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Effect of electrohydrodynamic (EHD) on condensation in presence of non-condensable gas

Hamid Omidvarborna, Arjomand Mehrabani-Zeinabad[*], Mohsen Nasr Esfahany
Department of Chemical Engineering, Isfahan University of Technology, Isfahan 84156-83111

Abstract

In this paper an experimental investigation on electrohydrodynamic (EHD) augmentation of heat transfer for in-tube condensation of flowing refrigerant R-134a in presence of non-condensable gas (NC) is presented. The test section is a 1 m long counter flow heat exchanger. The refrigerant flows in the inner tube and a rod electrode placed in the tube centre. Cooling water flows through the heat exchanger annulus. The effects of electrode rode diameter, presence of non-condensable gas concentration, and application of voltage on condensation are examined. Results show a reduction in heat transfer by factor 2.1 upon presence of 20% of non-condensable gas. In the presence of the 20% of NC and 12mm electrode, a maximum heat transfer enhancement of 1.9 is experienced by applying voltage of 8 kV.

Keywords: Electrohydrodynamic(EHD), Condensation, Non-condensable (NC) gas, Heat transfer enhancement

Introduction

Heat transfer duty of heat exchangers can be improved by implementation of heat transfer enhancement techniques. In general, these techniques can be categorized into two main groups of active and passive. The active techniques is based on applying external forces, e.g. electric field, acoustic or surface vibration, while the passive techniques require fluid additives and/or special surface geometries. Electrohydrodynamic (EHD) techniques have been introduced as an active heat transfer enhancement technique [1].

The electrohydrodynamic (EHD) enhancement of heat transfers refers to the coupling of an electric field with the fluid field in a dielectric fluid medium. In this technique, either a DC or an AC high-voltage with a low-current electric field is applied in the dielectric field medium flowing between a charged electrode and a receiving (grounded) electrode. Previous studies to the field of EHD augmentation of a two-phase flow has shown that the electric field induces an additional electrical body force on the flowing fluids [1]. A general expression for the electric body force is

$$f_e = qE - \frac{1}{2}E^2\nabla e + \frac{1}{2}\nabla < E^2\left(\frac{\partial e}{\partial r}\right)_T r > \tag{1}$$

The three terms on the right-hand side of Eq. (1) represent the electrophoretic, dielectrophoretic, and electrostrictive components of a electric force, respectively. The electrophoretic term represents the force acting on the free charge in the presence of an electric field, known as coulomb force. This force usually dominates for adiabatic single-phase flow under the application of direct current.

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[*] Arjomand@cc.iut.ac.ir

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 in comparison with the electrophoretic force for adiabatic single-phase flow as the permittivity of the working fluid is a weak function of the electric field. For a two phase flow, such as convective boiling and condensation, the dielectrophoretic force is dominate and have significant influence on the flow, and consequently heat transfer behavior.

The electrostrictive force is caused by the non-uniform electric field strength and variation of dielectric constant of the fluid with temperature and density [2,3].

Presence of NC gas has a negative effect in condensation process. In refrigeration units, air as an inert gas is often exist inside the condensers due to:

- Insufficient deaerating of the installation prior to charging of refrigerant.
- Existence of leakage.
- Insufficient leak tightness of the installation on the suction side of the compressor, where the pressure remains below the atmospheric pressure.

Since full elimination of NC gases in a bulk vapor of a refrigeration cycle is difficult and expensive, application of a suitable electrical field appears to be significant for overcoming poisoning effect of the NC gases on film condensation [4,5].

There have been few studies on effect of both EHD and NC gases on condensation process. Seth et al [6] were investigated the effect of applying an electrical field on film condensation in the presence of NC gases. The experimental investigation was carried out in a condensation loop using Freon 113 as the test fluid and air as a NC gas. Bologa et al [7] were investigated electric field induced enhancement of condensation heat transfer in the presence of a NC gas. They used R-113 and hexane as condensing agent, and air, helium and carbon dioxide as NC gases.

Experimental Rig

Experimental apparatus is composed of two sections, condensation heat transfer loop and high voltage power supply. It is designed to measure the heat transfer coefficient of R-134a in a test tube in horizontal and vertical orientations. As shown in Fig. 1, the major components of the test facility are: main condenser (Fig.2), final condensers, evaporator, compressor, hot water loop, cooling water supply, sight glass, electrode, and R-134a gas cylinder.

For the refrigeration loop, liquid refrigerant is passed through rotameter for measurement of the flow rate, and then the liquid passed through evaporator. The evaporator is a double pipe heat exchanger that supplies energy the liquid in order to provide vapor. The hot water in the evaporator was supplied by heater that is circulated by centrifugal pump. The generated R-134a vapor was passed through a sight glass for showing its quality as a single phase flow (vapor). Then the vaporized refrigerant is passed through a compressor to increase its pressure and consequently its temperature. Furthermore, the vapor flows through test section and second condenser. The main objective of condenser after the test section is total condensation of the vapor. In the condenser, open loop cooling water removes the vapor thermal energy.

The test section is a horizontal double pipe countercurrent flow heat exchanger. Surface temperatures of the test section tube are measured by six thermocouples along the axial direction these data are used to estimate of the average heat transfer coefficient on the refrigerant side of the of the condenser. A rotameter that is specially calibrated for R-134a is used to measure the refrigerant flow rate. In the all experiments cylindrical electrode, is used. It is fixed at both ends of the test section by polymeric spacer insulator.

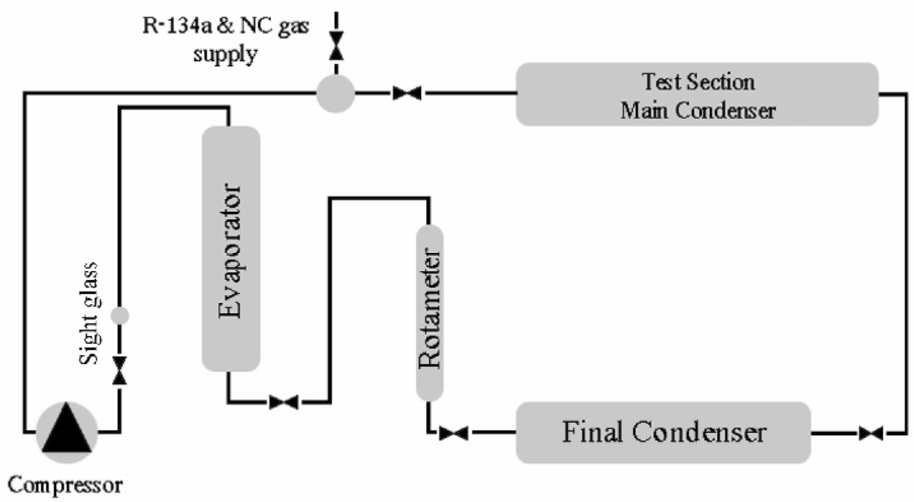

Fig. 1: Schematic of components in experimental condensation loop

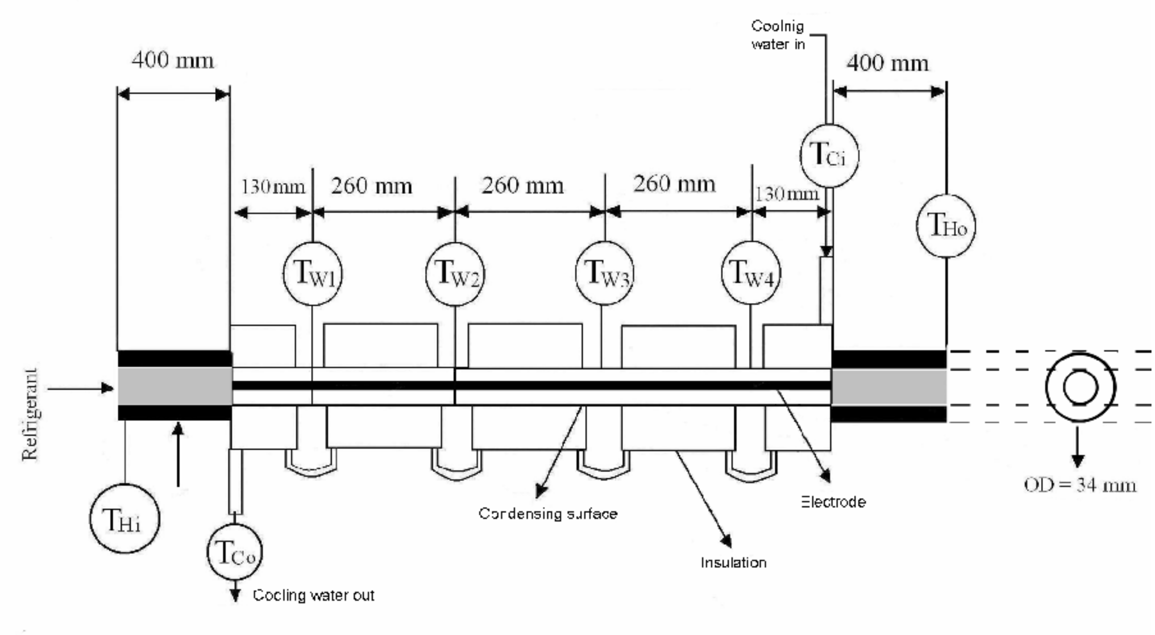

Fig.2: Positions of thermocouples on main condenser of the rig

Assuming that the average heat transfer coefficient is uniform both axially and circumferentially, the refrigerant side average heat transfer coefficient in the tube can be approximated as:

$$\bar{h} = \frac{Q_c}{A\left(\bar{T}_{sat} - \bar{T}_{wall}\right)} \tag{2}$$

Where
A: inner surface area of the tube,
T_{sat}: refrigerant saturation temperature,

Q_c: heat extracted by the coolant water.
The extracted heat rate can be obtained by cold water flow rate, inlet and outlet water temperatures.

$$Q_c = \dot{m}_c.\bar{C}_p.(T_{out} - T_{in}) \tag{3}$$

Arithmetic average of the surface temperature, $\bar{T}_{wall}$, was determined according to the temperature measurements.

$$\bar{T}_{wall} = \frac{1}{6}\sum_{i=1}^{6} T_i \tag{4}$$

Inner area of the condenser test section tube is function of its length, L, and its internal diameter, D.

$$A = p\,DL \tag{5}$$

Results and Discussion

The experimental results can be grouped in 3 sections of effects on EHD, NC, and combination of EHD and NC

- Effect of EHD on condensation

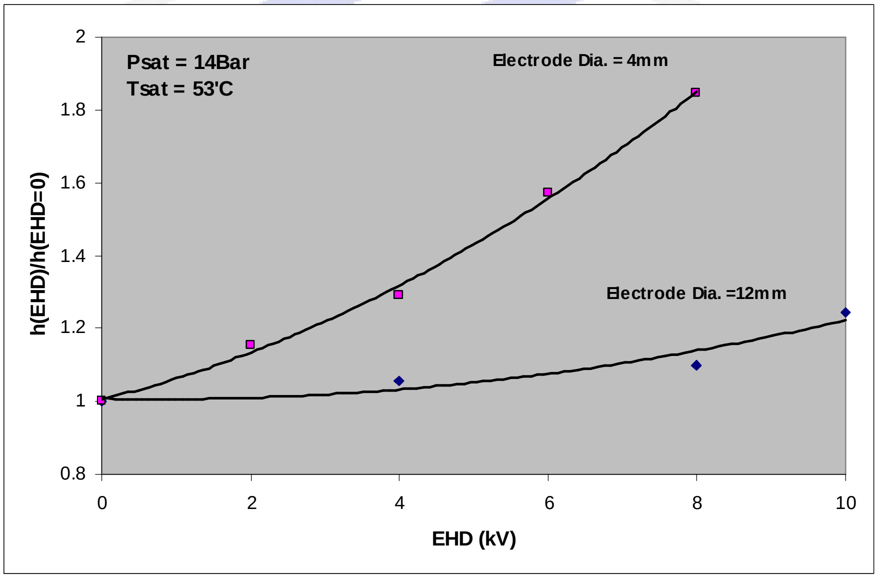

Figure 3: Effect of applying EHD on condensation heat transfer for two electrodes with diameter of 4 and 12mm.

Fig. 3 show the effect of EHD on average condensation heat transfer coefficient for two electrode diameters of 4 and 12mm. The heat transfer enhancement is shown in the form of enhancement ratio, $\bar{h}/\bar{h}_0$, where $\bar{h}$ is the average of heat transfer coefficient in presence of EHD and $\bar{h}_0$ is the average heat transfer coefficient without EHD, but in presence of electrode. The experimental data are collected for condensing media of R-134a, in the smooth tube at a saturation temperature of 53°C and flow rate of 23kg/hr.

During the normal condensation, the liquid film thickness gradually increases, and consequently the thermal resistance is increased which results in decrease of heat transfer rate. But in presence of high voltage, heat transfer rate increased due to instabilities at the liquid vapor interface. It is resulted from the molecules of refrigerant disturbed by EHD force and the liquid-extraction phenomenon. The EHD force pushes the refrigerant vapor with low dielectric permittivity to the inside tube surface. While the condensate phase with high dielectric permittivity that is from on the inside tube surface is pulled the electrode surface.

This phenomenon generates the secondary fluid motion inside the liquid film and leads to the reducing of condensate film thickness formed at the inside tube wall.

Furthermore, as the 12mm electrode applies greater electric field on the condensate surface higher heat transfer coefficient is resulted.

- *Effect of NC on condensation*

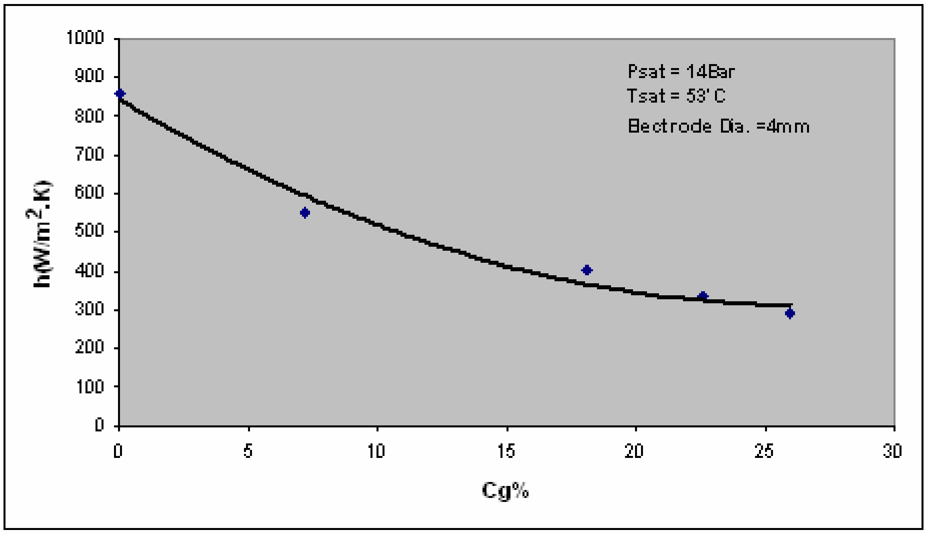

Figure 4: Effect of increasing NC gas content of refrigerant media

on condensation heat transfer coefficient

Fig. 4 shows the effect of the NC gas on heat transfer coefficient. The condensation heat transfer coefficient decreases by increasing percentage of NC gas in the condensation media. Since the NC gas is impermeable to the liquid film, it is accumulated at the film gas interface and increasing its concentration. So, the boundary layer thickness is increased and the concentration level is increased along the condenser tube length. The developing NC gas boundary layer acts as a strong resistance to condensation. This lead to a lower heat transfer coefficient.

- *Effect of both EHD and NC on condensation*

Fig. 5 and 6 shows that increasing percentage of air as non-condensable gas in condensing media, result in a reduction in condensation heat transfer coefficient. However application of EHD, enhances the heat transfer by thinning of the film, but amount of compensation does not cover the reduction.

The results show that at a constant percentage of NC gas, increasing of applied voltage enhance condensation rate. This issue can be gained by increasing of the electrode diameter.

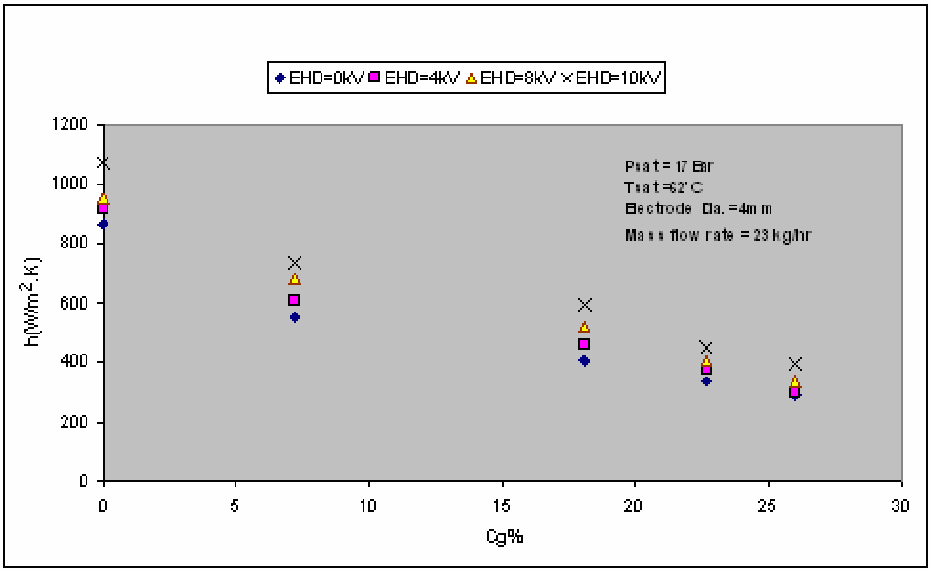

Figure 5: Effect of NC gas concentration and EHD voltage on heat transfer coefficient for electrode with diameter of 4mm

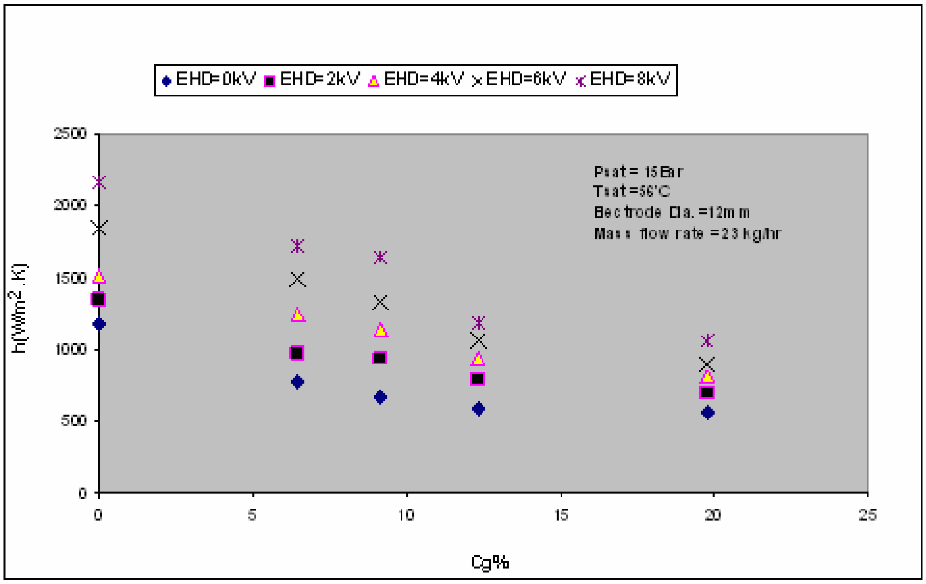

Figure 6: Effect of NC gas concentration and EHD voltage on heat transfer coefficient for electrode with diameter of 12mm

Conclusion

Application of EHD, or reduction of NC gas content enhance condensation heat transfer. But applying of both changes, varying voltage and varying NC gas content, the results show that at high concentration of NC gas, increasing of electrical field has lower effect on enhancement of condensation heat transfer. This issue is due to considerable effect of applied voltage on refrigerant of R-134a in comparison with its negligible effect on the content air. Consequently, increasing of applied voltage cannot absorb the air from active transfer area and leave it to the condensing vapor. However, it must be considered that there is a limitation on the amount applied voltage. This is due to occurrence of corona discharge.

Nomenclature

A	internal heat transfer area
C_g	relative volumetric concentration of component, $(P_{mix} - P)/P_{mix}$
$\overline{C}_p$	average specific heat of liquid
D	inner diameter
E	applied voltage
$\overline{h}$	average heat transfer
L	tube length of test section
$\dot{m}$	mass flow rate
q	electric field space charge density
Q	heat transfer rate
T	temperature

Greek symbols

e	electric permittivity of the fluid
r	density

Subscript

C	coolant
g	gas
in	inlet
Mix	vapor-gas mixture
out	outlet
Sat	saturation

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