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Heat transfer enhancement by an impinging ionic jet in a viscous transformer coolant

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ABSTRACT

The heat transfer performance of an ionic jet impinging on the upper surface of a heated plate is investigated. Ions are injected by a point, set at high voltage. The working fluid is the viscous dielectric ester MIDEL 7131, a refrigerant for power transformers. Different tests are performed on the working fluid, varying the composition, the shape and the polarity of the point, the applied voltage, the point-to-plane distance, and the imposed heat flux. Heat transfer coefficients are augmented up to 310% with respect to natural convection, a higher enhancement than the one obtained with traditional transformer oil. The electrohydrodynamic flow can be generated without significant power input (< 0.01 W in these experiments). Cooling of power transformers can be greatly enhanced by this technique.

1. Introduction

When an electric field is applied to a dielectric fluid, electro-thermal convection may occur under the simultaneous actions of thermal buoyancy and various electric forces [1–2]. The main benefits of employing active heat transfer enhancement and flow control by electric fields are: simple design, fast control and heat transfer modulation, no mechanical parts and vibrations, low power consumption and noise [3]. All these advantages make electrohydrodynamics an interesting technique for efficiently cooling power transformers [4], among many other applications.

Comprehensive reviews of theoretical aspects and experiments in both single-phase convection and pool boiling with heat transfer enhancement by electric fields are given in [5–6]. Particularly, in single-phase convection, heat transfer can be greatly enhanced by applying direct-current electric fields to dielectric liquids. Among the various electrohydrodynamic (EHD) techniques, ion injection from sharp points in an electrically-insulating liquid has already proven to be very efficient in cooling down a wall with negligible power consumption [7–12].

Although high heat transfer rates have been obtained in a variety of different configurations, the process has turned out to be critically influenced by the geometry (shape, radius of curvature, presence of microasperities, orientation), the composition and the polarity of the emitter (i.e. the high voltage electrode), as well as by the chemical, thermophysical, and electric properties of the working fluid [13–14].

The present work deals with an upward-facing heated plate impinged by an ionic jet, leaving from a point electrode. The operating fluid is MIDEL 7131, a highly-viscous ester mainly employed as a refrigerant in power transformers. To the best of the author's knowledge, unlike traditional transformer oil (for which heat transfer was augmented of 1.9 times by the ion injection process [15]), this liquid has never been tested in electrohydrodynamic heat transfer enhancement experiments.

2. Theory

A sufficiently high DC electric field (on the order of $10^6 \div 10^7$ V/m) in the proximity of a sharp electrode produces ions of the same polarity as the emitter through complex electrochemical reactions [16]. The created free charge, entraining the adjacent neutral molecules, induces a motion directed toward the facing grounded electrode, capable of augmenting the heat and mass transfer coefficients on its surface, as shown both experimentally and numerically [17–20]. In terms of thermo-fluid-dynamic behaviour, an analogy can be drawn between submerged impinging jets and the EHD-induced flow and an EHD Reynolds number of the ionic jet can be properly defined [7,21]. The similarity is clearly shown by heat transfer surface maps obtained by liquid crystal thermography [22–23].

The injection strength is controlled by the high-field electrochemistry of the metal/liquid interface [24]. In a non-polar, insulating liquid, electrochemical properties are determined by the extrinsic molecules having high electro-donor or electro-acceptor qualities. These impurities have a strong influence on the rate of ion formation. Also, the rate easily changes over a wide range by changing the concentration of an impurity [25].

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On the contrary, polar molecules can dissolve a great variety of species and are more likely to take part directly in the chemical reactions. In this way, they turn out to be almost insensitive to the concentration of any particular impurity, and the emission of ions is more likely to reach stable rates. As a drawback, polar molecules require larger power consumption, owing to their higher electrical conductivity. In fact, for a small increase of permittivity above the value of 2, the resistivity can drop off many orders of magnitude [16], and Joule heating losses within the dielectric may become relevant at high voltages.

3. Experimental apparatus

To evaluate the performance of an ionic jet in terms of heat transfer enhancement, a proper experimental apparatus has been built, allowing a high-voltage point electrode to be easily mounted perpendicularly to a grounded, heated plate at an adjustable distance.

3.1. Working fluid

The fluid employed in this experimental campaign is the nonpolar synthetic ester, named MIDEL® 7131 and produced by M&I Materials Ltd. (Manchester, UK). MIDEL 7131 is a halogen-free dielectric insulating fluid for transformers, tap-changers, and electrical control equipment. It is not classified as hazardous, thanks to its low toxicity, and is compatible with all insulating materials used in conventional transformer construction. It has a high moisture tolerance (playing an important role in enhancing the life of the cellulose transformer insulation) and very good lubricating properties. In terms of fire resistance, MIDEL has high flash and fire points; this, coupled with a slow heating rate due to its high specific heat and thermal conductivity, gives the liquid an extremely-high resistance to ignition. As for the environmental properties, MIDEL is non-water hazardous and readily biodegradable (99% after 28 days). In the case of ground spillage, it is converted naturally into water and carbon dioxide. Besides, it has a low vapor pressure under operating conditions. It appears as transparent yellowish.

The main physical properties of the liquid are reported in Table 1. Particularly notable are its low thermal coefficient of expansion, its good heat transfer properties, comparable with mineral oil, and its excellent dielectric properties. Besides, MIDEL, unlike mineral oil, has a dielectric strength that is not affected by humidity.

3.2. Test specimen

The liquid fills a transparent polycarbonate resin (Lexan®) vessel, for which the main elements are illustrated in Fig. 1. The inner dimensions of the pool are 130 (height) × 200 × 170 mm^3. The stainless steel plate is 113 × 109 mm^2, with a 5-mm thickness. It is placed horizontally and is uniformly heated from below by two electrical resistance heaters.

Table 1
MIDEL® 7131 physical properties (when applicable, taken at 20 °C).

Property	Value
Relative dielectric permittivity	3.2
Electrical conductivity [S/cm]	$2 \cdot 10^{-13}$
Transformer breakdown voltage, according to IEC 60156 [kV]	75
Flash point [°C]	275
Fire point [°C]	322
Auto-ignition temperature [°C]	438
Pour point [°C]	−60
Density [kg/m^3]	970
Kinematic viscosity [cSt]	70
Dynamic viscosity [cP]	68
Specific heat [kJ/(kg·K)]	1.88
Thermal conductivity [W/(m·K)]	0.144
Prandtl number	888
Volumetric thermal expansion coefficient [1/K]	$7.24 \cdot 10^{-4}$

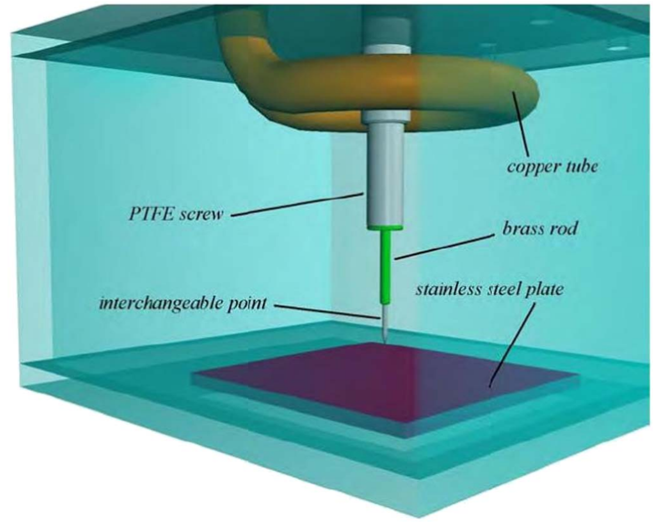

Fig. 1. Schematic of the experimental apparatus.

Seven type-T thermocouples are stuck on the lower side of the plate, in the narrow strip left between the two heaters, as shown in Fig. 2. Two more thermocouples are put inside the pool at about mid-height, to determine the bulk temperature of the fluid. Each thermocouple is connected to a zero-point reference junction and has an overall accuracy of ± 0.2 K. Water coming from a thermostatic bath flows inside the copper tube in the upper region, which functions as a heat sink.

A 60-mm-thick layer of thermal insulator covers the lower face of the vessel. Three type-T thermocouples are mounted at different locations within the insulator for detecting heat losses, which have been negligible for the entire campaign. The brass rod supporting the point is inserted in a PTFE (Teflon®) screw, which can move along its axis, fixing the distance between the high-voltage electrode and the grounded plate.

A DC reversible-polarity high-voltage power supply can impose up to 28.5 kV on the brass rod and, consequently, on the emitter. A picoammeter measures the current passing through the fluid, on the order of 10^{-7} A, with a relative accuracy of 0.4%. The instrument is protected against an incidental electrical discharge, as illustrated in Fig. 3.

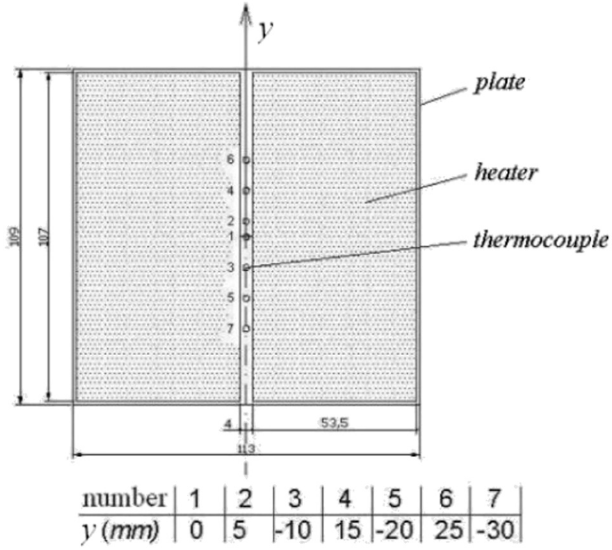

Fig. 2. Thermocouples' position under the plate (the distances are expressed in mm).