376 KSME International Journal, Vol. 13, No. 4, pp. 376~385, 1999

Electrohydrodynamic(EHD) Enhancement of Boiling Heat Transfer with a Lo-Fin Tube

Sang-Houn Han*, Min-Kyun Na*, Si-Doek Oh and Ho-Young Kwak***

(*Received September 3, 1998*)

The effect of D. C electric field on nucleate boiling heat transfer for refrigerants of R-11, HCFC-123 and FC-72 was investigated experimentally by using a single lo-fin tube shell-and-tube heat exchanger. The lo-fin tube which brought two times increase in the heat transfer area provided about 150% of boiling heat transfer enhancement compared to that of smooth surface. This experimental study has revealed that the electrical charge relaxation time was an important parameter for the boiling heat transfer enhancement under electric field. Boiling heat transfer enhancement was obtained up to 40% for R-11 which had moderate relaxation time of 1.3 s. However remarkable boiling heat transfer enhancement has been obtained up to three fold increase(300%) for HCFC-123 which has the electrical charge relaxation time of 0.89×10^{-3} s. For FC-72 having longer relaxation time than the bubble detachment one, no appreciable effect on the nucleate boiling heat transfer was observed.

Key Words: EHD, Nucleate Boiling, Lo-Fin Tube

1. Introduction

For utilizing low temperature waste heat source, one of major tasks is to develop more efficient heat exchanger equipment. An especially compact evaporator is an important thermal component for the plants such as Organic Rankine Cycle engine and large scale heat pumps.

Electrohydrodynamic(EHD) augmentation has been proved to be one of the most appropriate technique to enhance boiling heat transfer in dielectric liquids(Cooper, 1990) which are suitable working fluids for the low-temperature difference heat exchanger employed in the waste heat recovery plants. Dielectrophoretic force due to the difference in vapor/liquid permittivity and buoyancy force were known to play a crucial role to the bubble behavior in dielectric liquids under nonuniform electric filed(Snyder et al, 1996, Oh and Kwak, 1996a).

One of common findings from the previous investigations on EHD enhancement in nucleate boiling is that the number of bubble increases while the diameter of bubble decreases as the electric field increases(Basu, 1973; Cooper, 1990; Kawahira et al. 1990; Ohadi et al. 1992) which may be due to the intense electric field created in the vicinity of the heater surface(Snyder et al. 1996). Another interesting observation from previous experiments is the bubble coalescing on the lower part of heat transfer tube surrounded by six wire electrodes with equal spacing(Kawahira et al. 1990; Ohadi et al. 1992). Recently it has also been found that the bubble movement in electric field is the result of the combination of dielectrophoretic and buoyance forces(Snyder et al. 1996) so that the modified bubble behavior due to the nonuniform electric field enhances the nucleate boiling heat transfer coefficient(Oh and Kwak, 1996a). For concerning electrical properties of

* Mechanical Engineering Departiment Chung-Ang Univeresity Seoul, 156-756, Korea
** Industrial Machinery & Ergineering Team, Research & Development Institute 1006-2, Bangbae -Dong, Seocho-Ku Seoul, 137-063, Korea

working fluids related to EHD technique, it has been found that the electrical charge relaxation time of liquid is also one of crucial parameters to determine the influence of the electric field on the bubble behavior(Ogata et al. 1992). That is, if the relaxation time is much longer than the bubble detachment period, the bubble behavior is not affected by the presence of the electric field at all. However, most of experimental works on EHD enhancement in boiling heat transfer have been done by controlling the heat flux generated electrically. The nucleate boiling heat transfer data obtained by heat flux control, which shows better heat transfer curve, do not provide appropriate data for the design of evaporator utilized in waste heat recovery plants where waste heat rather than electricity is the main source of evaporation of working fluid. Systematic experiment on EHD enhancement by the temperature controlled method has been reported for small range of the wall superheat less than 10K(Cooper, 1990) and for various refrigerants with wide range of the wall superheat(Oh and Kwak, 1996a). Experiment on EHD boiling heat transfer enhancement in heat exchangers was done by Karayiannis et al. (1993).

In this study, experiments of nucleate boiling enhancement with combination of the passive lo-fin tube surface and the active EHD technology for refrigerants of R-11, HCFC-123(a proposed substitute for R-11) and FC-72 were done by using a single lo-fin tube shell-and-tube heat exchanger. For electrodes, six rows of carbon steel wires coated with copper were employed. In addition, eighteen rows of the wires were used to generate an uniform electric field near the heater surface, but intense nonuniform field inside fin(Cooper, 1986). Proper electrode configuration was chosen to help the buoyancy-driven bubble motion under the nonuniform electric field outside the heater surface. The shell side heat transfer coefficients were obtained by measuring the surface temperature of the tube. The wall superheat for boiling action was controlled by changing the temperature of the water flowing inside the tube. Effect of the wall superheat and the combined effect of augmented surface and electric field on nucleate boiling heat transfer were studied. Experimental results of compound enhancement on boiling heat transfer achieved by applying the EHD technique over horizontal lo-fin tube suggest the possibility of an effective heat exchanger design, and operational aspects. For working fluids, R-11, HCFC-123 and FC-72 which have different charge relaxation time in the order of magnitude scale were chosen.

2. Experimental Apparatus and Procedures

2.1 Experimental apparatus

A schematic diagram of the EHD augmentation boiling heat transfer unit is shown in Fig. 1. The experimental unit consists of a single tube shell-and-tube evaporator(①), condensers(②, ③), constant temperature bath circulator(④), hot water storage tank(⑤) and a high voltage supplier(⑥). The evaporator shell was made of stainless steel pipe of 150 mm inside diameter with two 125 mm diameter sight glasses mounted at its midsection to facilitate visual observation of the bubble behavior on the boiling surface.

The test tube in this study was made of brass one with smooth surface. The outside diameter of tube is 20.0 mm with 1. 2 mm wall thickness. The tube length available for heat transfer is about 687 mm. A detailed cross sectional view of the test tube is shown in Fig. 2. The tube fin profile and dimensions are shown in Fig. 3. The tube wall temperatures were measured at 5 axial stations with equal interval of 150 mm as shown in Fig. 4. Thermocouple junctions 3, 4 and 5 were used for the measurement of circumferential temperatures of the tube. Thermocouple junctions used were magnesium oxide insulation T type sheathed with the stainless steel tube. The stainless steel sheathed thermocouple of 1.6 mm diameter with bare junction was passed into the hole of 1.5 mm diameter in the wall and welded at the tube wall to maintain good thermal contact and to prevent leaking of working fluid into the tube. Two additional T type thermocouples were placed at the top and bottom of the shell to monitor the saturation temperature of the working fluid as

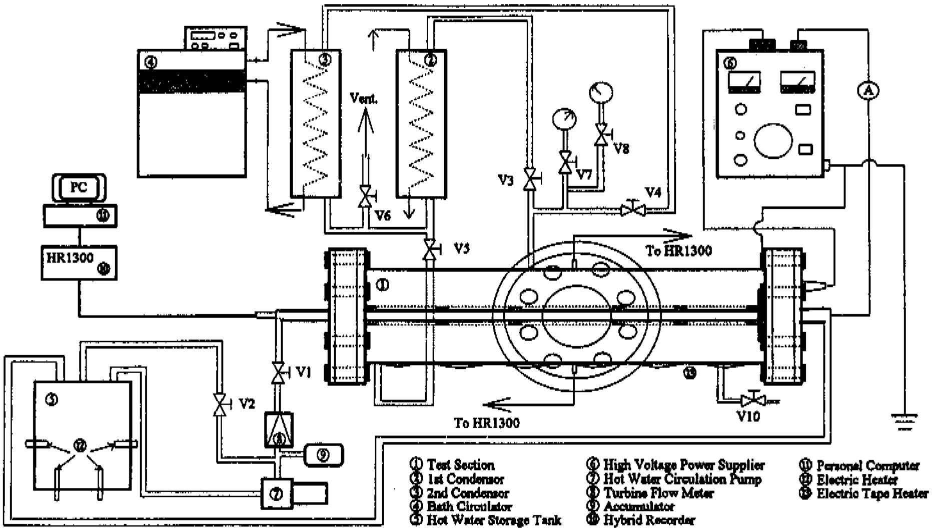

Fig. 1 A schematic diagram of experimental loop for boiling experiment.

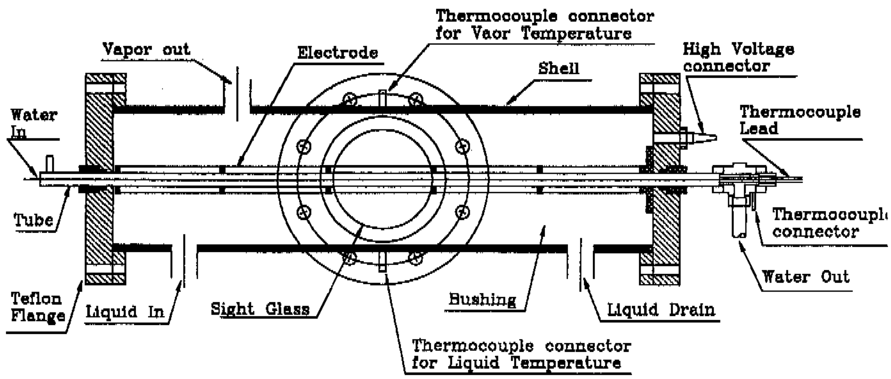

Fig. 2 Sectional drawing of the test section.

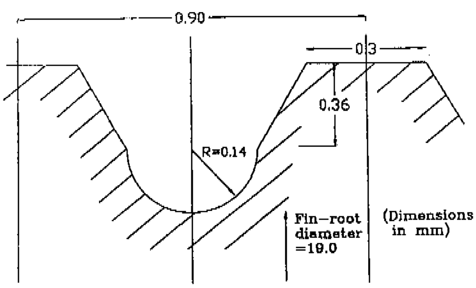

Fig. 3 Lo-fin profile.

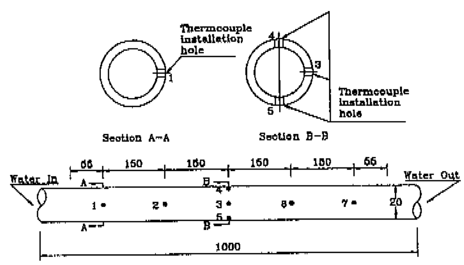

Fig. 4 Configuration of the test tube.

shown in Fig. 2. The pressure inside shell was measured by the Bourdon type pressure gauge.

Hot water to the tube was supplied from an aluminium water tank. The water was heated by two 1 kW and four 100 W immersion heaters adjusted by variacs. Fine control of the water temperature in the tank was done by a temperature controller connected to four 100 W heaters. A friction pump(⑦) with mechanical seal delivered the hot water from the tank to the tube. Hot water flow rate modified by the by-pass line was determined by means of a calibrated turbine

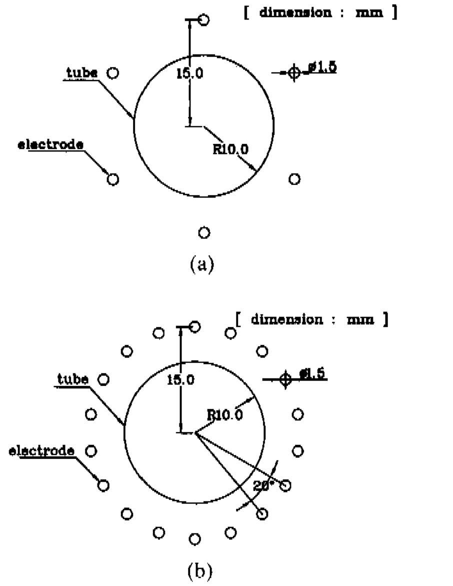

Fig. 5 Electrode configuration (a) 6-electrodes (b) 18-electrodes.

flow meter (⑧: Kobold Co., DF-48) in the liquid line. A diaphragm type accumulator (⑨) was installed in the liquid line to minimize the fluctuation in the flow rate. The vapor generated in the shell side tube was condensed and returned to the shell by the gravity. The cold water supplied from a constant temperature bath (④) circulated the cooling coil of the condenser.

A schematic of the electrode configurations used in this study is shown in Fig. 5. Such electrode configuration for the wire electrode has been proved to be the best to help the buoyancy driven bubble motion under the nonuniform electric field(Oh and Kwak, 1996a). The electrode was made of rather thick 1.2 mm diameter carbon steel wire coated with copper to prevent possible electrical breakdown in liquid(Ohadi et al. 1992). The corresponding equipotential lines due to electrode configurations are shown in Fig. 6. Generation of uniform electric field near the heater surface can be possible near the heater surface with many electrode wires as shown in Fig. 6. As can be seen in Figs. 1 and 2, these wires were supported and insulated from the shell and tube by six ring type teflon supporters fitted to the tube. This arrangement with supporters resulted in a constant electric field around the test tube circumference.

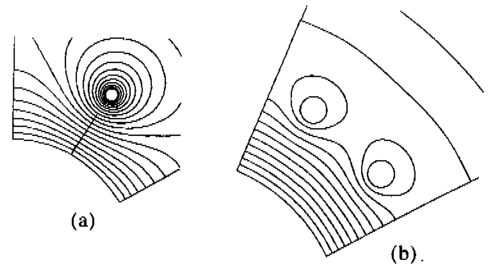

Fig. 6 Equipotential lines for the electrode configurations shown in Fig. 5 (a) 6-electrodes (b) 18-electrodes.

A high voltage generator (Pulse Electronic Eng., Japan, Model HDV-30K) was utilized to supply high voltage up to 30 kV to the electrodes. Also a voltage regulator was used to prevent DC ripples due to the change in the input AC voltage to the generator. The high voltage was fed into the EHD evaporator through a specially modified spark plug fitted in the teflon shell flange. The voltage and current to the electrode were measured by volt meter (Fluke, 80K-40) and multimeter (Barnet Co., TS 352B/U) respectively.

2.2 Experimental procedures

For each run, degassing of the test liquid was performed by the following procedure. After charging the shell with working fluid, the wire heater winding around the shell has been turned on and the hot water in the storage tank has been circulated when the temperature of the test liquid reached the predetermined value, which have been continued until the pressure inside shell reached 3 bar in gauge due to the ebullition of working fluid on the test tube surface. Then the cold water was circulated in the condenser coil until the vapor generated in the shell was condensed to reduce the system pressure of 1 bar in gauge. Next, the noncondensable gases were purged by opening the valve (⑥). The above procedures have repeated several times for degassing.

The wall superheat of the tube was adjusted by changing the power supply to the immersion heaters installed in the storage tank. Detail adjustment of the system pressure was done by controlling the cooling water flow rate and the temperature at the inlet of the condenser coil. If the temperature change of the vapor and liquid inside the shell were in the range of ±0.2 ℃, the system was assumed to have reached steady state. Once the steady state has been established, the temperature and pressure of the system, the temperatures of hot water at inlet and outlet, the temperatures of tube wall and the voltage and current to the electrode were recorded.

For all cases, the boiling experiment at a particular wall superheat without electric field was performed first. Next, the high voltage was applied to the electrode. The saturation temperatures which were maintained within ±0.4 ℃ during experiment were 25.0 ℃ for R-11, 27.6 ℃ for HCFC-123 and 56.0 ℃ for FC-72. The flow rate of hot water, which was very important factor for achieving stable experimental condition, was 8 l /min for all fluids tested.

2.3 Data reduction

The heat transfer coefficient, h was determined by

$$h = \frac{\dot{Q}/A}{T_{as} - T_s} \tag{1}$$

where T_s is the saturation temperature of test liquid, T_{as} is the average temperature of the tube wall and A is the heat transfer area of the tube, which is approximately 0.0371 m^2. The heat transfer rate to the working fluid inside the shell was assumed to be equal to the rate of energy loss of the hot water flowing inside the tube. This is given by

$$\dot{Q} = mC_p(T_{wi} - T_{wo}) \tag{2}$$

where $\dot{m}$ is the mass flow rate of the water inside the tube. The value of the specific heat of water, C_p was taken at the average value of inlet and outlet temperatures of the bulk water, i.e., $(T_{wi} + T_{wo})/2$. The average temperature of the tube wall, T_{as} was obtained by taking of the arithmetic mean of the temperatures at the five side wall stations along the tube length with a weighting factor. That is

$$T_{as} = \frac{(T_1 + T_2 + T_3 + T_4 + T_5)}{5} \cdot R_m \tag{3}$$

The weighting factor R_m is just the ratio of the arithmetic mean of the temperatures measured at the three circumferential stations to the temperature at the side wall, which is given by

$$R_m = \frac{(T_3 + 2T_4 + T_5)}{4T_3} \tag{4}$$

Same circumferential temperature profile was assumed at all cross sections relative to the corresponding tube side wall temperature to obtain this equation.

A typical way of obtaining the heat transfer coefficients is such that determines the local h based on local wall superheat, ΔT first and then averages all the local h's to determine the average. However the local heat transfer coefficient or the local heat flux is not defined here, because the temperature of the boiling surface is controlled by means of heat transfer to the surface, which justifies our method to determine the heat transfer coefficients. All T type thermocouples used were calibrated with a DC voltage/current standard generator (Yokokawa, 2553) and the semiconductor probe. The maximum calibration was −0.3 ℃ at 65 ℃. The acquisition of the data obtained from the T type thermocouples was done by Yokokawa recorder (HR 1310) connected to PC. The data collected from each thermocouple in 2 minutes at 2 second interval were averaged separately to make a data set.

The relative errors in the temperature and flow rate measurements were estimated to be approximately ±1.1 % and ±1.5 % respectively so that the calculated magnitude of the heat transfer coefficients were accurate within ±10 %. However the error increased up to ±25 % at the lowest heat flux tested.

3. Characteristic Times Related to the Bubble Behavior Under Electric Field

It is well known that the bubble departure frequency is fundamentally related to the heat flux achieved in the boiling heat transfer (Judd and Hwang, 1976). The frequency which is essentially governed by buoyancy force and surface tension is given by the following equation.

Table 1 Electric properties of test liquids and electrical charge relaxation times.

Liquid \ Description	Electrical conductivity [A/(Vm)]	Dielectric constant 8.86416×10^{-12}[F/m]	Charge relaxation time [s]
FC-72	1.0×10^{-13}	1.76	$1.56\times10^{+2}$
R-11	1.64×10^{-11}	2.28	1.30
HCFC-123	**	**	0.89×10^{-3}*

* From Ogata et al.(1992).

** Not available

$$f = C\left[\frac{\rho_l-\rho_v}{D_b\rho_l}\right]^{\frac{1}{2}} \tag{5}$$

where ρ_l and ρ_v are density of liquid and vapor respectively and D_b is bubble departure diameter. For the refrigerants tested in this study, the frequency is about 55.6/s with $C = 0.56$ for R 11. This value which depends crucially on the bubble departure diameter has the same order of magnitude for various refrigerants.

On the other hand, the charge relaxation time in addition to the bubble departure time turns out to play a crucial role affecting in the bubble behavior under electric field(Ogata et al. 1992). The relaxation time which is related to the electrical properties of liquid is given by

$$\tau_e = \frac{\varepsilon}{\sigma} \tag{6}$$

where ε and σ are the electric permittivity and conductivity of liquid respectively. The characteristic time defined in Eq. (6) is considered as the time taken for an electric field to affect the bubble. In Table 1, the relaxation times of electrical charge for various refrigerants with electrical properies are shown.

4. Experimental Results and Discussions

Experiments of nucleate boiling enhancement with combination of the passive lo-fin tube surface and the active EHD technology were done. Some experimental results are as follows.

Figure 7 shows the mean heat fluxes versus the wall superheats for R-11 with smooth and lo-fin surfaces along with the predictions made by the

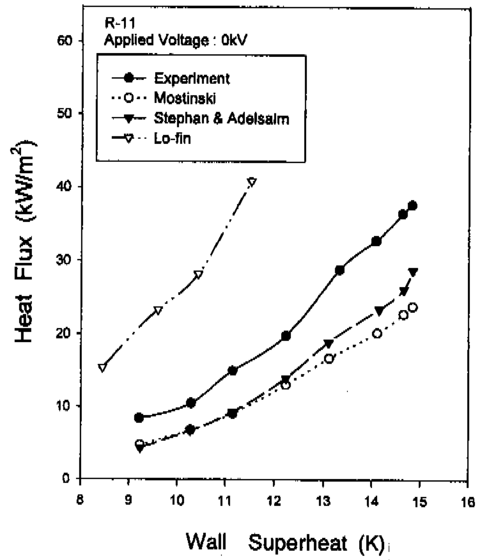

Fig. 7 Boiling curve for R-11 from lo-fin and smooth surfaces at $T_s=25.0$℃ along with predictions. Predictions are for smooth surfaces.

Mostinski equation(1963) and by the Stephan and Adelsalm correlation(1980). Experimental data obtained from the smooth surface were about 1. 5 time greater than those by Mostinski predictions. This difference may be due to the surface preparation of the tube employed in the experiment. However the boiling curves from the experiment and the prediction are very similar. As can be seen in this figure, considerable enhancement in nucleate boiling heat transfer coefficient can be obtained with lo-fin surface only. The lo-fin tube which brings two times increase in heat transfer area provides above 150% of the boiling heat transfer enhancement compared to that of the smooth one. The heat transfer area for lo-fin tube

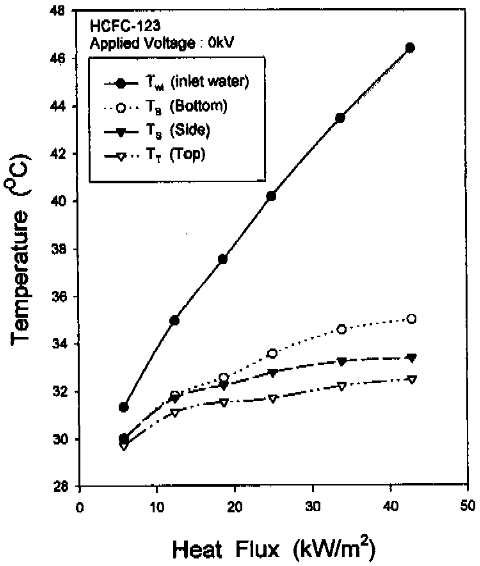

Fig. 8 Variation of local wall and inlet water temperatures in HCFC-123 at $T_s=27.6$ ℃ for lo-fin tube.

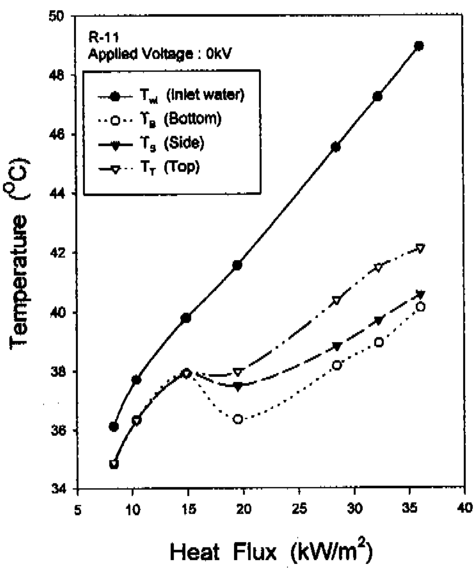

Fig. 9 Variation of local wall and inlet water temperatures in R-11 at $T_s=25.0$℃ for smooth surface.

was calculated by using the area of the smooth one.

The variation of the circumferential temperatures at midsection of the tube for different heat fluxes without electric field are shown in Fig. 8 for HCFC-123. The temperature drop due to the

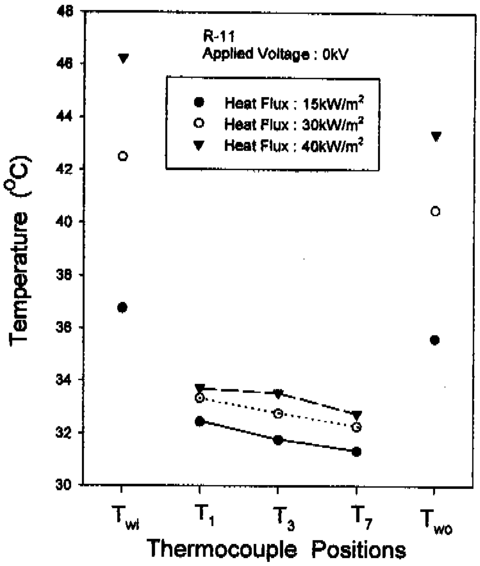

Fig. 10 Temperature variations along the tube for the case of R-11 at $T_s=25.0$℃.

onset of boiling, which occurs in the case of smooth surface as shown in Fig. 9 can be eliminated completely by using the lo-fin surface without help of a moderate electric field(Oh and Kwak, 1996). It is also noted that the circumferential temperature variation of the test tube appears distinctly for R-11 once nucleate boiling on the heating surface occurs. This is due to the fact that the buoyancy driven force enhances the boiling action at the top. On the other hand the boiling action is hindered by the buoyancy force at the bottom surface. The temperature difference between the top and bottom was found to be less pronounced for FC-72.

Temperature variations along the tube wall at several heat fluxes and inlet and outlet water temperatures in the tube for R-11 without electric field are shown in Fig. 10. Only slight changes in temperature along the tube can be seen. The maximum temperature difference along the tube is less than that between the top and bottom around the tube, which validates our method to determine the heat transfer coefficient.

The boiling heat transfer coefficients at zero and various electric voltages applied with the 18 wire electrode for R-11, HCFC-123 and FC-72 are shown in Figs. 11, 12 and 13 respectively. As

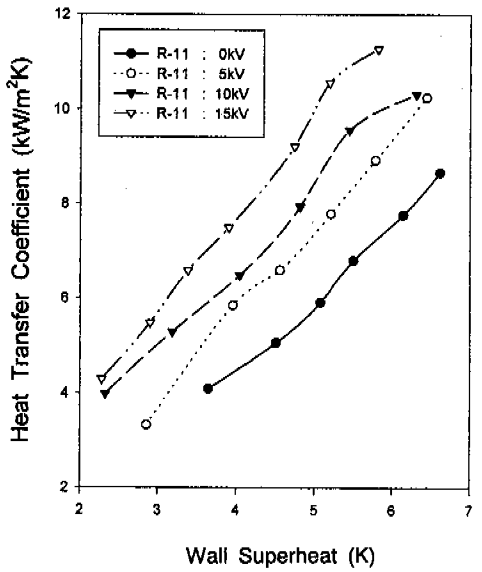

Fig. 11 Variation of heat transfer coefficients for R-11 on lo-fin tube with 18 wire electrode at T_s=25.5℃.

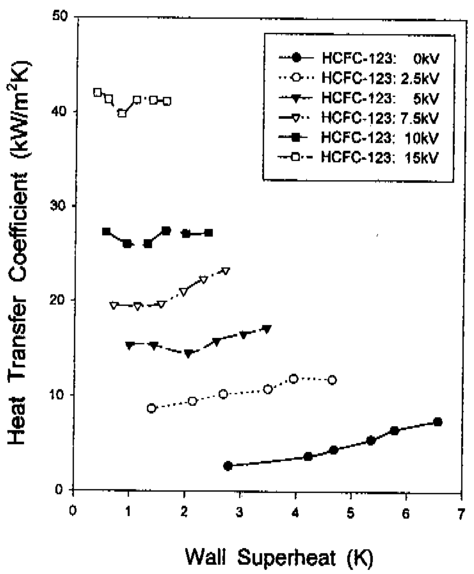

Fig. 12 Variation of heat transfer coefficients for HCFC-123 on lo-fin tube with 18 wire electrode at T_s=27.6℃.

shown in the figures, the electric field effect on the nucleate boiling heat transfer is less significant for R-11 and FC-72 than for HCFC-123. For R-11 about 100% enhancement in heat transfer coefficient at high voltage was obtained. Also the heat transfer coefficient increases as the wall superheat

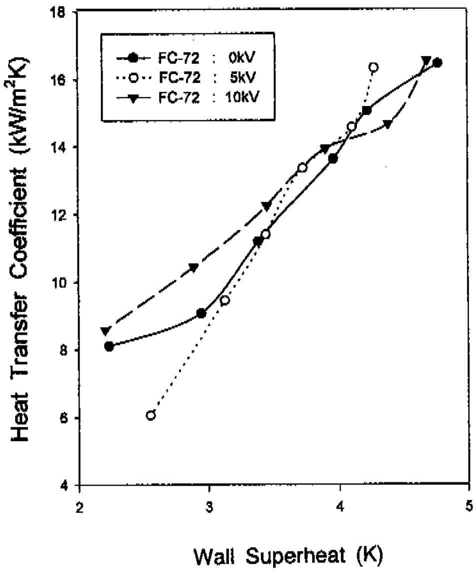

Fig. 13 Variation of heat transfer coefficients for FC-72 on lo-fin tube with 18 wire electrode at T_s=56.0℃.

increases, which is also true for normal pool boiling case. Less appreciable enhancement in the boiling heat transfer was obtained for FC-72 even at high voltage. Such insentiveness to the applied electric field for FC-72 has also been observed in the boiling experiment with smooth surface(Oh and Kwak, 1996a). This may be attributed to the longer charge relaxation time than the bubble departure one so that the bubble departure time or frequency is no longer influenced by the electric field(Kawahira et al. 1990).

However HCFC-123 exhibits a remarkable response to the EHD enhancement methodology with up to five fold increase in the heat transfer coefficients. This may be due to the fact that the charge relaxation time is less in the order of magnitude scale than the bubble departure one as shown in Table 1. In the range of electric field between 5 kV and 10 kV for HCFC-123, it is very hard to obtain reproducible heat transfer data, which indicates that unstable boiling occurs in this regime. Such sporadic boiling behavior under electric field was also observed for an azeotropic mixture of R-113+wt 4% ethanol mixture(Oh and Kwak, 1996b). Also it is noted that the wall superheat needed for boiling decreases with an

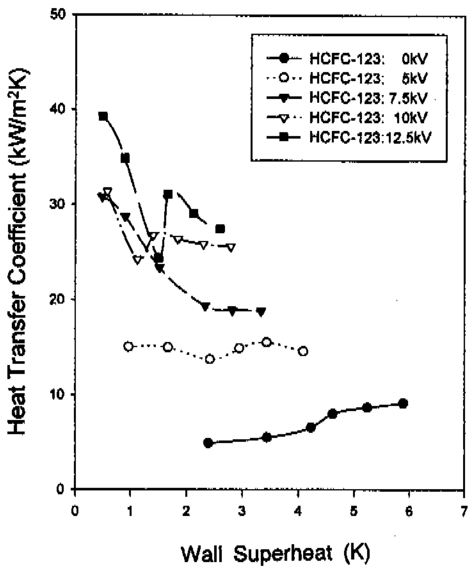

Fig. 14 Variation of heat transfer coefficients for HCFC-123 on lo-fin tube with 6 wire electrode at T_s=27.6℃.

increase in the electric field applied, which is similar to the nucleate boiling on high flux surfaces(Marto and Lepere, 1982). For the lo-fin surface whose boiling heat transfer data are shown Figs. 11, 12, and 13, the circumferential temperature variation vanishes at high electric field of 15 kV. At the moderate electric field below 10 kV, the wall superheat at the top surface is slightly greater than that at the bottom one. The ranges of wall superheat with such lo-fin tube are almost the same as those in the EHD experiment done by Cooper(1990). The maximum heat fluxes achieved in these cases are close to the value near the critical heat flux. Also note that the trends of the heat transfer coefficient depending on the wall superheat for HCFC-123 are quite different at high electric field, which was also observed by Singh et al. (1993). As shown in Figs. 12 and 14, EHD enhancement on the nucleate boiling heat transfer is noticeable at lower wall superheats, especially at higher applied voltage. This may be due to the action of dielectrophoretic force which helps detachment of small bubbles from the boiling surface early in their process of growth (Synder et al. 1996). On the other hand the boiling action due to the buoyance-driven force may be suppressed by the EHD force for the case where many bubbles from the boiling surface with slight increase in the wall superheats, which yields decrease in the heat transfer coefficients. However, the heat transfer coefficients increase again when the buoyance-driven force dominates over the EHD one at higher wall superheats.

In Fig. 14, the boiling heat transfer coefficients observed on the lo-fin surface with 6 wire electrode are shown. No appreciable change can be seen when this case is compared with the 18 wire electrode case. Thus, for the application of shell-and-tube heat exchanger, 6 wire electrode turns out to be favorable for installation aspect. Finally it is noted the change in the heat transfer coefficients with slight increase in the wall superheat for 6 electrode case is more notable than the case of 18 electrode. This may be due to the fact that 6 electrode around the heater surface produce more nonuniform electric field so that the EHD effect on the bubble growth at lower superheats brings more enhancement in nucleate boiling heat transfer coefficients. Thus it may be concluded that the competition between the EHD and the buoyance-driven forces on the bubbles may be changeable at the condition of higher electric fields and lower wall superheats for some fluids.

5. Conclusions

Boiling heat transfer enhancement with combination of the passive lo-fin tube surface and the active EHD technology was done by using a single lo-fin tube shell-and-tube heat exchanger. Boiling heat transfer enhancement was obtained with the value of about 40% for R-11. Up to three fold increase in the heat transfer coefficients were achieved for HCFC-123. However no appreciable enhancement is observed for FC-72 which demonstrates that the charge relaxation time is an important parameter also for EHD augmentation of boiling heat transfer. It has found that the surface preparation is very important for boiling inception and augmentation of boiling heat transfer by EHD methodology. It may be concluded that a working fluid with shorter charge relaxation time such as HCFC-123 is appropriate for the evaporator application in waste heat recovery plant.

Acknowledgement

The authors wish to acknowledge the Ministry of Education for supporting this work under contract No. ME 96-A-14.

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