 - Oil/Air cooler unit [4]**

#### 2.2.3.1 Air system (Fan)

In this case is needed to know the equations to calculate the heat dissipation and the power consumption.

$$P_{fan} = \omega_{fan} * \; T_{fan} * 2 * \pi$$

**Equation 2.4**

The $P_{fan}$ is the power of the fan that is equal to the velocity of the fan ($\omega_{fan}$ in rps) multiply by the torque of the fan ($T_{fan}$) multiply by 2π.

$$T_{fan} = 4 * E^{-6} * \omega_{fan}{}^2 + 6 * \ E^{-17} * \omega_{fan} - 3 * E^{-14}$$

**Equation 2.5**

This equation represents the torque characteristics for a fan (from the company ACS) used for cooling a system with a nominal power level of 150 kW. The fan driving power at 1500rpm is 1256 W.

For the heat dissipation is used the data from the Hydac International, Oil/Air Cooler Units Catalogue [4], here with a constant flow of 140 l/min, and the two velocities (1500rpm and 3000rpm) is collected the data to plot a graph with heat dissipation vs. fan velocity.

To get the regressions that shows the comportment of the heat dissipation with the flow velocity and the pressure drop with also the flow velocity. The data that is chosen is the case of the biggest fan (ELH5) for the two velocities represented (1500rpm, 3000rpm).

#### 2.2.3.2 Hydraulic cooling system

Collecting the data from the Hydac International, Oil/Air Cooler Units Catalogue [4], of the heat dissipation vs. flow velocity, to the case (ELH5). Is collected the two regressions for the two fan velocities.

$$HD = 7.4179 * \ln(q) - 7.0731$$

**Equation 2.6**

This case represents the Heat dissipation (HD) with the flow velocity (q), for an ELH5 cooling system, at 3000rpm. With an $R^2 = 0.9752$.

$$HD = 3.5375 * \ln(q) - 0.2929$$

**Equation 2.7**

This is the same as the last one but for a fan velocity of 1500rpm. With $R^2$ = 9769.

$$P_{losses} = q * \Delta P$$

**Equation 2.8**

The power losses $P_{losses}$(W) in the hydraulic system is equal to the flow q multiply by the pressure drop.

To calculate the pressure drop is used again the data from the cooling system ELH5. With that data collected the regression that shows the pressure drop with the flow velocity and is characterized by the following equation:

$$\Delta P = 0.0034 * q^{1.0877}$$

**Equation 2.9**

The equation gives the pressure drop of an ELH5 by the flow velocity with an $R^2$ = 0.9975.

# 3 MODEL DESCRIPTION

This study model is based on a theoretical equation 3.1 where we have as a first order approximation, the efficiency that can be expressed as a function only of velocity, torque, the maximum efficiency and the velocity/torque ratio at which this occur.

$$\eta = 1 - (1 - \eta_{max})\frac{(\omega^* + 1)^2 + \eta_{max}(\omega^* - 1)^2}{(\omega^* + 1)^2 - \eta_{max}{}^2(\omega^* - 1)^2}$$

**Equation 3.1**

To calculate our $\omega^*$ is used the equation 3.2 when the maximum efficiency $n_{max}$ and angular velocity /torque ration at maximum efficiency $(\omega/T)_{n_{max}}$ has to be adjusted according to the actual component characteristics.

$$\omega^* = \frac{\omega/T}{(\omega/T)_{n_{max}}}$$

**Equation 3.2**

In the figure 3.1 we have a plot $n$ vs. $\omega^*$ when we can see the relation these two parameters.

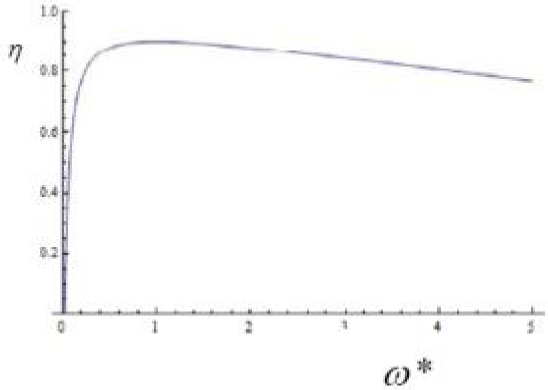


**Figure 3.1 - Ratio between η and $\omega^*$**

In this plot is possible to see that the maximum efficiency $n_{max}$ is when the dimensionless parameter ($\omega^*$) is around 0.9 and then the efficiency decrease as the parameter increase.

When more than one component exists in the hydraulic system, the real efficiency isn't the efficiency that the Figure 3.1 shows, because there is showed the behavior of the efficiency for one component.

The reality is that exist four components, so the efficiency of our hydraulic system will be $\eta^3$ instead the $\eta$ as is showed in the graphic below (Figure 3.2).

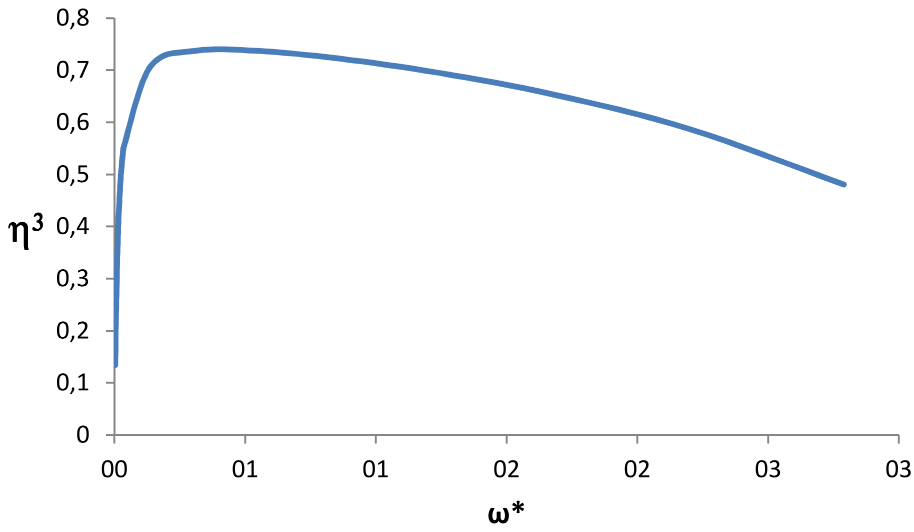


**Figure 3.2 - Ratio between η and $\omega^*$ for all components in the hydraulic system**

As expected the value of the efficiency decreased because, the efficiency of each component is multiplied to know the overall efficiency.

# 4 DIAGNOSTICS

## 4.1 System explanation

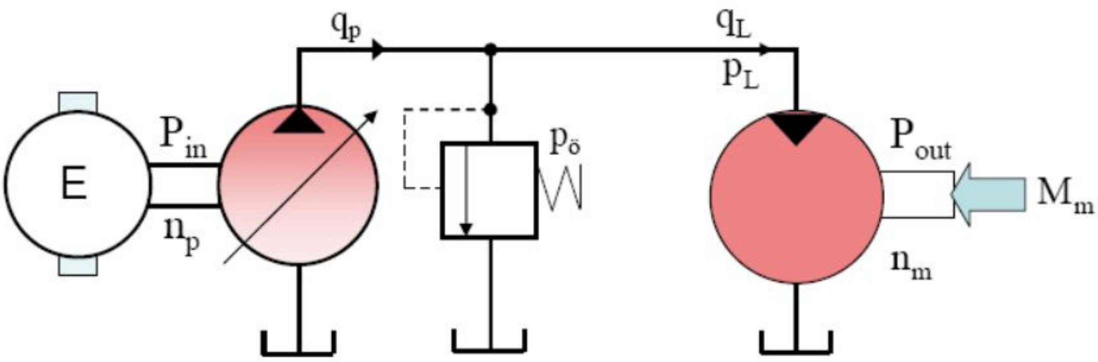


**Figure 4.1 - Model used in the efficiency study**

This system in the figure 4.1 is an example of the system used in the study. This system has four base components: the engine, the pump, the hydraulic system and the motor.

In the figure is possible to see all the components. In the left with the E there's the engine, that input in the system a power and velocity ($P_{in}$ and $n_p$), after that there's the pump that receive the power and velocity (the left circle in pink) and in the output moves the fluid ($q_p$), after that in the black lines there's all the hydraulic system.

The hydraulic system can be very complex, but for this study is used a basic hydraulic system.

In the end of the figure, the second pink circle, is the motor or as is called, the load side, that component receive the flow velocity ($q_L$) and power ($P_L$), without the losses in the hydraulic system, and have an output of power ($P_{out}$), velocity ($n_m$) and torque ($M_m$).

This is the scheme used in the model of the efficiency's in hydraulic systems.

## 4.2 Sensitivity study

In this case the sensitivity is based on the information collected from the different sources.

In the case of the scheme (Figure 4.1), the values used in the efficiency of the hydraulic system and pump are random values in a range, that range is collected from catalog's information, that information can change the results but the conclusion will be the same. The study is based on a global efficiency and not an individual, so the global efficiency is not compromise by using constant efficiency values in these two components.

About the engine and the motor (load side), there's also some sensitivity analysis to do. The values are collected from one engine, changing that engine can also change the results, but the base of the results will be the same and, as was already explained, the main goal is to study the global efficiency and that is not affected. The same appends with the motor (load side), the values used for maximum efficiency, velocity and torque are from one type, so is the same as the engine.

There's no problem in this case because, even because is used one type of component (engine, pump, hydraulic system, motor), the behavior of this component related to efficiency is almost the same in every case, so the global results are reliable. With some error that is admitted to exist but not important in the conclusions.

About the part of the thesis related to the power consumption and heat dissipation study. There's a percentage of error in the data. The equations used to calculate the heat dissipation and pressure drop is collected from the Hydac International, Oil/Air Cooler Units Catalogue [4], so exist some possible error from the values collected from the graphs, that error is less than 5% that is the percentage of error we admitted when a value is collected from a graph.

When the regression is mudded about the values collected, there's also a percentage of error in that process, that value is presented when the regression equations are showed in the report. That value is collected from the Excel sheet with the parameter $R^2$.

# 5 SIMULATION RESULTS

To study the behavior of the engine were made various studies before study the efficiencies and losses that the engine has.

To do the calculations is used the reference values of an electric motor with the following characteristic's:

- Maximum efficiency: 97%
- Velocity: 2000 rpm
- Torque: 100 Nm

The velocity changed between 500 rpm and 5000 rpm and the torque between 10 Nm and 400 Nm.

In the text below, a couple of the measurements are explained. The rest of the measurement can be found in appendix.

## 5.1 Engine's behavior

### 5.1.1 Constant Power

With this information is calculated the range of the efficiency's in the motor.

In the figure 5.1 there's the typical curve of velocity vs. torque.

Can be seen that the torque decrease when the velocity increase and vice versa.

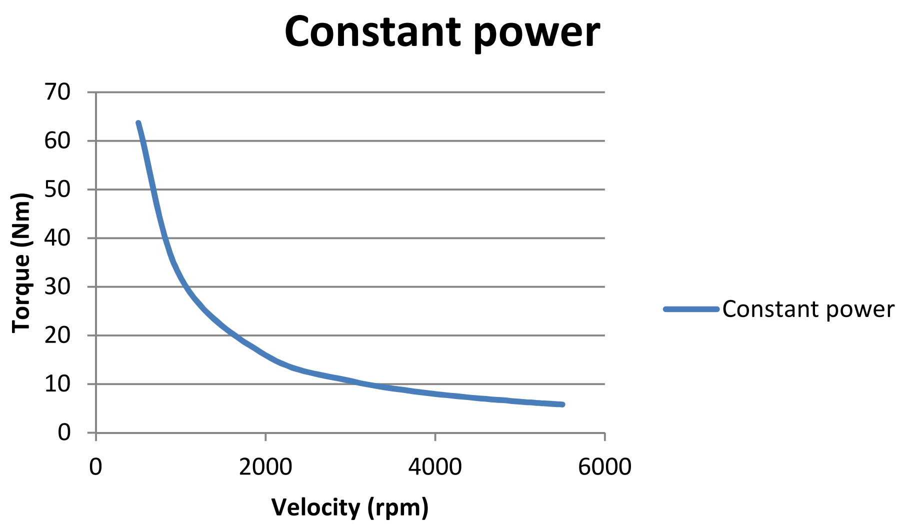


**Figure 5.1 - Constant power**

### 5.1.2 Constant Torque

With constant torque value in 200Nm, easily is viewed that when the velocity increase, the global efficiency of the system also increase as expected, that way the losses are more when we have high torque and low velocity.

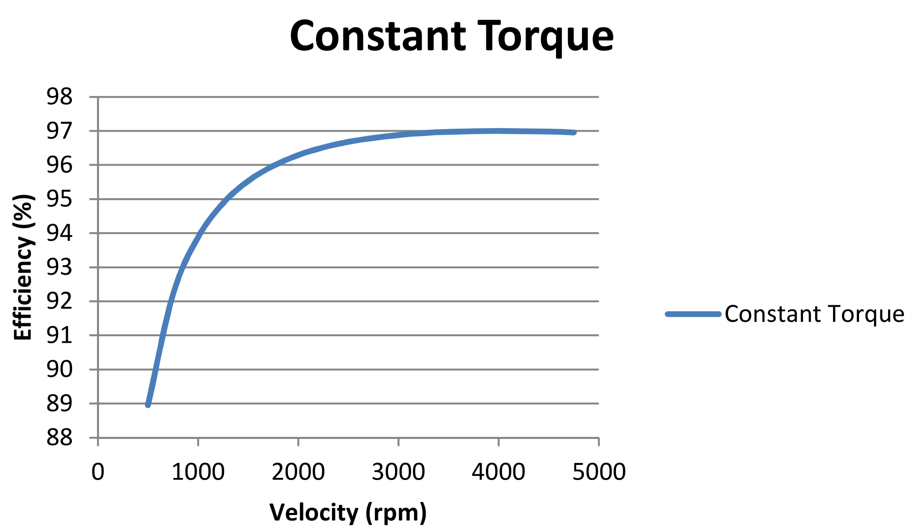


**Figure 5.2 - Constant torque**

## 5.2 Maps of efficiencies and losses

As is know the overall system efficiency will be bigger as minus components we have in the system that interfere directly with the calculation of the overall system efficiency.

The study of the overall system efficiency is divided in two phases. First of all the efficiency behavior until 10% of max velocity (low speed range) and then the behavior since 10% until 90% (high speed range) because in the beginning the power isn't constant once the engine is starting.

The graphic (Figure 5.3) shows that when the engine speed increase, the engine's efficiency also increase but the efficiency has it maximum between 1000 rpm and 2000 rpm.

After that the system has less efficiency because it enters in the high speed-low torque.

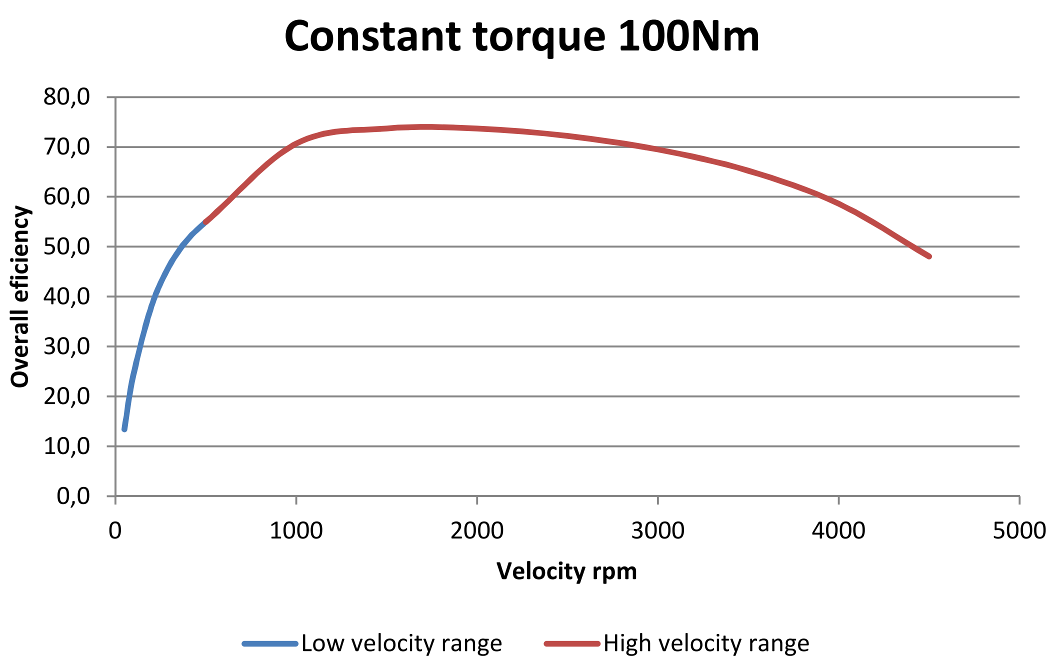


**Figure 5.3 - Overall system efficiency with constant torque @100 Nm**

As is seen in the plot of percentage of losses (Figure 5.4) the losses in the beginning are very high. They reach the minimum between 1000 rpm and 2000 rpm. After that the losses increases when entering in the high speed-low torque.

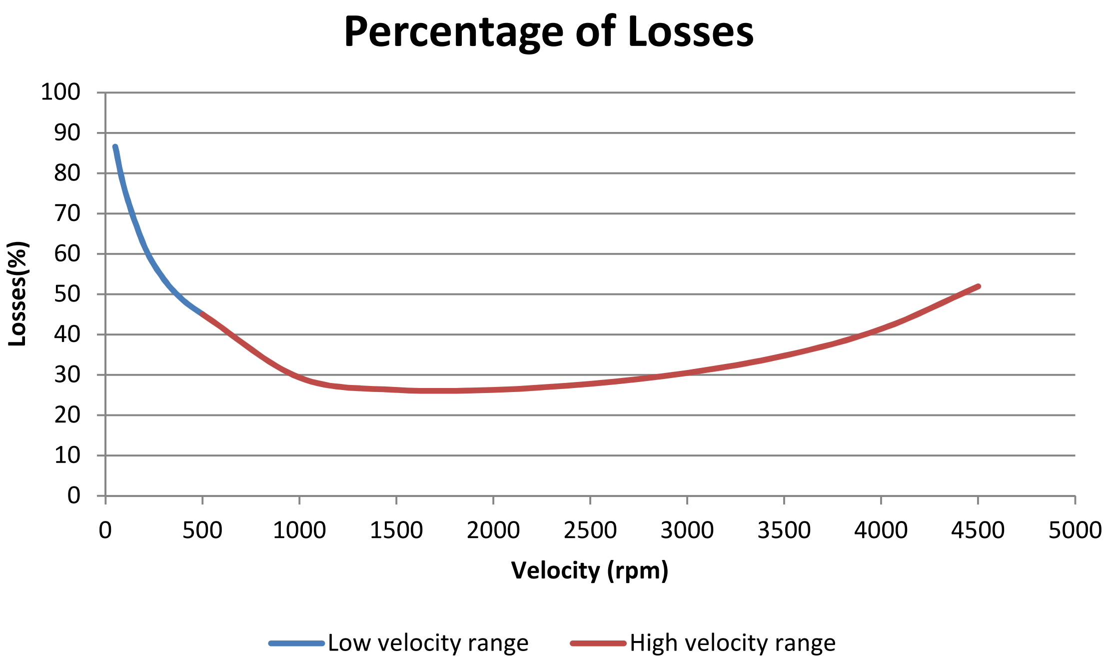


**Figure 5.4 - Percentage of losses**

When the maximum power is reduce to 50% (Figure 5.5), is possible to see that the behavior of the curve is quite similar to the behavior when we have the high range with 100% maximum power.

Even when is increased the torque and decrease the power, the behavior is the same. Only the velocity changes the behavior of the losses.

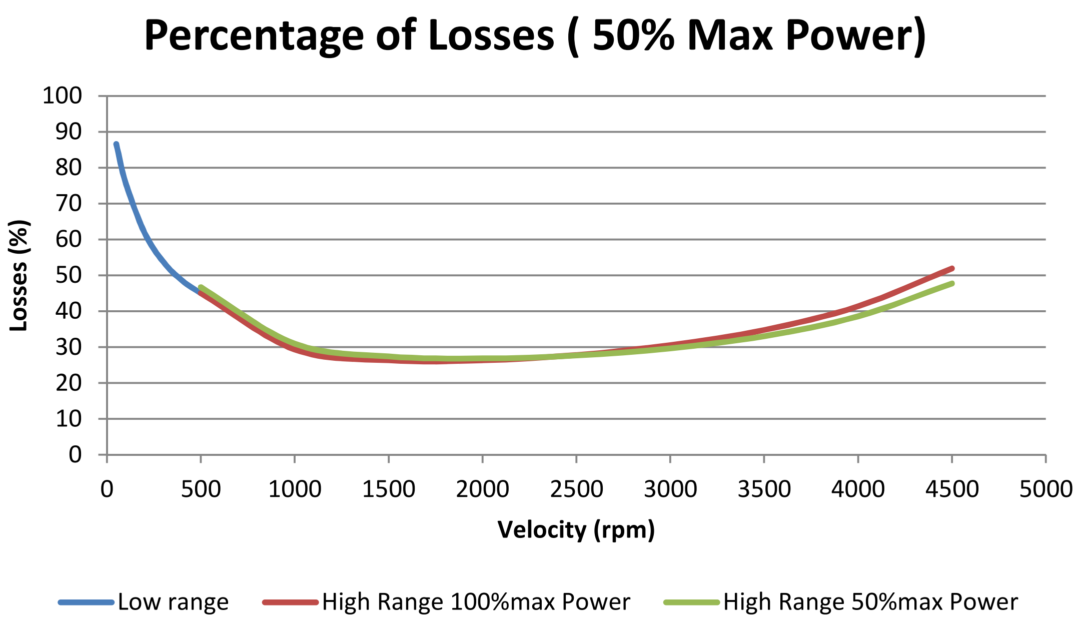


**Figure 5.5 – Percentage of losses when max power is reduced to 50%**

In the losses of the hydraulic system (Figure 5.6), we have the losses in the hydraulic system and the heat dissipation in two fan speed (1500rpm and 3000rpm) vs flow speed. It is possible to see that the losses have an exponential behavior and the heat dissipation a logarithmic behavior. So, it's important to know that to increase the heat dissipation is spent more power.

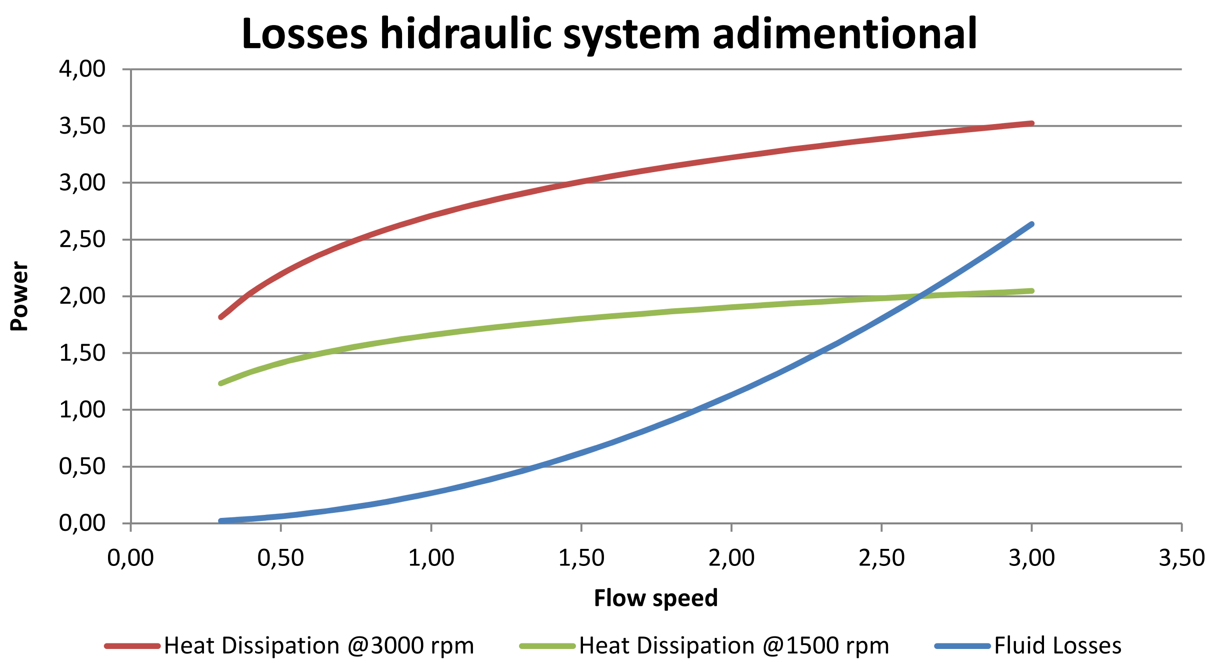


**Figure 5.6 - Losses in the hydraulic system**

The fan speed is other component that is analyzed. Is possible to see the heat dissipation and power consumption by the fan vs. the fan speed (Figure 5.7).

In this case is possible to see that the heat dissipation have a logarithmic behavior and the power consumption an exponential behavior. That way is understandable that to increase one point in the heat dissipation is necessary to increase more than one in the power consumption.

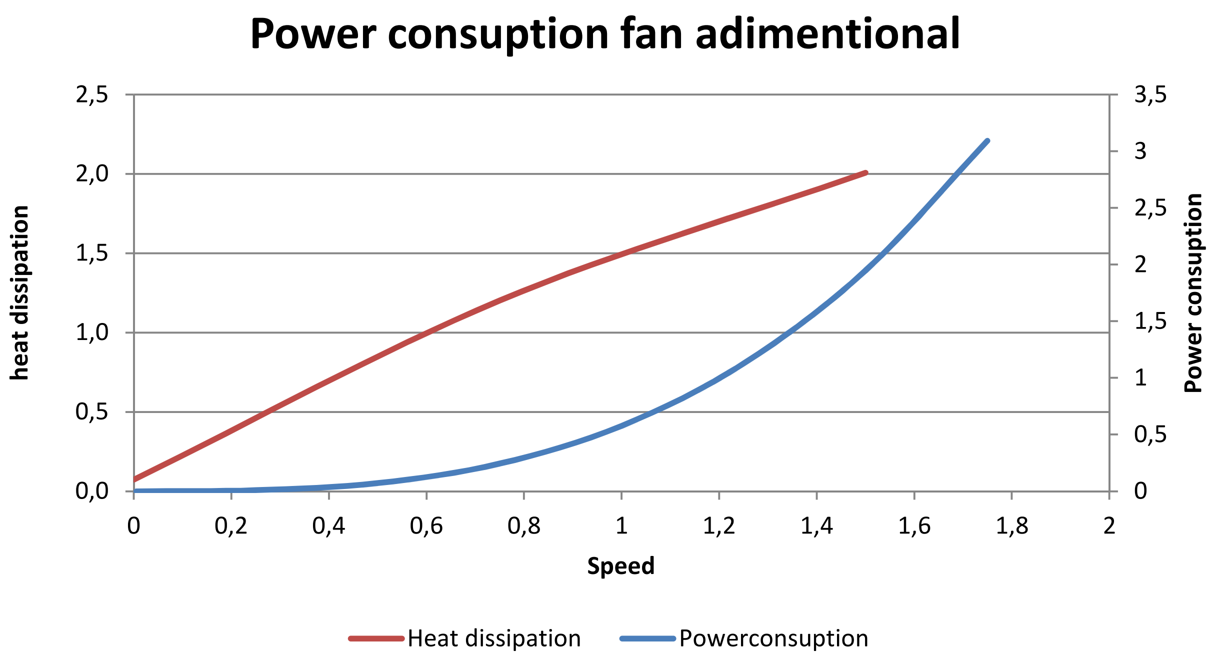


**Figure 5.7 – Heat dissipation and power consumption of the fan**

# 6 DISCUSSION

This data shows that the losses in the cooling system are representative. One point that is important to see is that the efficiency depends on the velocity of the engine more than the other variables (power, torque increasing or decreasing). Changing those variables the behavior is always the same. In low speed range the losses are high; they decrease until the maximum efficiency point and then start increasing again.

This project shows that the current way of cooling is not the most efficiency. Using the data of the work in the two phases is possible to see that the current way of using the velocity of the engine to work the fan and the pump is not effective. It’s possible to see in the graphs of losses vs. velocity that the losses are higher in low velocity, also in the graph of cooling capacity vs. velocity is known that the cooling capacity is lower, with that we will have a low cooling capacity in those regions of the velocity range.

It’s also shown in this thesis that the cooling capacity tends to stabilize with the increase of the velocity, with that the using of the velocity of the engine to move the fan and cooling pump in cases of high losses and high velocities is not available.

In the last part of the results, part of the fan and hydraulic cooling system, the power consumption increase more than the heat dissipation, so using the velocity of the engine, were the losses also increase with the increase of the velocity, is not available. An individual speed controller in the fan and pump with more efficiency is one best way to increase the efficiency of the cooling system.

# 7 CONCLUSION

Concluding the actual cooling systems are not the most efficiency, far away from that, the cooling capacity is not always enough to cool the engine and also some times the cooling capacity is higher than the needs.

With that is proved that in the current days the cooling systems can be more improved to create new ones with better efficiencies, in an era when the efficiencies are an important subject in the construction of vehicles and machines, should be spend more time and work in this subject.

In extreme cases like heavy machinery that creates a big problem, those machines work always in low velocities. With that velocity, and the size of engines is proved that a low cooling capacity will reduce the efficiency of the work or cause damages in the engine.

A better cooling system can be developed. A cooling system with individual speed controllers and electric motors for each component, pump and fan. These cooling systems have a much better efficiency and also the engines have the cooling capacities more satisfied. But why is that not used in common vehicles?

And with that comes a question to our minds: “Why the cooling systems are not more efficiency in today’s days?”

One possible answer to that question is, as always, the price, building a cooling system and introduction it in a normal vehicle makes it more expensive, and in today’s days that the economy rules the world, the benefits in cooling capacity and cooling efficiency is not valuable for the value that the vehicle will be increase, and the vehicle company’s know that the price is more important subject for the buyer than the efficiency.

This could be an answer for the question, but the questions remains open.

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# 9 APPENDICE

## 9.1 Graphs

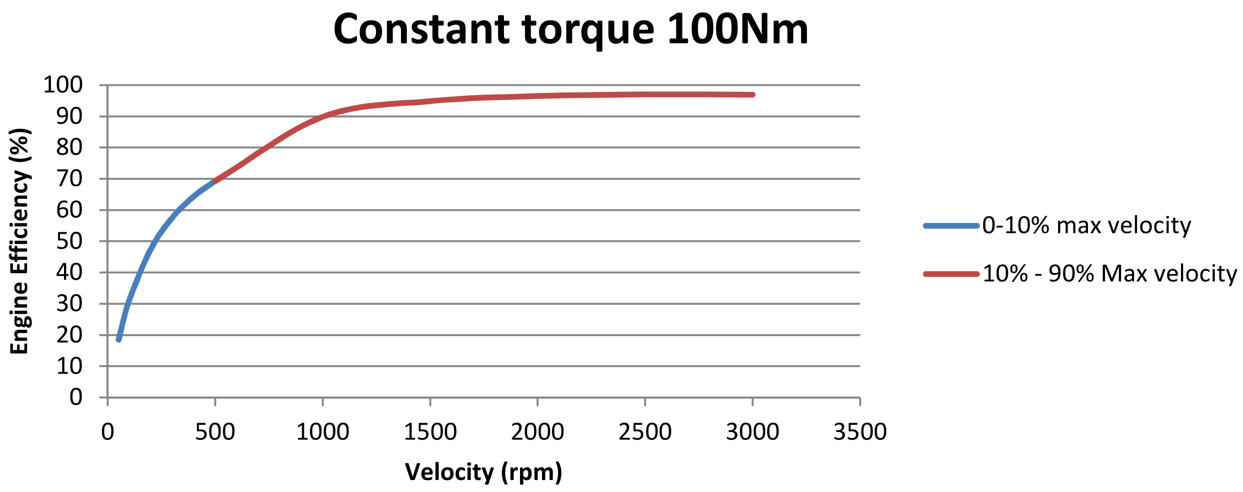


**Figure 9.1 - Velocity vs. Engine efficiency**

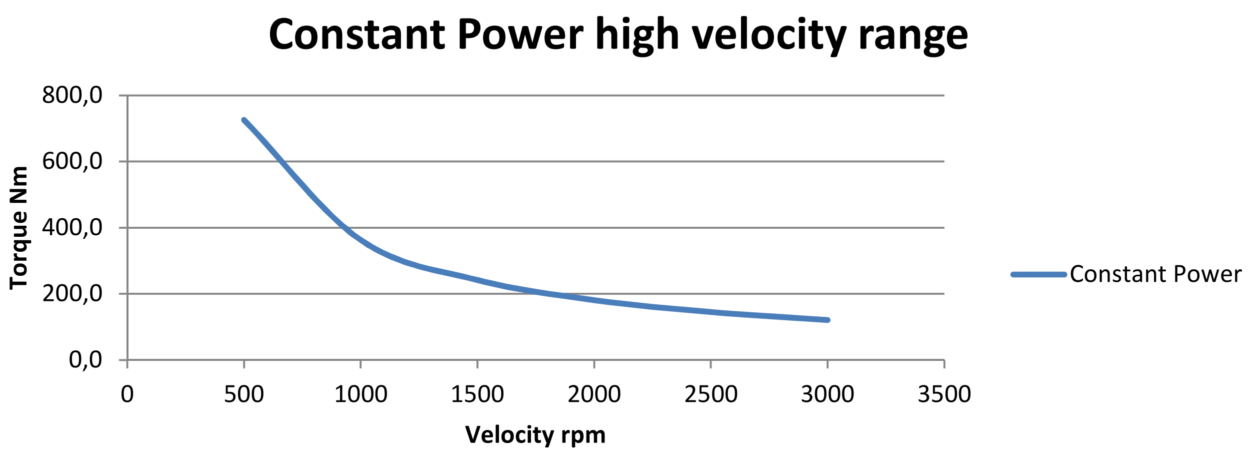


**Figure 9.2 - Velocity vs. torque with constant power**

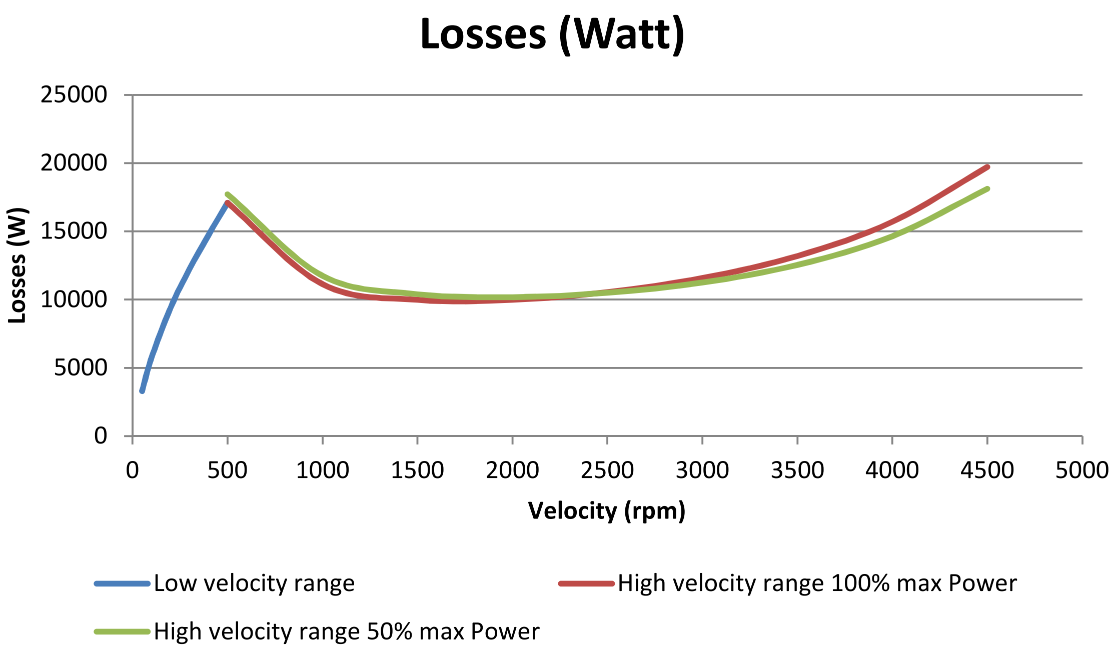


**Figure 9.3 – Velocity vs. Losses in Watt**

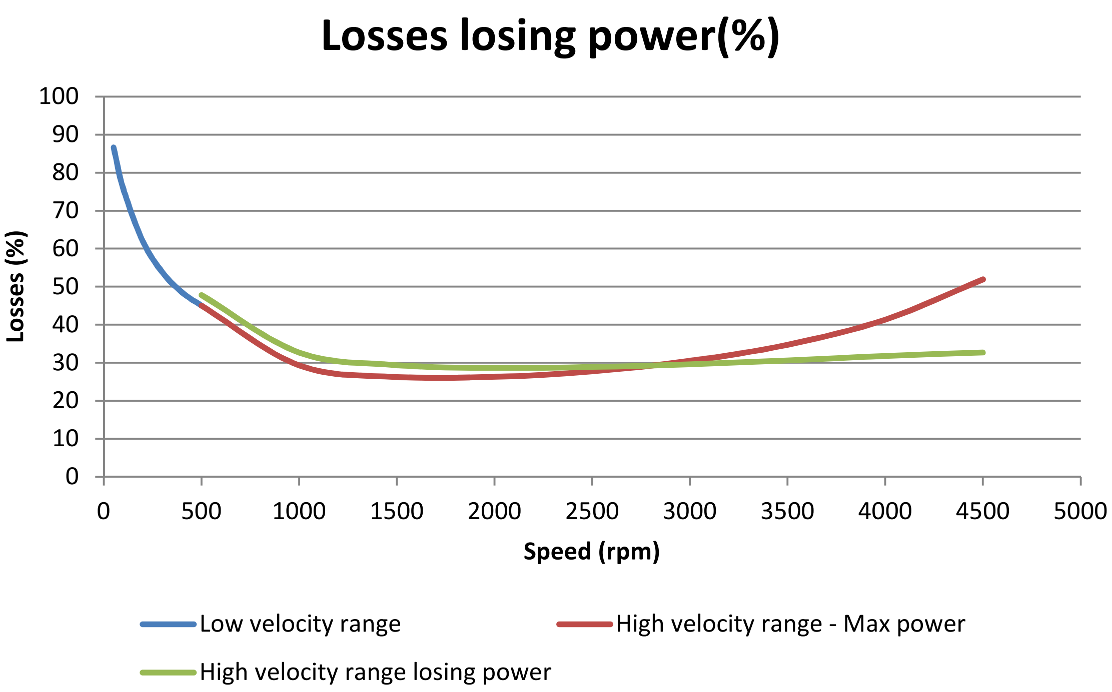


**Figure 9.4 - Velocity vs. Losses in percentage losing 10% of the power every time the velocity increases.**

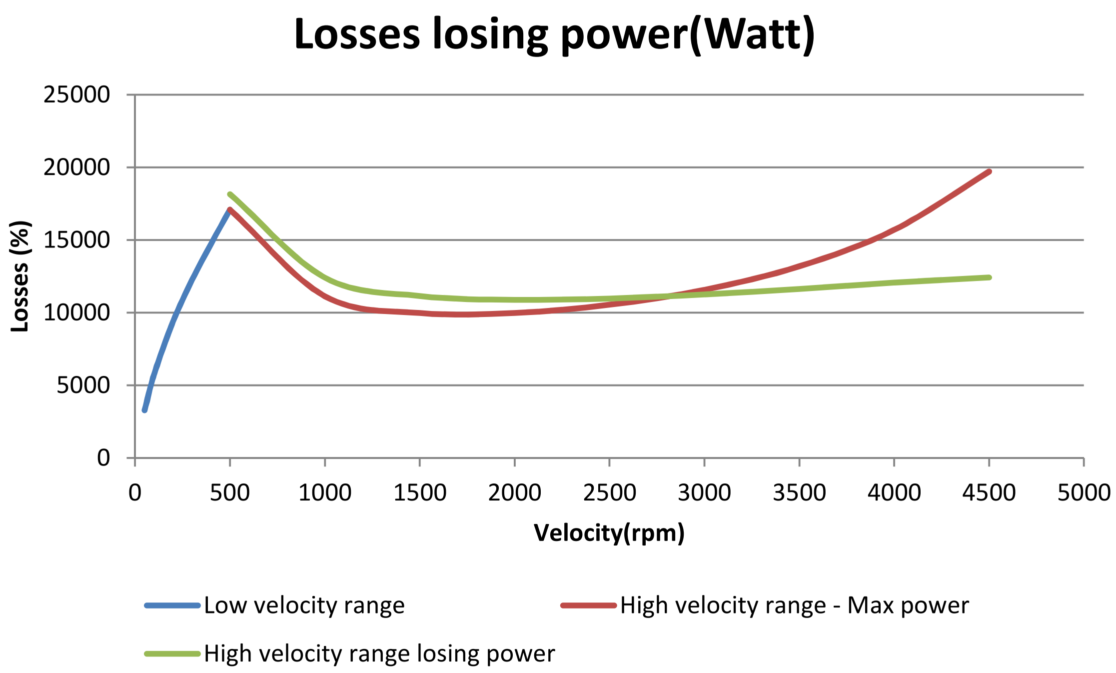


**Figure 9.5 - Velocity vs. Losses in Watt losing 10% of the power every time the velocity increases.**

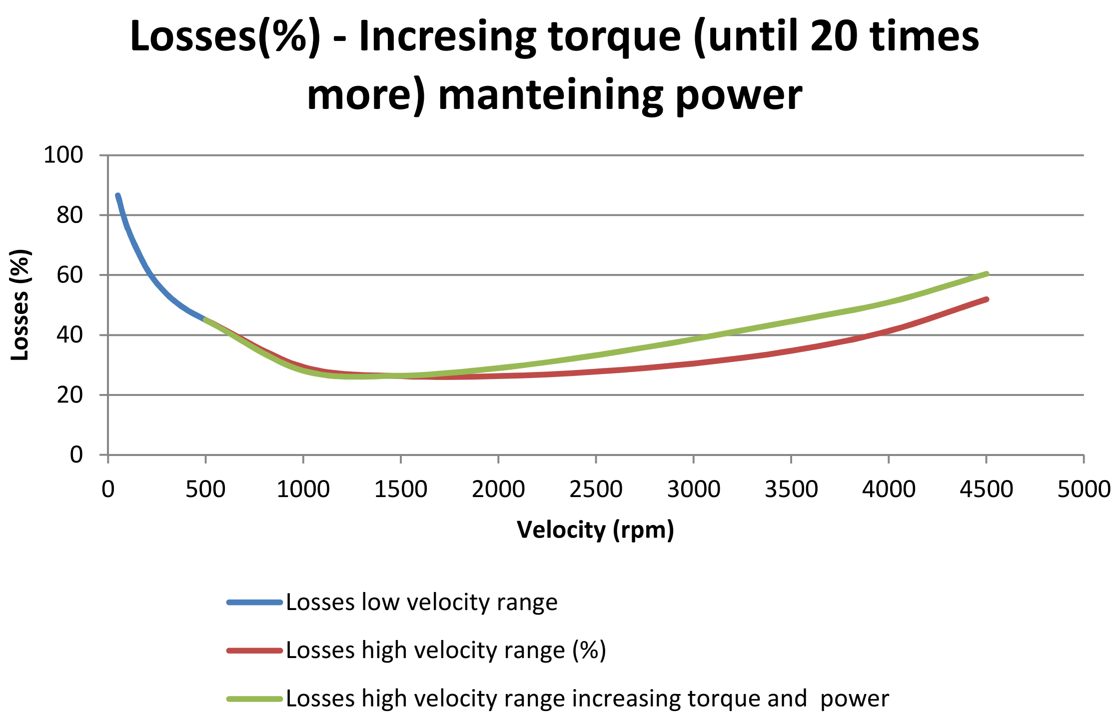


**Figure 9.6 - Velocity vs. Losses in percentage increasing torque when the velocity increases**

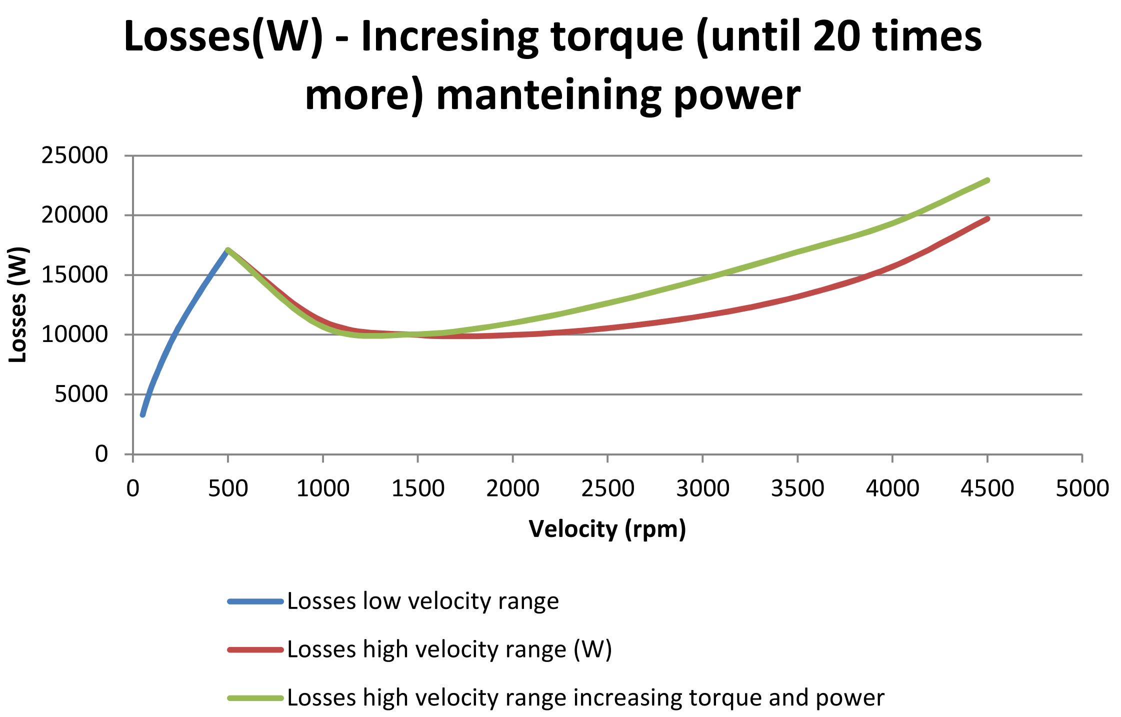


**Figure 9.7 - Velocity vs. Losses in Watt increasing torque when the velocity increases**

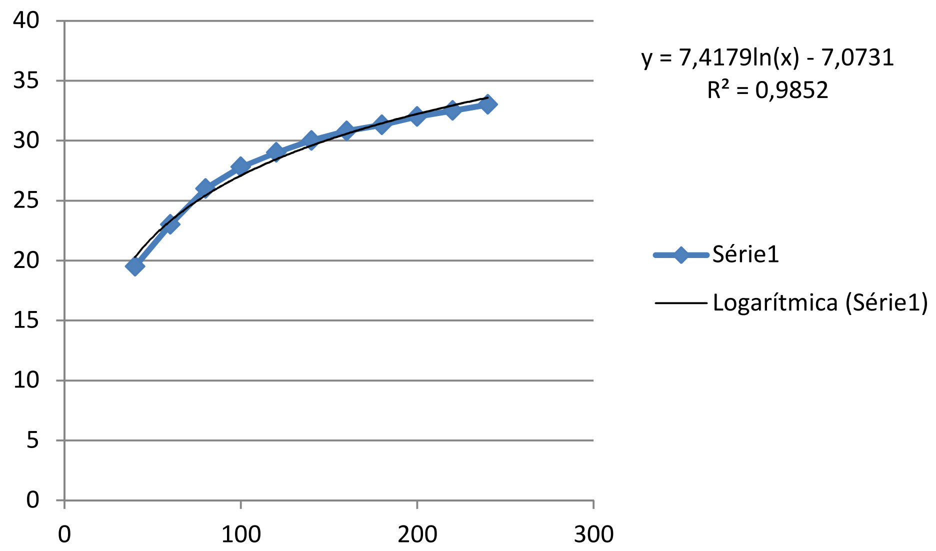


**Figure 9.8 – Regression to know the heat dissipation from the cooler unit at 3000rpm**

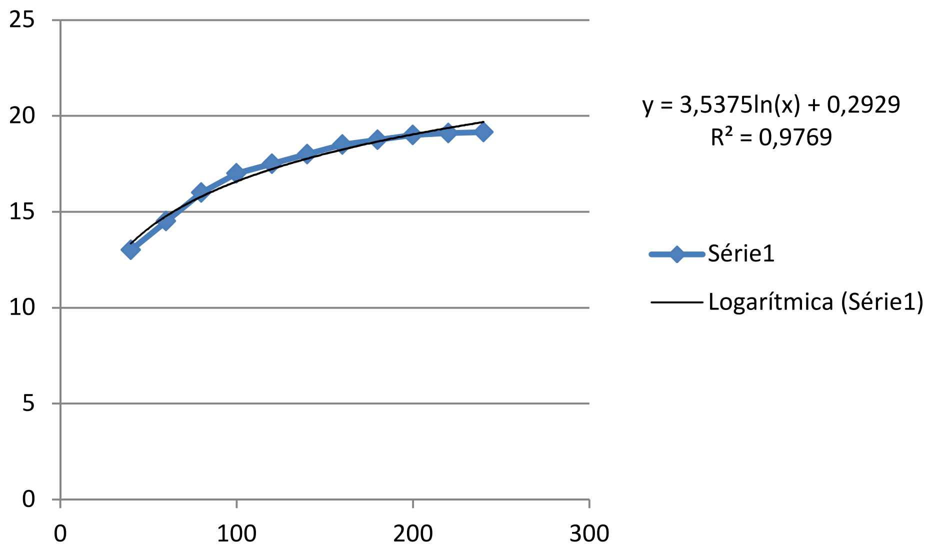


**Figure 9.9 - Regression to know the heat dissipation from the cooler unit at 1500rpm**

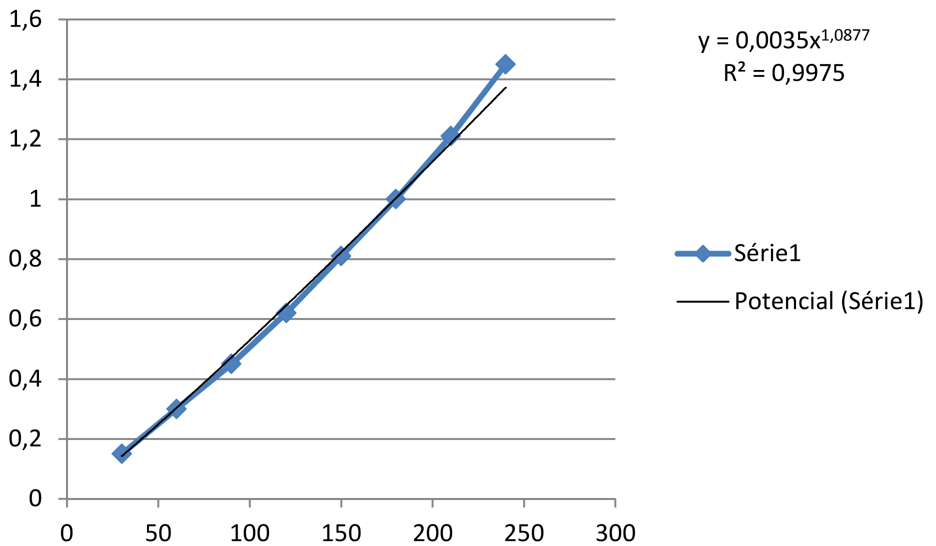


**Figure 9.10 - Regression to know the pressure drop from the cooler unit**

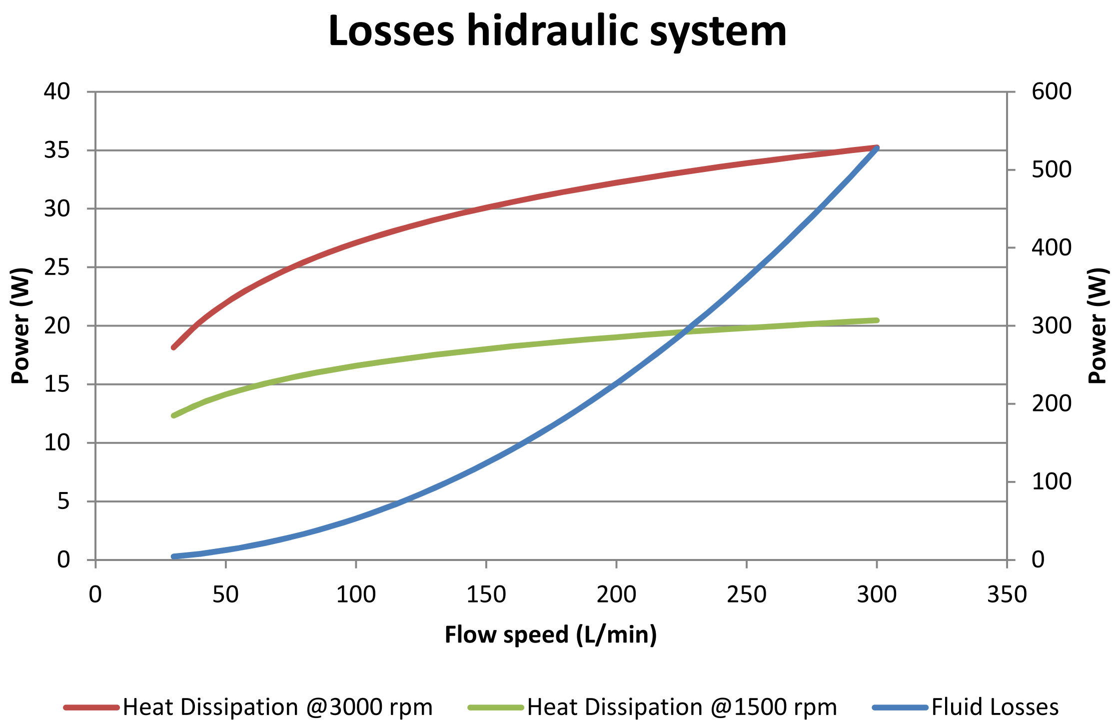


**Figure 9.11 - Losses in the hydraulic system with heat dissipation (1500rpm and 3000rpm) and Fluid losses**

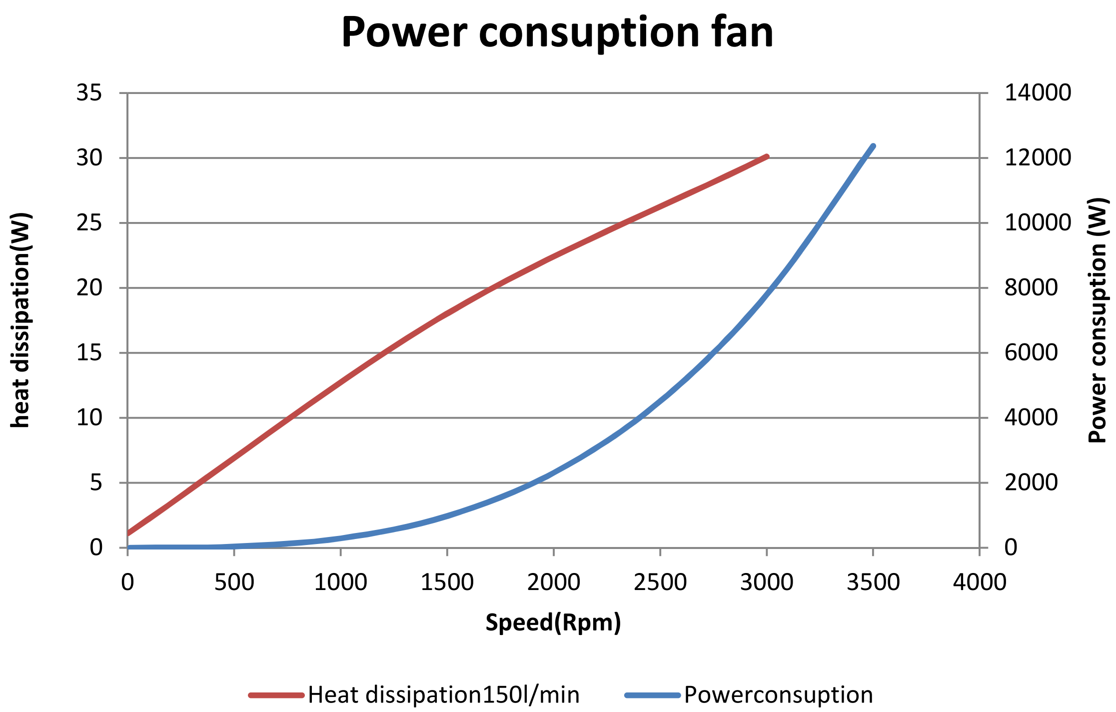


**Figure 9.12 – Losses in the air system and heat dissipation of the fan (150 L/min)**