Application of heat pipe based refrigeration system for an electric train traction converter. An experimental study case

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Keywords

«Cooling», «Power semiconductor device», «Rail vehicle», «Thermal design», «Traction application»

Abstract

Refrigeration systems of railway traction inverters have experienced crucial progress recently. The use of assisted convection has been one of the most significant improvements, being heat pipe based heat sinks (HPHS) the main application. Due to the operating principle of a heat pipe, which lies in evaporation and condensation of a fluid, the HPHS is a very non-linear device. Several variables play a critical role and a simple theoretical analysis by itself does not provide enough information for an accurate model. As a result, in order to evaluate the performance of a HPHS for a generic traction converter, we have developed an experimentation process. It consists of aerodynamic tests in an airport and thermal tests in a self-designed wind tunnel. The objective of this method is the complete characterisation of the HPHS and thereby, the prediction of the behaviour of the refrigeration system for the real operation of a train. During the aerodynamic tests we have deduced the relationship between the air-flow through the HPHS and the train speed. Besides, we have analysed some extra phenomena, such as the double-cavity flow and the air-leakage of the system. The thermal study has allowed us to determine the thermal resistance network, working out the influence of the power losses of the inverter and the air velocity in the overall efficiency of the HPHS. In addition, we have examined transient response and the importance of natural convection. The paper summarizes both series of tests carried out with the system subject to study and presents the main results and conclusions.

Introduction

Railway electric traction has evolved rapidly over the past few years. The development of transistor based Variable Voltage Variable Frequency (VVVF) traction converters involved a revolution in the field. These converters are responsible for converting the single-phase DC voltage in a three-phase AC system for the asynchronous traction motors. The principle of operation is the fast commutation of the transistors, which currently have high power capability and rapid-response. These semiconductors have to be cooled, since they generate important power losses. The refrigeration system of the inverter evacuates the heat, preventing the temperatures of the semiconductor's junction from rising above maximum allowable limits and therefore avoiding their failure.

These systems have witnessed dramatic improvements, as well. Up to now, cooling was generally carried out by water or forced air. Nevertheless, high performance of modern transistors enables the use of assisted convection devices. This main advance resides on cooling the semiconductors with the air-flow originated by the movement of the unit. This approach offers great advantages compared to other cooling systems thanks to its absolutely passive operating principle. Reliability and absence of maintenance are among the major benefits. Furthermore, these systems are absolutely environmentally friendly, since they neither make noise nor consume energy.

In order to profit from assisted convection heat pipe based heat sinks (HPHS) are commonly used. Basically, a HPHS consists of a plate, heat pipes and fins. Power semiconductors are placed over the plate, which acts as a heat sink. The heat flows through the pipes and it is transferred to the air by the fins. Figure 1 shows an example of the device:

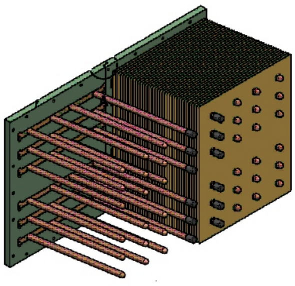

Figure 1. Heat pipe based heat sink (HPHS): heat sink, heat pipes and fins

The main purpose of the work has been the modelling of the HPHS so that its performance can be predicted for different applications, and consequently, different requirements. In order to thoroughly characterize the system we have defined an experimental methodology. The process consists of aerodynamic tests, carried out with a van in an airport and thermal tests, performed in a self-designed wind tunnel. Our second major goal has been the validation of this method. As a result, first of all the operation of the HPHS is explained, together with the physical phenomena that takes place in the heat pipes. Secondly, the aerothermal experimentation methodology is exposed. After that, both testing stages are summarized, defining the set-up and outlining the most important results. Finally, we present the main conclusions of the work.

HPHS operation

The behaviour of a HPHS is mainly determined by the performance of the heat pipes. Therefore, the physical principles governing the operation of the heat pipes play a vital role. This section includes a brief summary about the phenomena that drives the performance of a heat pipe and the operation of the HPHS.

Heat pipe operating principles

A heat pipe is a sealed vacuum enclosure containing a liquid in equilibrium with its vapour. Its operating principle is based on the phase change of the coolant it contains. The heat pipe consists of 3 main parts: hot or evaporator zone, adiabatic zone and cold or condenser zone. As heat is applied in the evaporator, the fluid evaporates and the originated pressure gradient forces the vapour travel along the adiabatic zone to the condenser. There, it condenses again giving up its latent heat of vaporization. The liquid returns to the evaporator by gravitational force or capillary effect through the wick structure. As a consequence, a closed loop process that continues as long as heat is applied. Therefore, heat pipe operation is completely passive and continuous, being driven only by the transferred heat. The thermal performance of the heat pipe is clearly above other conventional refrigeration systems.

In the particular case of the HPHS subject to study, the heat in the evaporator is generated by the semiconductor modules and environmental air is used for the condensation.

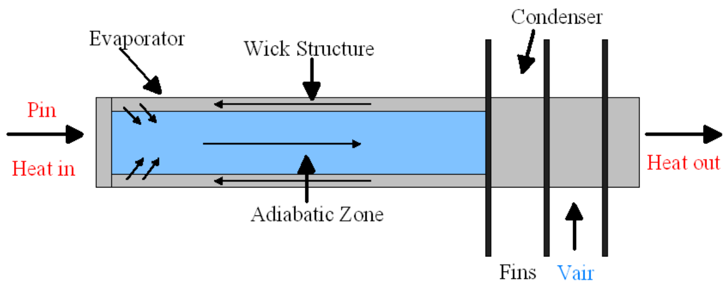

Figure 2. Heat pipe parts and operation

HPHS operation

The performance of the HPHS is influenced by two main factors: air-flow through the heat pipes and power losses to be evacuated. Both parameters are directly related to heat pipe operation: air-flow determines the behaviour of the condenser, while power losses play an important role in the evaporator efficiency. According to DeHoff and Grubb [3], although a more detailed model can readily be created using a computational fluid dynamics package, this resistance network is a good approach to determine design feasibility. The HPHS can be represented by the resistance network shown in following table:

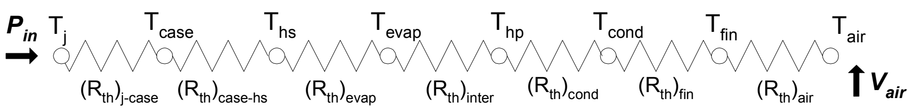

Table I: Resistance network

Temperatures	**Description**	**Resistances**	**Description**
T_j	Semiconductor's junction	$(Rth)_{j\text{-}case}$	Between semiconductor's junction and case
T_{case}	Semiconductor's case	$(Rth)_{case\text{-}hs}$	Semiconductor-heat sink contact
T_{hs}	Heat sink surface	$(Rth)_{evap}$	Evaporator of the heat pipe
T_{evap}	Evaporator of the heat pipe	$(Rth)_{inter}$	Heat pipe internal: vapour flow and liquid return
T_{hp}	Heat pipe	$(Rth)_{cond}$	Condenser of the heat pipe
T_{cond}	Condenser of the heat pipe	$(Rth)_{fin}$	Conduction along fins
T_{fin}	Fins of the heat pipe	$(Rth)_{air}$	Convection between fins and cooling air
T_{air}	Cooling air-flow	$(Rth)_{hp}$	Overall: whole heat pipe

Gathering together the thermal resistances between case and air, the overall (Rth)hp is obtained. This overall thermal resistance takes into account all the effects that take place in the HPHS: contact with semicoductors, evaporation, condensation, vapour flow, fin efficiency etc. As (Rth)j-case is known for each semiconductor module, determining (Rth)hp allows the complete characterization of the network. These thermal resistances vary with the power losses and the air-flow, which as stated before, represent the determining factors in the behaviour of the refrigeration system.

Aerothermal experimentation process

The operation of the HPHS is determined by the air-flow through the heat pipes and the power losses to be evacuated. In order to evaluate the performance of a HPHS as a function of both parameters, an aerothermal experimentation process has been developed. It consists of aerodynamic and thermal tests. The objective of this method is the complete characterisation of the HPHS and thereby, the prediction of its behaviour for the real operation of a train.

The heat losses of the inverter depend on the application. They are estimated by other means and the calculation is out of the scope of this paper.

However, the available air-flow must be determined since it is the responsible for cooling and condensing the fluid within the pipes. It depends on the vehicle speed, the shape of the HPHS and its location.

For this specific study case, the flow around the HPHS corresponds to a double cavity flow, as can be seen in Figure 3. The pipe-bench of the HPHS behaves as a porous membrane between two cavities.

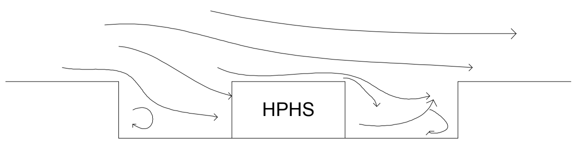

Figure 3. Double-cavity flow in the surroundings of the HPHS. Top view

The first step of the experimental methodology has been the characterization of the aerodynamic behaviour of the HPHS, getting to know the exact air-flow through the HPHS as a function of the vehicle speed for the given shape and location. For this purpose, we have performed a series of aerodynamic tests. We have analysed different topics:

- Air-flow through the HPHS depending on vehicle speed
- Impact of improvement ideas: transition deflectors and conduction vanes
- Relationship between air-inlet and –outlet speeds
- Influence of accelerations and brakings
- Near-wall behaviour of the air
- Tools for measuring air speeds: Pitot probes and hot wires

The target of this second stage has been the thermal analysis of the HPHS in order to attain a detailed model for different power losses and air-flow conditions. We have studied several aspects:

- Steady state overall thermal resistance of the heat pipe: (Rth)hp
- Transient phenomena
- Temperature distribution over the heat sink
- Influence of heat load variation in the thermal resistance
- Influence of air-flow variation in the thermal resistance
- Impact of high speed of the cooling air
- Evaporator limit
- Condenser limit

In conclusion, the thermal study of this second step entails the determination of the entire thermal resistance network working out the influence of the power losses of the inverter and the air velocity in the overall efficiency of the HPHS.

To sum up, the combination of the two stages of the experimentation method leads to the prediction of the behaviour of the HPHS for the real operation of the vehicle:

1. The air-flow through the HPHS is determined thanks to the first stage of the experimental process, since its dependence on the vehicle speed is obtained. As a result, the speed of the vehicle, and the geometry and the location of the HPHS are needed as input for this step.

2. The thermal behaviour of the HPHS is determined with the results of the second stage of the tests. The temperatures in the semiconductors' junction can be estimated and, as a result, the validity of the refrigeration system can be examined.

The following figure shows a scheme of the process:

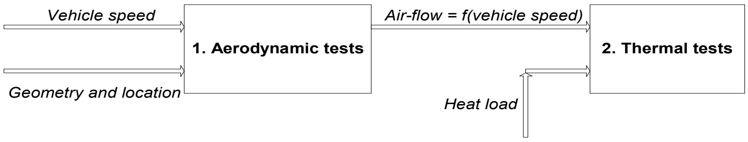

Figure 4. Aerothermal experimentation process

Tests

We have carried out aerodynamic and thermal tests. This section introduces both testing stages, including the description of the test set-up and the presentation of the main results.

Aerodynamic tests

In order to predict the behaviour of the HPHS, it is necessary to study the air-flow through it. For this purpose a series of aerodynamic tests have been performed using real scale models. The main objective of these tests has been the determination of the relationship between vehicle speed and air speed in the HPHS outlet.

Test set-up

The tests were held in the runway of the Agoncillo airport (Logroño, Spain), which belongs to AENA (Aeropuertos Españoles y Navegación Aérea). The runway is 2km long. We used a van in order to model the train side. In the right side of the van, we set up a lateral mock-up of the train. This lateral model had the HPHS assembled to its structure. It was protected against external aggressions, since the air inlet and outlet and the upper and lower faces are covered with grids. Figure 5 represents a diagram of the top view of the assembly:

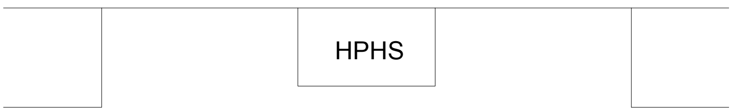

Figure 5. Configuration 1: basic

A photograph of the van and the HPHS assembly is shown in Figure 6.:

Figure 6. Test rig

In order to increase the air-flow through the HPHS, we devised different gadgets. It must be considered that, for this particular application, one of the requirements is the symmetry, since the vehicle has to operate in both senses. With this restriction, we proposed and tested 2 extra configurations apart from the basic one (Config.1, Figure 5): the use of conduction deflectors (Configuration 2, Figure 7) and transition smoothers (Configuration 3, Figure 8). Conduction deflectors are expected to redirect extra flow among the fins. Smoothers pretend to soften the transition, avoiding the detachment.

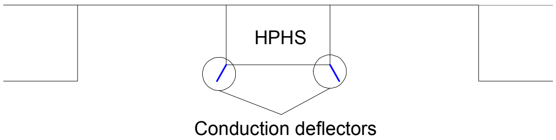

Figure 7. Configuration 2: basic + conduction deflectors

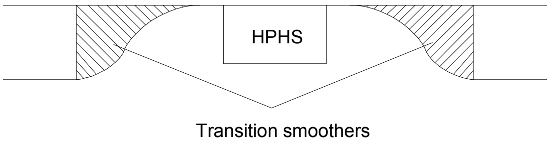

Figure 8. Configuration 3: basic + transition smoothers

We measured vehicle speed and air speed through the HPHS by different means in order to compare and obtain accurate values. We measured vehicle speed, on the one hand, by GPS, and on the other, by a Pitot transducer located within the free air-stream. For the air speed through the HPHS we used Pitot probes and hot wire transducers both in the inlet and outlet. Apart from these velocities, we measured ambient temperature and van acceleration.

Results

The interest of this study is the air-flow crossing the whole HPHS. Therefore, we have focused the analysis in the outlet air-speed, since this is the air that crosses the entire device.
The tests consisted of vehicle runs at constant speeds. As a result, for the determination of the air-speed in the HPHS outlet we have calculated the mean value of every transducer measurement for each constant van speed. Then, we have obtained the average for all transducers, as the dispersion is minimal and thereby negligible. Finally, we have combined the values for each van speed step in order to obtain the regression curve.

After analysing and processing the available data, final results are presented:

1. Configuration 1. We have determined the air speed in the outlet for each vehicle speed (refer to Figure).
2. Configuration 2. Using conduction deflectors increases the air-flow through the HPHS. This improvement only occurs for high speeds (above 40km/h) of the vehicle. The mouth effect allows more air to cross the HPHS. See Figure 10.
3. Configuration 3. The use of transition smoothers does not cause an increase in the air-flow through the HPHS (Figure 10). It seems that the effect of these deflectors is similar to the behaviour of the air in the basic configuration. We believe the recirculation zone in both extremes of the cavities (see Figure 9) acts as a natural air-cushion. The low air speed originates a high-pressure zone, preventing the rest of the air from entering there.

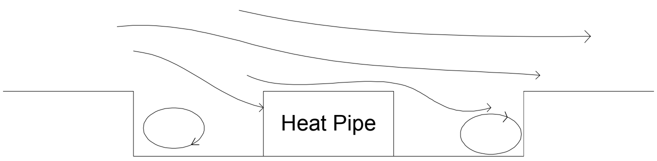

Figure 9. Recirculation effect

The results for all configurations are shown in Figure 10. They represent the relationship between the train speed and the air-flow through the HPHS.

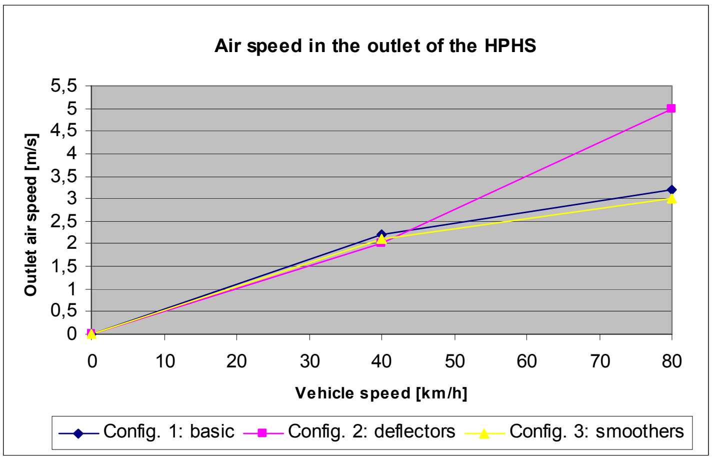

Figure 10. Air speed in the heat pipe outlet for configurations 1, 2 and 3

These results lead to what the aerodynamic tests are mainly focused on: the prediction of the system's behaviour for a real operating cycle of the vehicle subject to study. In our case, for the specific application of the HPHS for a traction converter, we have defined a model starting-braking cycle, which represents a typical but restrictive metro route between two stations, since it does not have coasting. We have calculated the air speed in the HPHS outlet for this cycle and it is shown in Figure 11. Configurations 1 and 2 are presented, so that the improvement of adding conduction deflectors can be seen. The benefits are obvious, above all, for high vehicle speeds, when the power to be dissipated increases.

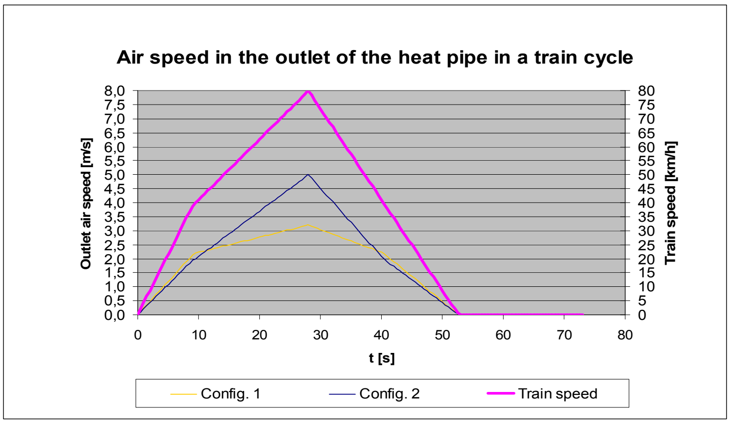

Figure 11. Air speed in the HPHS outlet for a typical train starting-braking cycle. Config. 1 and 2

4. <u>Obstruction factor.</u> We have defined a parameter called the obstruction factor (fo), which measures the air-flow loss along the heat pipe when it is not covered. We have calculated an average value taking into account all the tests (the deviation is insignificant):

$$f_o = 1 - \frac{v_{out}}{v_{in}} \Rightarrow \overline{f_o} = \frac{\sum_{i=1}^{n} (f_o)_i}{n} = 0.80 \qquad (1)$$

It means that an 80% of the air in the inlet does not cross the whole HPHS. It leaks from upper and lower faces of the device.

Thermal tests

Once the aerodynamic behaviour of the HPHS is known, we have defined the second stage of the experimental process, which covers the thermal study of the system. This stage aims to evaluate the thermal performance of the HPHS for different boundary conditions. We have designed and built a wind tunnel in our facilities in order to undertake the tests. The test rig allows us to vary the critical factors: the cooling air velocity and the heat load (Pin). Therefore, it permits the simulation of real working cycles of the vehicle (the train, in our case).

The goals of these tests have been the calculation of thermal resistances and estimation of junction temperatures for semiconductors for real operating conditions.

Test set-up

The tests took place in Beasain (Spain). We used an up-to 15m/s self-designed wind tunnel for controlling the air-flow. It basically consists of a diffuser, a settling chamber and a nozzle. We generated the air-flow by a fan, commanded by a three-phase generator which permits to completely control the air-flow in the operating range. Figure 12 shows the scheme of the tunnel and Figure 13, a photograph:

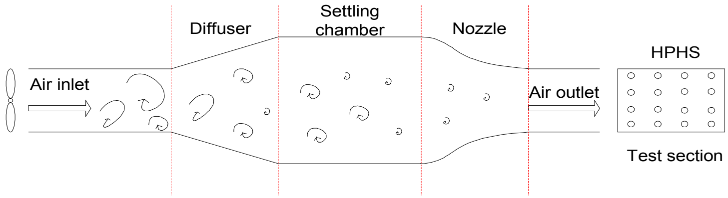

Figure 12. Wind tunnel scheme

Figure 13. Wind tunnel photograph

We used power resistors for the generation of the heat losses over the heat sink. The energy for the resistors was supplied by a single phase rectifier and the power losses were regulated by a variable load in series. Therefore, both determining factors affecting the HPHS performance are completely adjustable: air-flow and heat load. Along the tests we measured Tcase and Ths by thermocouples and Pt100 transducers, respectively. We have also measured temperatures of the incoming and outcoming air with hot wires. Finally, in order to know the exact power losses per semiconductor module, we have measured electrical variables: applied voltage and current.

Results

During these tests we measured temperatures and from the results, we have calculated thermal resistances. For the calculation of the overall thermal resistance per semiconductor module we have used the following equation:

$$\left(R_{th}\right)_{hp} = \left(R_{th}\right)_{case-air} = \frac{\left(T_{case}\right)_i - \left(T_{in}\right)_i}{\left(P_{in}\right)_i} \qquad (2)$$

, being (Pin)i the power generated in each module and (Tin)i the temperature of the incoming air for each module. After analysing and processing the available data, final results are presented:

1. Overall thermal resistances for different conditions of inlet air speed and power losses (see Figure 14).

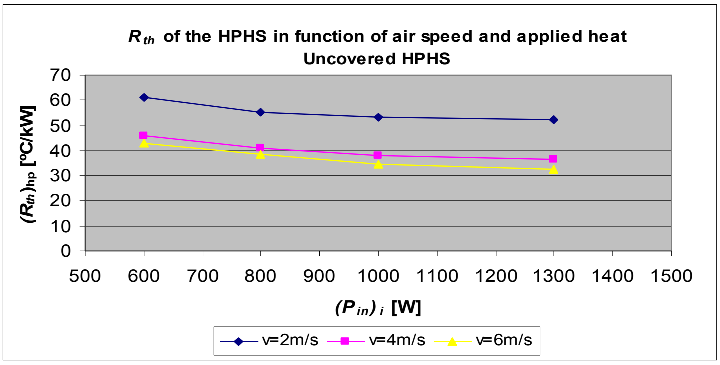

Figure 14. Overall thermal resistances for different boundary conditions

2. Thermal improvement decrease at high speeds. The case and heat sink temperatures are not reduced for speeds higher than 6m/s (Figure 14). In fact, although there is a big reduction of thermal resistance from 2 to 4m/s, there is almost no difference between 4m/s and 6m/s results. The thermal resistances remain nearly equal. This demonstrates that the condenser limit is reached, since although more air is used for cooling, no more heat can be dissipated. This limit can be estimated in 6m/s and 4m/s is close to the optimum flow.

3. Optimum power level of the HPHS. We have also estimated the evaporator limit and thereby the optimum power level. The comparison of thermal resistance values for high power levels demonstrates that there is only a petty deviation among them (Figure 14). The evaporator limit corresponds to about 1300W power losses per semiconductor. This was expected, since the heat pipe was manufactured taking into account these values. Vacuum pressure was chosen for optimizing phase-change temperature of the pipe fluid according to them.

4. Rth = f (P, v). We have defined a function which represents the influence of the air-flow and the heat load in the overall thermal resistance for this particular application. This function, represented as Rth = f (P, v), does not work properly beyond the defined limits (evaporator and condenser), but it is a very useful tool, since it allows to calculate the thermal resistance for any combination of boundary conditions within the range. Figure 15 shows curves for several couples of values (Pin, vin):

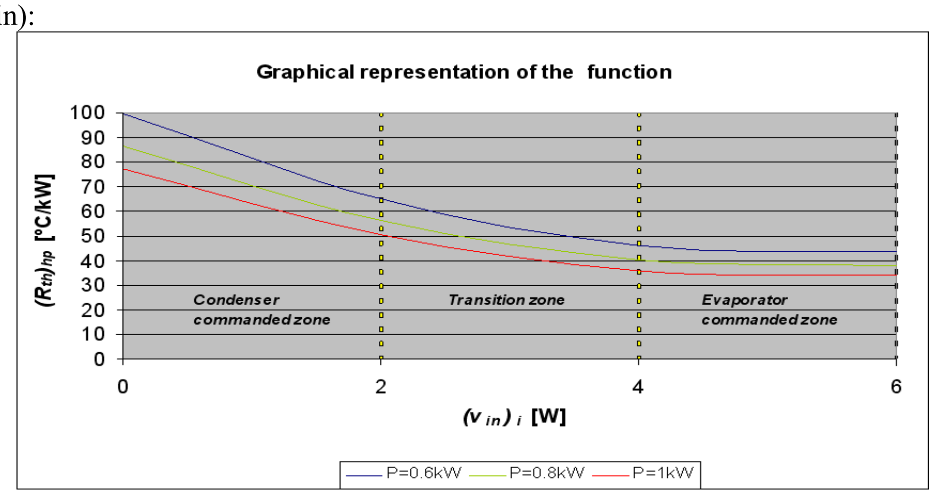

Figure 15. Rth = f (P, v) for different (Pin, vin) values

This function permits to see which of the thermal resistances of the HPHS is prevailing: condenser or evaporator. As can be seen in Figure 15, until about 2m/s the overall thermal resistance is commanded by the condenser, since for a small change in the air speed the overall thermal resistance decreases rapidly. From 2 to 4m/s, there is a transition zone where both resistances are balanced and the curve is smoother. Finally, from around 4m/s on the evaporator governs the overall resistance and the function has a horizontal tangent for 6m/s.

5. Influence of natural convection. We have observed that natural convection should not be neglected. Even for a motionless vehicle the heat that the HPHS can evacuate is considerable. In order to evaluate the importance of natural convection against assisted one, we have considered the following inequality:

$$\frac{Gr}{\mathrm{Re}^2} > 10 m \cdot s \tag{3}$$

If this criterion is fulfilled, natural convection is dominant. For an inlet air speed of 2m/s, the ratio results in 0.07m/s. For higher inlet speeds, the ratio decreases, so assisted convection prevails clearly. Both transference mechanisms would be balanced for a speed of 0.36m/s. Nevertheless, the results of he tests demonstrate that a dissipation of as much as 500W per semiconductor can be achieved without any air-flow through the HPHS at all. This represents a 30% of the maximum design power of our inverter.

6. Effect of operating temperature. The heat pipe presents a high dependence on operation temperature. When it is cold, a sharp transient peak is observed in Tcase measurements. This peak is critical, since it goes far beyond the steady state value. On the contrary, if the HPHS is already hot when heat is applied, the transient response is avoided and the temperature increases softly until steady state condition is reached.

Figure 16 shows a graph where this temperature effect can be seen. Tcase evolution is shown. When the device is cold it has a marked transient behaviour, even for low heat generation. On the contrary, when the device is hot there is no transient peak at all. Furthermore, steady state temperature is slightly higher in cold operation. We think this phenomenon is caused by bubble formation, due to inappropriate filling of the heat pipes. As a result, keeping the heat pipe hot is obviously beneficial, due to its efficiency augmentation.

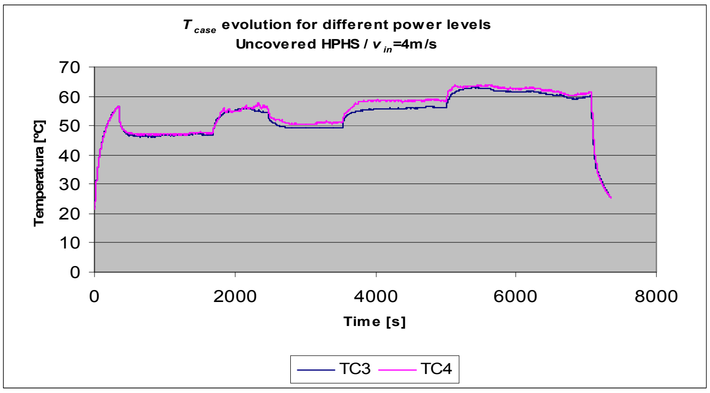

Figure 16. Tcase evolution for cold and hot operation. Transient response

Conclusions

We have performed aerodynamic and thermals tests with a HPHS for railway applications. The main objective of the experimentation process has been the modelling of the device. From the obtained results we can conclude that:

1. Characterisation of the HPHS. We have achieved the major goal of the procedure described in this paper: the complete characterisation of a HPHS for a generic traction converter. With

the obtained data we have developed a computational model and we have predicted the behaviour of the refrigeration system for the real operation of a train.

2. Aerothermal experimentation process. We have developed a method of aerothermal experimentation for the HPHS testing, combining mobile and fixed test rigs. The process consists of aerodynamic tests with a van in an airport and thermal tests in a self-designed wind tunnel. The results of both stages allow the determination of crucial parameters for the model of the refrigeration system.
3. Furthermore, this method might be applicable to a great number of other applications. The process represents a very cost-effective option, providing an acceptable accuracy and avoiding the high waiting-times and expenses of larger scale wind-tunnel facilities. Hiring the runway of a small airport and building a simple tunnel is much cheaper, provides great flexibility and allows the integration of thermal and aerodynamic tests.
4. Determining factors of HPHS performance. We have identified and analysed the two main factors governing the HPHS performance: air-flow and applied heat. Both parameters represent heat transfer limits, since they are directly related to the heat pipe operation. The air-flow determines the behaviour of the condenser and the heat load plays a decisive role in the evaporator efficiency. We have determined the entire thermal resistance network of the HPHS in function of these parameters and we have defined the Rth = f (P, v) function, a particular curve which represents the phenomena for our specific application.
5. Relationship between vehicle speed and air-flow through the HPHS. We have deduced the relationship between the train speed and the air-flow through the HPHS during the aerodynamic tests. The curve can be divided into 2 linear parts, with a clear inflexion for a vehicle velocity of about 40km/h. From this point on, the air-to-train speed ratio is reduced, yielding to smaller flow increase than for low velocities. However, the slope of the function could be maintained if conduction vanes are used in order to redirect more air into the HPHS.
6. Influence of natural convection. In order to evaluate the importance of natural convection against assisted one, we have calculated Gr/Re2 ratio. Although assisted is clearly dominant, natural convection cannot be neglected. As much as a 30% of the maximum design power of the inverter can be achieved without any air-flow through the HPHS at all.
7. Obstruction factor. We have defined and calculated a parameter which measures the air-leak through the HPHS: the so-called obstruction factor. When the device is uncovered, almost no air crosses the whole heat pipe, entailing a considerable waste of cooling capability. As a result, it is critical to orient the air properly into the HPHS. A permeable cover should be designed, which permits natural convection but conducting the air-flow through the HPHS.
8. Influence of operating temperature. We have studied the influence of operating temperature in the transient response of the HPHS. It is a critical parameter when the filling of the heat pipes is inappropriate: at low operating temperatures the application of heat leads to high transient peaks, due to bubble formation.

The conclusions reached promote further research focused on the HPHS theoretical optimization: depending on the application, power losses per semiconductor will vary, so the HPHS should be manufactured considering new conditions; the evaporator should be optimized again, adapting the cross section, contact and so on. On the other hand, condenser might be optimized, too, changing the fin pitch, fin quantity etc. Vacuum pressure and fluid election should be analysed, too. Finally, new HPHS prototypes could be tested in the wind tunnel in order to compare their thermal performances.

References

[1] R. D. Metha, The aerodynamic design of blower tunnels with wide-angle diffusers, Prog. Aerospace Sci., Vol. 18, pp. 59-120, 1977

[2] J. B. Barlow, W. H. Rae Jr. and A Pope, Low-speed wind tunnel testing, Hohn Wiley&Sons, Inc., 1999

[3] R. DeHoff and K. Grubb, Heat Pipe Application Guidelines, www.thermacore.com

[4] B. Palm, Short notes on heat transfer, Kungliga Tekniska Högskolan (Department of Energy Technology)