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Submitted via email to Карпова Наталья n.karpova@spbu.ru and Чирков Владимир Александрович v.chirkov@spbu.ru

Regarding: Review of PhD thesis prepared by Albert Vladimirovich Gazarian
Thesis Title: Numerical and Physics-Related Problems in the Development of single-phase electrohydrodynamics heat removal systems
Specialization 1.3.13 — Electrophysics, electrophysical installations

The PhD Thesis is devoted to developing numerical models and multiple experimental studies of single-phase EHD flows for different heat transfer systems using dielectric medium. Specifically, the research focuses on the development of a coupled experimental and computational methodology to advance surface charge injection function estimation and is applied to different electrode configurations, electrode materials and dielectric fluids and their temperature dependence. The charge injection function methodology is then applied to a novel 2D numerical analysis towards the design and experimental verification of an EHD heat exchanger. Finally, a perforated foil-coated EHD pump is developed that is scalable and has high performance compared to best in class EHD pumps in published literature.

The introduction of the thesis outlines the relevance of the topic and clearly presents the research objectives and proposed contributions of the research. The literature review is sufficiently detailed to identify the current state of the art in our understanding of the mechanisms of electric charge formulation and EHD flows and computer simulation methods used to model EHD including a detailed summary of the injection charge formation and the Wien effect. A brief summary of the application of EHD to single phase and two-phase boiling and several experimental studies and numerical investigation of EHD flow is presented. The critical review clearly presents the relevance of the thesis and scientific novelty of the work it defends. Chapter 2 reviews the mathematic models that describe the EHD phenomena including the EHD body force, charge, injection and dissociation and recombination theory with a solid focus on the application to EHD pumps. In addition, the mathematical models of EHD flow and computer modelling with a focus on FEM using the commercial software package COMSOL used in the current research is discussed.

Although studied for over 70 years the mechanics of surface charge injection for the generation of EHD flows are still poorly understood. There is no universal injection function as there is a strong dependence on electrode configuration, electrode material and surface conditions (eg. roughness), dielectric fluid combinations as well as other factors such as impurities, temperature and charge

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accumulation. The current research focuses on the coupling of an experimental study on multiple EHD thermal management system designs to measure dynamic current-voltage characteristics and analogue numerical models to estimate the form of the proposed injection function, a Heaviside step function and its constants. The charge density from the numerical model is then integrated to compare the total current until convergence of the current waveform is satisfied. The numerical flow is then compared to PIV measurements and similarities in flow pattern and velocity scales were successfully verified. Combining the experimental and numerical findings, the candidate quantified the applicability of his injection function estimation methodology and the proposed Heaviside equation through comparison of the flow structure and current-voltage characteristics for several systems. Two key questions from the proposed methodology are regarding:

1) The hysteresis effect. What are the physics behind this effect, is the decrease in voltage really linear or is there and effect of non-uniform charge accumulation affecting the results. What about the effect of flow due to the positive voltage cycle?
2) The investigation into the “Plane-six wire-plane” configuration with nichrome wires was inconclusive as the 100 and 150um wires tested were “poorly described” by the injection function estimation developed from the 50um system even though the AISI 303 stainless steel configuration estimation was successful. In the former case, was the nichrome wire sourced from the same supplier, material tested for oxides, roughness measured?

Overall, the research has direct applicability in a number of engineering applications that can take advantage of the proposed method of establishing a surface charge injection function for a range of applications including EHD pumps, controllable EHD heat exchangers and phase change material (PCM) based thermal storage systems. In fact, the Heaviside step surface charge injection function proposed by Mr Gazarian has been successfully adopted by one of my PhD students for the latter application of PCM thermal storage.

In Chapter 2.3.2 the velocity field validation was presented, and the PIV technique used to measure the velocity was discussed, it was noted that borosilicate glass hollow microspheres were used as visualizing particles. Further, concentrations not exceeding 0.15 g/l based on the work of Daaboul [86] (who used SiO_2) were selected. I recommend more detail regarding the selection of the seed particle and size be included in the manuscript. How did the density and dielectric constant (ε~4.6) of the seed particles compare with the dielectric fluid used in this study (ε~2.1 to3)? The densities are also different by as much as 20%. How were gravitational and dielectrophoretic effects determined to be negligible? Was a study done on the effect of particle concentration in your fluids?

The results of the numerical simulations are presented in Chapter 3. Initially, the simulation focuses on a 2D representation of the blade design (Figure 2.15) which in the experiments appear to have curved edges and there are edge effects in the guard region likely leading to three dimensional flows and non-uniform charge injections. How was this addressed in the comparison of experimental and integrated

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numerical total current waveforms? Further, how was the temperature uniformity of the dielectric fluid from a single thermistor embedded in the plane surface electrode assessed. During the elevated temperature dependence studies how were heat losses addressed, the temperature difference between the dielectric fluid and surroundings were as high as 40°C.

I believe that Mr Gazarian has successfully developed an adoptable methodology for estimating the surface charge injection function and the Heaviside function seems appropriate although the focus should likely be on the positive voltage application as hysteresis and reverse modulation paths requires further investigation. I agree further study of this hysteresis effect could provide “additional information about the peculiarities” and potentially new verification approaches to the non-uniform charge accumulation. Although further work is needed to understand the effect of materials, such as in the case of the nichrome wires, the findings and conclusion presented by Mr Gazarian are well verified through the application of the approach to subproblems two and the assessment of EHD flow through the five-electrode heat exchanger, presented in Chapter 4.

\Finally, Chapter 5 presents the design of a EHD pump with the primary contribution of charge formation based on the Wien effect. The study included the selection of the appropriate heat transfer fluid based on the previously discussed low and high voltage conductivity tests with dodecane doped with 1ml of Span 85 surfactant ($\sigma_0 = 8 \cdot 10^{-9}$ S/m) as selected fluid. Two configurations of the novel metal-coated dielectric barriers pair design with drilled holes (after several manufacturing approaches were assess) was selected as most suitable electrode system design and numerical analysis was used to study the electric field intensity of dissociation and velocity modules and pressure. Initially, the numerical simulations could not be validated against the experimental electrical and mechanical characteristics. It was then hypothesized this was due to the “discrepancy between the real and theoretical values of the recombination coefficient”. This was numerically tested with a lower recombination coefficient and found to be a plausible reason for the discrepancy. Finally, a comparison was made against previously published EHD pump performance data and the proposed electrode configuration was comparable to the best-in-class EHD pumps. With the relatively simple and expandable fabrication process this makes the proposed design a strong candidate for commercial application.

The thesis overall is clear and without shortcomings. Mr Gazarian has presented new and relevant information regarding surface charge injection function determination and its application to heat exchangers and has proposed, and numerically and experimentally evaluated, a novel high performance Wein based EHD pump. With these accomplishments, he has successfully defended his primary thesis statements presented on page 144 of the thesis.

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I believe that this work has scientific novelty and provides an original contribution to knowledge and should thus be considered acceptable for publication and the partial fulfilment of the Ph.D degree completion of Mr. Albert Vladimirovich Gazarian. The thesis and published peer reviewed journals present evidence of rigour and introduced the appreciation for the wider field of scholarship. The thesis was well written and provides a clear and concise examination of important scientific and engineering phenomena relevant to the Specialization 1.3.13 — Electrophysics, electrophysical installations. The degree should be awarded for the thesis with some very minor revisions as suggested above and that we can discuss during the defence.

Yours Sincerely,

James S. Cotton, Ph.D., P. Eng.,
Professor