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Assessment of contribution of EHD to the cooling of power semiconductor devices immersed in dielectric liquids

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Abstract — This paper presents an experimental study of EHD heat transfer enhancement in dielectric liquids, and an evaluation of its contribution to cooling of power electronic components. Heat transfer measurements are carried out in a vertical coaxial electrode system filled with benzyltoluene liquids. The influence of voltage wave shape (AC, DC, impulses), frequency, and liquid viscosity on heat transfer enhancement are measured. The optimal heat transfer occurs for a specific frequency with ac and impulse voltages, and liquids of lower viscosity. Unfortunately, in a typical power electronics module geometry (power diode on a ceramic substrate), almost no improvement of the diode cooling is recorded when this structure is filled with a liquid.

Keywords—heat transfer, power modules, high voltage, high temperature, cooling, electrohydrodynamic (EHD), dielectric liquids.

I. INTRODUCTION

Power modules based on wide band gap (WBG) materials such as SiC or GaN enable operation at temperatures much above 200°C [1]. However, existing encapsulation materials (e.g., silicone gel) cannot be used above maximum continuous temperature of 200°C, limiting the potential of WBG power semiconductors. On the other hand, several dielectric liquids are compatible with high temperature as well as high electric fields, and can constitute a promising alternative to silicone gel. Benzyltoluene are insulating liquids with excellent electrical properties, and have the ability to be used at high temperature as reported in previous papers [2, 3]. In addition to electrical insulation, dielectric liquids within power modules may also contribute to enhance the cooling of semiconductor chips, since EHD-induced liquid motion should occur in their vicinity due to high local electric fields. The objective of this study is first to evaluate experimentally the EHD heat transfer enhancement occurring with conditions close to those existing in a power module: high local electric fields (up to 10 kV/mm), high temperatures (above 150°C) and large temperature gradients. Then, the contribution of EHD to the cooling of a power diode in a typical power module structure will be investigated.

II. EXPERIMENTAL SYSTEM

A. Heat transfer measurement test cell

The test cell consists of vertical coaxial copper electrodes separated by gap $d = 2$ mm as shown in Fig.1. The inner electrode is grounded and contains a heating resistance with a maximum power $P = 230$ W. Its temperature T_i is measured with a thermocouple placed close to the electrode surface. High voltage V is applied on the outer electrode. Its temperature (T_o) is maintained close to room temperature using forced air cooling, and monitored with an infrared thermometer. Without applied voltage, a heater power $P = 45$ W increases the inner electrode temperature (T_i) up to 160°C. A large temperature gradient (60°C/mm) then appears, and heat is carried from the hot inner electrode toward the cold outer electrode by natural convection.

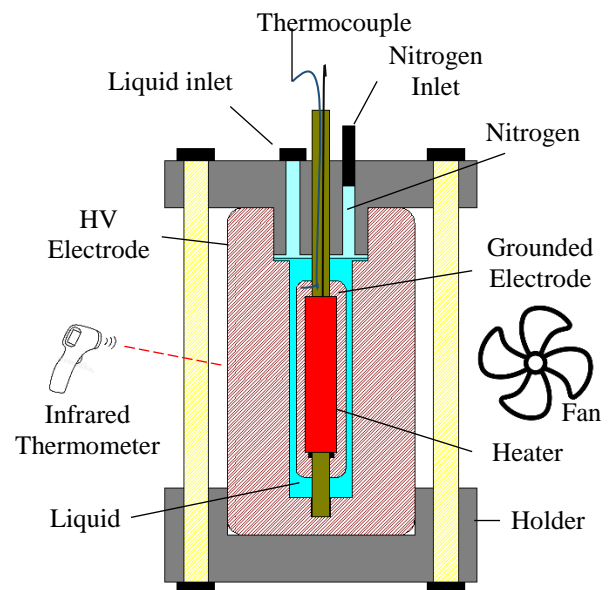


Fig.1. Heat transfer measurement test cell

B. Sample preparation and measurement procedure

The test cell is thoroughly cleaned with acetone. It is then filled with fresh mono-benzyltoluene (BT06) or di-benzyltoluene (refer Table 1.) The cell is then placed under vacuum with inner electrode heated to 60°C for about 2 hours to remove trapped moisture and gases. Dry nitrogen is then introduced above the liquid surface. The heat transfer measurements are done for different voltage types: DC, AC, unipolar rectangular impulses (UI), bipolar rectangular impulses (BI) using a high voltage amplifier TREK 10/10B.

Table 1. Technical data for benzyltoluene liquids at 20°C [4]

Properties	BT06	DBT
Viscosity (mm.s ⁻¹)	5.90	50.09
Thermal conductivity (W.m ⁻¹ .K ⁻¹)	0.130	0.128
Density (kg.m ⁻³)	1008	1044

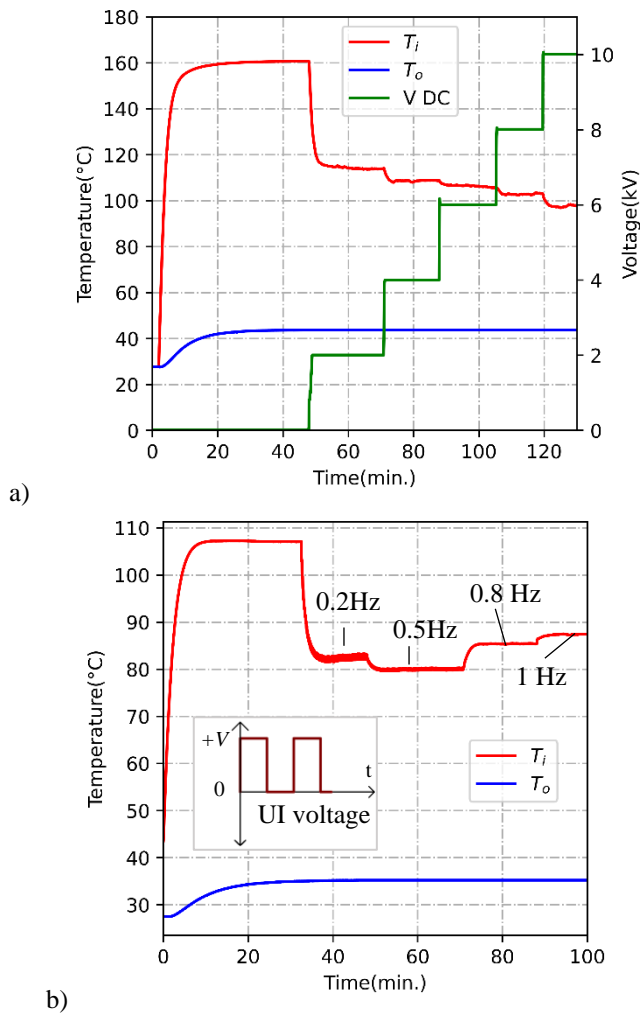


Fig.2. Typical temperature recording in DBT with DC-applied voltage (a, $P = 45$ W), and unipolar impulses UI of different frequencies (b, $P = 25$ W, $V = 1$ kV)

Figure 2 shows typical results obtained with DC and UI impulses of different frequencies. With $V = 0$ V, it takes 30 to 40 minutes to measure stable temperatures T_i and T_o . Interestingly, as soon as V is increased, a sharp drop in temperature T_i occurs for both DC, AC and impulses of different frequencies f (in the range between 0.2 Hz – 1 Hz).

This indicates an increased convective heat transfer resulting from EHD-induced motion of the liquid. The overall heat transfer coefficient h (W.m⁻². K⁻¹) is calculated from the temperature difference $\Delta T = T_i - T_o$, the power P , the surface area A of inner electrode ($A=3167$ mm²):

$$h = \frac{P}{A \Delta T} \quad (1)$$

Preliminary thermal modelling showed that heat losses due to conduction through the inner electrode holder is negligible. Therefore, all the heater power P is carried via the liquid up to the colder outer electrode.

III. RESULTS

A. Heat transfer enhancement with different voltages and frequencies

The heat transfer coefficient h_o (without applied voltage) for DBT is around 100 W.m⁻². K⁻¹ as shown in Fig.3. This value is much greater than the value h_c (60 W.m⁻². K⁻¹) calculated from only the quoted thermal conductivity k of DBT (Table 1). This shows that without field, heat transfer is due to natural convection, and not conduction alone. At $V = 10$ kV under DC, h is enhanced by EHD by 2.6 times compared to $V = 0$ V.

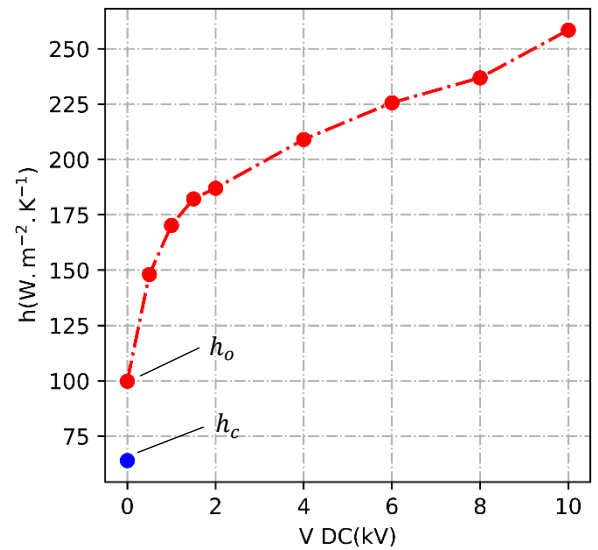


Fig.3. Heat transfer coefficient in DBT (DC, $P = 45$ W)

Fig. 4 shows a comparison of heat transfer coefficient h under DC and AC, UI, BI of different frequencies for a fixed voltage of $V = 1$ kV. With AC, UI and BI an increase of heat transfer versus frequency f is first measured, until it reaches a maximum value at frequency (f_m). The best efficiency is observed with bipolar impulse voltage at 0.5 Hz resulting in 2.6 times increase compared to h_o without voltage. This frequency is certainly related to the time-of-flight TOF of the liquid across the gap. TOF depends on the charge mobility μ :

$$\mu = \frac{d^2}{V TOF} \quad (2)$$

The typical EHD charge mobility in DBT deduced from conduction measurements is close to $\sim 10^{-9}$ (m²/V. s) as

reported in [4], which corresponds to $TOF \sim 2s$ (i.e., 0.5 Hz frequency) at 1 kV and 2 mm electrode gap. It is also observed that at fixed voltage, changing the type of voltage (UI, BI or AC) does not change the frequency f_m at which the maximum heat transfer occurs. With further increase in frequency, hot liquid layers cannot any more cross the gap. Liquid moves back and forth over a limited distance, and the heat transfer efficiency rapidly drops. Above 10 Hz, there is almost no more influence of EHD on the heat transfer at $V = 1$ kV: h becomes equal to h_0 (i.e., with no applied voltage). At very low frequency, h becomes logically close to that measured under DC. Similar results on influence of frequency on heat transfer enhancement have been reported with EHD pump heat transfer apparatus [5]. Unfortunately, the direct observation of the liquid motion was not possible in the coaxial test cell, to better assess these assumptions.

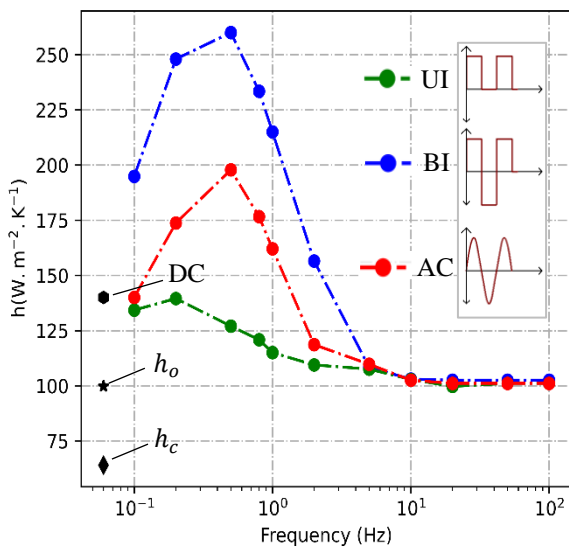


Fig.4. Heat transfer enhancement in DBT with various voltage shapes and frequencies ($V = 1$ kV, $P = 25$ W): UI (0 / 1 kV impulses), BI (-1 kV / +1 kV impulses), AC (1 kV rms voltage)

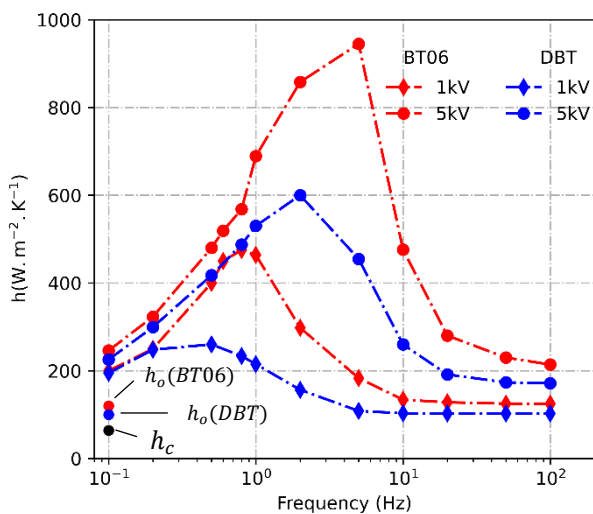


Fig.5. Comparison of heat transfer in DBT and BT06 under bipolar impulse voltage (BI)

B. Liquids with different viscosities

A significant increase in heat transfer enhancement is observed with BT06 compared to DBT (fig. 5). This is due to the 10 times lower viscosity of BT06 (see Table 1). Both liquids have almost the same thermal conductivity (k). At $V = 0$ V, h_0 increases from $100 \text{ W.m}^{-2} \cdot \text{K}^{-1}$ in DBT to $120 \text{ W.m}^{-2} \cdot \text{K}^{-1}$ in BT06, depicting the influence of viscosity on natural convective heat transfer.

Ion mobility is inversely proportional to the viscosity of liquid and does not vary much with voltage [6]. Logically, f_m should be higher for a liquid with lower viscosity, as observed in the comparison between BT06 and DBT at the same voltage (Fig.5). The maximum enhancement of heat transfer h / h_0 with $V = 5$ kV is close to 8 with BT06 ($f_m = 5$ Hz), and 6 with DBT ($f_m = 2$ Hz).

IV. CONTRIBUTION TO COOLING OF POWER SEMICONDUCTOR DEVICE

A typical geometry of power converter module is shown in Fig.6. In order to prevent exceeding the semiconductor maximum temperature, the heat generated by semiconductor devices (diodes/IGBT) has to be extracted as much as possible toward the heat sink, through a metalized substrate with good thermal conductivity (usually a ceramic), also providing electrical insulation between semiconductors and heat sink. Almost no heat extraction occurs through the encapsulation material (typically silicone gel) due to its low thermal conductance. If liquid is used instead of gel, convective heat transfer within the encapsulation could occur, and be enhanced by:

- either an external pump to circulate the liquid;
- or EHD liquid motion within the module

The latter is desirable since it does not involve any external bulky components. We may postulate that the EHD liquid motion could contribute to homogenize temperature above semiconductors, and to favor the heat transfer toward the ceramic substrate.

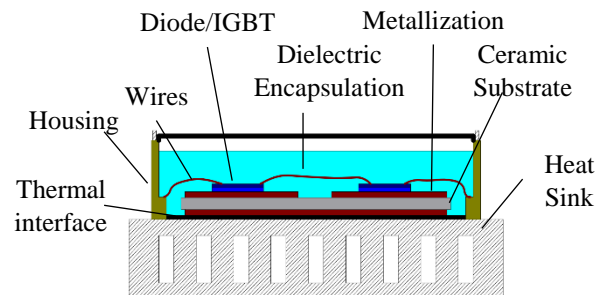


Fig.6. Typical structure of a power converter module

A test sample was prepared with two diodes (ABB5SLY12E1200) soldered on Silicon Nitride (Si_3N_4) ceramic substrate with silver coated copper metallization, as shown in Fig.7. The sample is placed in a metal box made of thin copper sheet, and is clamped on a cold plate, acting as a heat sink with regulated temperature. At interfaces between the substrate and the box, as well as between the box and the heat sink, a silicone pad thermal interface material is used. In

order to estimate the diode junction temperature T_j , a semiconductor thermal analyser (AnalysisTech® Phase12) is used. The junction voltage drops V_j of the diode for a current of 10 mA was used as thermo-sensitive measurement parameter. After calibration up to 135°C, the $V_j = f(T_j)$ plot shows a linear dependence with a slope of -2.2 mV/°C.

During tests, the diode was heated by the application of a regulated current inducing a fixed power dissipation of 25 W, and the temperature of the heat sink was maintained at 26°C. Once the steady state was reached, the temperature was deduced from V_j @ 10 mA. The copper box was either empty, or filled with either BT06 or DBT.

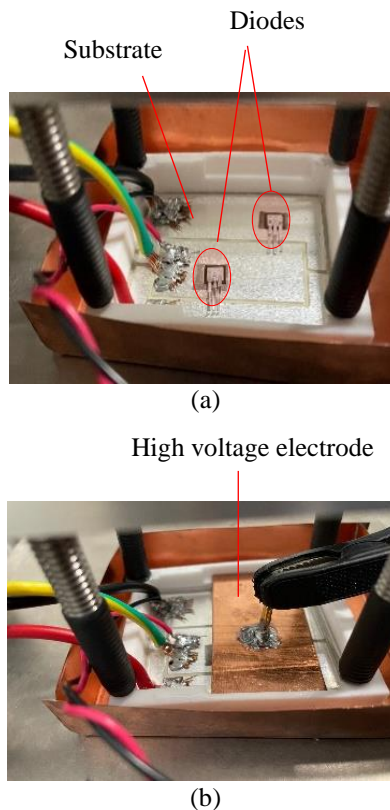


Fig.7. Test setup for studying EHD heat transfer contribution to cooling of diodes; (a). Natural convection in air, (b). In liquid with $V = 1$ kV

With no liquid embedding the diode, the junction temperature (T_j) in open air was 80°C. When the box was filled with DBT or BT06, T_j slightly decreased to 78.5°C, indicating a minor influence of convection in the liquid on the diode cooling.

To check the influence of EHD, a copper plate was added 5 mm above the diode as shown in Fig. 7b, and tied to 1 kV voltage with different shapes (DC, bipolar impulses with frequency from 0.1 Hz to 100 Hz). Whatever the voltage shape used, the measured T_j remained around 78°C, indicating no significant impact of EHD to enhance the cooling of the diode in this geometry. The high thermal conductivity of the Si_3N_4 substrate ($k=85 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and its low thickness (0.3 mm) both induce a low thermal resistance

between the semiconductor chip and the heat sink. This explains why the liquid surrounding the diode provides only a minor contribution to the heat transfer: most of heat is carried toward the heat sink via the ceramic substrate. The thermal convection occurring in the liquid above the diode does not contribute significantly to further cooling it.

V. CONCLUSION

When a dielectric liquid is placed between a hot and a cold electrode inducing a quasi-uniform electric field, the convective heat transfer from the hot to cold electrode can be considerably enhanced by the EHD motion of the liquid, up to about x8 times with optimized conditions in this study. However, in a typical power electronic module geometry, replacing the standard gel encapsulation by a liquid in which EHD motion takes place does not lead to an appreciable increase of semiconductor cooling.

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