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Experimental and numerical study of cooling efficiency of a channel cooling with EHD flows

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A combined numerical and experimental study was conducted on a model channel cooling system utilizing forced air convection and auxiliary electrohydrodynamic (EHD) flows generated by a corona discharge. Geometric parameters of the channel and the power supplied to the devices generating the cooling flows were varied. For the given conditions, the range of effective use of EHD flows was demonstrated, and a non-linear relationship between the channel wall temperature and the power of the corona discharge generating the EHD flow was revealed.

Keywords: Electrohydrodynamics (EHD); Electric wind; Plasma turbulator; Channel cooling systems.

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Introduction

The current trend in electrical engineering development is characterized by a steady growth of the speed of electronic components and their constant miniaturization. This inevitably leads to a significant rise in the heat release rate from the surfaces of active elements. A wide range of cooling systems (CS) are currently used for heat removal: those based on calorimetric and thermoelectric effects, those utilizing heat and mass transfer via electrohydrodynamic (EHD) flow, liquid-based systems, etc. [1, 2]. A typical feature of many forced convection cooling systems is the use of channels through which cooling gas is pumped. To control the flow in the channel and create mixing disturbances to intensify heat exchange between heated surfaces and gas, special inserts in the flow [3] can be used, which, however, add to the aerodynamic resistance. In recent years, researchers have been

focusing on the possibility of using so-called “electric wind” or electrohydrodynamic flow as a secondary flow generator [4–6]. The EHD flow is generated in the gas discharge and is caused by collisions of formed charged particles with gas molecules in a strong electric field. Advantages of its use include the absence of moving mechanical parts, relatively low aerodynamic resistance of the electrodes creating the discharge, and the possibility of creating distributed cooling systems with randomly shaped electrodes that can be integrated into hard-to-reach areas of a cooling system. Their exploitability as part of CSs has been repeatedly demonstrated both by experiments in open air [7] and by simulating in variously shaped channels [8, 9]. At the same time, there is few experimental data on the operation of the combined CS of this kind in the available literature.

The aim of this work was to experimentally investigate the effectiveness of cooling heat-

loaded elements in a channel using both an independent EHD flow generated by a corona discharge (CD) and in combination with forced convection created by a fan.

Setup Description

A structure representing a horizontal channel assembled of ABS plastic (Fig. 1) was used as a model cooling system. The structure's dimensions were $115 \times 55 \times 2d$ mm³, where d is the distance from the plates to the mounting points of electrode for creating EHD flows. Forced convection in the channel was created by a centrifugal fan through a designed power-controlled laminarization unit (0.3–1.2 W; 1–3 m/s in the channel, gas flow rate $m = 0\text{--}2$ g/s). The inner walls of the channel were made of grounded, thermally insulated plates made of polished aluminum. The plates was heated from their ends using film ceramic resistors, with the heating power varying from 10 to 30 W. Temperature of the plates was monitored with type K thermocouples attached at their centers and connected to CENTER 303 instrument (accuracy ± 0.7 °C).

To generate the EHD flow, copper wires with a diameter of 50 μm were stretched

transversely in the middle of the channel. These wires were connected to stabilized negative-polarity high-voltage DC power supply Spellman SL20*2000, with the current in its circuit measured with Fluke 17B+ multimeter, which allowed for estimating the average CD power P_{CD} . The wire-to-plate distance (d) and wire-to-wire distance (L) could be varied in the range of 6–10 mm.

The fan and heating resistors were powered from stabilized, controlled DC power supplies. Heating power was adjusted to maintain temperature of $T_0 = 100$ °C at the plate center under conditions of natural convection without EHD flow. The temperature of the air injected into the channel was 22 °C with 40 % humidity.

As part of the experiments, the temperature drop relative to steady-state values, $\Delta T_{CD} = T_{vent} - T_{comb}$, was recorded. It was defined as the difference between the plate temperature under forced convection, T_{vent} , and under its combination with EHD flow, T_{comb} . Values were read off at various combinations of corona discharge power P_{CD} , fan flow rate m , and different channel widths d . To determine the effectiveness of EHD flow application, the ratio of the temperature drop to the consumed CD electrical power, $\Delta T_{CD}/P_{CD}$, was calculated.

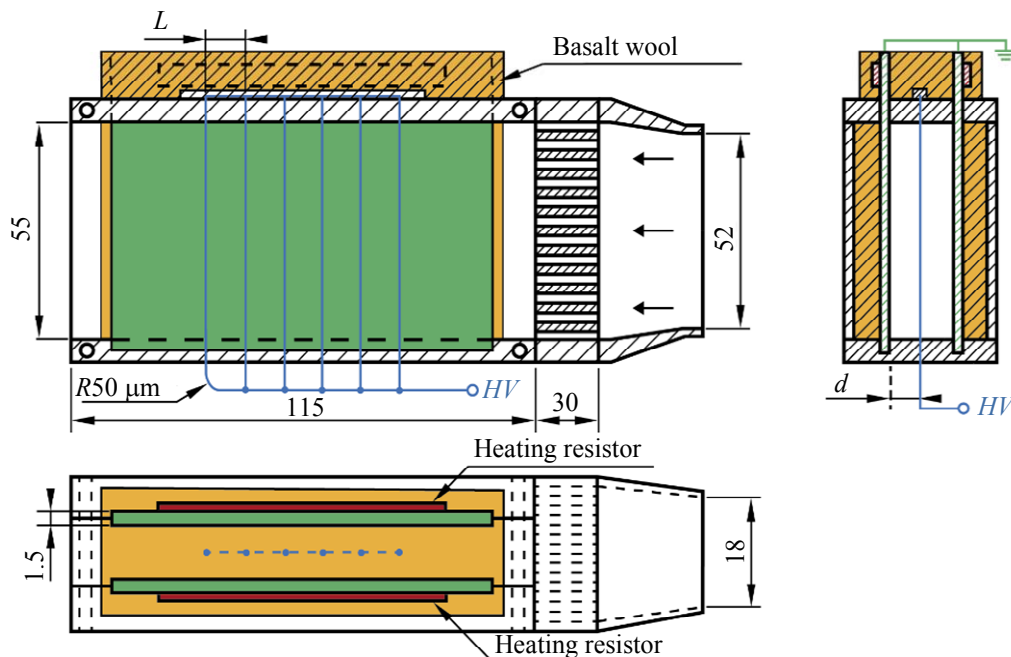


Fig. 1. Schematic of the experimental cooling channel featuring forced convection (shown with arrows) and the capability for generating EHD flows (heating resistors shown in red, plate anodes in green, wire cathodes in blue)

Key results of the parametric study are shown in Fig. 3. The increase in the additional cooling temperature ΔT_{CD} as a function of corona discharge power is shown to correspond to a squared relationship, which is consistent with the current-voltage characteristic of the discharge recorded during the experiment.

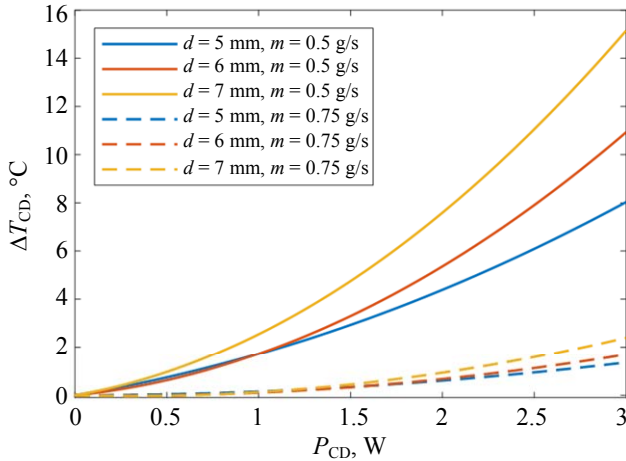


Fig. 3. Calculated curve of temperature drop ΔT_{CD} of the cooled plates vs. corona discharge power for various channel widths d and volumetric flow rates m .

As can be seen from the curves in Fig. 3, the flow velocity is the determining parameter. At a mass flow rate of 0.75 g/s, the energy contribution of bulk forces to the total power of mass transfer is insufficient to have a significant influence on the temperature distribution, and the magnitude of ΔT_{CD} remains relatively small. In the case of a lower flow rate equaling to 0.5 g/s, a pronounced increase in additional cooling (rise of ΔT_{CD}) is observed for all investigated distances between the wire and the aluminum plate (5, 6, and 7 mm): as the gap increases, the channel expands, the average velocity decreases, and cooling efficiency grows.

The spatial distributions of temperature and velocity fields derived from the calculation also showed that, within the parameter range under consideration, the “blocking effect” [4] is practically absent: the vortex structures formed

by the discharge do not lead to noticeable disruption of the through-flow.

Experimental Results

Figure 4a shows the curve of steady-state temperature drop ΔT_{CD} after corona discharge ignition vs. its power P_{CD} for the fixed fan volumetric flow rate $m = 0.8$ g/s. It can be noted that the EHD flow demonstrates the highest efficiency in the range of low CD power values (up to 0.5 W) under the studied conditions, which is consistent with the calculated results. Subsequently, the temperature drop changes over to saturation, and increasing the CD power become impractical.

The maximum ratio of the temperature drop achieved during cooling by the EHD flow to the power consumed for its generation, calculated across the entire dataset for different forced convection flow rates m and channel widths d (Fig. 4b), supports the conclusions about the necessity of ensuring that EHD flow bulk forces are sufficient to change heat and mass transfer processes near heated surfaces, which will intensify heat exchange most effectively. At the air flow rate around 0.8 g/s, it is possible to achieve a temperature reduction of 30-40 °C per 1 W of electrical power input into CD.

However, several contradictions can be found in the simulation results. Channel width d has a relatively weak and non-systematic influence on the ΔT_{CD} values recorded during the experiments at fixed air flow rates m . Furthermore, the saturation effect of ΔT_{CD} is not reproduced in the calculations, with P_{CD} increasing. It can be assumed that this may be related to both gas heating by intense CD [12] and development of conditions for the formation of stagnant zones near heated surfaces [4]. This calls for a more detailed reproduction of the channel's geometric features, operation of the pressure fan, and CD burning conditions.

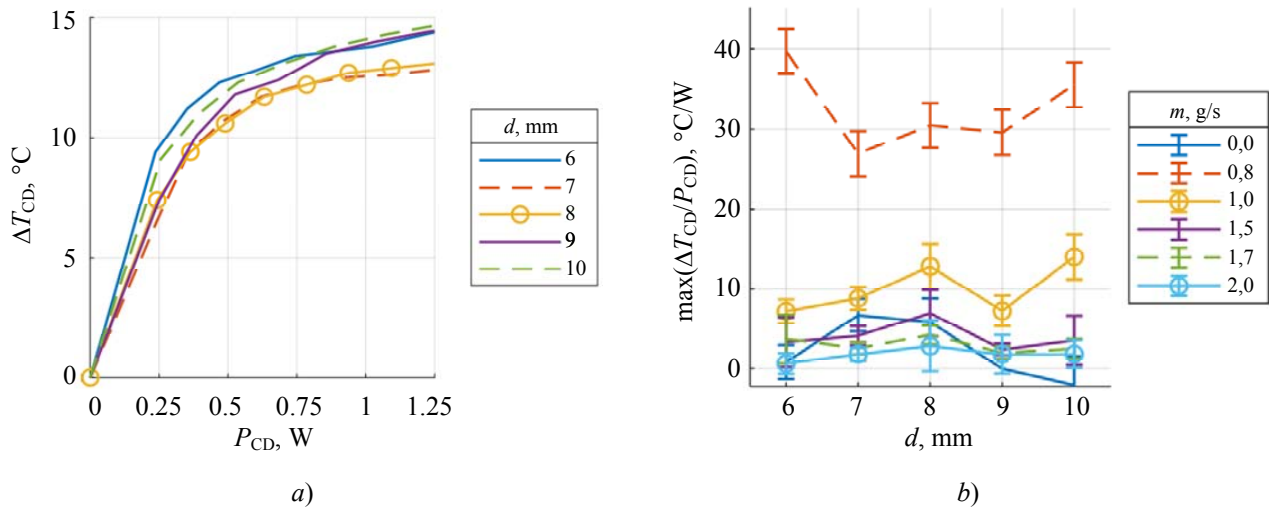


Fig. 4. Temperature drop ΔT_{CD} vs. CD power P_{CD} for various channel widths d at fixed fan flow rate $m = 0.8$ g/s (a) and maximum $\Delta T_{CD}/P_{CD}$ ratio at various d and m (b)

Conclusions

The study performed to calculate the effectiveness of cooling using EHD flows in a rectangular channel with forced air convection has shown that the application of EHD flows is energy-efficient provided that the energy contribution of the generated bulk forces is sufficient to modify the main flow. Experimental results revealed a complex dependence of the channel wall temperature reduction on the channel's geometric parameters and EHD flow power, which may be related to air heating

processes within the discharge or development of a “blocking effect”. The obtained data will be used for further development of a combined cooling device utilizing EHD flows.

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