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STATIONARY TEST BENCH FOR EVALUATION OF THE HEAT EXCHANGE OF AUTOMOTIVE RADIATORS

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Abstract. *Automotive radiators are equipment charged with dissipating the thermal energy of internal combustion engines to the environment. Both the internal combustion engines and the automotive radiators have evolved together over the years, due to the direct relation between the power produced by the engine and the energy that must be dispersed from it. Currently, the thermal dissipation capability in automobiles is considered as the main obstacle to the implementation of more powerful engines in the new models. The present work describes a stationary test bench to evaluate the thermal exchange of automotive radiators. This bench consists of a wind tunnel, which simulates the car in motion, and a heating system, which simulates the heat to be rejected from the engine. The methodology used to test the truck radiator followed the guidelines of the Japanese standard JIS D-1614: 1991 Radiators for automobiles - Test method of heat dissipation. A truck radiator provided by an automotive company has been thermally analyzed, thus determining its thermal dissipation for various coolant flows as a function of the imposed airflow. Additionally, the pressure drop caused by the radiator in wind tunnel and cooling system were all estimated. Finally the results were presented in the format stipulated by the abovementioned standard. This work consists of the initial stage of a project that aims to improve the thermal efficiency of automotive radiators.*

Keywords: *Radiator, Thermal rating, Radiator characterization, Stationary stand*

1. INTRODUCTION

The automotive radiator is a device that is part of the cooling system of internal combustion engines. It is responsible for keeping the engine’s moving components and other parts of the engine block at safe temperature levels, ensuring their integrity. For instance, Herbert and James (1992) recommend that the wall temperature of the cylinders should not exceed 300°C. According to them, high wall temperatures may cause the coating oil film to break, thus losing its lubricating properties.

Radiators are classified as compact heat exchangers due to the ratio between thermal exchange area and its volume. For the case of automotive radiators, on the air side, this ratio is higher than 700m²/m³. Compact heat exchangers are commonly found in many aerospace and automotive applications. For these cases, since weight and volume directly influence on fuel consumption and on aerodynamics, smaller, lighter and more efficient equipment are always desired.

The main parameter to take into account when characterizing a radiator is its thermal rejection capability. In the automotive field, there are two ways of evaluating the thermal efficiency of radiators. The first consists in install measurement instruments on the radiator, directly in the automobile. This characterization is known as on-board evaluation and it requires very specific instruments, due to spatial constrains. It also requires many hours of tests on the road, and given its application, it is a challenge to maintain steady state conditions.

A second way is to construct a stationary test bench. In this case, the radiator is removed from the automobile and installed on a test bench that can simulate the operating conditions. The radiator is placed in a wind tunnel, capable of simulating the airflow equivalent to that of the moving car. In addition, the device is also connected to a hydraulic system that heats the coolant to the conditions of thermal exchange of the engine. One of the main advantages is that the stationary bench assures the ability to reach and maintain the permanent regime in each test configuration, as well as their repeatability.

The present work describes a stationary bench for thermal evaluation of automotive radiators that was designed, built and tested in the Laboratory of Heat Pipes and Thermosyphons (LABTUCAL-UFSC).

2. LITERATURE REVIEW

Internal combustion engines are thermal machines, and as such, follow Lord Kelvin's postulate that it is impossible to transform all thermal energy extracted from a single source into work. Therefore, the fraction of thermal energy that is not used to perform work is transferred to another source at a lower temperature.

Pulkrabek (1997) states that of all the chemical energy released in the combustion of an automotive engine, approximately 35% is converted into useful work, 30% is released together with the exhaust gases in the form of enthalpy and chemical energy, and about one third of the total energy, is dissipated into the environment through cooling systems. Therefore, the need for more power is directly linked for more efficient cooling systems and the need for the design and construction of a stationary bench for the thermal characterization of radiators.

The Brazilian Association of Technical Standarts (ABNT) does not have any standard that specifies a methodology for the evaluation and thermal characterization of automotive radiators. However, the following two international standards were found:

- JIS D-1614:1991 Radiators for automobiles – Test method of heat dissipation
- IS 13687:1993 Internal combustion engines - Radiators - Heat dissipation performance - Method of test

Both the JIS D-1614 standard regulated by the Japanese Industrial Standards Committee (JIS) and the IS-13687 standard of the Bureau of Indian Standards (IS) establish a method for the thermal evaluation of radiators in stationary test benches. Basically, they estipulate the parameters of the test bench, the measurement instruments required, the test conditions and methodology, the method of calculation and the presentation of results.

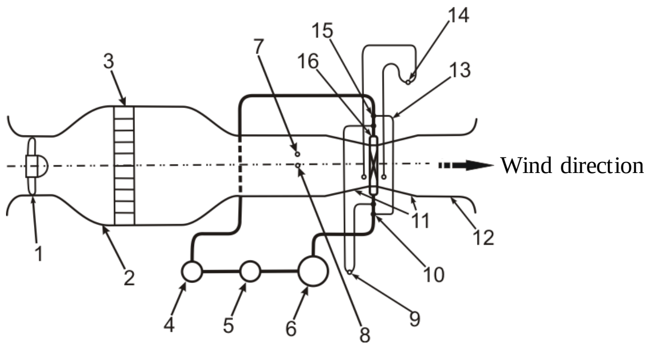
The bench design presented in this text follows the guidelines of the JIS D-1614 standard, since it is more explicit in its fundaments, and since it also served as a basis for the IS-13687 standard.

To thermally characterize a radiator, the technical standard stipulates that an energy balance must be made on the cooling fluid circuit, through the radiator. If the fluid inlet and outlet properties of the control volume (radiator) are known, it is possible to determine the heat rejection, as stated in Eq. (1).

$$Q_w = \dot{m}_w Cp_w (T_{w,i} - T_{w,o}) \quad (1)$$

Equation 1 expresses the amount of heat dissipated by the cooling fluid (Q_w). This calculation determines the change of sensible heat that the coolant experiences when passing through the radiator. In this equation, $\dot{m}_w$ represents the mass flow of cooling fluid, Cp_w is the specific heat of the fluid and $T_{w,i}$ and $T_{w,o}$ are the inlet and outlet temperatures of the cooling fluid, respectively.

The standard establishes that the bench must consist of two circuits, a cooling fluid circuit and an air circuit (henceforth referred to as wind tunnel). Both systems must ensure that the actual radiator operating conditions are met in the tests. The bench is equipped with measuring instruments to determine the inlet and outlet characteristics of both coolant and air. Fig. 1 depicts an example of the test apparatus, as shown on the JIS standard D-1614.



1. Blower **2.** Wind tunnel body **3.** Honey comb **4.** Water flowmeter **5.** Water pump **6.** Warm water tank **7.** Air-inlet thermometer **8.** Wind flowmeter or anemometer (Pressure gauge) **9.** Differential pressure gauge for water side pressure loss **10.** Thermometer for water oulet **11.** Connecting tube **12.** Discharge tube **13.** Temperature difference gauge for water inlet and outlet **14.** Differential pressure gauge for air side pressure loss (Pressure gauge) **15.** Water-inlet thermometer **16.** Specimen radiator

Figure 1. Example of the stationary test bench for radiators according to JIS D1614.

The standard allows flexibility in the design of the bench, as long as air and coolant liquid present the actual operation conditions of the car. Therefore, the stationary bench was designed following indications found in the literature.

The tunnel design followed the recommendations of Metha (1977) and Metha and Bradshaw (1979). These works present the principles for designing low-speed wind tunnels. On the other hand, the coolant circuit is designed as a hydraulic circuit, based on theoretical on the concepts of fluid mechanics, in accordance to Fox et al. (2004).

The JIS D1614 standard requires Eq. (1) to be validated for several liquid flow rates and diverse air flows. Thus, for each liquid flow, a thermal dissipation curve is obtained as function of the variation of the air flow. These dissipation curves, grouped and presented in a single graph, together with the pressure drop curve for the air and for the coolant, thermally characterize an automotive radiator.

3. MATERIALS AND METHODS

Water was chosen as the cooling liquid, and the operating conditions of the radiator were set as required by the company providing the radiator. From these operating conditions, it is feasible to design the circuits that make up the test bench. Table 1 shows the dimensions of the radiator and the conditions of entry of both air and water.

Table 1. Dimensions and operating conditions of the radiator to be tested.

Item	Value
Radiator core height	0,81 m
Radiator core length	0,54 m
Radiator Width	0,1 m
Air inlet temperature	40 °C
Mass air flow	2,61 kg/s
Water inlet temperature	100 °C
Water mass flow	3,122 kg/s

The bench was designed to be installed in a space of 7.7m in length and 1.8m in width. Based on the operating conditions and available physical space, the dimensions of the ducts and components of the bench were determined.

3.1 Wind tunnel

Following the works of Bradshaw and Metha (2003), Metha (1977), and Metha and Bradshaw (1979), a subsonic low speed open circuit wind tunnel (type) Blower was chosen. A representation of this type of tunnel with its parts is shown in Fig. 2.

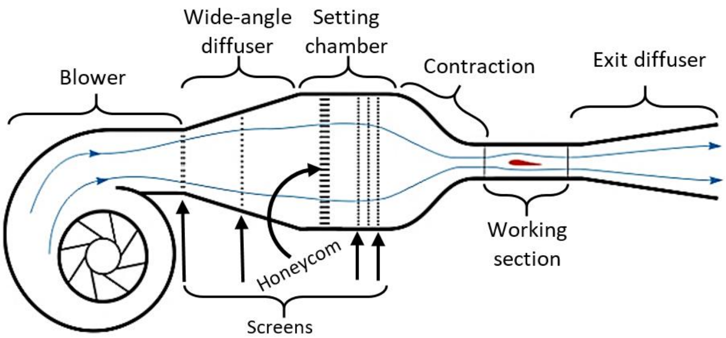


Figure 2. Blower type wind tunnel

The chosen configuration was based on several models of wind tunnels, which were reported as successful. The aforementioned researchers studied each major component of the wind tunnel: blower, wide-angle diffuser, setting chamber, flow conditioners (screens and honeycomb), contraction, working section and exit diffuser.

A schematic drawing of the wind tunnel designed for LABTUCAL is shown in Fig. 3. In this figure, each of the tunnel forming parts is referenced.

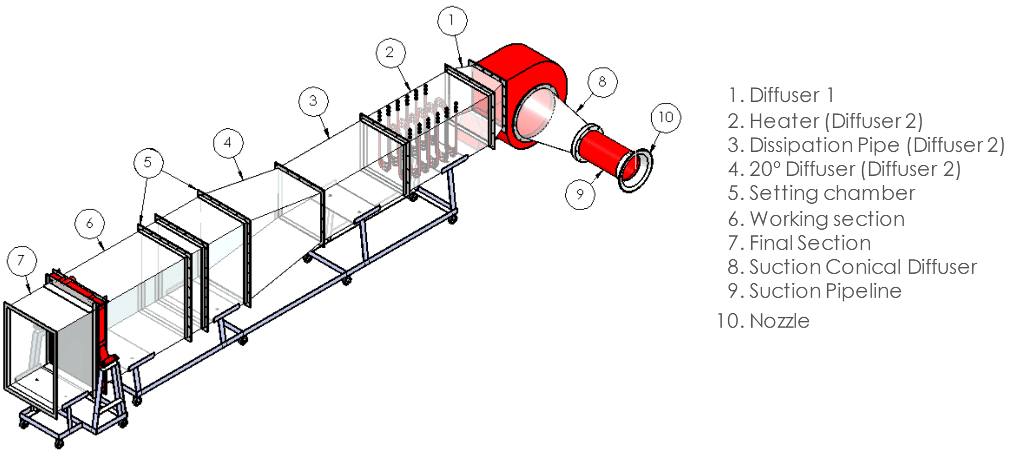


Figure 3. Schematic drawing of sections of the wind tunnel

As seen in Fig. 3, the tunnel was built in different sections. This way, the fabrication and assembly is facilitated and gives flexibility to the design. This also allows the incorporation of future modifications into the testing section, thus making the tunnel usable for other projects.

3.2 Hydraulic system

For the operating condition, as stated in Table 1, the water inlet and outlet temperatures were given at 100 and 96.5 °C, respectively. For other conditions, it was required to maintain 100 °C as the radiator inlet temperature. Since the inlet temperature is equal to the saturation temperature of the water at atmospheric pressure, two possibilities to avoid phase change were considerate: (1) build a pressurized circuit or (2) increase local water pressure in some specific places.

Due to its easier implementation, the option of increasing the local pressure of the water was chosen. The system was designed so that a water reservoir was located at a height of 3m in relation to the suction side of a pump. This reservoir is open to the atmosphere and receives water after passing through the radiator, at 96.5 °C. The 3m column of water increases the pressure on the line before reaching the pump section, which prevents cavitation. As the water leaves the pump in a pressurized state, this also prevents the phase change in the heater and radiator. A schematic drawing of the hydraulic system is shown in Fig. 4.

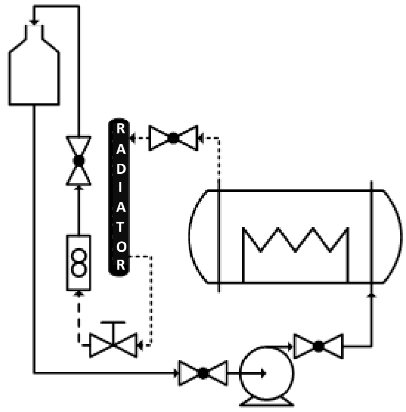


Figure 4. Elements of the hydraulic system

As shown in Fig. 4, the hydraulic system consists of a reservoir, a centrifugal-type kinetic pump, a rotameter installed after the radiator, five valves (four ball valves and one, drawer valve), and a shell and tube heat exchanger. The continuous lines represent the stretches of galvanized steel pipes, which allow joining all the elements of the system, and the dotted lines represent sections of hoses that facilitate the coupling of the radiator with the hydraulic system, as well as the instrumentation and connection of the radiator with the wind tunnel.

In addition to the two previously mentioned systems, the bench must be able to measure flow, pressure and temperature for the two circuits. These were measured on the two fluids through the following instruments: nozzle (measuring air flow), rotameter (measuring water flow) and pressure transducers and thermocouples installed in both systems. The signals emitted by the 12 thermocouples and the three differential pressure transducers were captured, processed and stored by a NATIONAL INSTRUMENTS data acquisition system, composed of the NI SCXI-1000 module, the NI SCXI-1303 terminal and the code developed in LabVIEW software.

Fig. 5 shows two photos of the radiator stationary bench, in which the wind tunnel, the hydraulic system, the measurement system and the automotive radiator can be noticed. (Flechas apontando qual é qual)

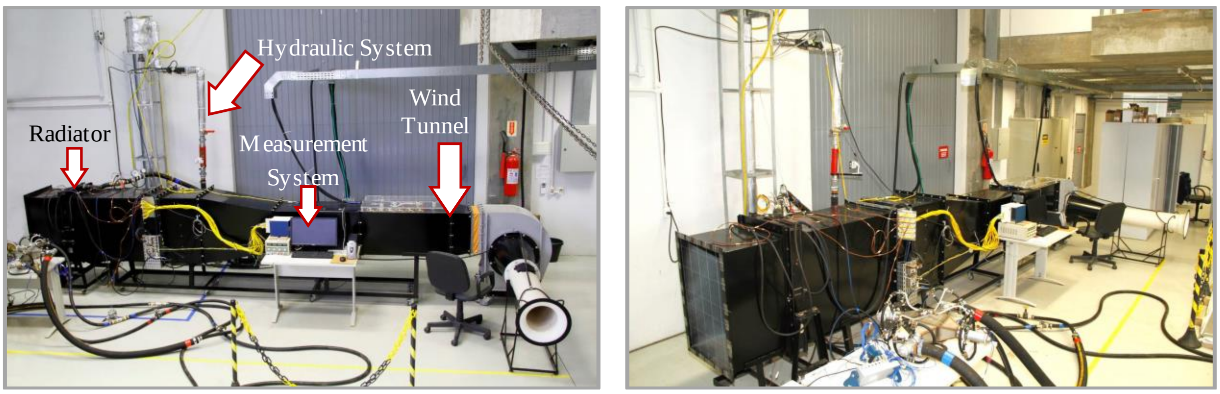


Figure 5. Side and isometric view of experimental bench

3.3 Test Methodology

The methodology used to characterize the truck radiator thermally followed the indications established in JIS D1614, where the test element is subject to three simultaneous measurement and analysis: amount of heat dissipated, pressure drop in the water and air circuits. By incorporating the results of the various tests into a single graph, it is possible to represent the thermal behavior of the radiator.

The radiator was evaluated in a permanent regime for three liquid flows (4000, 8000, and 12000 l/h). At each of these flows, the radiator was imposed at seven air velocities, starting at 2.0 m/s until 5.0 m/s, with each speed step representing an increase of 0.5 m/s.

With the obtained measurements, the thermal power dissipated by the coolant fluid will calculated using Eq. (1). Afterwards, the mass velocity of the air in the front radiator area will determined through Eq. (2). This equation determines the mass rate of air per unit of frontal area.

$$\gamma_{uaf} = \frac{\dot{V}_a}{A_f}\rho_a \tag{2}$$

Equation 2 makes it possible to compare the performance of radiators with several frontal areas. In this equation, $\dot{V_a}$ is the volumetric air flow, A_f is the front area of the radiator and ρ_a is the specific mass of the air.

The standard JIS D1614 stipulates that the difference between the inlet temperatures of the two fluids in the radiator should be maintained at 60 ° C.However, since it is difficult to maintain this temperature difference during the tests, the same standard gives Eq. (3), which allows to correct small changes of this temperature gradient.

$$Q = Q_w \frac{60}{T_{w,i} - T_{a,i}} \tag{3}$$

The term $T_{a,i}$, of Eq. (3), corresponds to the air temperature at the radiator inlet.

Through these calculations it is possible to graphically represent the thermal behavior of the radiator for each of the combinations of chosen liquid flow rates and air velocity. Once each bench component was designed, constructed and tested, they were deemed appropriated to characterize the radiator thermally and the results obtained are presented below.

4. RESULTS

The results of the tests with the three liquid flows (4000, 8000, and 12000 l/h) and the seven air velocities chosen are shown in Tab. 2, 3 and 4. The data shown in these tables represent the mean value of the data measured when the bench reached the permanent regimen at each level of these three tests.

Table 2 - Average values obtained for flow of 4000 l/h, atmospheric pressure of 100.5 kPa and gauge pressure in the water of entrance to the radiator of 40.5 kPa.

Air velocity (m/s)	ΔP Nozzle (Pa)	ΔP Water (Pa)	ΔP Air (Pa)	$T_{w,i}$ (°C)	$T_{w,o}$ (°C)	$T_{a,i}$ (°C)	$T_{a,o}$ (°C)	T_{env} (°C)
5,0	1368,6	5110,3	215,2	100,6	81,7	39,8	81,4	25,0
4,5	1089,5	5110,8	177,4	101,1	83,5	39,8	83,3	25,2
4,0	861,4	5098,4	144,7	101,0	84,8	39,8	84,6	25,2
3,5	665,8	5074,7	115,3	100,9	86,0	39,8	85,7	25,8
3,0	487,9	5084,2	87,0	100,5	87,5	39,9	86,7	25,7
2,5	339,9	5057,7	62,1	100,3	89,0	39,9	87,3	24,6
2,0	223,6	5068,7	41,4	100,2	90,7	39,8	87,9	24,0

Table 3 - Average values obtained for flow of 8000 l/h, atmospheric pressure of 100.64 kPa and gauge pressure in the water of entrance to the radiator of 49.3 kPa.

Air velocity (m/s)	ΔP Nozzle (Pa)	ΔP Water (Pa)	ΔP Air (Pa)	$T_{w,i}$ (°C)	$T_{w,o}$ (°C)	$T_{a,i}$ (°C)	$T_{a,o}$ (°C)	T_{env} (°C)
5,0	1363,6	12356,1	216,6	100,0	88,0	40,0	84,7	25,0
4,5	1086,3	12807,9	178,0	99,8	89,0	40,0	85,9	25,3
4,0	858,4	12669,7	145,2	99,7	89,8	40,0	86,8	25,5
3,5	658,5	12515,7	114,8	99,7	90,7	40,0	87,7	24,4
3,0	484,1	12499,2	86,7	100,2	92,2	40,1	88,8	24,8
2,5	339,3	12678,6	62,1	100,2	93,4	40,0	89,3	24,6
2,0	211,8	12654,0	39,4	100,3	94,7	39,9	89,5	24,0

Table 4 - Average values obtained for flow of 12000 l/h, atmospheric pressure of 102 kPa and gauge pressure in the water of entrance to the radiator of 70 kPa.

Air velocity (m/s)	ΔP Nozzle (Pa)	ΔP Water (Pa)	ΔP Air (Pa)	$T_{w,i}$ (°C)	$T_{w,o}$ (°C)	$T_{a,i}$ (°C)	$T_{a,o}$ (°C)	T_{env} (°C)
5,0	1307,5	29012,6	210,5	101,2	93,4	40,0	88,0	26,0
4,5	1126,0	27554,2	184,8	100,7	93,2	40,0	88,2	26,0
4,0	841,5	29846,0	143,8	100,2	93,9	40,0	89,0	26,0
3,5	657,0	29297,9	115,1	100,8	94,9	40,0	90,0	26,0
3,0	486,2	29484,1	87,5	100,9	95,7	40,0	90,6	26,0
2,5	337,2	29302,6	61,8	100,1	95,7	39,9	90,2	25,9
2,0	225,1	30096,7	41,7	99,7	96,1	39,9	89,8	25,7

For the seven air velocities, the wind tunnel pressure loss was measured. It was observed that it decreases greatly with the decline of the air velocity.

Simultaneously, the pressure drop in the hydraulic system was measured in each test and its value remained almost uniform throughout the test. However, when value is compared between tests for different coolant flows, it was observed that it increases with increases on the water flow.

Using the Eqs. (1), (2) and (3), the thermal characterization graph for the supplied radiator was obtained, as shown in Figure 6.

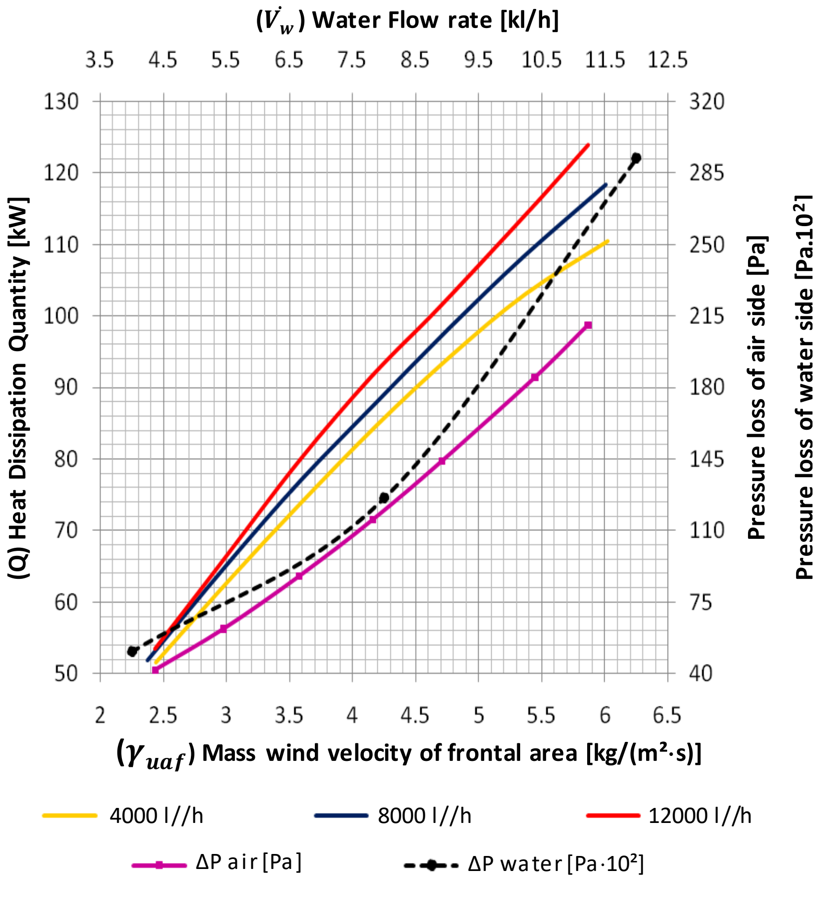


Figure 6. Thermal characterization of the truck radiator

It must be noted that Fig. 6 shows secondary axes in both abscissa and ordinate. In the vertical left axis, data for the dissipated thermal power are shown, while in the vertical right axis, the pressure losses caused by the presence of the radiator in both the wind tunnel and the hydraulic system are shown. The lower horizontal axis shows the mass flow rate of the air per unit of frontal area and, while the volumetric flow rate of the liquid is shown on the upper horizontal axis.

Readings are made starting from the horizontal axes. The upper horizontal axis is used only to determine the loss of pressure in the liquid. The other data, thermal dissipation or loss of pressure in the air, are obtained from the lower horizontal axis.

The conditions estimated as critical to the operation of the radiator (Table 1), correspond to the combination of liquid flow of 12000 l/h with the mass air flow per unit of front area equal to 5.9 kg/(m²s). As a result of this combination, a heat rejection for the environment of 123.8 kW, a pressure loss in the hydraulic system of 29 kPa and an air loss of 210.5 Pa were obtained.

These data were compared with those documented in the internal reports of the partner company, where a thermal dissipation of 120kW is reported for these operating conditions. This proves that the stationary test bench can reliably reproduce the critical operating conditions of the truck radiator.

It has been estimated that the 29kPa of the pressure drop in the hydraulic system represents approximately 58% of the total pressure supplied by the truck's cooling system pump.

5. CONCLUSIONS

Construction of the stationary test bench for evaluation of the heat exchange of automotive radiators was necessary due to the need to know and improve the thermal exchange processes of these equipment. The ideal scenario of any vehicle assembler company is to be able to incorporate more powerful engines in the new automotive models, without drastically modifying the layout of the existing models. Achieving this objective is only possible if the thermal efficiency of automotive radiators can be improved.

The thermal characterization of a radiator consists of testing its thermal dissipation capability for various cooling fluid streams at various air velocities. These thermal dissipation curves, grouped and presented in a single graph, along with the pressure drop curve for the air and the cooling fluid, represent the thermal characterization graph of a radiator.

The advantage of having a stationary bench to characterize thermally radiators, compared to the evaluation in-site, is that the bench does not require the dedicated use of a vehicle to carry out the tests, as occurs in the evaluation on board. Besides, it also ensures that the tests always have the same contour conditions and greater reliability.

The behavior of the results obtained for the supplied radiator were in accordance with those described in the JIS D1614 standard. That is, higher flows in the fluids (air or water) promote a better heat transfer, which increase the efficiency of the radiator and improve the heat rejection to the environment.

For the condition described as critical, liquid flow rate of 12000 l/h and mass air flow per unit of frontal area equal to 5.9 kg / (m²s), a rejection capacity of 123.8 kW was obtained, a loss of load in the system hydraulic pressure of 29kPa and an air loss of 210.5Pa. These values are consistent with the data reported in the internal reports of the partner company, proving that the stationary test bench can reliably reproduce the conditions of operation of the truck radiator, thus validating the bench design.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Bradshaw P. and Mehta R., Wind Tunnel Design, (Online guide for the design of wind tunnels) Stanford, Stanford University, última atualização: 8 set, 2003, Disponível em: <http://navier.stanford.edu/bradshaw/tunnel/index.html> Access in: 1 mai, 2014

BUREAU OF INDIAN STANDARDS, IS 13687:1993 Internal combustion engines - Radiators - Heat dissipation performance - Method of test, New Delhi, 1993.

Fox, R.W., McDonald, A.T. and Pritchard, P.J.; Introdução à Mecânica dos Fluidos, LTC, 6ª ed. (2004)

Herbert, E. E. and James, D. H., Manual para ajuste de motores y control de emisiones, 2a ed., Tomo 1, Prentice Hall Hispanoamericana S.A., México, 1992

JAPANESE INDUSTRIAL STANDARDS COMMITTEE, JIS D-1614:1991 Radiators for automobiles – Test method of heat dissipation, Japan,1991.

Mehta, R. D., and Bradshaw, P., Design Rules for Small Low-Speed Wind Tunnels, Aero Journal (Royal Aeronautical Society) 73 (1979): pp. 443-453

Mehta, R. D., The Aerodynamic Design of Blower Tunnels with Wide-Angle Diffusers, Prog Aerospace Sci 18 (1977): pp. 59-120.

Pulkrabek, W., Engineering Fundamentals of the Internal Combustion Engine, Prentice Hall, New Jersey, 1997

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