# AN EXPERIMENTAL THERMAL SIPHON BUSHING

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ABSTRACT: An experimental thermal siphon bushing was constructed and tested. The thermal siphon was made from the hollow conductor of a paper-resin bushing with water as heat transport fluid. The test shows that this bushing has almost uniform temperature distribution under its critical current and the temperature of its hottest spot is close to the boiling temperature of water. The current carrying capacity of this thermal siphon bushing is 50% more than that of the same bushing without thermal siphon. Simple formulas are proposed to determine the critical current of a thermal siphon bushing and estimate the temperature of the hottest spot if the bushing with thermal siphon is operated above the nameplate rating.

KEY WORDS: Condenser bushing, critical current, current carrying capacity, heat run, temperature rise, thermal siphon.

## INTRODUCTION

There are two types of natural cooling bushings in service: bushings with and without oil circulation. From the thermal point of view, the bushings with oil circulation are much more efficient because the oil circulation brings the heat out of the hot conductor to the cool outer surfaces of the bushing quickly. But some bushings, such as paper-resin bushings, cannot be designed with oil circulation because there is no oil circulation path or no oil at all. In this case the heat pipe concept [1,2] can be used to improve cooling of the bushing. F. G. Arcella and colleagues [3] have shown that heat pipe cooling could double the current density of a high voltage bushing.

A thermal siphon is similar to a heat pipe but without a wick. Like the heat pipe, the thermal siphon relies on the evaporation-condensation cycle of the heat transport fluid to move the heat from its hot zone to its cold zone promptly.

Because the latent heat of evaporation is huge, a large amount of heat can be transported with very small temperature difference. Therefore, the thermal siphon made from a thin wall copper pipe can have much higher axial thermal conductivity than a solid copper rod with the same diameter.

In a thermal siphon, the condensed fluid at the cold zone of the siphon flows back to the hot zone by gravity. Therefore, the hot zone must be in the lower end of the siphon.

When we studied methods to improve the current carrying capacity of paper-resin bushings in 1992, we considered adapting the evaporation-condensation cycle to help cooling the bushing. Because a thermal siphon is easier to construct than a heat pipe, an experimental bushing with thermal siphon was initially studied to explore the feasibility of using the evaporation-condensation cycle in high voltage bushings.

## TEST SET-UP AND TEST RESULTS

An experimental thermal siphon bushing is constructed from a 350kV BIL 1200A paper-resin bushing. The bushing has a paper-resin capacitance core with porcelain as its upper housing. The conductor is a 1778 mm (70”) long copper tube with 38.1 mm (1 1/2”) OD and 22.2 mm (7/8”) ID. Water is used as the heat transport fluid. The hollow conductor is vacuumed, half-filled with water and sealed. The test set-up is shown in Fig. 1.

During the test, the lower end of the bushing is immersed in 95°C oil while the top end is in ambient air. The heat source is the resistance loss in the conductor. The thermocouples are pinched into the conductor to measure the temperature distribution along the conductor.

The temperature distribution profiles of the thermal siphon bushing are shown in Fig. 2. The profiles have two features:

1. The hottest spot is located at the very bottom of the bushing, and the temperature of the hottest spot at different currents is close to 100°C, the boiling temperature of water, as shown in table 1. Actually, the temperature of the hottest spot is a little higher than 100°C and increases slightly with the current.

2. Each profile consists of a temperature plateau followed a temperature decline. The plateau begins from the bottom end of the bushing and the decline ends at the top of bushing with a temperature of the top terminal. As the current increases, the plateau extends towards the top end of the bushing. For this experimental bushing, the plateau reaches the top of the bushing when the current is 1800A

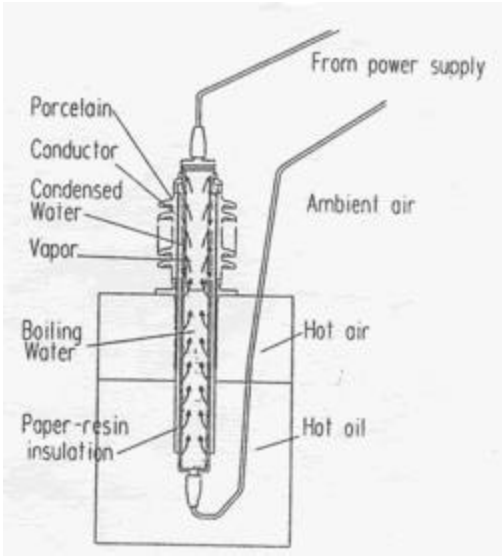



Fig. 1. Test set-up of the experimental thermal siphon bushing

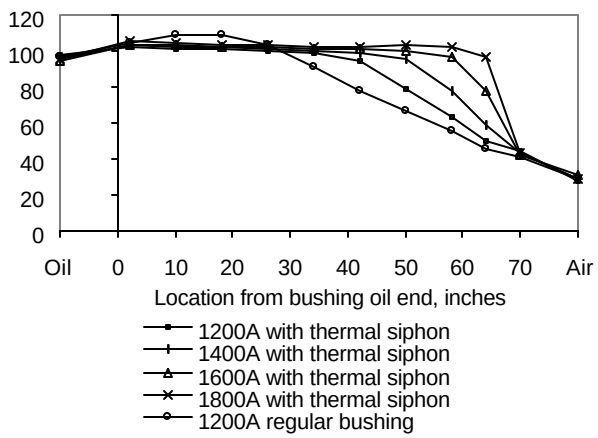



Fig. 2. Temperature distributions of the experimental thermal siphon bushing

According to bushing standard IEEE C57.19.00-1991[4], when a bushing with temperature index 105 insulation works under rated conditions, the temperature rise of the hottest spot shall not exceed 65°C, and the temperature of the hottest spot shall not exceed 105°C. Because the temperature of the hottest spot of the thermal siphon bushing depends on boiling temperature of water. It is obvious that the temperature rise of the hottest spot over the ambient air does not increase with the current but changes with the ambient air temperature. Therefore, the temperature rise of the hottest spot over the ambient air cannot be used to determine the current rating of the thermal siphon bushing. Rather, the temperature of the hottest spot must be used to decide the current rating of the thermal siphon bushing.

From the test results, this experimental thermal siphon bushing passed 1800A heat-run test based on 105°C temperature of the hottest spot while the regular bushing barely passed 1200A heat-run test based on 65°C temperature rise of the hottest spot. Thus, the thermal siphon enhances the current carrying capability of the bushing by 50%.

Table 1. The temperature of the hottest spot in the experimental thermal siphon bushing (at the very bottom end of the siphon)

| Current, A | Temperature, °C | | | H.S. Rise, °C |
|---|---|---|---|---|
| | Oil | Air | H.S. | |
| 1200 | 97.7 | 28.2 | 102.5 | 74.3 |
| 1400 | 96.0 | 28.8 | 102.8 | 74.0 |
| 1600 | 94.6 | 30.8 | 103.0 | 72.2 |
| 1800 | 95.2 | 28.8 | 105.1 | 76.3 |

## DISCUSSION

All the thermal features of the thermal siphon bushing can be attributed to the evaporation-condensation cycle of the heat transport fluid, which is water in the experimental bushing. Under normal conditions, water boils at 100°C and its vapor (steam) condenses when the temperature is lower than 100°C. The boiling and condensing temperature increases with pressure slightly. For example, the boiling temperature of water increases from 100°C to about 120°C when the pressure increases from the normal atmosphere to 2 atmospheres (absolute). The latent heat of evaporation-condensation of water is 539 cal/g that means the phase change can transfer heat promptly.

In the thermal siphon bushing, the conductor heats up when the current flows. The heat is generated near uniformly along the conductor. Because the surrounding temperature at its bottom end is high, the lower portion of the conductor becomes hotter first. When the temperature of the lower portion reaches 100°C, water boils and thereafter the temperature of the water remains at 100°C. Vapor carries the heat from the hotter bottom portion of the conductor to the cooler top portion of the conductor. When the vapor reaches the top portion with the temperature below 100°C in the conductor, the vapor condenses and the condensation runs down along the inner surface of the conductor. This process maintains continuous water supply in the bottom of the thermal siphon bushing. The condensation may evaporate again before it merges with the water supply in the bottom of the bushing to eliminate a local hot spot above the water supply.

The hottest spot of the thermal siphon bushing is located at the bottom because the pressure of the water column in the bottom is slightly higher than that at its top. When current increases, more heat is produced. The more the heat, the more the vapor, and then the higher the pressure in the thermal siphon. Therefore, the temperature of the hottest spot will

increase with current slightly.

The heat generated in the conductor eventually dissipates from all the surfaces of the bushing when the temperature reaches a steady state. The heat dissipating from a surface is the ratio of the temperature differential to the thermal resistance from the conductor to the surrounding medium at this surface. In the thermal siphon bushing the heat generated in the hotter bottom is brought to the cooler top to dissipate, therefore the thermal siphon bushing is more efficient than conventional bushing without oil circulation.

The rising vapor begins condensing as soon as it touches the inner surface of the conductor where the temperature is below condensation temperature. Thereafter there is not enough vapor to rise, so the temperature begins declining. When the current is high, more heat and vapor generate. More vapor requires more surface to cool and condense. Therefore, the plateau extends up towards the top end of the bushing.

Fig. 3 shows the heat flow distribution of the thermal siphon bushing with the temperature profiles of the ambient and the conductor as references.

We define the current that pushes the temperature plateau to the top of the bushing as a critical current of the thermal siphon bushing. At the critical current, there is almost no axial temperature gradient along the conductor, and the whole conductor is near at the same temperature. Therefore, a simple method can be used to determine the critical current of a thermal siphon bushing and calculate the temperature of the hottest spot in the bushing when the current is above the critical current.

According to the diagram shown in Fig. 3, the bushing can be divided into three sections: below oil level, between oil level and flange mounting surface, and above flange mounting surface.

The heat dissipated $Q_i$ from each section is

$$Q_i=(T_0-T_i)/ R_i,$$

where: $T_0$ - the boiling temperature of water in the thermal siphon

$T_i$ - the temperature of the surrounding media

$R_i$ - the thermal resistance from the conductor to the surrounding medium.

The heat generated in the conductor is

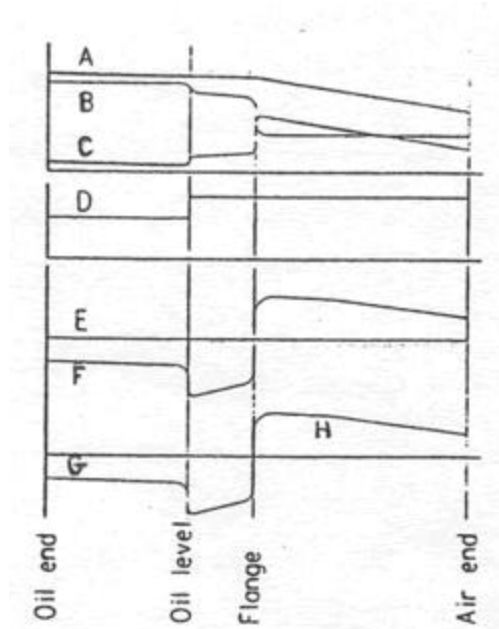
$$Q=(\rho l/s)*I_c^2,$$

where: $\rho$ - AC resistivity of the conductor

$l$ - length of the conductor

$s$ - conductor cross section area of the conductor

$I_c$ - critical current of the thermal siphon bushing.




A. Temperature distribution of the conductor
B. Temperature distribution of the surrounding media (ambient)
C. The differential of temperature between the conductor and the surrounding media
D. Thermal resistance distribution (from the conductor to the surrounding media)
E. Heat distribution generated in the conductor
F. Heat distribution dissipated from the outside surface of the bushing
G. Heat distribution carried out via evaporation
H. Heat distribution delivered via condensation

Fig. 3. Heat flow distribution of the thermal siphon bushing

At the steady state condition

$$(\rho l/s)*I_c^2 =\Sigma((T_0-T_i)/R_i),$$

and then the critical current can be determined as the follows

$$I_c=\{\Sigma((T_0-T_i)/R_i))/ (\rho l/s)\}^{1/2}.$$

When a thermal siphon bushing works at a current I which is above the critical current of the thermal siphon bushing, the temperature T of the hottest spot in the bushing is

$$T=\{(\rho l/s)*I^2+\Sigma(T_i/R_i)\}/ \Sigma(1/R_i).$$

Because the evaporation-condensation cycle of water stabilizes the temperature of the whole siphon and the boiling temperature of water self-adjusts with pressure, we can expect the thermal siphon bushing handle overload better than the conventional bushing without oil circulation as long as there is enough water in the siphon.

When a thermal siphon bushing is rated at the critical current, the pressure inside the thermal siphon (determined by 105°C - the allowable temperature of the hottest spot) is 1.17 atmosphere (absolute), slightly greater than normal atmospheric pressure. When this bushing is operated under overload conditions, the pressure inside the thermal siphon

increases with the load. According to IEEE Guide [5], the hottest spot of conductor in contact with temperature index 105 insulation is limited to 150°C under overload conditions. Based on this temperature, the pressure inside the thermal siphon bushing does not exceed 4.6 atmospheres (absolute) under the maximum overload. This pressure shall not cause mechanical problem in the thermal siphon bushing because the wall of the conductor is quite thick compared with its diameter.

The test results in this thermal siphon bushing are very positive. A bushing with the thermal siphon can be rated 50% higher than a conventional bushing without oil circulation. This means the thermal siphon can be easily used in the vertically mounted bushing. If a bushing is mounted horizontally, the heat pipe with wick may be required.

The test was performed in 1992 and it is only a preliminary test to develop a compact, high-current bushing with paper-resin core. More detailed research should be done before using the thermal siphon or heat pipe in bushings. For example, we need to find the optimum heat transport fluid for the thermal siphon bushing, the fluid level in a given bushing and the technology to manufacture a thermal siphon used in bushings.

ACKNOWLEDGEMENT

The author appreciates Lapp Insulator Company's permission to publish this paper

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BIOGRAPHY

Daxiong Zeng received his BS and MS degrees in high voltage engineering and electrical measurements from Tsinghua University, Beijing, China.

During 1968~1985 he worked at Xi-an Power Rectifier Company in China to develop AC-DC and DC-AC energy conversion systems and at the Electrical Engineering Institute of Chinese Academy of Sciences to develop high-voltage impulse generators and work on high-voltage insulation projects.

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