Electrically enforced condensation related to effects of the corona discharge

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Abstract -- The effect of corona discharge in the steam on the rate of nucleation and condensation of the liquid phase is investigated theoretically and experimentally in means of implementation with the steam condenser for the improved phase-change rate. The considered phenomena include the nucleation of water vapor on mobile charge carriers, the electrohydrodynamic vapor flow toward the condenser wall and the thermodynamics of the charged micro-droplet. The prototype of the device is built and investigated. Obtained results confirm the improvement in the condensation rate.

Index Terms—Corona, Dielectrophoresis, Thermal engineering

I. INTRODUCTION

The phase-change heat exchangers are widely used from miniature heat pipes in notebooks to steam condensers of power plants where the liquefying typically occurs due to the passive thermal exchange. The temperature on the condensing wall is lowered below the dew point and the depletion (due to the condensation) of vapor phase is constantly compensated by the diffusion. Because the mass flow rate (and the carried heat flux) depends on the gradient of vapor pressure, the high thermal flux is achieved by the intensive cooling of condenser that is the energy consuming (in the best case) or even impossible with the air convection cooling at summer time. In fact, the geothermal power 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 that decreases the heat extraction from the geothermal brine to lower the temperature. In general, the air-cooled condensers significantly contribute to the cost of generating electrical power, because of their size, associated capital cost (about 20% to 35% of the total plant cost), and the fan power consumed for the circulation of air. Therefore, any intensification of condensation potentially results in the additional generated power.

The presented work describes the concept of electrostatically enforced condensation, which is developed on base of our previous works in the dielectrophoretic vapor enrichment [1-3]. This concept is based on the dielectrophoretic nucleation of vapor in the high-gradient electrical field of charged droplets generated by corona discharge or electrospray.

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II. THEORY

The electrostatically enforced condensation (EEC) is based on the dielectrophoretic nucleation of vapor on electrically charged centers. These nucleation centers are ions generated by the corona discharge or electrically charged droplets produced by the electrospray atomization. The dielectrophoretic force is directed toward the charged center as shown in Fig. 1.

Because the removal of molecule from the charged droplet requires the additional work against the dielectrophoretic force, the droplet acquires the negative dielectrophoretic potential, which may be interpreted either as the increased latent heat of evaporation or the increased surface tension. As a result, the evaporation of droplet is suppressed that shifts the evaporation/condensation equilibrium toward the condensation and thus decreases the equilibrium vapor pressure if compared to the droplet of same radius and at the same temperature but without the electric charge. The depletion of vapor phase near droplet is compensated by diffusion and charged droplet growth until the dielectrophoretic potential decreases below kT. Because this new equilibrium exists until the droplet carries the electric charge, when charged nanodroplets are electrostatically transferred to the heat exchanger walls and discharged, they start to evaporate. As a result, the local vapor density near the wall exceeds the saturation level of vapor phase over the flat surface of liquid at given temperature and condensation occurs at a higher temperature.
than it would occur at without electrostatic enforcement. This is exactly the desired effect of EEC.

The dielectrophoretic potential of the charged water droplet may be estimated numerically. It is well known that water droplets are easily generated on ions [4] due to the native polarity of water molecules, which have a natural dipole moment $\rho_o = 6.17 \times 10^{-28}$ C·cm. Any particle with a dipole moment, $\rho_o$, if placed in the gradient electric field of magnitude, $E$, experiences the dielectrophoretic force $F_{dp} = \rho_o \nabla E$, directed to the side of the increased field $E$. Polar water molecules drift in the gradient electric field and produce the gradient of vapor concentration. The stable state occurs when the dielectrophoretic drift and local diffusion flows are equal, which leads to the classic Maxwell distribution, $n = n_0 \exp(U/kT)$, where the potential energy, $U$, of a molecule at distance, $R$, from the point charge, $q$, can be calculated by integration of dielectrophoretic force from distance $R$ to infinity

$$U = \frac{\rho_o}{\varepsilon_0} \int_{R}^{\infty} \nabla E \, dr = \frac{\rho_o q}{\varepsilon_0 R^2}. \quad \text{(1)}$$

Therefore, the gradient electric field induces the enrichment of water vapor, $y_l = pR/pv = \exp(U/kT)$ ($kT = 0.026$ eV), near the charged particle or very thin wire electrode. When the vapor density exceeds the saturation level, the nucleation occurs.

If small droplets are not electrically charged, they easily evaporate, as demonstrated by Kelvin’s equation for the saturated vapor pressure, $p_0^d$ near the surface of a drop with radius $R$

$$p_0^d = p_\infty \exp(2\sigma v_l/(N_A kT R)),$$  \quad \text{(2)}

where $v_l$ is a molar volume in liquid, $N_A$ is Avogadro’s number, $p_\infty$ is the pressure of saturated water vapor above a flat surface, and $\sigma$ is the surface tension of water at temperature $T$. The vapor oversaturation (relative to the saturation pressure of vapor over the liquid flat surface) near the small droplet is illustrated in Fig. 2.

Fig. 2 shows that droplets of any size are not stable if proximity to the bulk water surface is close enough for the diffusion of vapor molecules. Nevertheless, in the absence of bulk water surface, droplets coalescence through the vapor phase – small droplets evaporate and locally increase the density of vapor, which leads to the growth of bigger droplets through condensation.

Because of the dielectrophoretic potential of a charged droplet (see Fig. 3), the energy barrier for evaporation from such a droplet is increased, which may be interpreted as the decrement of effective surface tension (see Fig. 4) and, correspondingly, the saturated vapor pressure near the surface is lowered, as shown in Fig. 5.
Therefore, the electric charge significantly, in the range of a few percent, decreases the saturated vapor pressure relative to the neutral droplet of the same size while the surface tension is decreased by less than 1 percent. As a result, while the decrement of saturated vapor pressure does not change the instability of the droplet relatively to the bulk water, the droplets grow until equilibrium with the vapor phase is reached. The drift of the droplet toward the water surface due to the electrostatic force leads to the direct deposit of the condensed phase to the bulk condensate. When a charged droplet reaches the boundary region with the flat liquid surface (for example, the surface of the condenser), it begins to evaporate due to the lower vapor pressure in this region. Therefore, the EEC process allows for highly localized condensation in the volume of vapor, with the subsequent acquisition of water clusters at the condenser surface.

The direct additional deposition of water to the condensate by EEC is limited by density of corona current and effective dielectrophoretic radius of charged droplet, i.e. the distance where the droplet can attract the vapor molecule. This distance may be expanded by the increased charge carried by the droplet. While ions produced by corona carry the single charge, \( e = 1.6 \times 10^{-19} \) C, the electrospray produces droplets with charge, \( q_R \), at which the Rayleigh limit is exceeded and fission occurs

\[
q_R = 8\pi \sqrt{\varepsilon_0 \gamma \cdot r^3}
\]  (3)

Eq. (3) shows that the total charge, \( q_R \), carried by the droplet increases with the droplet radius, \( r \), i.e. larger electrospray droplets bear charge, which significantly exceeds the single ion charge carried by droplets created due to the nucleation of water vapors on ions in the humid air. This is illustrated in Fig. 6, which presents the results of the numeric calculation of the carried charge at varied radius of electrospray droplet that is based on Eq. (3).

It’s not surprising that the bigger aerosol droplets collect the aerosol at the larger distance. Fig. 6 shows that the tenfold increase in the electrospray radius elevated the effective dielectrophoretic radius ~5 times.

\[
F_{dp} = \alpha \cdot E \cdot \text{grad} |E| = \frac{\alpha}{2} \frac{\text{grad}E^2}{\varepsilon_0 R^2} = \frac{2\alpha q^2}{3 \varepsilon_0 R^2}.
\]  (4)

Supposing the threshold value for dielectrophoretic potential, \( \Phi_{dp} \), is equal to \( kT \), the equation for effective dielectrophoretic radius, i.e. radius of sphere, which limit the space around the electrospray droplet of radius, \( r \), where all neutral particulate with radius, \( r_p \), will be collected:

\[
\Phi_{dp} = \int_{r_p}^{r} F(q_r, r_p) \, dx = kT.
\]  (5)

The solution of Eq. (5) accounting for Eq. (4) and supposing the water-based aerosol, \( \varepsilon = 80 \varepsilon_0 \) for R at varied radius of electrospray droplet, \( r \), and radius of aerosol particle, \( r_p \), is presented in Fig. 7.

III. PRELIMINARY EXPERIMENTS

To evaluate the effect of EEC of the steam, we assembled an experimental setup, which utilizes a cooled condenser channel equipped with an array of nine corona electrodes. All of the electrodes were energized to the same positive high voltage, producing a corona current across the condenser channel through which the steam passed on its way through the apparatus. The temperature of the condensing wall was monitored with the thermocouple.

To detect the change in the steady state temperature in the condenser, the measurements were done when the temperature is fully established. Because the efficiency of EEC in this experiment was unknown, the power of thermoelectric cooler was varied and temperature was measured both for applied corona voltage and without the corona voltage. As Fig. 8 shows, the increment of temperature with high voltage applied is systematic, and the absolute difference in temperature increases with the power
applied to the thermoelectric coolers.

The increased efficiency of EEC at very low thermoelectric cooling power (practically negligible at the applied current of 250 mA, while the nominal current is 16 A) demonstrates the enforced heat exchange, with the practically passive exchanger, to the external heat sink.

IV. CONCLUSIONS

The feasibility of developed basic model for the electrostatically enforced condensation is demonstrated by the preliminary conceptual test.

REFERENCES