Liquid-Phase Flow Distribution Control in Meso-Scale with Directionally Reversed Electrohydrodynamic Conduction Pumping Configuration

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***Abstract*—Electrohydrodynamic (EHD) conduction pumps generate pressure to drive dielectric liquids via the electrical Coulomb force exerted on the space charge within heterocharge layers in the vicinity of the electrodes. EHD conduction pumping can be applied to enhance and control mass and heat transfer of both isothermal and non-isothermal liquids as well as two-phase fluids. It also shows its potential as an active control technique of flow distribution for multi-scale systems in both terrestrial and microgravity environment. Single-phase liquid flow distribution control based on EHD conduction pumping operating in the same direction as the mechanically generated main fluid flow direction has been previously investigated. This study experimentally examines its capability in actively controlling liquid-phase flow distribution with directionally reversed EHD conduction pumping configuration and focuses on how the formation of heterocharge layer and thus EHD conduction pumping mechanism would be affected by the upstream flow velocity. The working fluid is refrigerant HCFC-123. The experimental results indicate that the reversed pumping direction configuration of EHD conduction pump is more effective than the same pumping direction configuration, for example, in terms of initiating the flow divergence between the active and the inactive branches. This is due to the heterocharge layers alteration when the EHD conduction pumping pressure generation opposes the mainstream flow.**

I. Introduction

Efficient pumping and control of the working fluid is a critical requirement for heat transport devices, especially for meso- and micro-scale cooling system used in various applications, such as aerospace components and power electronics. Due to the advances in microelectronics, innovative heat transport systems must be developed to handle heat loads in small scales, while incorporating desired characteristics such as low power assumption, low cost, and rapid and smart redistribution of flow to localized hot spots. Flow distribution based on electrohydrodynamic (EHD) conduction pumping is a suitable method to address the above challenges [1].

EHD conduction pumping has been previously studied in details by several researchers. Atten and Seyed-Yagoobi [2] were the first to theoretically show that EHD conduction pumping is capable of generating significant pressure head and liquid flow. Yazdani and Seyed-Yagoobi [3] studied the effects of unequal positive and negative charge mobility on the heterocharge layer structure and generated flow with symmetric and asymmetric electrode designs. Experimental studies of EHD conduction pumping in macro-scale by Jeong and Didion [4] and in meso- and micro-scale by Pearson and Seyed-Yagoobi [5,6] have showed that the EHD conduction pumping mechanism could be used as an effective technique for generating pressure and fluid flow in single- and two-phase heat transport devices. Pearson and Seyed-Yagoobi [6] investigated pumping liquid within a two-phase loop that contains a microchannel evaporator with an EHD micropump. Additional EHD electrodes were embedded within the evaporator, which could be energized separately from the adiabatic pump. The effect of these embedded electrodes on the heat transport process, flow rate, and pressure in the micro-evaporator and on the two-phase loop system is characterized. The reverse effect that phase-change has on the EHD conduction pumping phenomenon is also quantified in the study. Chirkov et al [7] investigated the characteristics of EHD pump of dissociation type for low and high voltage ranges. They presented the computer simulation results for a single section of EHD conduction pump with and without taking into account the enhancement of the dissociation rate under the action of the strong electric field. Their numerical analysis showed that the enhancement of the dissociation rate could lead to the reversion of EHD flow direction with increasing voltage. Mahmoudi et al. [8] investigated the static pressure generation of a micro-scale conduction pump using three different dielectric liquids; 10-GBN Nynas and Shell Diala AX transformer oils, and N-hexane. They also performed a numerical simulation to further verify the experimental results. Kano and Nishina [9] examined the arrangement of microscale electrode patterns assembled in the EHD pump and concluded that the effect of the deviation between the upper and lower electrode patterns strongly affected the static pressure, while the asymmetric electrode configuration slightly affected the static pressure. Yan et al [10] investigated the characteristics of an EHD impinging dielectric liquid jet in blade-plane geometry. They observed two patterns of electrohydrodynamic velocity profiles of jet when the applied high voltage varied. They also measured electric current with particle image velocimetry and observed two electrical current regimes according to the potential difference. Recently, Patel and Seyed-Yagoobi [11] developed a meso-scale, active two-phase flow heat transport device driven solely by EHD conduction pumping, which was also utilized in the current study, and determined its heat transport capacity. Their experimental results led to a new and improved understanding of net EHD conduction pressure generation. Dryout recovery was achieved in meso-scale for an EHD-driven two-phase flow heat transport system.

Feng and Seyed-Yagoobi [12] were the first researchers who studied the capability of EHD conduction pumping as an active way to control liquid phase flow distribution in a two parallel branch loop. Utilizing an EHD conduction pump in one branch, they successfully controlled liquid phase flow distribution in macro-scale. The EHD conduction pump, once energized, was able to redistribute the flow in the two branches, resulting in higher flow rate in the branch containing the EHD conduction pump and retarding or even completely stopping the flow in the other branch. Feng and Seyed-Yagoobi [13] then applied EHD conduction pumping to a two phase flow distribution system in macro-scale. They investigated EHD conduction pump for active thermal control of the parallel heat exchanger, instead of the existing passive solutions, in a convective experimental apparatus with HCFC-123 as the working fluid. The EHD conduction pump was installed at the entrance of one branch line of the convective apparatus. Their experimental work showed successful control of dielectric liquid/vapor flow distribution between two parallel branch lines utilizing an EHD conduction pump up to a certain mass flux level and vapor quality level under adiabatic condition.

Recently, Yang et al. [14] experimentally and numerically examined isothermal liquid flow distribution control among two parallel tubes (1mm in diameter) utilizing EHD conduction pumps in meso-scale. Liquid flow distribution control in terms of redistribution of equal initial flow and recovering from a maldistribution of flow with EHD conduction pumping was successfully demonstrated in meso-scale. The numerical simulation results showed reasonable success at predicting the system's behavior. Yang et al. [15] then extended the previous work by experimentally investigating the two-phase flow distribution control between two meso-scale parallel evaporators downstream of each pump in each branch and they concluded that an EHD conduction pump could effectively control the two-phase flow distribution between the two parallel meso-scale evaporators and facilitate the recovery from dry-out condition in two-phase system. Talmor et al. [16] experimentally characterized the performance of an EHD conduction driven, single phase flow distribution system for parallel micro-channels. Their results showed that EHD conduction driven flow distribution is still effective in a micro-scale system, and has comparable performance in terms of mass fluxes to similar systems at larger size and thus confirmed the potential for effective EHD conduction pumping driven thermal control systems in micro-scale. In all of the above mentioned studies, the EHD conduction pumping was operated in the same direction as the mechanically generated main flow stream.

Sinnamon [17] was the first researcher who demonstrated the successful control of flow distribution between two parallel lines using the EHD pump in two configurations: the first configuration oriented the EHD pump such that the net pumping forces acted in the same direction as the flow velocity and the second configuration oriented the EHD pump such that the net pumping forces acted in the direction opposite to the flow velocity. For the second configuration, increasing the main flow velocity enhanced pressure generation rather than suppressing it, contrary to the first configuration. Based on the comparison of results from the two flow distribution tests, He concluded that the second configuration was more effective than the first configuration for increasing flow in one line.

This study is an extension of the work by Yang et al. [14 and 15] except that the EHD conduction pump is operated in the opposing direction. Two different scenarios are considered for this purpose: alteration of uniform flow distribution and flow maldistribution correction. Its capability of actively controlling the flow distribution is examined in terms of the value of applied potential for initiation of flow divergence or flow equalization, the complete suppression of flow in the active branch, and the flow rate difference between the two branch lines when the applied potential is at its maximum allowed value. The comparison of experimental results with those achieved with the same EHD pumping direction configuration is also provided in order to investigate the effect of upstream flow velocity on the formation of heterocharge layer and EHD conduction pumping mechanism which was briefly discussed in [14]. A qualitative explanation for the better performance of EHD conduction pumping in the reverse mode is also given.

II. Experimental Setup and Procedure

A. Experimental Setup

The existing EHD conduction pump driven single-phase liquid flow distribution control experimental setup operated under the same EHD pumping direction configuration [15] was modified by simply reinstalling another identical EHD pump in branch 2 in a reverse mode as shown in Fig. 1 and only one EHD pump was activated for a given test. The fact that identical EHD pumps were utilized allowed for the two branches to be similar in dimensions. As the electrodes in both EHD pumps were flush with the tube wall, the directionality did not affect the dynamic flow resistance.

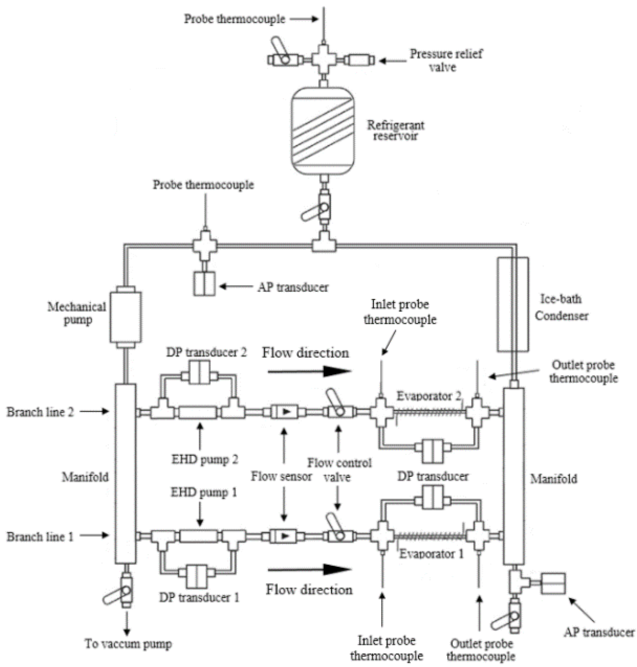

Fig. 1. EHD conduction pump driven liquid flow distribution control experimental setup

The copper evaporators and condenser stayed idle for liquid phase study. Refrigerant HCFC-123 was used as the working fluid and its properties are given in Table 1 [18-20]. The entire setup was evacuated to 500 mTorr over a time period of one hour and HCFC-123 was then allowed to enter the experimental setup until it was fully filled. National Instruments PCI 6024E, USB-6009, USB-6211 and USB-9219 data acquisition system were used to acquire experimental data along with an NI LabVIEW Virtual Instrument software program.

TABLE 1: PROPERTIES OF LIQUID REFRIGERANT HCFC-123 AT 25°C AND 1 ATM [18-20]

Physical Properties	HCFC-123
Chemical Formula	CF3-CHCl
Boiling Point at 1 atm	27.85 °C
Density	1463 kg/m^3
Thermal Conductivity	0.08 W/m·K
Viscosity	0.456 mPa·s
Electrical Conductivity[20]	4.7×10^{-11} S/m
Electrical Permittivity[20]	42.43×10^{-12} F/m

The systematic errors associated with all measurement devices are listed in Table 2. The differential pressure transducers had a range of 0-860 Pa with an accuracy of ±0.25% of the full scale range, and the absolute pressure transducer had a range of 0-140 kPa with the same accuracy as the differential pressure transducer. The flow sensors had a range of 0-80 ml/min with an accuracy of ±10% of the measured value and a repeatability of ±1.5% of the measured value. The high voltage power supply was used in the range of 0-1.5 kV with an accuracy of ±1% of the full scale range plus ±1% of the voltage setting and a repeatability of ±0.1% of the full scale range. The current was in the range of 0-100 µA with accuracy and repeatability in the same percentage values as the voltage.

TABLE 2: SYSTEMATIC ERRORS OF ALL MEASUREMENT DEVICES

Measurement	Maximum systematic error
Temperature	±0.2°C
Differential Pressure	±2 Pa
Absolute Pressure	±350 Pa
Flow Rate*	±0.3 mL/min
Voltage of HV Power Supply	±30 V
Current of HV Power Supply	±2 µA

* Unlike other quantities, flow rate error is based on maximum measured value during the experiment and not the full scale range of the device.

B. Electrohydrodynamic Conduction Pump Design

The electrodes design of EHD conduction pumps used in the current study is the same as the ones used in previous studies of Patel et al. [21 and 22] and is shown in Fig. 2. The electrodes and spacers dimensions are given in Table 3.

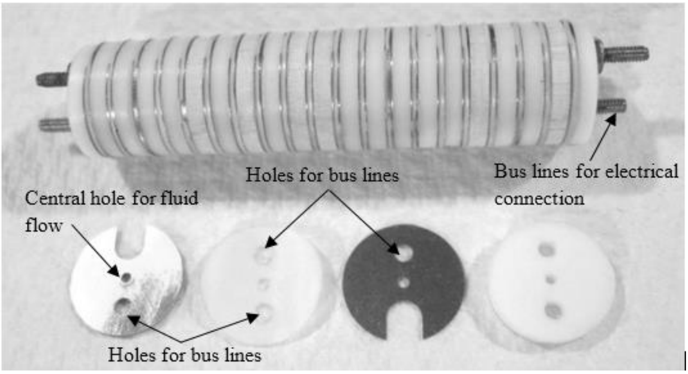

Fig. 2. Assembled EHD conduction pump with 20 electrode pairs and individual electrodes and spacers [21 and 22]

TABLE 3: EHD CONDUCTION PUMP ELECTRODES AND SPACERS DIMENSIONS [21 AND 22]

Component	Thickness
Narrow electrode	0.127 mm
Narrow spacer	0.127 mm
Wide electrode	0.381 mm
Wide spacer	1.588 mm

C. Experimental Procedure

All the liquid phase flow distribution experiments discussed herein can be classified into two categories: initially uniform flow redistribution cases and flow maldistribution correction cases. For both categories, the liquid flow distribution was regulated by either activating the same direction EHD pump (installed in branch 1, see Fig. 1) such that the flow in the active branch was facilitated and the flow in the inactive branch was suppressed, or by activating the reverse direction EHD pump (installed in branch 2, see Fig. 1**Error! Reference source not found.**) in order to oppose the main flow stream, enhancing the flow in the other inactive branch (i.e., branch1). The voltage applied to the EHD pump for all cases was gradually increased from 0V to 1.5kV in increments of 100V. After each increment, the system was allowed to settle until no measurable changes were observed in the recorded flow rate and pressure measurements for at least 30 seconds. The upper limit of the applied voltage to the EHD conduction pump was set to 1500V, due to the maximum electric field that could be applied on the working fluid without initiating breakdown, and potential failure of the EHD conduction pump when exceeding this voltage.

III. EXPERIMENTAL RESULTS

A. Flow Redistribution

For all flow redistribution cases, the initial flow rates in both branches were adjusted to be equal. Flow distribution control with the activation of reverse EHD conduction pump was examined in this study and compared to those of the EHD pumping operating in the same direction.

The measured steady state flow rates in both branches are shown in Fig. 3 for an initially equal flow distribution of 0.5 mL/min, 1 mL/min, and 2 mL/min in each branch. As shown in Fig. 3, for 0.5 mL/min case, the flow rates began to differ between the active branch 2 and inactive branch 1 immediately after a 100V of voltage was applied. The measured flow rate in active branch 2 became smaller than zero at 1000V and kept further decreasing as higher voltages were applied, indicating that flow from the main loop entered only the inactive branch and partially circulated back through the active branch as fluid always flows thorough the path with minimum pressure drop which was the active branch in this case. At an applied voltage of 1500 V, the flow rate difference between active and inactive branches reached a maximum, which was 1.8mL/min.

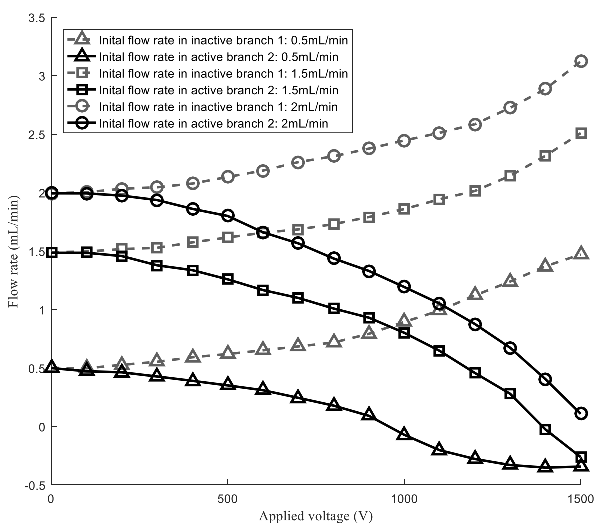

Fig. 3. Measured flow rates in both branches for the reverse EHD pumping direction configuration (0.5 mL/min, 1.5 mL/min, and 2 mL/min case)

The incipient voltage for flow rate divergence between two branches was postponed to 200V when the initial flow rates were increased to 1.5 mL/min and 2 mL/min in each branch. The complete suppression of flow in the active branch 2 was also observed for 1.5 mL/min case, but it was no longer possible for 2mL/min case. As the initial flow rates in both branches were increased, it required higher pressure generation by the EHD conduction pump in order to completely stop the flow in the active branch, the reverse flow would not be observed if the EHD conduction pump could not generate enough pressure and flow power for the corresponding initial flow rate, which was 2 mL/min in this case. The flow rates separation between two branches are summarized in Table 4**Error! Reference source not found.** with total flow rate of both branches at an applied voltage of 1500V. A maximum of 3.01 mL/min of flow rate separation was achieved for an initial flow rate of 2 mL/min in each branch. The differences between initial and final total flow rate of both branches for 1.5 mL/min and 2mL/min cases are related with the increased pressure load on the mechanical pump in the main loop. Considering the Poiseuille's law (the liquid flow in both branches is predominately laminar), if the initial total flow rate is divided into two branches equally, the pressure loss will be one half of that of a single branch receiving the total flow rate. This means the pressure load on the mechanical pump increases as all flow was redirected to the inactive branch, and therefore the total flow rate can no longer be maintained.

TABLE 4: FINAL FLOW RATES DIFFERENCE BETWEEN TWO BRANCHES AND TOTAL FLOW RATE OF BOTH BRANCHES

Initial flow rates in each branch	Initial total flow rate	Final flow rates difference	Final total flow rates
0.5 mL/min	1 mL/min	1.81 mL/min	1.01 mL/min
1.5 mL/min	3 mL/min	2.77 mL/min	2.25 mL/min
2 mL/min	4 mL/min	3.01 mL/min	3.23 mL/min

Additional experiments were conducted to determine the limit of the reverse EHD conduction pump being used to diverge the flow as an active flow distribution control mechanism. Measured flow rates in both branches for cases of initially equal flow distribution of 5 mL/min, 8 mL/min, 10 mL/min and 12 mL/min in each branch are shown in Fig. 4. The corresponding applied potential for initiating flow divergence were 500V, 700V and 900V for 5 mL/min, 8 mL/min and 10 mL/min case, respectively. It is clear that the influence of EHD conduction pump on the flow distribution control became weaker as the initial flow rates increased. A higher flow rate required a higher applied potential to the EHD pump to initiate flow divergence between the two branches. At about 12 mL/min in each branch, the EHD pump considered in this study was not able to influence flow distribution even at the maximum applied potential of 1.5 kV.

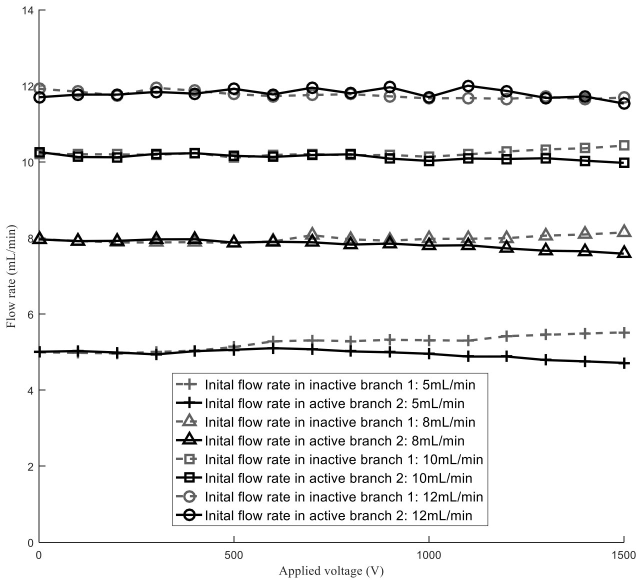

Fig. 4. Measured flow rates in both branches for the reverse EHD pumping direction configuration (5 mL/min, 8 mL/min, 10 mL/min and 12 mL/min case)

Control experiments were conducted for comparisons of measured flow rates in both branches between activating the reverse direction pump and activating the same direction pump, which are shown in Figs. 5 and 6 for initial flow rates of 0.5 mL/min and 2 mL/min. It can be seen in these figures that the same direction EHD pumping allowed for more flow on the branch where EHD pump was installed and reduced the flow on the other branch, whereas the reverse direction EHD pumping allowed for more flow on the branch with no EHD pumping and reduced the flow on the branch where EHD pump was installed.

The incipient voltage for the onset of flow rate difference between two branches for the same pumping direction configuration was about 400V for 0.5 mL/min case and was further postponed to 700 V for 2 mL/min case, while those values were not affected significantly for the reverse pumping cases. It is clear that the reverse pumping direction configuration was more favorable to initiating flow redistribution than the same pumping direction configuration. The final flow rates separation with both pumping directions are similar for 0.5 mL/min case, whereas for 2 mL/min cases, a much larger final flow rates difference could be achieved with reverse EHD pump, showing that the reverse pumping direction configuration can be utilized to attain a higher maximum flow rate separation.

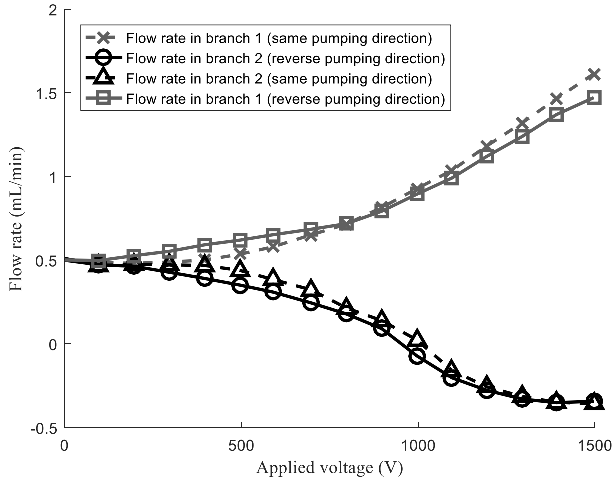

Fig. 5. Comparison of measured flow rates in both branches between the two pumping direction configurations (initially equal flow distribution of 0.5 mL/min in each branch)

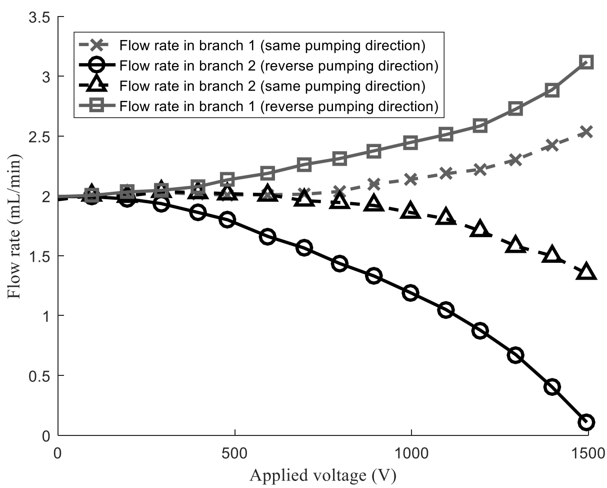

Fig. 6. Comparison of measured flow rates in both branches between the two pumping direction configurations (initially equal flow distribution of 2 mL/min in each branch)

More significant influence the reverse pumping direction configuration had on flow distribution control can be further explained with the comparison of measured differential pressure across EHD conduction pumps sections for both pumping directions that are illustrated in Fig. 7**Error! Reference source not found.**. For all the tests, the upstream pressure of EHD pump minus the downstream pressure was used as the measured differential pressure. It should be pointed out that the absolute value of measured pressure was used for comparison as it was negative and decrease with applied voltage of EHD pump for the same pumping direction cases and was positive and increase with applied voltage for the reverse pumping direction cases. The negative pressure difference leads to suction of more liquid into the active branch for the same pumping direction cases, whereas the positive pressure difference hinders the flow from entering the active branch for the reverse pumping direction cases. In either case, it is the pressure generated by the activated EHD conduction pump that regulated the flow distribution between the two branch lines.

The non-zero measured differential pressure in Fig. 7 have a good agreement with the incipient flow divergence showed in Figs. 5 and 6, it was at 400V and 700V applied voltages for 0.5 mL/min and 2 mL/min cases for the same pumping direction configuration and was almost immediate for the reverse pumping direction cases. The delayed flow divergence effect for the same pumping cases was explained in detail in the study of Yang et al. [15]. The difference of incipient flow divergence between the same and reverse pumping directions can be attributed to the effect of flow directions on the interior flow condition within the EHD pump as well as the EHD conduction pumping mechanism. Once the EHD conduction pump is activated, the flow condition inside its inner channel is very different than elsewhere as the velocity profile near channel wall induced by EHD pump are superimposed to main flow, resulting in a higher velocity close to the wall for the same pumping direction and a lower velocity near the wall for the reverse pumping direction. The higher velocity causes higher flow resistance of the same pumping direction and impairs the capability of EHD pump of regulating the flow. The opposite effect of the reverse pumping direction strengthens its influence on the flow control.

This difference in flow condition also manifest itself in the aspect of the amount of space charges in the heterocharge layers that form near the walls of the EHD pump’s electrodes. The net space charge density depends on the ratio between the electric relaxation time and the transit time of ions across the gap between the electrodes [23]. For the reverse pumping direction, the flow velocity in the heterocharge layers is reduced, resulting in longer ion transit time and thus higher net space charge density. Coulomb force associated with space charge density is therefore increased and the EHD pump becomes more effective. The decrease in flow resistance inside the EHD pump and increased Coulomb force generation combine to make the reverse pumping direction more efficient. A numerical study is currently being conducted to investigate these effects quantitatively.

The trend of change in flow rate in the active branch of reverse EHD pump is another factor for its favorable performance as it kept decreasing with applied voltage, whereas for the same pumping direction configuration, the flow rate kept increasing in the active branch. Lower flow rate in the active branch of reverse EHD pump results in lower flow resistance and, in turn, strengthen its influence on the inactive branch. It is concluded that the higher space charge density within the heterocharge layer, thus higher Coulomb force and pressure generation, combined with lower flow resistance in the active branch, makes directionally reversed EHD conduction pumping a better pumping configuration.

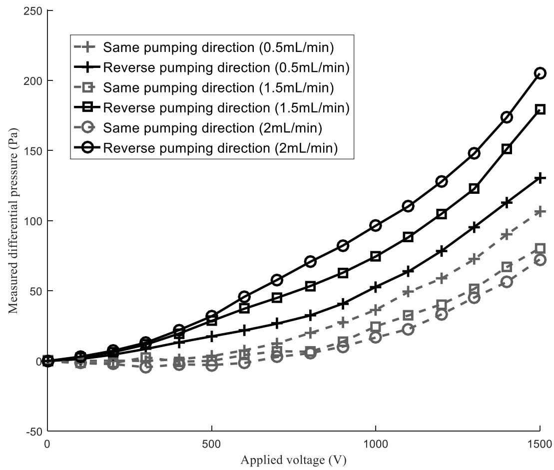

Fig. 7. Comparison of measured differential pressure across EHD conduction pumps in the active branch between the two pumping direction configurations (0.5 mL/min, 1.5 mL/min and 2 mL/min cases)

Fig. 8**Error! Reference source not found.** illustrates the current and power consumption levels of the EHD conduction pump in the active branch for both pumping direction configurations. The current and power consumption of EHD conduction pump increased with applied voltage but always stayed below 110 µA and 0.3 W, respectively.

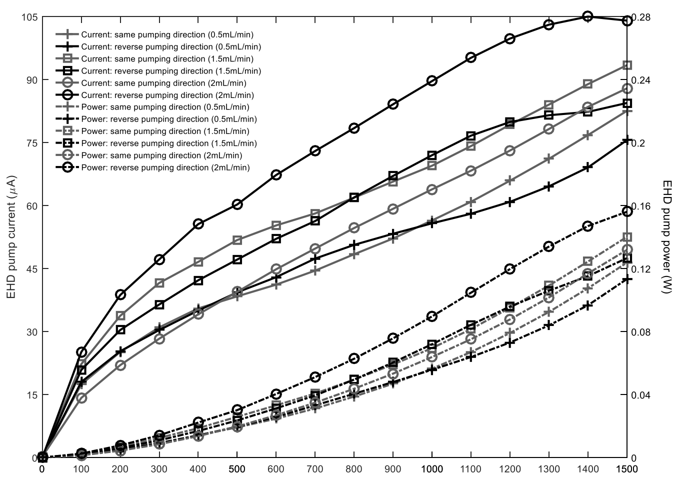

Fig. 8. Comparison of EHD pump current and power in the active branch between the two pumping direction configurations (0.5 mL/min, 1.5 mL/min and 2 mL/min cases)

B. Flow Maldistribution Correction

The reverse pumping direction configuration was also examined with its capability of equalizing an initially maldistributed flow, and then compared with the same pumping direction configuration. Two different initial maldistributed flow distributions were tested: 1.15 mL/min and 1.75 mL (0.6 mL/min difference) and 0.55 mL/min and 2.35 mL (1.8 mL/min difference), the total flow rate was kept at 2.9mL/min for better comparison and the experimental results are shown in Figs. 9 and 10 respectively.

For all the cases, the flow rate difference between the two branches diminishes with the activation of the EHD pump either by facilitating the flow in active branch 1 for the same pumping direction configuration or by reducing the flow in active branch 2 for the reverse pumping direction configuration. A comparison of Figs. 9 and 10 shows that as the difference in initial flow rates increased, the flow rate equalization between the two branches was postponed as it required higher pressure generation of EHD pump with higher applied voltage to overcome larger flow rate difference, it was achievable for an initial flow rate difference of 0.6 mL/min case, but unfulfilled for 1.8 mL/min case which shows the limit of EHD pump being able to equalize the flow rates in two branches from an initial maldistribution condition for both pumping direction configurations.

Similar to flow distribution cases, compared to the same pumping direction configuration, an almost immediate control on the initial maldistributed flow was realized with the reverse pumping direction configuration and therefore the flow equalization between two branches was advanced. The more favorable inner flow condition inside the EHD conduction pump and lower flow rate in the active branch in the reverse pumping direction configuration accounts for these better performance.

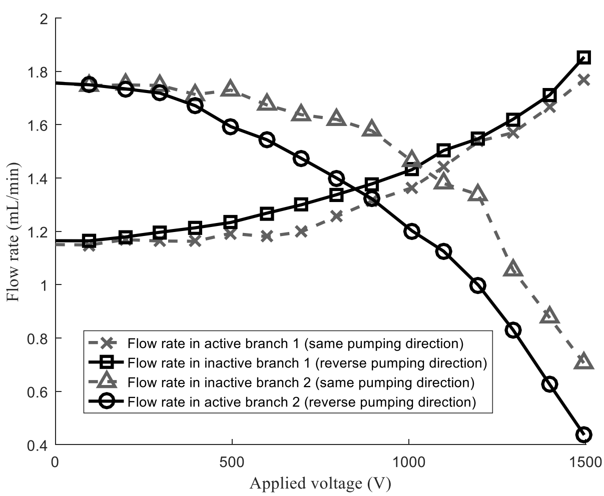

Fig. 9. Comparison of measured flow rates in both branches between the same pumping direction and the reverse pumping direction (initially maldistributed flow distribution of 1.15 mL/min and 1.75mL/min)

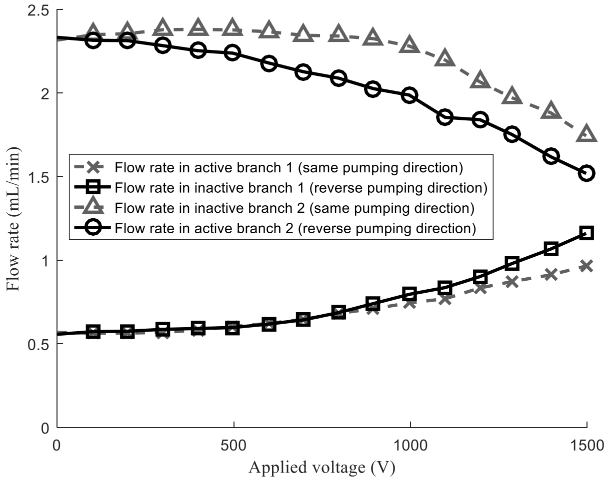

Fig. 10. Comparison of measured flow rates in both branches between the same pumping direction and the reverse pumping direction (initially maldistributed flow distribution of 0.6 mL/min and 2.3 mL/min)

IV. Conclusion

Liquid-phase flow distribution control in meso-scale with reverse EHD conduction pumping was experimentally investigated. Experimental results showed that the same direction EHD pumping allowed for more flow on the branch in which EHD pump was installed and reduced the flow on the other branch, while the reverse direction EHD pumping allowed for more flow on the branch with no EHD pumping and reduced the flow on the branch in which EHD pump was installed. The results also showed that the reverse pumping direction configuration was more effective than the same pumping direction configuration: 1. Almost immediate influence on the flow distribution with lower applied voltage on EHD conduction pump. 2. Advancing the flow equalization for the maldistribution correction cases. 3. Attaining larger flow separation between the active and inactive branches. The better performance of reverse EHD conduction pumping was believed to be related to the favorable heterocharge layer development which is also affected by the main flow including its direction with respect to the pumping direction. A quantitative numerical study of comparison between the same and reverse pumping direction configurations is in progress and will be provided in the near future.

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REFERENCES

[1] Seyed-Yagoobi, J., 2005, “Electrohydrodynamic pumping of dielectric liquids,” J. Electrostatics, vol. 63, pp. 861-869.

[2] Atten, P. and Seyed-Yagoobi, J., 2003, “Electrohydro-dynamically induced dielectric liquid flow through pure conduction in point/plane geometry”, IEEE Trans. Dielectr. Electr. Insul., vol. 10, pp. 27-36.

[3] Yazdani, M. and Seyed-Yagoobi, J., 2014, “Effect of Charge Mobility on Dielectric Liquid Flow Driven by EHD Conduction Phenomenon”, Journal of Electrostatics, vol. 72, pp. 285-294.

[4] Jeong, S.I. and Didion, J., 2008, “Performance characteristics of electrohydrodynamic conduction pump in two-phase loops,” J. Thermophysics and Heat Transfer, vol. 22, No. 1, pp. 90-97.

[5] Pearson, M.R. and Seyed-Yagoobi, J., 2011, “Experimental study of EHD conduction pumping at the meso- and micro-scale”, J. Electrostatics, vol. 69, pp.479-485.

[6] Pearson, M.R. and Seyed-Yagoobi, J., 2013, “EHD Conduction Driven Single- and Two-Phase Flow in Micro-Channels with Heat Transfer”, ASME Journal of Heat Transfer, Vol. 135, pp. 101701-1 to 10.

[7] Chirkov, V.A., Stishkov, Yu.K. and Vasilkov, S. A., 2015, "Characteristics of Electrohydrodynamic Pump of the Dissociation Type: Low and High Voltage Ranges", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 22, pp.2709-2717.

[8] Mahmoudi, S.R., Adamiak, K., Peter Castle, G. S. and Ashjaee, M., 2011, “Study of Electrohydrodynamic Micro-pumping through Conduction Phenomenon”, IEEE Trans. on Industry Applications, vol. 47, No. 5.

[9] Kano, I. and Nishina, T., 2013, "Effect of Electrode Arrangements on EHD Conduction Pumping", IEEE Trans. on Industry Applications, vol. 49, No. 2.

[10] Yan, Z., Louste, C., Traore, P. and Romat, H., 2013, "Velocity and Turbulence Intensity of an EHD Impinging Dielectric Liquid Jet in Blade-Plane Geometry", IEEE Trans. on Industry Applications, vol. 49, No. 5.

[11] Patel, V. and Seyed-Yagoobi, J., 2015, “A Mesoscale Electrohydrodynamic-Driven Two-Phase Flow Heat Transport Device in Circular Geometry and In-Tube Boiling Heat Transfer Coefficient Under Low Mass Flux”, IEEE Transactions on Industry Applications, Vol. 137, pp. 041504-1 to 9.

[12] Feng, Y. and Seyed-Yagoobi, J., 2006, “Control of Liquid Flow Distribution Utilizing EHD Conduction Pumping Mechanism”, IEEE Transactions on Industry Applications, Vol. 42, No. 2, pp. 369-377.

[13] Feng, Y. and Seyed-Yagoobi, J., 2006, “Control of adiabatic two-phase dielectric fluid flow distribution with EHD conduction pumping”, Journal of Electrostatics 64 621–627.

[14] Yang, L.,Talmor, M., Shaw, B., Minchev, K., Jiang, C. and Seyed-Yagoobi, J., “Flow Distribution Control in Meso Scale via Electrohydrodynamic Conduction Pumping”. IEEE Transactions on Industry Applications (in press).

[15] Yang, L.,Talmor, M.and Seyed-Yagoobi, J., 2016, “Flow Distribution Control between Two Parallel Meso-Scale Evaporators with Electrohydrodynamic Conduction Pumping”. Proceeding of the ASME 2016 International Mechanical Engineering Congress & Exposition, Phoenix, AZ, USA.

[16] Talmor, M., Yang, L., Larkin, T., Kamat, O., Dancy, T. and Seyed-Yagoobi, J., 2016, “Flow Distribution Control in Micro-Scale via Electrohydrodynamic Conduction Pumping”. Proceeding of 2016 Electrostatics Joint Conference, West Lafayette, IN, USA.

[17] Sinnamon, S., 2009, "Coolant Distribution Control in Satellite Structural Panel using Electrohydrodynamic Conduction Pumping", Master thesis.

[18] DuPont, 2005, DuPont HCFC-123 Properties, Uses, Storage and Handling, DuPont Fluorochemicals, Wilmington, DE.

[19] DuPont, 2005, Thermodynamic Properties of HCFC-123 Refrigerant, DuPont Fluorochemicals, Wilmington, DE.

[20] Bryan, J. E., 1998, "Fundamental Study of Electrohydrodynamically Enhanced Convective and Nucleate Boiling Heat Transfer," Ph.D. Thesis, Texas A&M University, College Station, TX.

[21] Patel, V. K., Robinson, F., Seyed-Yagoobi, J., 2013, “Terrestrial and Microgravity Experimental Study of Microscale Heat-Transport Device Driven by Electrohydrodynamic Conduction Pumping”, IEEE Transactions on Industry Applications, vol. 49, pp. 2397-2401.

[22] Patel, V. and Seyed-Yagoobi, J., 2014, "Long-Term Performance Evaluation of Microscale Two-Phase Heat Transport Device Driven by EHD Conduction." IEEE Transactions on Industry Applications, vol. 50, pp. 3011-3016.

[23] Yazdani, M. and Seyed-Yagoobi, J., 2009, “Electrically induced dielectric liquid film flow based on electric conduction phenomenon,” IEEE Trans. Dielectr. Electr. Insul., vol. 16, No. 3, pp. 768-777.