Environment-Friendly Vertical Air-Cooling Heatsink: Heatpipe-Based Heatsink "POWER KICKER®"

by *Takeshi Takahashi* *, *Kazuhiro Konishi* *, *Junji Sotani* *,
Takayuki Kikuchi *2, *Satoru Isogai* *3 and *Yuichi Kimura* *3

ABSTRACT A variety of heatsinks of high efficiency has been used in electric power devices for power conversion to maintain their performance. Recently, these heatsinks are required to have small footprint and environment-friendliness —such as small ozone depletion and reduced environmental impact— as well as high heat-dissipating performance. Accordingly, the authors have developed and put into practical use, jointly with a certain company, "POWER KICKER®" —an environment-friendly vertical air-cooling heatsink— for heat dissipation of high heat-generating devices to replace conventional heatsinks that use CFCs and CFC substitutes. This paper reports on the performance and practical applications of the new heatsink.

1. INTRODUCTION

In recent years, electric power devices for power conversion have much improved in performance due to the development of electronics, making these high-capacity power devices easily available. Thus, high-capacity semiconductor devices such as GTO (Gate Turn-Off) thyristors, IGBTs (Insulated Gate Bipolar Transistor) and power diodes as shown in Photo 1 are widely used in electric railway substations.

Normally these devices for substations have been using natural air-cooling heatsinks in order to reduce the cost of maintenance. In the electric railway substations, in particular, boiling-type heatsinks using CFCs or CFC substitutes have generally been employed for performance maintenance because of the large heat the power conversion devices generate. But as the CFC control regulation comes into force and awareness of preventing the global warming increases in recent years, use of environment-friendly heatsinks is extensively required.

Furukawa Electric has long established a track record of supplying POWER KICKER® —a registered trademark of Furukawa Electric for heatpipe-based heatsinks for high-heat generating semiconductor devices— to various fields as heatsinks for electric power conversion devices. In addition the company has recently developed, jointly with a certain company, a new series of heatpipe-based vertical air-cooling heatsinks that feature environment-friendliness and small footprint to be applied to power devices such as circuit breakers in electric railway substations. This paper reports on the features, application examples and recent trends of this vertical air-cooling heatsink POWER KICKER.

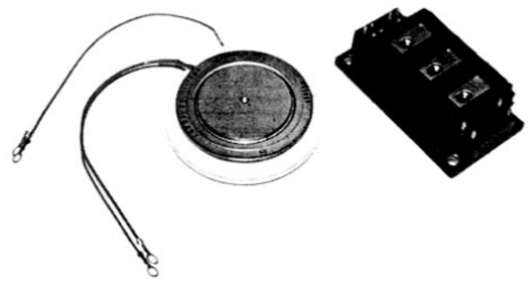


Photo 1 Flat-type thyristor and power module for power conversion.

2. CONVENTIONAL HEATSINKS FOR POWER CONVERSION DEVICES IN ELECTRIC RAILWAY SUBSTATIONS

Transmission and reception system of electric power in Japanese railways is such that the primary power for motor driving is supplied to electric vehicles on the rail track together with the auxiliary power for lighting and the like, and conversely, the recovered power generated by the driving motors onboard is received from the vehicles. And varied power conversion accompanied by the transmission and reception of electric power is controlled at

* Thermal and Antenna Solutions Dept., Electronic Components Div., Electronics and Automotive Systems Co.
*2 Okano Electric Wire Co., Ltd.
*3 Ecology and Energy Lab., R&D Div.

the electric railway substations, where power control systems are installed to provide stable supplies of electric power to the vehicles by globally controlling the AC and DC transformation subsystems. See Figure 1.

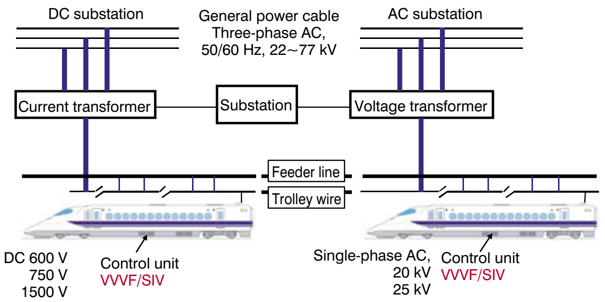


Figure 1 Power control system at electric railway substations in Japan.

In the substations where high-capacity power conversion devices are used in various systems, high-performance heatsinks are needed to maintain the performance of the power devices, so that, conventionally, a heatsink based on the CFC boiling-tank method has been largely used as shown in Figure 2. With this heatsink, the conversion elements are immersed and cooled in the insulating medium contained in the boiling tank, where large quantities of CFC or CFC substitute are used. Other cooling methods including those based on individual boiling-tank heatsinks or heatpipe-based heatsinks are also used. Table 1 shows a comparison of these cooling methods.

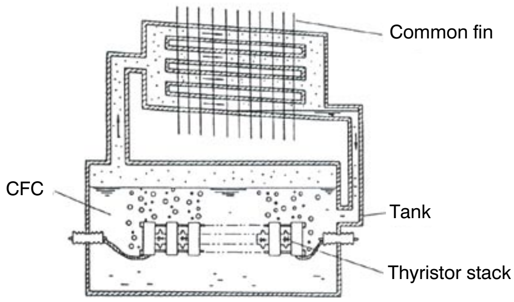


Figure 2 Schematic of CFC boiling-tank cooling system conventionally used.

3. APPLICATION OF HEATPIPE-BASED HEATSINKS TO ELECTRIC RAILWAYS

Application of heatpipe-based heatsinks has early been studied for their non-power-driven operation and ease of maintenance, and POWER KICKER products —air-cooling, heatpipe-based heatsinks using water— are already in practical use in some substations.

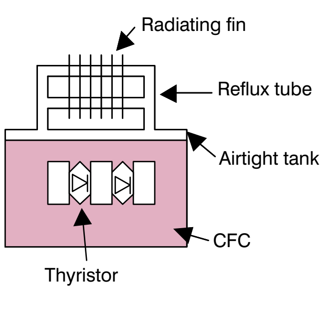
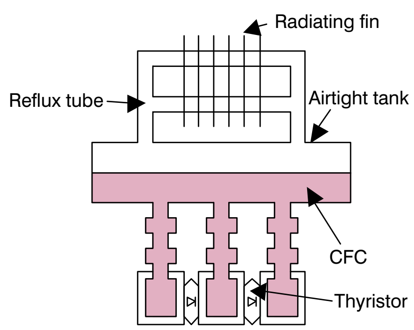
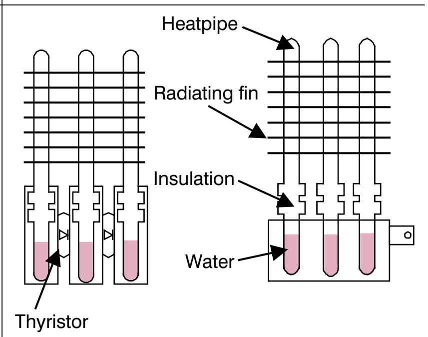
Conventional heatpipe-based heatsinks have been used in such a configuration that two heatsink units are arranged on the both sides of each power conversion element such as GTO sandwiching it to receive the generated heat, which is then transferred via the heatpipes embedded in the unit to be dissipated by the heat-radiating fins provided at the radiating section. Owing to such a structure of individual cooling mechanism, the heatpipe-based heatsinks feature, besides environment-friendliness, high redundancy in terms of reliability and ease of maintenance, so that replacement of the power element is facilitated unlike heatsinks of boiling-tank type.

It is to be noted that conventional heatpipe-based heatsinks were basically installed in a horizontal position with an inclination angle of 3~5 degrees to the horizontal plane, in consideration of efficient heat dissipation from the fins taking advantage of natural convection. Photo 2 shows a horizontal-type product with a heat-dissipating length of 1000 mm and a thermal resistance of 0.06 K/W against a heat generating rate of 500 W. The one shown in Photo 3 is 1500 mm in length to provide a thermal resistance of 0.04 K/W.

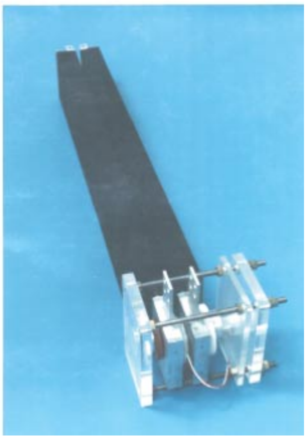
4. DEVELOPMENT OF HEATPIPE-BASED VERTICAL AIR-COOLING HEATSINK

Horizontal-type heatpipe-based heatsinks have a long track record thanks to their environment-friendliness, ease of maintenance and long-term reliability. Because of their long fin sections, however, they inevitably need considerable space for installation. Thus these heatsinks have the disadvantage that it is sometimes difficult to use them to replace existing heatsinks of other type —the

Table 1 Comparison of heatsinks for electric railway substations.

	Boiling-tank heatsink	Individual boiling-tank heatsink	Heatpipe-based heatsink
Structure			
Size	Large	Large	Small
Weight	Heavy	Heavy	Light
Working fluid	CFC or CFC substitute	CFC or CFC substitute	CFC substitute or water
Reliability	Low	Low	High (due to separated cooling)

(a) Power conversion equipment where POWER KICKER is installed



(b) Horizontal POWER KICKER (Radiator length: 1000 mm)

Photo 2 Horizontal POWER KICKER and its applications.

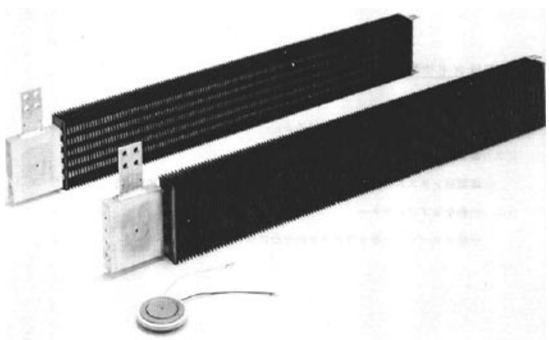


Photo 3 Horizontal POWER KICKER (Radiator length: 1500 mm)

mainstream was boiling-tank type conventionally— or that it is occasionally impossible to install them because of the limited open space available.

Accordingly we have developed, jointly with a certain company, a new heatsink based on the following concept.

(1) To provide thermal performance equivalent to that of horizontal-type heatpipe-based heatsink.

(2) To minimize the installation space, it should be a compact heatsink with heatpipes in a vertical position.

We have developed and put into practical use the new heatsink through multifaceted studies and evaluations with regard to the following design problems.

(1) To reduce the thermal resistance of heatpipe itself.

(2) To reduce the thermal resistance of radiating fin section.

In particular, heatpipe-based heatsinks tend to have a large ratio between the thermal resistance of the radiating fin section and that of the whole heatsink. To solve this problem, we devised countermeasures to make the shape and pitch of the fins suitable for effective air-cooling in a limited space of installation, thus succeeding in developing a heatsink that achieves the developmental objectives. See Photo 4.

Figure 3 shows schematics of the cooling mechanism for heatpipe-based vertical air-cooling heatsink (hereinafter called HP-VAH). The slanted fins developed here are provided at the radiating section to generate drafts enabling efficient natural convection, resulting in the cooling performance that is virtually equivalent to that of the horizontal-type heatpipe-based heatsinks conventionally used. This has realized a reduction in the footprint to one half or less that of earlier Furukawa products.

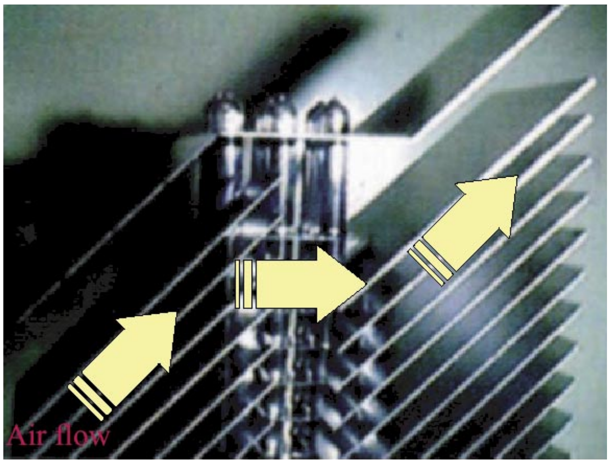


Photo 4 Fin configuration of HP-VAH.

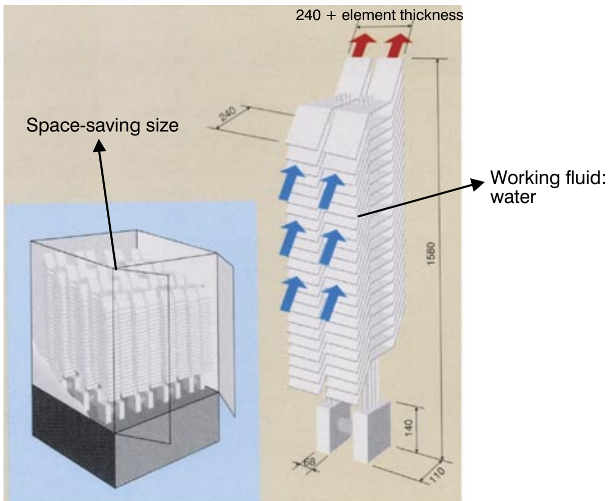


Figure 3 Cooling mechanism for HP-VAH.

Photo 5 Appearance of three standard models of HP-VAH.

Table 2 Standard specifications of HP-VAH.

Model	Thermal load (W)	Dimensions (Block) × (Fin) × Total (mm)	Thermal resistance (K/W per pair)
A	300	(140 × 110 × 68) × (120 × 242) × 850	0.12
B	500	(140 × 110 × 68) × (120 × 242) × 1155	0.072
C	800	(140 × 110 × 68) × (120 × 242) × 1580	0.044

5. BASIC COOLING CHARACTERISTICS OF HP-VAH

There are three standard models of HP-VAHs as shown in Table 2 and Photo 5.

Basically, the heatsinks are used in pairs like horizontal-type heatsinks, i.e. two heatsinks are arragnged on the both sides of one heat-generating element. Based on this configuration, the standard models can cope with thermal loads of 300 W, 500 W and 800 W, respectively.

With regard to their basic thermal characteristics, the standard models of the heatsinks are type-tested to obtain: 1) steady-state thermal resistance characteristics, 2) transient-state thermal resistance characteristics and 3) low-temperature start-up characteristics.

Below will be outlined the thermal evaluation method of the basic cooling characteristics for the heatsinks. The characteristics were evaluated in accordance with practical applications following the procedures and methods described below. See Figure 4.

(1) Assembly of the power conversion element with the heatsink and installation method
A metal block with a heater is used to simulate the power conversion element, and the block and two heatsinks are assembled to make a test assembly in a vertical position, and a specified quantity of heat Q is applied to the heater block.

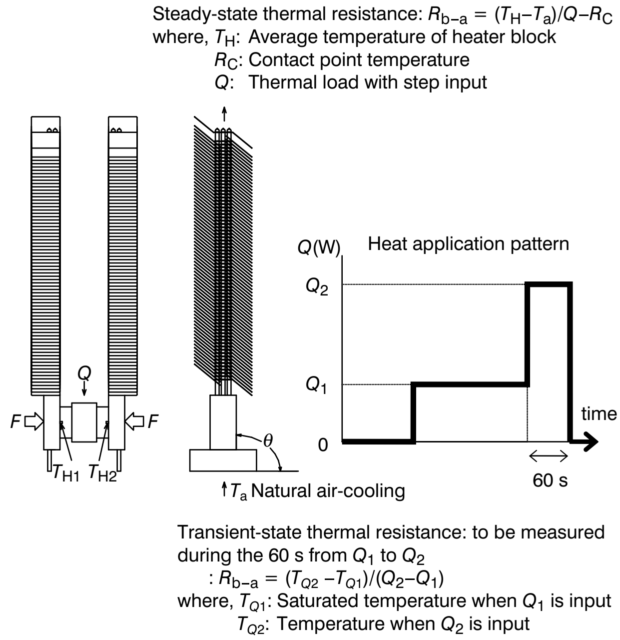


Figure 4 Evaluation method of thermal characteristics of HP-VAH.

(2) Temperature measurement and calculation of temperature increase at the block: ΔT
Using the thermocouples installed on the heater block, temperatures at the inlet of airflow and the block are measured to calculate the temperature increase at the block: ΔT = Heater block temperature − Airflow inlet temperature.

(3) Definition and calculation of thermal resistance: R
The thermal resistance is defined as

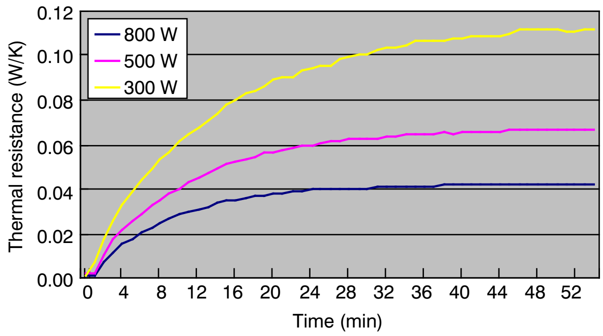
$$R=\frac{\Delta T}{Q}-R_c$$

where, R_c is the contact thermal resistance at the interface between the heatsink and the heater block, to be obtained experimentally.

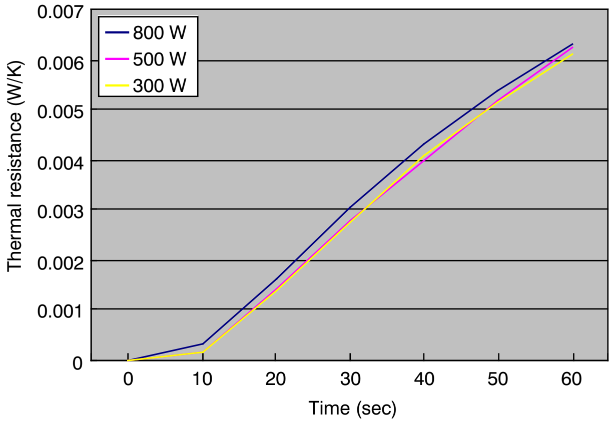
(4) Manner of thermal load application
a) Thermal resistance behavior when a thermal load Q is input in a stepwise manner is referred to as steady-state thermal resistance characteristics, and the stabilized value is defined as steady-state thermal resistance.
b) Transient behavior of thermal resistance during a short period —30 or 60 sec— after a thermal load Q_2 is input to the stabilized state with a heat input of Q_1 is referred to as transient-state thermal resistance characteristics, and the value measured after a specified time is defined as transient-state thermal resistance.

In practical applications for power conversion devices, heatsinks are usually used under the combined conditions of steady-state and transient-state thermal inputs, so that the characteristics of both the steady-state and transient-state thermal resistances become essential. Figure 5 shows the steady-state and transient-state thermal resistances of standard models of HP-VAHs.

Besides the steady-state and transient-state thermal resistances, start-up characteristics at low temperatures are a crucial performance indicator. This is because there is a possibility that an alarming phenomena may occur whereby the water used as a working fluid in the heatpipes freezes at ambient temperatures of 0°C and below rendering them unable to work. It is thus necessary to evaluate the low-temperature characteristics of the heatpipe for confirmation if they normally work at low ambient temperatures during winter.



a) Steady-state thermal resistance



b) Transient-state thermal resistance

Figure 5 Thermal resistance of HP-VAH.

Figure 6 shows the test result of low-temperature start up characteristics of C-type standard model with 800 W rating, whereby the thermal performance was evaluated while the ambient temperature was kept at −5°C. It has been confirmed that the standard models using water as the working fluid can start up smoothly at an ambient temperature of −5°C or higher. At temperatures lower than that, conventional heatpipe-based heatsinks found it difficult to start up smoothly, because water freezes at these temperatures. As a result of many improvements made in heatpipes, however, recent products of HP-VAHs can start up at temperatures lower than −5°C, e.g. −15°C.

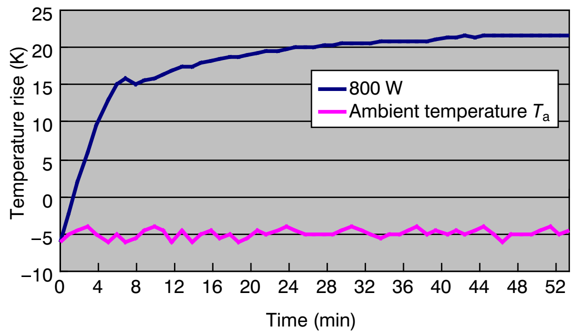


Figure 6 Low-temperature start-up characteristics of HP-VAH.

6. APPLICATION EXAMPLES OF HP-VAH

Photo 6 shows a power controller for DC substations for electric railways in which silicon rectifiers and circuit breakers are used together with HP-VAHs. To cool the power elements, C-type standard model of POWER KICKER with 800 W rating is used. The heatsink consists of a nickel-plated copper block, six heatpipes 15.88 mm in diameter and 1600 mm in length and 74 heat-radiating fins. The heatpipe is tin-plated for corrosion proof, and the fins are treated with black alumite aimed at long-term use and corrosion proof.

Photo 6 Power controller for electric railways using POWER KICKER.

7. RECENT TRENDS IN HP-VAH AND DEVELOPMENT OF INSULATED HP-VAH

While Furukawa Electric has built up a track record of supplying many HP-VAHs thus replacing boiling-tank heatsinks, there has been in recent years a trend toward the use of insulated HP-VAHs that is required from the viewpoint of safety. In conventional boiling-tank heatsinks, insulation is basically provided between the semiconductor elements and the radiating fins because these are immersed in CFCs or CFC substitutes. Accordingly, there is a potential need for a HP-VAH that is similarly provided with an insulation function to assure a higher level of safety.

To provide insulation in heatpipe-based heatsinks, it is a common practice to insert insulators made of aluminum nitride between the power conversion element and the heatsink. This method, however, leads to an increase in the thermal resistance thereby deteriorating heat dissipation globally, and in addition, to a potential decrease in insulation if the insulators are damaged by any chance. We also have a track record of insulated heatpipe-based heatsinks in which an insulating working fluid is used to assure safety and compactness, but it was considered difficult to use non-insulating working fluids such as water to ensure insulation, so that no such heatsinks were in practical use.

Against this background, we have succeeded in developing a new insulated heatpipe-based heatsink in which water is used as working fluid, thus realizing the world's first product. The insulating HP-VAH, an improved version of HP-VAH, with intrinsically insulated heatpipes that use water as working fluid thus eliminating the disadvantages of using insulators are already applied to some substation facilities of electric railways.

8. FEATURES OF HP-VAH

HP-VAH has been developed based on our expertise in horizontal-type heatpipe-based heatsinks. Its features may be summarized as follows.

(1) Environmental consciousness
It uses water as working fluid eliminating CFCs or CFC substitutes, making itself an environment-friendly heatsink.

(2) Compactness and space-saving
Footprint has been reduced to one half or less that of conventional horizontal-type heatpipe-based heatsinks.

(3) Improvement in maintainability
Since heatpipe is a passive device for heat transmission without necessitating power source, its maintenance is easy.

(4) Consideration on and improvement in reliability and safety
Since individual cooling method is employed for heat-generating devices, the redundancy is high and hence high reliability.
In addition, taking active advantage of the vertical configuration of specially shaped fins together with new technologies, insulation function was given to the heatpipe that uses water as working fluid, realizing a high level of safety.

9. CONCLUSIONS

This paper has outlined the development of the heatpipe-based vertical air-cooling heatsink POWER KICKER. Under the current social situations where space saving and environment-friendliness are always required for products, the development included many solutions to cope with unconventional new requirements, but we have eventually succeeded in offering the new product to the marketplace. At the same time, it is a great pleasure for us development engineers that, due to the developmental tasks of making the product more user-friendly, we could build up proprietary technologies accompanied by the new product. We intend to make further efforts to respond to the market needs to be able to supply better products.

The development and productization of the heatpipe-based vertical air-cooling heatsink have been realized by the advice and suggestions provided by many people. In closing, the authors would like to take this opportunity to express their appreciation to all of them.

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