Electrospray as an Enforcement of Steam Condensation

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***Abstract*— The effect of electrospray produced micro-droplets on the condensation of polar vapors is investigated theoretically and experimentally with the steam condenser. The considered phenomena include the equilibrium charged micro-droplet with the vapor phase and the electrohydrodynamic vapor flow induced by the drift of charged droplets. Experimental investigation of electrospray-supported condensation confirms the significant improvement in the condensation rate.**

I. Introduction

The fundamental problem of condensation on an electrically charged nucleus was intensively researched in the 1970s and 1980s in connection with the matter of atmospheric physics [1,2] and the chemical kinetics of the nucleation [3]. The theoretical treatment has been given in terms of a reduction of the Kelvin effect, i.e., essentially a reduction of surface tension caused by the presence of electric charges. The electric charge was accounted for only by the Coulomb interaction, which produces the surface interfacial (Maxwell-Wagner) polarization that affects the thermodynamic potential of droplets. In principle, this leads to a relative decrease of the water vapor pressure at the surface of the particle; i.e., the evaporation rate of charged droplets is reduced. Only in 2002 [4] was it recognized that the interaction between gas-phase water dipoles and charged droplets actually overrules the surface tension effect in many real applications, while the consideration was mostly directed to the evaporation of droplets.

The present research is related to the effect of charged droplets on the opposite effect, the condensation of steam. It was experimentally demonstrated that water droplets are easily generated on ions [5,6] with an average size of a droplet of ~10 nm. Previously the nucleation of steam on ions and electrically charged nanosized droplets were investigated [7, 8] in terms of dielectrophoretic interaction between the charged droplet and vapor molecules. The developed model predicts the critical size of the nucleus, which depends on the charge density in the droplet as well as on the polarizability of the vapor molecule. The dielectrophoretic interaction of droplets and vapor is presented in terms of additional potential that adds to the evaporation energy barrier on the surface of droplet. Because the dielectrophoretic force depends on the gradient of the electric field, there is a critical radius of a droplet for the dielectrophoretic condensation that defines the biggest droplet, the growth of which is not affected by the dielectrophoretic forces any more.

The investigated problem has the applied engineering aspect related to the process of condensation, which is widely used in power plants (recovery of the working fluid from the vapor), distillation, dehumidification, etc. The supply of vapor molecules to the cold liquid or solid surface by diffusion requires a significant pressure gradient to match the mass flow to the thermal flow for the removal of latent heat. Both of these flows depend on the temperature gradient in the corresponding media: mass flow toward the cold surface depends on the temperature gradient (that results in a pressure gradient) in the vapor phase, and the thermal flux through the cold wall depends on the temperature gradient across the wall. If the temperature behind the cold wall (temperature of cooling media) is defined (for example, by the ambient temperature in the case of dry, air cooling), the temperature on the condensing surface of a wall increases correspondingly. This leads to the elevated temperature (and pressure) of vapor at the input of the condenser. In the case of distillation or other phase-conversion chemical process, this results in the decrement of process productivity. But in the case of traditional, Rankine cycle power plants, the elevated pressure in the condenser directly affects the power conversion efficiency of the turbine, which means that more power will be dissipated without any purpose. This case is especially important for geothermal plants; since geothermal resources are typically located in arid regions of the U.S., an air-cooled heat exchanger is commonly used instead of a water evaporative heat rejection system. Thus, the performance of geothermal power plants is very sensitive to elevation of the ambient temperature. In fact, the plant's output drops to less than two-thirds of the rated capacity during the hotter portions of the year, primarily due to increased condenser pressure, which decreases the energy extraction from the geothermal brine [9].

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II. Concept of Investigation

A. *Analysis of Physical Processes*

The electrostatic enforcement of vapor condensation is based on the synergetic effect of a high-gradient electrical field and the vapor dielectrophoretic nucleation on charged nanodroplets generated by the electrospray atomization. Of course, it is applicable only to polar vapor molecules. Due to the negative dielectrophoretic potential of the droplets, their evaporation is suppressed, which leads to depletion of the vapor phase compensated by diffusion. As it was shown previously [7,8], the energy barrier for evaporation from a charged droplet is increased because of the dielectrophoretic potential of such a droplet. This may be interpreted as the decrement of effective surface tension and, correspondingly, the saturated vapor pressure near the surface is lowered.

Experimental data [7,8] show the ~16% improvement of condensation due to the corona discharge when the nucleation occurs on the ions and all nuclei have the same, single electron charge. If charged droplets are injected by the electrospray, the charge in the single droplet is limited only by the Rayleigh limit, when the electrostatic forces exceed the surface tension forces. In this case the dielectrophoretic potential increases proportionally to the charge in the droplet and correspondingly adds to the latent heat for evaporation of this droplet. Fig.1 illustrates that this increment in the evaporation energy is significant only for small, <10 μm, droplets but the total latent heat for evaporation of these droplets is relatively small. As a result, the dielectrophoretic potential notably affects the stability of small droplets only.

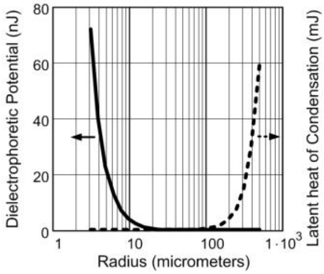


Fig. 1. Dielectrophoretic potential of a droplet (solid line, left vertical axis) compared with the latent heat evaporation of this droplet (dotted line, right vertical axis). Note that the dielectrophoretic potential reaches the significant magnitude for small, less than 10 mm, droplet while the latent heat of condensation notably increases for larger droplets.

The effective radius for the collection of vapor is compared to the radius of a charged droplet in Fig. 2. Similarly to Ref. [4], we defined this effective radius as a distance where the dielectrophoretic potential exceeds kT. Therefore, the effective radius for vapor collection by the dielectrophoresis decreases at elevated temperatures due to the higher energy of thermal fluctuations

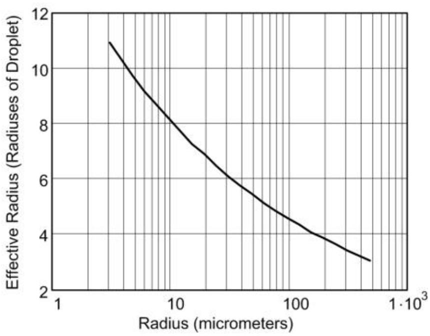


Fig. 2. Effective radius of vapor collection for the droplet charged to the Rayleigh limit. This radius is related to the distance where the dielectrophoretic force creates the centripetal flow of vapor.

The effective radius in Fig. 2 defines the area where the charged droplet affects the vapor. The centripetal dielectrophoretic force works against the diffusion flow and creates the gradient of vapor pressure near the charged droplet. Because the steady state radius of droplet is defined by the equilibrium of evaporation and condensation, the real vapor pressure over the surface of droplet depends on the vapor pressure in the surrounding space.

B. The Electrostatic Model of the Electrospray Injector

If the use of an electrospray injector is considered, the space charge of the electrospray has to be accounted for. Fig. 3 shows results of the field modeling in the FlexPDE environment, where the lagging of electric potential behind the plane of the grounded extraction electrode is limited to a fraction of this electrode radius. Nevertheless, the electric field lines are directed toward the grounded condensing wall.

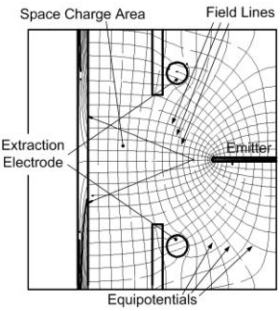


Fig. 3. Map of equipotentials and field lines for the electrospray with extraction electrode. Effective radius of vapor collection for the droplet charged to the Rayleigh limit. This radius is related to the distance where the dielectrophoretic force creates the centripetal flow of vapor.

Fig. 4 illustrates the shielding effect of the space charge carried by the electrospray. The electric current (charge transfer) density is repelled from the axial zone, while the electric field still is directed toward the wall. This phenomenon leads to the expansion of the electrospray; i.e., charged droplets are deposited on a wider area of the condensing wall.

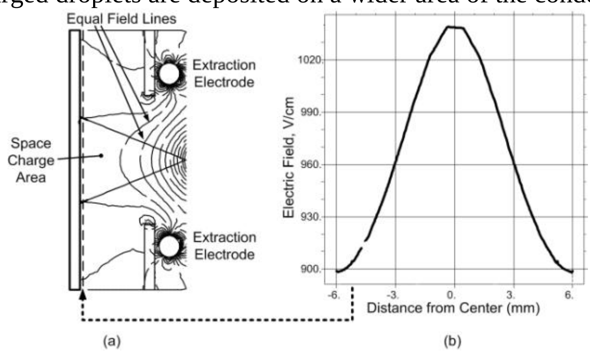


Fig. 4. The effect of space charge on the distribution of electric field during the electrospray: (a) Map of electric field and (b) the distribution of electric field on the target that illustrates the spreading of electrospray due to the space charge in the mainstream of charged droplets.

The practical outcome of this modeling is the possibility to install the electrospray heads relatively close to the target (condensing wall) because the charged droplets will be spread over the wide area, about 2 diameters of the extraction electrode.

III. Evaluation of Electrospray for Injection of Charged Droplets into the Vapor Condenser

To investigate the effect of electrospray charge injection on the steam condensation, two experimental setups were established: the benchtop setup and the upgraded full size industrial condenser. Both setups used the electrospray head design shown in Fig. 5.

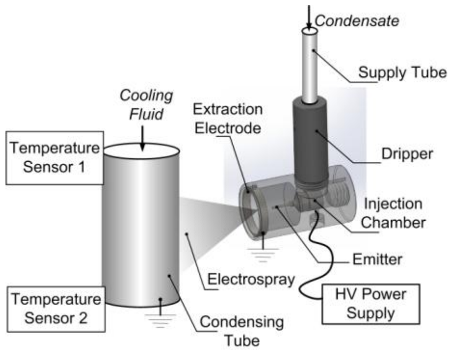


Fig. 5. Design of the electrospray head that implements the tandem scheme — the water from the grounded source is supplied to the electrospray needle at a high voltage through the electrostatic dripper, which uses the voltage difference.

The tandem scheme shown in Fig. 5 allows to use the electrospray with grounded target and condensate (water) supply because the emitter is separated from the supply tube by the electrostatic dripper and the extraction electrode is grounded.

A. Evaluation of Benchtop Setup

The benchtop setup consisted of acrylic chamber with a single copper loop as a condensing tube. The cooling water was pumped at a rate of 50 mL/min, and the difference in temperature in the cooling water before and after the test setup. This allowed for the calculation of the rate of latent heat extraction instead of the condensate collection due to the intensive condensation of steam on walls of chamber. Fig. 6 presents data for this experiment carried out with and without electrospray.

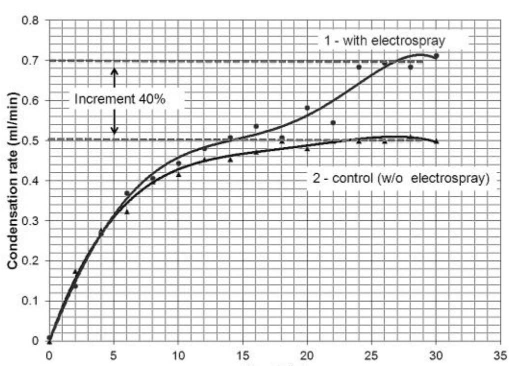
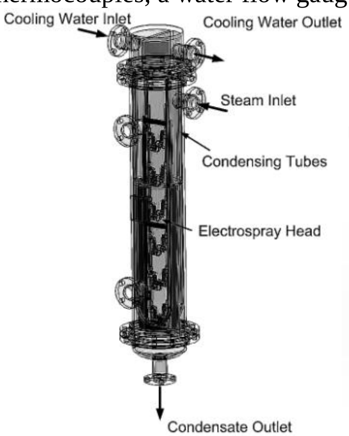


Fig. 6. Evaluation of electrospray for the enforcement of steam condensation. These data are obtained by the conversion of the heat extraction rate.

The time in Fig. 6 was counted after the initiation of steam injection. The initial, transition period is related to the filling of the chamber with steam and the establishment of equilibrium in the steam condensation on the walls of the chamber. The effect of electrospray during the initial transition period (~20 min) is low due to the low humidity in the chamber. The humidity in the chamber slowly increases while the steam displaces air. The steady-state condition shows the 40% increment in the condensation rate.

B. *Evaluation of Modified Industrial Condenser*

To evaluate the performance of the electrostatically enforced condensation in conditions that are maximally close to the real application, the smallest available industrial condenser (12-3/4 in. diameter × 73 in. shell height) was custom ordered from Fulton Systems (Norcross, GA). The customization was related to the number of tubes installed on the cooling water head. The condenser contains four tubular loops (instead of 92!) to allow for the installation of an electrospray fixture between them as shown in Fig. 7. The experimental setup also included a steam generator, model JG1-5A1F from Reimers Electra Steam Inc. (Clear Brook, VA) that provided 1.5 kW boiling power, and a 3 ton capacity chiller AS-3 from Mokon (Buffalo, NY). The chiller supports flow rates from 7.2 to 25 gpm with pressure up to 30 psi (~2 atm). The setup was also equipped with multiple thermocouples, a water flow gauge, and an electronic manometer.



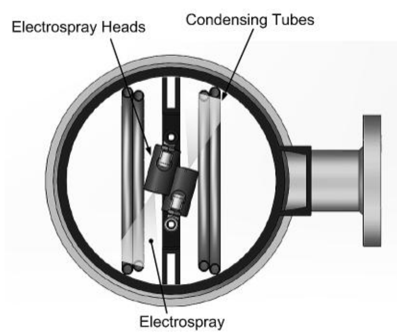


Fig. 7. Engineering design of the electrospray array installed in the steam condenser: (a) 3-dimensional presentation of upgraded condenser; (b) horizontal cross-section of the condenser

Using the capabilities of the setup components, tests were carried out at three flow rates and two temperatures of cooling water as shown in Table 1. To exclude condensation on the walls of the prototype, the control test was run without the electrospray and cooling water for 30 min. The amount of condensate collected (1,125 mL) was subtracted from all test data.

TABLE 1: PARAMETERS USED DURING TESTS

Parameter	Values
Flow of cooling water	126.2 mL/s; 189.3 mL/s; 252.4 mL/s
Temperature of cooling water	10°C and 18.33°C
Initial steam pressure	60 psi
Water electrosprayed in 30 min	75 mL

Fig. 8 shows the average condensation rate achieved in 30 min tests carried with and without the electrospray. To exclude the transition period (~ 15 min), the averaging was applied only to data collected during the last 15 min of test.

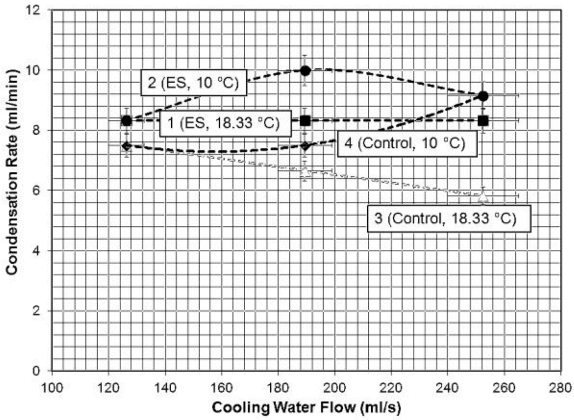


Fig. 8. The condensation rate at varied flows of cooling water: (1) With electrospray, cooling water temperature of 18.33°C; (2) With electrospray, cooling water temperature of 10°C; (3) Without electrospray, cooling water temperature of 18.33°C; (4) Without electrospray, cooling water temperature of 10°C.

In Fig. 8, data in curves 1 and 3 (temperature of cooling water 18.33°C) should be compared, as well curves 2 and 4 (temperature of cooling water 10°C). The decline in condensation rate at the elevated flow of cooling water is attributed to the limited power of the boiler used. In other words, the supply of steam was too weak for the industrial condenser and powerful cooler. As a result, the pressure in the boiler gradually decreased from 60 psi to 5 10 psi over 30 min.

One interesting result is the different behavior of the condensation rate with and without the electrospray upon elevation of the flow rate in the cooling circuit. While the condensation without electrospray increased with the flow rate at the lower temperature (curve 4), there was a clear decrease in condensation if the cooling water was supplied at higher temperatures (curve 3). This is explained by the condensation at lower steam pressure by the colder water. On the other hand, the condensation with electrospray at lower temperature of cooling water (curve 2) shows slight decline with flow >200 mL/s, but elevation with flow rates with lower circulation of the cooling water. The electrostatically enforced condensation at higher temperature (curve 1) practically does not depend on the flow rate of cooling water. We attribute this to the predicted intensified heat flux through the condensing wall due to the electrospray at when the temperature of cooling water is increased (curve 1). The removal of latent heat is completely supported by the cooling at lower temperatures (curve 2) if the flow of cooling water is high enough while the electrospray improves the vapor supply to condensing wall if the natural, diffusion driven vapor flow limits the condensation rate.

Fig. 9 presents the improvement with the electrospray compared to the same conditions but without the electrospray.

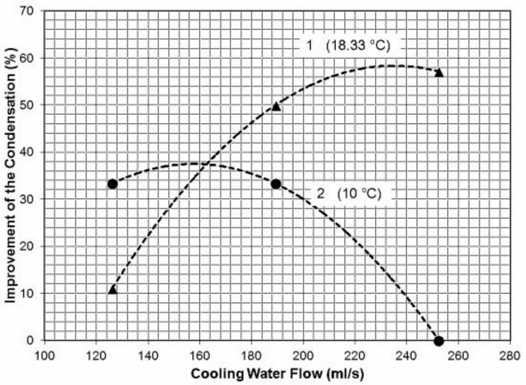


Fig. 9. Improvement of the condensation rate with the electrospray at varied cooling water flows and temperatures of this water: (1) 18.33°C, and (2) 10°C.

This plot clearly shows that the electrospray of charged droplets improves the condensation by ~ 33% at low flow rates of cold cooling water (curve 2), but this improvement disappears with the elevation of the flow rate in cooler. In contrast, the electrospray consistently improves the condensation with the elevated temperature of the cooling water (curve 1), which exactly corresponds to the problem to be solved.

The maximal improvement at the low temperature in the cooler (~33%) is in good agreement with data obtained with the benchtop prototype (see Fig. 6). This is not surprising because both tests were carried out with low pressure of the steam. The maximal improvement at the higher temperature of the cooling water (~57%) is a very inspiring result. It should be noted that a 57% improvement is achieved, compared to the lowered condensation without the electrospray, as seen in Fig. 8, curve 3. The same figure shows that the electrospray compensates for the elevated temperature in the cooler (by 8.33°C or 15°F) if the flow rate in the cooler is sufficient (over 200 mL/s in our prototype) to remove the released latent heat.

Data obtained during the evaluation shows the positive effect of electrospray on the rate of condensation:

- Application of electrospray in the steam condenser improves heat exchange limited by the thermal gradient, but the heat flow should be still dissipated to the environment. As demonstrated by our investigation, the improvement due to electrospray varies from 50% (very hot ambient temperature and insufficient power handled by the cooling system) to nothing (cold environment and powerful cooling system).
- The rate of condensation and removed heat flux increases compared to the same temperature of supplied chilling water and rate of the steam supply while the pressure in the condenser decreases. Because the temperature of exhaust chilling water

increased correspondingly, this should improve the heat exchange with the air if air cooling is used. The intensified condensation leads to a drop in pressure in the condenser that should improve the efficiency of the power plant (increase the pressure difference applied to the turbine).

- The same condensation rate as without the electrospray is achievable at higher temperatures of supplied chilling water. This allows for the stabilization of power plant productivity when the temperature of the ambient air is elevated (during the summer).

IV. Conclusion

The present research proves that the mass flow of vapor by diffusion may be overrun by the directional flow of electrically charged centers for vapor nucleation. This outcome creates three means for the improvement of mass flow: (1) the nucleation of small droplets that depletes (decreases the pressure of) the vapor phase; (2) the Coulomb drift of charged droplets toward the condensing wall, which delivers the already condensed liquid phase and simultaneously creates the drag of the vapor (electrohydrodynamic flow) toward the condensing wall; and last but not least for the condenser in a power plant, (3) the replacement of the pressure gradient needed for the diffusion-driven mass flow by the electrostatically driven flow of vapor towards the condensing wall, which allows the temperature of this wall to increase, and, as a result, cooling fluid temperature to rise. The elevated temperature on the condensing surface supports a higher condensing rate than in a conventional, passive-flow condenser since the discharge of droplets leads to the increase of entropy and, correspondingly, the specific heat capacity in the droplets. Because of this, the discharged droplet is cooled, and it condenses additional vapor near the wall. To support the removal of released latent heat, the temperature on the wall increases. As a result, electrostatic enforcement of condensation allows either for keeping the required condensation rate at the higher temperature of the cooling fluid or for elevating the condensation rate (i.e., lower pressure in the condenser) at the same heat flow through the condensing wall.

References

[1] A.I. Rusanov, "Thermodynamic Theory of Nucleation on Charged Particles," J. Colloid and Interface Science, vol. 68, pp. 32–47, 1979.

[2] M.D. Cohen, R.C. Flagan, J.H. Seinfeld, "Studies of Concentrated Electrolyte Solutions using the Electrodynamic Balance: 1. Water Activities for Single-electrolyte Solutions," J. Physical Chemistry, vol. 91, pp. 4563–4574, 1987.

[3] F.M. Kuni, A.K. Shchekin, A.I. Rusanov, "Theory of Nucleation on Charged Cores: 2. Thermodynamic Parameters of an Equilibrium Nucleus," Colloid Journal of the USSR, vol. 44 (6), pp. 935-941, 1982.

[4] V.B. Lapshin, M.Y. Yablolov, A.A. Palei, "Vapor Pressure over a Charged Drop," Russian J. Phys. Chem., vol. 76, pp. 1727–1729, 2002.

[5] S. Sakataa, T. Okada, "Effect of Humidity on Hydrated Cluster-Ion Formation in a Clean Room Corona Discharge Neutralizer," J. Aerosol Science, vol. 25, issue 5, pp. 879-893, 1994.

[6] M. Alonso, F.J. Alguacil, "Particle Size Distribution Modification During and After Electrical Charging: Comparison between a Corona Ionizer and a Radioactive Neutralizer," Aerosol and Air Quality Research, vol. 8, No. 4, pp. 366-380, 2008.

[7] M. Reznikov, P. Williams, "Corona Discharge in the Steam for Electrostatically Enforced Condensation," Proc. 2012 Electrostatics Joint Conference (ESA, IEJ, IEEE-IAS, SFE), Cambridge, Ontario, Canada, June 12–14, 2012.
[8] M. Reznikov, "The Electrostatically Enforced Condensation Related to Effects of the Corona Discharge," Proc. 2012 Annual Meeting of the Industrial Applications Society of IEEE (Las Vegas, NV, Oct. 7–11, 2012), Session #23, Electrostatic Processes I, presentation 2012-EPC-321, 2012.
[9] D. Bharathan and G. Nix, "Evaluation of an Absorption Heat Pump to Mitigate Plant Capacity Reduction Due to Ambient Temperature Rise for an Air-Cooled Ammonia and Water Cycle," National Renewable Energy Laboratory Preprint NREL/CP 550 30125, 2001.