The Effect of Frequency and Duty Cycle on Heat Transfer and Pressure Drop for Convective Condensation under Pulsed Electric Field

H. Sadek, C. Y. Ching, and J. S. Cotton
Department of Mechanical Engineering, McMaster University, Canada

Abstract—The effect of pulsed electric fields on heat transfer and pressure drop in horizontal in-tube convective condensation has been investigated. In particular, the effect of the frequency and duty cycle of an applied pulse wave between 0 and 8 kV was studied for frequencies in the range 0.5 Hz to 1.5 kHz and for 25 %, 50 % and 75 % duty cycles. The electric field was applied through a central electrode along the centerline of the tube. The experiments were performed for a constant mass flux of 58 kg/m²s and average vapor quality of 45 % which corresponds to stratified flow with the liquid level below the electrode (without EHD). The heat transfer enhancement ratio decreases with an increase of frequency for frequency range less than 60 Hz. Beyond 60 Hz, the heat transfer enhancement remains nearly constant and independent of frequency. The corresponding pressure drop ratio increases with an increase of frequency for frequency range less than 80 Hz. For frequencies more than 80 Hz, the pressure drop decreases with an increase of frequency. The heat transfer enhancement ratio and pressure drop ratio increase with an increase of the duty cycle for a given frequency of the applied signal.

Keywords—Convective condensation, heat transfer, electrohydrodynamics, frequency, duty cycle, flow pattern.

Nomenclature

\[ E \] electric field strength (V/m)
\[ f \] frequency (Hz)
\[ f_c \] electric body force (N/m³)
\[ G \] mass flux (kg/m²s)
\[ T \] temperature (°C)
\[ t \] time (sec)
\[ x \] vapor quality
\[ \varepsilon \] dielectric permittivity (N/V²)
\[ \rho_e \] charge density (C/m³)
\[ \rho \] mass density (kg/m³)

I. INTRODUCTION

Active and precise control of heat transfer and fluid flow is very important in many engineering applications, such as refrigeration, air conditioning, energy, fuel cell and heat recovery systems. Electrohydrodynamics (EHD) is one of the most promising techniques available to control heat transfer and fluid flow. In EHD, the interaction of the applied electric fields with the fluid flows can result in heat transfer coefficients that are several times higher than that obtained by more conventional techniques. EHD can be applied relatively non-intrusively, it is simple in design, non-mechanical, and allows a high degree of local control. The EHD forces induced by the electric fields on the fluid can be expressed as [1, 2].

\[ f_e = \rho_e E - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[ \varepsilon^2 \frac{\partial \varepsilon}{\partial \rho} \right] \]  \hspace{1cm} (1)

The three terms on the right-hand side of (1) represent the electrophoretic, dielectrophoretic, and electrostrictive components of the electric force respectively. The electrophoretic component represents the force acting on the free charge in the presence of an electric field (also known as the Coulomb force). This force is usually dominant for adiabatic single-phase flow. The dielectrophoretic component represents the force due to the spatial change of the permittivity of the dielectric medium as a result of temperature gradients and/or differences in the phases. The dielectrophoretic force is weaker than the electrophoretic force for adiabatic single-phase flow because of the weak dependence of the permittivity of the working fluid on the electric field. However, in two-phase flows such as in convective boiling and condensation, this component can be significant at the vapor-liquid interface due to the large difference in permittivity between the two phases. This force can cause interfacial instabilities and force the liquid with higher permittivity to move to regions of higher electric field. This phenomenon is usually referred to as liquid extraction [3, 4] and can result in a flow regime transition in two-phase flows. The electrostrictive force is caused by both the inhomogeneity in the electric field strength and the variation in the dielectric constant of the medium with temperature and density.

There have been several studies on EHD heat transfer enhancement and detailed reviews are given by [5-7]. The recent work of Singh et al. [8], Gidwani et al. [9], Feng and Seyed-Yagoobi [10], and Sadek et al. [11] investigated the effect of DC electric fields on tube-side convective condensation heat transfer using a concentric wire electrode configuration. Most of the previous studies concluded that applying EHD will enhance heat transfer, and that the augmentation level will decrease with an increase of the mass flux and the quality. Cotton et al. [12], Bryan and Seyed-Yagoobi [13] and Sadek et al. [11] proposed that the heat transfer enhancement is...
due to the flow regime redistribution caused by the induced interfacial electric forces. The flow regimes with and without the applied electric fields were deduced based on the surface temperature profiles along the top and bottom surfaces of the tube.

Most previous research on EHD enhanced tube-side convective condensation has been performed under applied DC voltages. There is no published work examining the effect of different parameters of other waveforms (e.g. frequency, amplitude and DC offset) on flow regime redistributions and therefore heat transfer and pressure drop. Nevertheless, it is thought that using other waveforms (e.g. pulse waveform) can provide a wider range of control with a potential of independent control of the heat transfer and pressure drop compared to an applied DC voltage. This is because more parameters can be manipulated to achieve the required heat transfer with potentially a minimum pressure drop penalty. The objective of this study was to experimentally determine the effect of frequency and duty cycle of high-voltage pulsed electric fields on flow regime redistributions, heat transfer and pressure drop for tube-side convective condensation.

II. EXPERIMENTAL FACILITY

The experimental test facility is a closed loop charged with refrigerant HFC-134a. The main components of the loop are the gear pump, electrically heated sections, water heated section, test section, condenser, and pressurizer along with various measuring devices (see [11] for the details of the experimental facility). The test section consists of a horizontal, single-pass, counter-current heat exchanger as depicted in Fig. 1. The outside surface of the inner tube was instrumented with 12 thermocouples in three equidistant axial locations (4 thermocouples in each location as shown in Fig. 1). A 3.18 mm diameter stainless steel rod electrode was placed along the center of the inner tube to apply the electric field across the annular gap formed by the electrode, which was connected to the high voltage source and the grounded surface of the inner tube of the counter flow heat exchanger. The electric field was established by amplifying the signals from a signal generator using a high voltage amplifier. In the current experiments, the flow visualization test section at the exit of the heat exchanger was made of quartz tube coated with an electrically grounded transparent conductive film of Tin Oxide. The flow was visualized using a high speed camera at a record rate of 2000 fps.

III. RESULTS AND DISCUSSION

In this section, the effect of pulse repetition frequency on heat transfer and pressure drop is reported for 3 different duty cycle values of 25%, 50%, and 75%. The duty cycle is defined as the percentage ratio between the time of the pulse to the time period of a complete cycle. The effect of EHD on heat transfer during stratified flow convective condensation is believed to be
due to three factors: (1) Liquid extraction from the bottom stratum to the core of the test section which reduces the thermal resistance due to the stratified liquid layer [2, 12-13], (2) destabilization of the thermal boundary layer at the heat transfer surface for both the liquid stratum and the annular liquid film due to the applied electric field [14] and (3) thinning of the circumferential liquid film which might leads to pseudo drop-wise condensation [15, 16]. The increase in pressure drop due to EHD can, in addition to the above mechanisms, be attributed to the momentum transfer at the inner electrode. This can be significant due the intensive electrically induced liquid-vapor interactions at the electrode surface, which will not be reflected in the heat transfer.

The effect of frequency on heat transfer ratio and pressure drop ratio for duty cycle values of 25 %, 50 % and 75 % is shown in Figs. 2 and 3 respectively. Both the heat transfer ratio and the pressure drop ratio increases with an increase of the duty cycle. The effect of duty cycle on heat transfer is more significant in the low frequency range (less than 60 Hz) compared to the higher frequency range. For example, for the 50 % duty cycle, the heat transfer ratio decreases from 1.9 at a frequency of 1 Hz to 1.34 at a frequency of 60 Hz. This suggests that, in this frequency range (less than 60Hz), there is a sufficient time to complete the liquid extraction from the bottom stratum to the upper part of the tube within one cycle. These results are validated by flow visualization experiments which show the appearance of liquid jets/tornados above the electrode which indicates the liquid extraction from the bottom stratum. For the 25 % duty cycle, the variation of the heat transfer ratio with frequency is not very prominent. There is a small decrease initially with frequency and then it remains nearly constant (1.4) for frequencies greater than 10 Hz. This is likely because the fraction of time which the flow is subjected to the 8 kV (25 % of the time period) is not sufficient to cause significant liquid extraction. In this case, the main reason for the heat transfer is the electrically induced liquid vapor interactions which destabilize the thermal boundary layer. For the 75 % duty cycle, the fraction of time at which the two-phase flow is subjected to EHD (75 % of the time period) is greater than that for the 25 % and 50 % duty cycles. This leads to higher heat transfer ratios (2.4 at 0.5 Hz and 1.65 at 60 Hz) because of a greater amount of liquid extraction from the bottom stratum.

For frequencies greater than 60 Hz, the heat transfer ratio is nearly constant for the three duty cycles; however the ratio increases with an increase in the duty cycle. The flow visualization results for this frequency range show no liquid extraction above the electrode. This is likely due to the relatively high frequency of the applied signals to which the bulk two-phase flow system can not respond. The flow visualization results, however, show a continuous formation and destruction of liquid droplets due to the relatively high frequency applied pulsed electric fields. The liquid droplets oscillate with the same frequency as the applied voltage signals up to 100 Hz which agree with [17]. Although the frequency of the droplet oscillations follows the frequency of the applied voltage signals, the value of the heat transfer ratio remains relatively unchanged in this frequency range. This suggests that the heat transfer enhancement in this range is mainly due to the thermal boundary destabilization which is not significantly affected by the oscillations of the droplets. The heat transfer ratio in this range (frequency greater than 60 Hz) remains relatively constant at a value of 1.3, 1.4 and 1.6 for 25 %, 50 %, and 75 % duty cycles. These values lie between the values at applied DC voltage of 0 kV (heat transfer ratio of 1) and 8 kV (heat transfer ratio of 2.7).

The corresponding pressure drop ratio increases with an increase of duty cycle in the same frequency range (frequency less than 100 Hz) (Fig. 1b). The pressure drop increase for the current flow configuration is likely due to (i) momentum transfer at the wall and (ii) to the momentum transfer at the electrode surface. The latter will not contribute to any heat transfer enhancement. For the 25 % duty cycle, the pressure drop increases with an increase of frequency for frequencies less than 100 Hz. This is due to an increase of the intensity of the liquid-vapor interactions with both the
A spectral analysis of the droplet oscillations shows that the liquid droplets respond to the applied signals up to 100 Hz. For frequency greater than 100 Hz, the pressure drop decreases with an increase of frequency. This is mainly because the response of the two-phase flow (and the liquid droplets) to the applied signals decreases with a resultant decrease in intensity of the liquid-vapor interactions and therefore the pressure drop. The spectral analysis of the liquid droplet oscillations shows no response of the liquid droplets to the applied signals for frequencies more than 100 Hz.

The effect of the AC pulse electric field on pressure drop can be divided into two factors (i) the percentage of the time period the flow is subjected to the applied 8 kV, which increases with the duty cycle and (ii) the frequency of the sudden changes in the applied voltage levels, which increases with the frequency. At lower duty cycles (25 %), the effect of frequency will be more significant causing higher rates of changes in heat transfer and pressure drop compared to the higher duty cycles.

To determine the frequency response of the heat transfer and pressure drop to the applied pulsed waves, the FFT spectra of the temperature and the pressure fluctuations are examined in Figs. 4 and 5 respectively for 50 % duty cycle pulsed wave. The frequencies of the applied signals are shown within the figures. The results show that the two-phase flow is responding to the applied pulse signal up to 10 Hz. For frequencies more than 10 Hz, the FFT spectra does not indicate any response to the applied signals although the time averaged pressure drop ratio results (Fig. 3) show that frequency has a significant effect on the flow at frequencies higher than 10 Hz.
discrepancy between the FFT spectra results and the time averaged results is likely due to limited time response of the temperature and pressure sensors in the current experiments. To confirm the time-averaged experimental results, image processing of the flow visualization used to estimate the two-phase response to the applied signals. A commercial image processing software (ProAnalyst) was used to track the droplets and calculate the FFT spectra of the droplet oscillations. Fig. 6 shows a representative case for the FFT spectra for 25 % duty cycle and 60 Hz. The results show that the two-phase flow is able to respond to the applied signals up to 100 Hz, beyond which the droplet oscillations are diminished.

IV. CONCLUSION

Experiments were performed for horizontal in-tube condensing two-phase flow under the influence of pulsed high-voltage electric fields. The effect of frequency and duty cycle on flow regime redistribution, heat transfer and pressure drop was studied at frequencies in the range of 4 Hz to 2 kHz for a 25 %, 50 % and 75 % duty cycles and amplitude of 8 kV. The heat transfer and pressure drop values were found to depend on the frequency and the duty cycle of the applied pulsed signals. This suggests that the heat transfer and pressure drop can be controlled by changing the pulsed signal parameters. The heat transfer and pressure drop ratios varied from 1.2 to 2.3 and from 1.5 to 3.5, respectively. At the lower frequencies, the flow is able to respond to the applied voltage frequency, resulting in an increase in the heat transfer and pressure drop. The frequency effect diminishes as the frequency increases. At the higher frequencies, the duty cycle has more significant effect on heat transfer and pressure drop.

REFERENCES