Passive system of cooling and refrigerant fluid circulation, assisted by capillary pumping

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Abstract. We propose a concept design of a cooling system, primarily targeting gas-insulated switchgear enclosures which use a mixture of a refrigerant fluid, such as Novec™ 649, and a non-condensable gas for electrical insulation. The novel open-loop system relies on evaporative cooling assisted by capillary pumping, and refrigerant vapor condensation on the walls of the system enclosure. The results of experiments on a laboratory prototype are presented and discussed. Besides cooling, a major benefit of the system is in facilitating the circulation of the gas mixture in the enclosure.

1. Introduction

Thermal management of gas insulated switchgear poses considerable problems related to poor heat transfer efficiency of gases used for dielectric insulation of heated elements at high electrical potential. A way to improve the cooling performance, while maintaining the dielectric strength required for medium- and high-voltage applications, is in employing evaporative two-phase cooling such that the working fluid vapor serves as an electrically insulating medium as well. This double-purpose application of the fluid puts special requirements on its dielectric properties, compared to conventional refrigerants. It is often necessary to add into the device enclosure some amount of non-condensable gas (NCG) with high dielectric strength at low operating temperatures. The resulting fluid mixture potentially provides both dielectric strength and cooling capacity.

In many applications, an emphasis is on reliability and maintenance-free operation over decades. It is, therefore, advantageous to develop methods that are intrinsically passive, not relying on pumps for delivering the refrigerant liquid to hot areas inside the enclosure.

2. Concept and operation principle

A conceptual design [1] is sketched in figure 1 and figure 2. A grounded enclosure contains at least one hot element, such as a current-carrying busbar, that requires both cooling and dielectric insulation. The inner volume of the enclosure contains a specially selected mixture of two fluids. One of them is a refrigerant fluid at a partial pressure \( P_R \) such that the saturation temperature \( T_{\text{sat}}(P_R) \) is higher than the temperature of the enclosure, or at least a part of the enclosure. The rest of the vapor mixture is a non-condensable gas. The refrigerant fluid is in a saturated state, with the liquid fraction forming a pool at the bottom of the enclosure. An evaporator is attached to the busbar with a good thermal contact. The evaporator consists of a thermal conductor, a porous wick, and a fitting. The wick has a compensation chamber, a part of the outer surface in contact with the thermal conductor, and a part of the outer surface
open to the enclosure volume for free convection of the vapor mixture. The fitting provides a hermetic connection between the compensation chamber and one end of a liquid supply line, fluidly connecting the evaporator and the liquid pool.

![Figure 1. Schematic drawing of the conceptual design.](image1)

![Figure 2. Schematic arrangement of the evaporator.](image2)

At normal operating conditions, the liquid supply tube and the compensation chamber are filled with the refrigerant liquid while the wick is fully or partially filled with the refrigerant liquid; the wick capillary structure provides a sufficient pressure difference to hold a liquid column between the liquid pool and the wick. The refrigerant fluid, which evaporates from the evaporator open surface, is replenished by the flow of refrigerant liquid from the liquid pool through the liquid supply line and into the wick compensation chamber, as in the biomimetic transpiration cooling system proposed in ref. [2]. The evaporated refrigerant would eventually condense on inner surfaces of the enclosure and return into the liquid pool by gravity. This achieves: (a) an effective cooling of the busbar, (b) enriching the enclosure inner volume with the refrigerant vapor, thus improving electrical insulation of parts at an electrical potential, and (c) a buoyancy-driven circulation of the vapor inside the enclosure, thus improving homogeneity of the vapor mixture.

### 3. Experimental setup

The enclosure was approximated by a cylindrical glass vessel of 15 cm diameter, as sketched in figure 3. The bottom part had a deepening for the liquid pool. A water-cooled condenser was installed in the upper part in order to facilitate vapor condensation, with water at room temperature RT=25°C.

3M™ Novec 649 Engineered Fluid (perfluoroketone C₆F₁₂O, below referred to as “C6”) was selected as the refrigerant fluid, and air served as NCG. This combination has been demonstrated to have excellent dielectric properties [3].

The evaporator was comprised by a rectangular copper block with a hole accommodating a cylindrical wick of 45mm length and 30mm diameter. The wick was made of commercially available porous PTFE with nominal pores diameter of 5 μm and porosity of about 35%. The evaporator was elevated above the liquid pool, in two sets of experiments, at either 17 cm or 29 cm. A PTFE tube of 1/8” inner diameter served as the liquid supply line.

Temperature was recorded at several locations (see figure 3), namely the ambient air temperature outside of the enclosure ($T_a$), the liquid C6 temperature inside the compensation chamber ($T_{Cc}$), the temperature of the heated copper block ($T_b$), the temperature of the C6 liquid pool ($T_p$), the temperatures of the vapor mixture about 1 cm above and below the evaporator ($T_{v,a}$ and $T_{v,b}$), and the temperature of the condenser surface ($T_{co}$).

The priming procedure consisted of (1) evacuating the enclosure, (2) adding refrigerant fluid into the enclosure, sufficient to form a liquid pool fully covering the lower opening of the liquid supply line, (3) adding liquid refrigerant on the evaporator until the refrigerant liquid fully saturates the wick, (4)
adding the predefined amount of NCG into the enclosure. Step (3) was essential for forming a hydraulic lock for the liquid inside the compensation chamber. Otherwise, NCG penetrates into the compensation chamber and the liquid column in the supply line breaks down.

Figure 3. Schematic drawing of the experimental setup. The points denote positions of temperature sensors.

Figure 4. Steady-state heater block temperatures $T_b$ as a function of the heating power $Q$ for $P_0 = 0.71$ bar and $h = 29$ cm. Double arrows illustrate the method of estimating $dQ(T_b)$.

4. Results

With a fixed amount of NCG in the partial pressure range 0.3-0.9 bar and a fixed elevation ($h$) of the evaporator, the heater power $Q$ was varied stepwise. For each $Q$ value, the steady-state temperature values were recorded. After each run with the liquid in the wick and in the supply line (“wet wick” run), the hydraulic lock was intentionally broken and the test runs repeated (“dry wick” run); a representative set of steady-state values of the heater block temperature $T_b$ for $h = 29$ cm and $P_0 = 0.71$ bar ($P_0$ is the total pressure at room temperature in the cold state $Q = 0$) is shown in figure 4.

The “wet wick” $T_b(Q)$ values are always lower than the “dry wick” ones, which is attributed to additional cooling provided by the refrigerant liquid evaporating from the wick. As only radiation and free vapor convection contribute to the dry-wick cooling, the contribution of the evaporating refrigerant and enhanced fluid circulation can be evaluated as the heater power difference $dQ = Q_{\text{wet-wick}} - Q_{\text{dry-wick}}$ between the wet-wick and the dry-wick experiments for the same $T_b$, same elevation and same NCC concentration, as illustrated by arrows in figure 4 for one dry/wet wick dataset pair. The resulting values of $dQ(T_b)$ are presented in figure 5.

The experiments revealed several essential features and trends:
At the beginning of each wet-wick run, the temperature difference in the gas mixture above and below the evaporator \((T_{v,a} \text{ and } T_{v,b})\), respectively becomes small after a start-up time, due to an intensified vapor circulation. In some cases, a fine mist was observed flowing downwards out of the evaporator.

Each \(dQ(T_b)\) curve in Figure 5 consists of two distinctly different parts. At lower temperatures of the heater, the evaporative cooling contribution \(dQ(T_b)\) increases with temperature. Above a certain transition temperature, \(dQ\) becomes practically independent on both pressure and temperature.

The transition temperatures are higher for mixtures with higher amount of NCG. Figure 6 demonstrates that the transition temperatures coincide with the saturation temperature of C6 at the given absolute pressure in the system, \(T_{sat}(P)\).

In the high-temperature part of each \(dQ(T_b)\) curve, evaporative cooling is weaker at the higher elevation \(h\). In the low-temperature region, no clear correlation of \(dQ\) with \(h\) is observed. The last three features may be explained by the following scenario. In the low-temperature regime \((T_b < T_{sat}(P))\), the wick is fully saturated, and evaporation takes place from the open surfaces of the wick. In the high-temperature regime \((T_b > T_{sat}(P))\), a part of the wick adjacent to the heater block is heated above the saturation temperature of the refrigerant fluid, forming a liquid-vapor front inside of the wick; some evaporation still takes place from the open surfaces of the wick, but the major contribution to vapor generation is inside of the wick, as in conventional loop heat pipes [4].

**Figure 5.** Contribution of the refrigerant evaporation to the total cooling power as a function of heater block temperature, for two evaporator elevations and different amounts of NCG.

**Figure 6.** The points denote the measured pressure as a function of the temperature of the transition between two cooling regimes illustrated in figure 5. The solid line is the saturated pressure of pure C6.

### 5. Conclusions

A concept of passive cooling and dielectric insulation for medium- and high-voltage enclosures is proposed. The feasibility of the concept is demonstrated on a laboratory prototype setup. Two regimes of evaporation from the capillary evaporator have been identified.

### References

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