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Electrohydrodynamic technique of condensation enhancement

Abstract. *This paper concentrates on condensation heat transfer augmentation by means of active condensate drainage in strong electric field. The electrohydrodynamic (EHD) technique is suitable for dielectric media used in refrigeration, ORC cycles and heat pump devices. In presented experiment, a condenser with condensation on the outer surfaces of horizontal tubes was investigated. The electric field was generated between each tube and two rods placed externally. The electric field influences the draining of the liquid (condensate) film from the tubes surface. Presented in this paper experimental research of a tubes bundle with a rod electrode for each tube have not been published in the literature so far.*

Streszczenie. *Niniejsza praca skupia się na intensyfikacji procesu wnikania ciepła podczas kondensacji, poprzez poprawę spływu skroplin wskutek przyłożenia silnego pola elektrycznego. Taka elektrohydrodynamiczna (EHD) metoda jest odpowiednia dla dielektrycznych czynników roboczych stosowanych w chłodnictwie, obiegach ORC i w pompach ciepła. W omawianym eksperymencie badano kondensację na zewnętrznych powierzchniach pęczka poziomych rur, wchodzących w skład skraplacza. Pole elektryczne przykładano pomiędzy każdą z rur a parą elektrod prętowych, umieszczonych w pobliżu zewnętrznej powierzchni rury. Pole elektryczne wpływa na spływ filmu cieczy (kondensatu) tworzącego się na powierzchni rury. Zaprezentowane w pracy wyniki eksperymentalne dla pęczka rur, z elektrodami prętowymi przy każdej z nich, są unikalne i nie były dotychczas publikowane.* ***Intensyfikacji procesu wnikania ciepła podczas kondensacji***

Keywords: electrohydrodynamics, condenser, heat transfer enhancement.
Słowa kluczowe: elektrodynamika, skraplacz, intensyfikacja wymiany ciepła.

Introduction

For the majority of working fluids used in refrigeration or air conditioning apparatus, heat pumps and nonconventional thermal power plants (ORC cycles) as well as for heat transfer fluids in heat transport pipes, low heat transfer coefficients are usually obtain during the condensation of the working medium.

This is unfavourable effect because of which the heat transfer is inefficient. That also motivates the efforts to enhance the effective heat transfer.

Generally, one can consider two different heat transfer enhancement techniques: passive and active ones [1]. The passive techniques do not require the application of the external power, whereas the active techniques require activator or power supply to bring about the enhancement.

The facts mentioned above make up a good justification of the exceptional attention paid to research concerning the heat transfer intensification during the refrigerants condensation process. Among many available methods, application of the electric field offers promising and effective solution. Based on existing studies, the presence of electro hydrodynamic forces affecting the condensation process can yield benefits, such as [2]:

- reduction of of the liquid film thickness as a result of stripping of fluid from the condensation surface;
- change of the character of the phenomena, from a film to (pseudo) dropwise condensation;
- dispersion of the condensate as a result of electrostatic atomization of the fluid;
- prevention of agglomeration of non-condensable gasses in the vicinity of the phase boundary;
- induction of perturbations and waviness of the condensate at the surface of the liquid film.

Heat transfer intensification obtained by the application of the EHD method, expressed as a ratio of heat transfer coefficients with and without presence of the electric field, in some cases can reach few hundred percent.

Application of EHD heat transfer intensification is significantly effective in heat exchangers operating with working mediums which are dielectrics [3,4]. In such a case, despite high voltage reaching up to tens of kV applied to the electrodes, current flowing between them is low. As a result, the demand for additional electric power supplied to the heat exchanger with activated EHD, is negligible. EHD method can be applied even in one phase heat transfer cases, although best performance is achieved for processes with phase change, namely evaporation and condensation.

First studies on the subject of electrohydrodynamic intensification of film condensation were conducted relatively recently. Among the earliest articles covering this subject are papers [5,6,7,8]. The first and the second of them relate to condensation on vertical surfaces and the latter ones describe this phenomenon on horizontal surfaces – flat and cylindrical (external pipe wall).

Currently there are available comprehensive literature overviews presenting results of experimental studies on condensation enhancement by the means of electric field. Such overviews are covered within papers [2,9-11]. They demonstrate the special attention which is paid to the problem of film condensation intensification with the use of EHD, both on vertical and horizontal surfaces. Most of the studies concerns application of steady electric field.

Most of the works found in the literature describe the results of studies on individual tubes of the condenser, missing are works depicting the impact of EHD forces on liquefaction process in real, complete condensers. For example, experiments for a single tube with outside rod (electrode) were presented [12]. Presented in current paper experimental research for a bundle of tubes with a rod for each tube have not been presented in the literature so far. Our experiment was performed for semi-technical size of a new design of shell-and-tube heat exchanges.

Idea of using EHD force to enhance the process of condensation

The idea of the EHD condensate drainage enhancement technique is illustrated in Fig. 1a. The main feature of it is the arrangement of the tube-electrodes system. In this case the electric field is generated between by the two rod-type electrodes and the lower part of the finned tube. There are two positive phenomena related to the heat transfer augmentation in the considered case. The first one follows from the Gregorig effect which takes place on the upper part of the tube (not disturbed by the EHD forces) and the second one is due to the EHD forces pulling down the condensate from the bottom part of the tube in direction of drain electrodes. It is seen that in this method the EHD forces influence only the condensate drainage process but not the condensation phenomenon itself. The electric field affects the behavior of liquid phase by potency of EHD force. Acting of the force on the liquid film causes faster removal of condensate from flooded areas of condenser tube (bottom), particularly in the areas between the fins on the tubes. The EHD force influence on the liquid generated by an electric field is given by formula:

$$f_e = qE - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\rho\right], \tag{1}$$

where: q – electric charge, ε – electric permittivity, E – electric field. The EHD force consists of Coulombs forces, electrostriction and dielectrophoresis effects.

The main goal of the experimental investigations was to provide the data to confirm the theoretical expectations of EHD condensation enhancement according to the idea shown in Fig. 1. Experiments covered determination of the heat transfer coefficient during condensation of refrigerant HFE-7100.

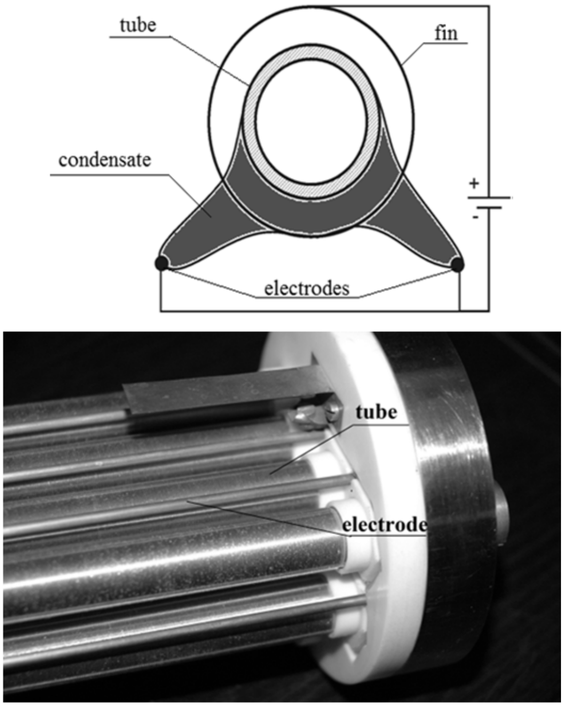

Fig.1. Idea of EHD condensate drainage enhancement technique and the photograph of condenser tubes bunch: a) idea of EHD condensate drainage enhancement, b) the photograph of the tubes bunch in the condenser

The authors used a condenser containing a bundle of ten pipes. Each pipe is adjacent to two drainage electrode rods (external electrodes). The electric potential was applied to the electrodes, while the pipes were grounded. The range of the applied voltage was from 0 kV to 12.5 kV. The Spellman SL 40 1200 PN 230 power supply was used to generate high voltage potential at the electrodes. The measured current flow between electrodes was up to 0,05mA (for whole condenser).

The outer diameter (including fins) of the tubes is 16 mm, inner diameter is 13 mm, the length is 290 mm, electrode diameter is equal to 3 mm. The distance between the electrodes and the tube is 3 mm. The tubes and electrodes were made of brass. The photograph of the condenser is shown in Fig.1b.

Experimental stand and experimental data analysis

An experimental investigation was conducted on the laboratory stand presented in Fig. 2. The most important elements of experimental stand were condenser and vapour generator. The photograph of the EHD condenser installation before insulating is shown in Fig. 3.

First-class K-type thermocouples were applied for the experiments. The thermocouples were calibrated before each measurement with total accuracy of 0.2 K. For all circuits the Coriolis mass flow metres of accuracy 0.15% were used.

Sight-glasses were installed at various locations to observe the flow. The test rig was equipped with two additional loops: the first one for the thermal load for the evaporator and the second one for the condenser cooling. These systems allow for adjusting refrigerant flow rates as well as changing the operation parameters in a wide range. The condenser cooling system was equipped with an automatically controlled dry cooler. The thermal load system was equipped with automatically controlled electrical heater.

The data acquisition was based on two National Instrument systems. The first one is the real time NI Compact FieldPoint system, designed for industrial control. The second one is NI modular SCXI system. The NI Compact FieldPoint is programmable automation controller (PAC)–which logs all main parameters and controls valves, pumps, electric heaters and safety system. NI modular SCXI system is based on the SCXI e 1001 low-noise chassis with precise, dedicated amplifiers which is connected to NI PCIe-6251 M high-speed multifunction DAQ installed in the PC. The computer uses a LabVIEW software with additional toolkits. The real time measurements are shown on the computer screen while all measured data are stored in a data file.

The measured pressure, temperatures and mass flow rates allowed for determination of overall heat transfer coefficient and the influence of EHD forces on its value. In these calculations average temperature values of cooling water and condensing HFE-7100 fluid were calculated first. The average water temperature t_w was determined as

$$t_w = \frac{t_{w2} - t_{w1}}{\ln\dfrac{t_{w2}}{t_{w1}}}, \tag{2}$$

where t_{w1} and t_{w2} are water inlet and outlet temperatures, respectively. Average condensation temperature t_c was calculated from measured pressure p and the approximation of HFE-7100 saturation line

$$t_c = t_{sat}(p) = \frac{3641.9}{22.415 - \ln p}, \tag{3}$$

where the units are [Pa] for pressure and [K] for temperature [1].

The overall heat transfer coefficient k for the investigated heat exchanger is defined as

$$k = \frac{\dot{Q}}{A\,\Delta T_{\log}}, \tag{4}$$

where: $\dot{Q}$ is condensation heat transfer rate, proportional to the vapour mass flow rate and latent heat, A is heat transfer total surface area and $\Delta T_{\log}$ is logarithmic mean temperature difference.

The results of overall heat transfer coefficient k calculations are shown in Fig. 4. During condensation with no voltage applied, the value of k was equal to 353 W/m^{2}K. After applying the voltage to the electrodes, enhancement of heat transfer was observed. For 7 kV the increase of k is small but significant. For higher voltages the heat transfer coefficient increases further. The maximum voltage applied was limited by avalanche breakdown. During the experiments the value of 12.5 kV was reached, for which coefficient k was about 380 W/m^{2}K. Thus, the heat transfer was enhanced by about 8 %.

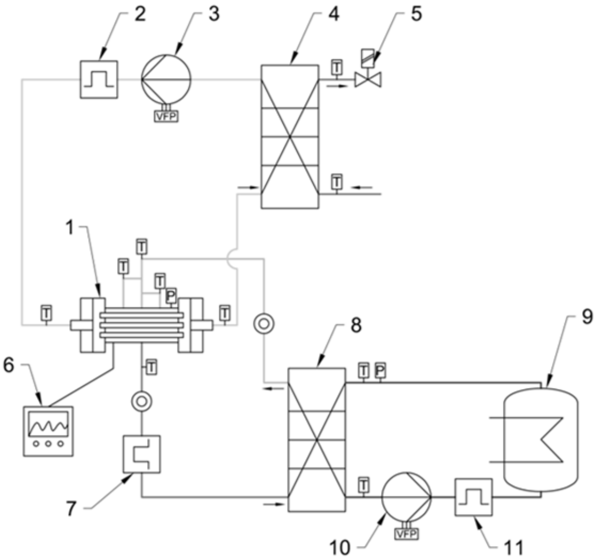

Fig.2. Schematic diagram of the test apparatus: 1 – condenser, 2 – coriolis liquid flow meter, 3 – pump, 4 – cooling circus heat exchanger, 5 – control valve, 6 – high voltage supply, 7 – coriolis condensate flow meter, 8 – vapour generator, 9 – electric heater, 10 – pump, 11 – coriolis flow meter.

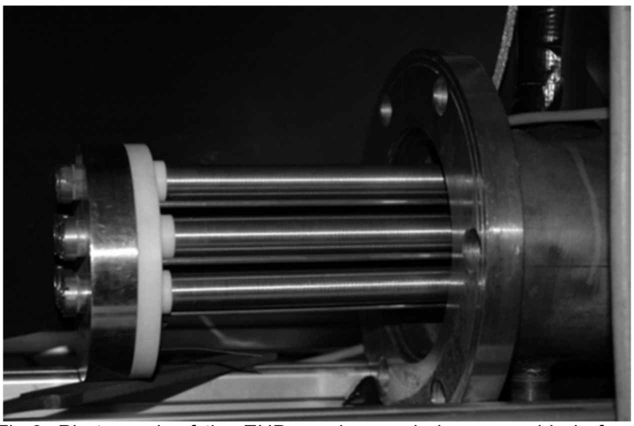

Fig.3. Photograph of the EHD condenser during assembly before insulating

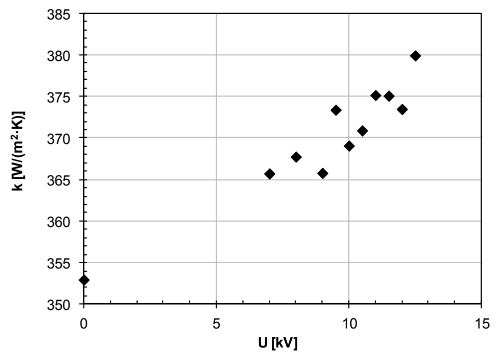

Fig.4. Overall heat transfer coefficient k dependence on applied EHD voltage U.

Summary

The results of experimental investigation of EHD condensation enhancement were presented in the paper. Presented results show that the active technique of condensation enhancement may be achieved by applying the electrohydrodynamic condensate drainage augmentation. Presented in this paper experimental research for a bundle of tubes with a pair of rod electrodes for each tube have not been presented in the literature so far. The results obtained show that the use of the electric field for enhancement the condensation was possible not only on a single tube but also complete shell-and-tube heat exchanger.

An important aspect of the presented results is their high application potential, in particular in power cogeneration. The fluid HFE 7100, used in the experiments, is one of the main media utilized in small power ORC plants. Enhancement of the process of condensation in condensers of these power plants has a beneficial effect on their efficiency.

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