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Active enhancement of evaporation of a liquid drop on a hot solid surface using a static electric field

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Abstract—This study aims at further improvement of evaporation or boiling heat transfer using an electric field. Active enhancement using an electric field would be extremely effective in film boiling, but favorable effects would be expected on nucleate and transition boiling, and on the maximum and minimum heat fluxes. In this paper the results of our preceding studies are first summarized. We have found that the application of an electric field enhances, to a great extent, the evaporation of a liquid drop on a hot solid surface. The time needed for a single drop to evaporate completely reduces to one-twentieth of that for evaporation without an electric field, when 300 V is applied to a drop of ethanol. The results of an additional experiment are presented in this paper. The heat transfer coefficient during evaporation of a liquid drop on a platinum surface is measured while the volume of the drop suspended at the tip of a thin needle nozzle is kept constant. The voltage applied between the drop and the heat transfer surface is varied from 0 V to 2000 V (for R113) or to 250 V (for ethanol). The maximum enhancement ratios of the evaporative heat transfer coefficients at the highest voltages are 7.6 for ethanol and 2.8 for R113.

INTRODUCTION

THE EFFICIENT removal of heat from high-temperature objects is one of the most important issues in the heat transfer technology. It is demanded in effective use of thermal energy generated by combustion or nuclear reaction, in rapid cooling in materials processing, in electronic equipment cooling, and in many other industrial processes. The use of heat transfer with a change of phase, such as boiling and evaporation, is considered the most promising way.

We have been attempting to enhance boiling and evaporative heat transfer with an active technique utilizing an electric field [1–8]. The use of an electric field seems to be very effective, particularly in the case of a heat transfer surface with a high superheat at which film boiling takes place. Heat transfer in nucleate and transition boiling regimes, and the maximum and minimum heat fluxes, may also be improved.

The mechanism of enhancement of boiling or evaporative heat transfer by an electric field is due to electro-hydrodynamic (EHD) forces acting on both vapor and liquid phases, resulting in an instability of the vapor–liquid interface. Thus, the effect of an electric field varies depending upon timewise or spatial distribution of the field, the physical properties of the liquid, and the mode of boiling or evaporation.

We have focused attention mainly on film boiling, and tried to elucidate the mechanism of enhancement. In other words, we have been investigating, both experimentally and theoretically, the relationship between the criteria for onset of instability at the vapor–liquid interface and the liquid properties (polarity, charge relaxation time, etc.) or the characteristics of the electric field (DC/AC, uniform/nonuniform, etc.).

In this paper, the results of our investigation over the past few years are summarized first. Then the findings of a recently conducted experiment are reported.

SUMMARY OF PREVIOUS STUDIES

We have confirmed in a series of experimental studies [1–8] that the application of an electric field is very effective in enhancing boiling and evaporative heat transfer. Its mechanism has been made clear. The effectiveness of the electric field is found to be particularly prominent in the regime of film boiling.

Table 1 summarizes the experimental results showing the effect of electric field on evaporation of a liquid drop on a hot surface. Figure 1 shows the schematic diagram of the experimental apparatus. A liquid drop suspended at the tip of a thin wire is placed on a solid surface which is heated electrically from below. An electric voltage is applied between the thin wire and the heated surface. The time needed for the drop to evaporate completely (which is called evaporation time) was measured. (See refs. [1, 2] for more details of the apparatus and experimental procedure.) In this case the drop placed on a hot solid surface evaporated very slowly taking a spheroidal shape because a stable vapor film was formed underneath the drop due to a high superheat of the surface. The application of an electric field enhanced evaporation to a great extent. In Table 1 comparison is made under an applied elec-

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Table 1. Summary of the results of experiments on EHD enhancement of evaporation of a liquid drop on a hot surface

Liquid	Electrical conductivity σ (℧ m^{-1})	Dielectric constant (F m^{-1})	Electrical relaxation time τ(s)	Equivalent dia. d (mm)	Enhancement ratio at 300 V (surface temp.)	Critical voltage† E_{cr} (kV)
Water	4×10^{-6}	6.95×10^{-10}	1.74×10^{-4}	3.2	× 3 (400°C)	19
KCl solution (0.01 N)	1.28×10^{0}	—	—	3.2	—	—
Ethanol	1.35×10^{-7}	2.22×10^{-10}	1.64×10^{-3}	2.2	× 20 (300°C)	13
R113	2.20×10^{-11}	2.13×10^{-11}	0.97	—		15
Carbon tetrachloride	2.2×10^{-13}	1.98×10^{-11}	90.1	—	—	16
Toluene	1.0×10^{-12}	2.11×10^{-11}	21.1	—		14
Cyclohexane	1.9×10^{-12}	1.78×10^{-11}	9.37	2.7	× 1.3 (300°C)	14
Hexane	1.7×10^{-16}	1.67×10^{-11}	9.82×10^{4}	—	—	12
o-Xylene	$< 1.0 \times 10^{-13}$	2.27×10^{-11}	$2.27 \times 10^{2} >$	—	—	15.5
n-Butane	$< 10^{-11}$	1.70×10^{-11}	$1.70 >$	—	—	12

†The voltage above which the calculated minimum value of the unstable wavelength becomes less than 20 mm (which is the diameter of the liquid surface) when the electrode-to-liquid surface distance is 8 mm.

tric voltage of 300 V, at which the observed ratio of enhancement of evaporation was the highest. However, comparison under other voltages is of course possible.

Of the ten liquids listed in this table, evaporation experiments have been done with water, aqueous solution of potassium chloride (KCl), ethanol and cyclohexane. However, the measurement at 300 V has not been made with KCl solution. We defined the rate of enhancement of evaporation by the ratio of evaporation time under zero volts to that under an electric field. The highest ratio was obtained with ethanol (approximately 20 times), then water (~3 times) and cyclohexane (~1.3 times). The relaxation time of electric charge of each of the liquids is in increasing order as above. Since, from a qualitative point of view, the effect of electric field may be less remarkable for a liquid with a longer charge relaxation time, the result stated above seems to be understandable. However, a quantitative interpretation has not yet been made satisfactorily.

Shown on the rightmost column of the table are the calculated values of the minimum electric potential above which the horizontal, free liquid surface is destabilized by the application of an electric field. In this case a planar electrode is assumed to be placed above and parallel to the liquid surface with 20 mm diameter and is at a distance 8 mm apart from the surface. It corresponds to our experiment using an apparatus shown in Fig. 2 [3, 4]. A liquid is filled in a cylindrical container with an inner diameter of 20 mm. A disc electrode is immersed in the liquid some depth below the surface. Another disc electrode is placed above the surface with some gap. An electric voltage is applied between these two electrodes. If the voltage is gradually increased up to a certain critical value, the surface of the liquid, which was initially

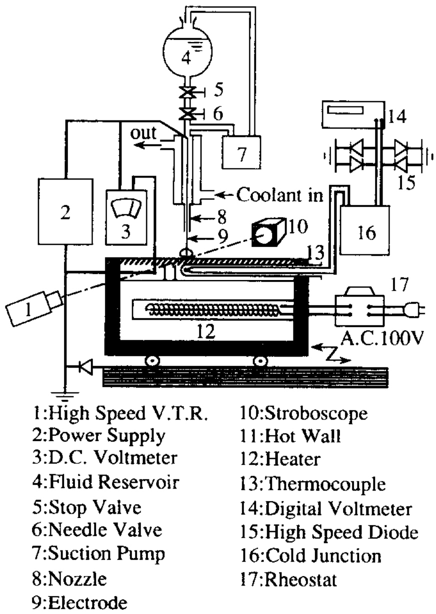


FIG. 1. Experimental apparatus for evaporation of a drop under an electric field (transient measurement).

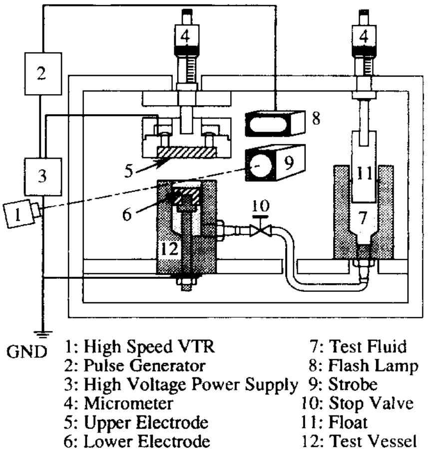


FIG. 2. Experimental apparatus for measuring the critical voltage for the onset of instability on a liquid surface.

quiescent, becomes unstable, a cusp shaped wave appears on the surface, it grows in height, and finally a thin column of liquid rises from the tip of the cusp up to the upper electrode. Thus, we can determine the critical voltage above which the liquid surface is destabilized. According to Table 1 the minimum intensity of the electric field that can destabilize the 20 mm free surface of ethanol is about 1.6 kV mm^{-1}, and it is roughly the same for the other liquids. Although the value of the minimum field intensity varies with liquid properties such as dielectric constant, density and surface tension, the theoretically derived values shown in Table 1 agree very well with the values observed by experiment. The agreement between the theory and the experiment has been confirmed for electrode-to-surface distances between 0.5 and 16 mm. The detailed results of our previous studies on the effect of an electric field on evaporative heat transfer are published in refs. [1–6].

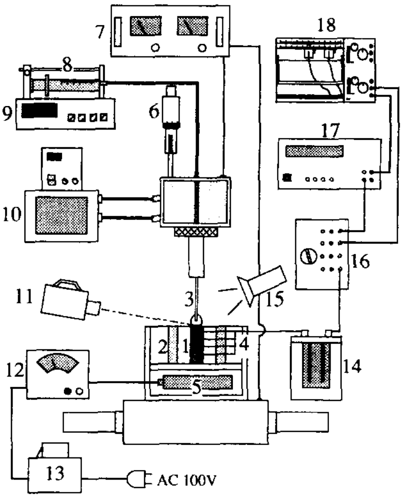
PURPOSE OF THE PRESENT STUDY

In the preceding experiments on evaporation of a liquid drop on a high-temperature surface, the degree of heat transfer enhancement with an external electric field was compared by measuring the time elapsed for the drop to evaporate completely. Although such comparison seems very straightforward and easily understood, there are some issues to be discussed.

Firstly, the surface temperature of the heated plate changes during the process of evaporation. Although the time needed for a single drop to evaporate completely was compared at the same initial surface temperature, the surface temperature itself did not remain constant during evaporation but must have decreased considerably. Also, the speed and degree of the surface temperature decrease must have affected the evaporation time. Secondly, the distance between the heat transfer surface and the bottom of the drop became markedly larger at the final stage of the evaporation process because an interfacial tension between the drop and the electrode wire pulled up the drop, the weight of which was reduced considerably at the end of the evaporation process. Thirdly, the heat transfer surface made of stainless steel must have been oxidized during the experiment. It has been known that the oxidized layer on the surface may change the surface characteristics which affect the boiling heat transfer.

Thus, we have attempted to measure steady-state heat transfer coefficient of evaporation while the volume of a drop is kept almost constant.

Until now, the heat flux supplied to a single liquid drop which evaporates keeping a spheroidal state (i.e. Leidenfrost evaporation) on a heated surface has been measured by Makino and Michiyoshi [9], Kutateladze [10], Xiong and Yuen [11] and Min *et al.* [12]. In every one of those experiments, however, the heat flux was calculated using the result of transient measurement conducted until a single drop vanished by evaporation. No experiment has been carried out under a steady state. Thus, the result of the present experiment will offer new and useful information on the heat flux during evaporation of a liquid drop in Leidenfrost state.

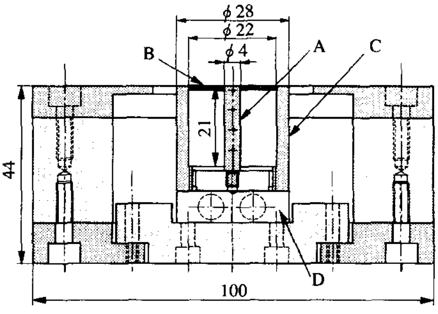


1.Test Block
2.Nickel Ring
3.Needle Nozzle
4.C-A Thermocouple
5.Cartridge Heater
6.Micrometer Head
7.Power Supply
8.Syringe
9.Syringe Pump
10.Constant Temp. Bath
11.High Speed VTR
12.Ammeter
13.Rheostat
14.Cold Junction
15.Strobe
16.Selecter Switch
17.Digital Voltmeter
18.Pen Recorder

FIG. 3. Experimental apparatus for evaporation of a drop under an electric field (steady-state measurement).

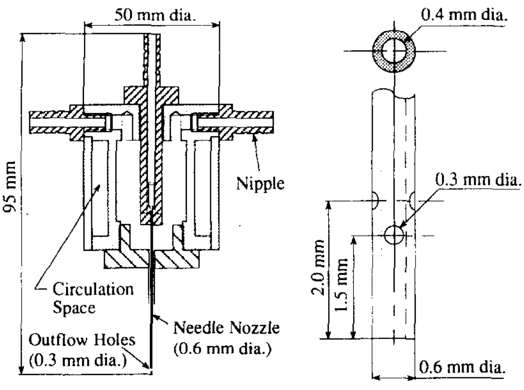
Figure 3 illustrates an outline of the experimental apparatus. This consisted of a heat transfer surface, a main and a guard heater, thermocouples, a nozzle for liquid injection, a syringe pump (Harvard Syringe Pump: flow rate = 8.9 ml min^{-1} ~0.1 μl h^{-1}), a thermostatic bath, a high-voltage power supply (Gamma High Voltage Power Supply: Model RR50-3R), a Strobo, and high-speed video facilities (Nac High Speed VTR, HSV-200 and HSV-1000).

The details of the heat transfer surface are shown in Fig. 4. One end of a solid cylindrical rod (4 mm



A: Platinum Heat Transfer Block
B: Ceramic Layer
C: Nickel Ring
D: Copper Block with Heaters

FIG. 4. Details of the heat transfer surface.



(a) (b)

FIG. 5. Needle nozzle for supplying liquid.

diameter and 21 mm long) made of platinum was used as the heat transfer surface. Platinum was employed because of its excellent resistance to oxidation. Four sheathed thermocouples of K-type (chromel–alumel) with 0.5 mm outer diameter were embedded on the central axis of the platinum rod. The distances from the heat transfer surface were 1, 6, 11 and 16 mm, respectively. Heat flux was obtained from the temperature gradient inside the rod, whereas the surface temperature was obtained by extrapolating the gradient to the surface. To reduce the heat loss from the heat transfer block the platinum rod was fitted to a nickel tube of 28 mm outer diameter and 21 mm length. Nickel was selected because its thermal conductivity ($65.5\ \mathrm{W\,m^{-1}\,K^{-1}}$ at 600 K) is close to that of platinum ($73.0\ \mathrm{W\,m^{-1}\,K^{-1}}$). The periphery of the heat transfer block and nickel tube was insulated fully with fiber insulator and the upper surface was coated with ceramic adhesive to avoid invasion of liquid.

Figure 5(a) shows a schematic diagram of the nozzle used for injection of liquid. A needle nozzle made of stainless steel with 0.4 mm inner diameter and 0.6 mm outer diameter was attached to a support. The base part of the needle was placed in a chamber made of brass in order to keep the liquid temperature constant during the measurement. Water with a constant temperature (30°C in the present experiment) from a thermostatic bath was circulated in the chamber.

The details of the tip of the needle nozzle are illustrated in Fig. 5(b). The nozzle was a circular tube made of platinum, the outer and inner diameters being 0.6 mm and 0.4 mm, respectively. Four small holes of 0.3 mm diameter were drilled on the side wall at distances of 1.5 and 2.0 mm from the tip. The liquid used for the test oozed out of these holes. In the present experiment the tip of the needle nozzle was placed at a distance approximately 0.5–1 mm from the surface.

Prior to measurement, the flow passage from the syringe pump to the needle nozzle was cleaned, and the passage was filled with a test liquid. Care was taken that no air bubbles entered in the liquid. Then the temperature of the test liquid was controlled at 30°C by circulating water from the thermostatic bath in the chamber as mentioned before. After this the heat transfer surface, which had been preheated, was moved to just underneath the needle nozzle and a prescribed amount of the liquid was supplied onto the surface by operating the syringe pump. A prescribed electric potential was applied between the needle nozzle and the heat transfer surface with the use of the high-voltage power supply.

It was most important in this experiment to generate a relatively large and constant-volume drop on the surface, since our aim was to obtain the heat flux at a steady state. For such a purpose we controlled both the flow rate from the pump and the heat input to the heat transfer block, thus keeping steady both the drop volume and the temperature distribution inside the platinum rod.

The heat flux and the surface superheat were obtained by fitting a straight line to the emfs from the four thermocouples in the heat transfer block after a steady state was established. The thermal conductivity of platinum corresponding to the average temperature of the block was employed to calculate the heat flux. The heat loss from the heat transfer block and the heat flux equivalent to the sensible heat of the injected liquid were subtracted from the total heat flux. The heat loss was estimated from the value obtained by insulating the heat transfer surface with fiber insulator. The heat flux by evaporation could be obtained from the flow rate to the liquid drop and the sensible heat of the supplied liquid. The heat flux obtained in this way coincided with the one described above, within a difference of 10%.

A static DC voltage was applied between the needle nozzle and the platinum rod, with the former as a positive electrode and the latter as a negative electrode. Great care was taken in this case to keep the drop stable since the drop was susceptible to deformation and vibration.

The aspect of evaporating drops was video-recorded through a camera placed right above or at an angle to the surface. Filming rates were 200 and 1000 frames per second.

RESULTS AND DISCUSSION

The experiment was carried out using a refrigerant R113 and ethanol. An experiment using water was not successful because violent movements of the drop prevented us from forming a drop with constant volume. Figures 6 and 7 show the dependence of the heat flux on the surface superheat for the two liquids. Different symbols in the figures correspond to different voltages applied between the liquid drop and the heat transfer surface. The voltage is raised from 0 to 2000 V (in the case of R113) and to 250 V (in the case of ethanol).

Six solid lines, A–F, drawn in the figures indicate the Leidenfrost heat fluxes calculated using the cor-

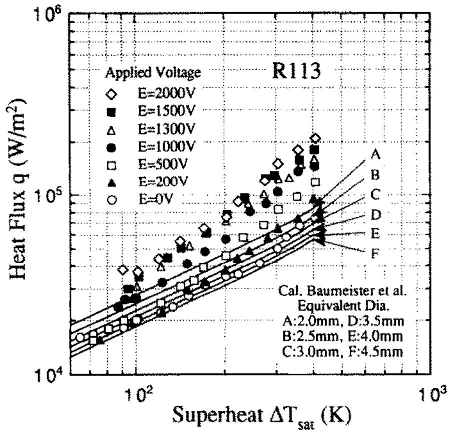


FIG. 6. Dependence of heat flux on surface superheat (R113).

relation proposed by Baumeister *et al.* [13]. Each of the solid lines corresponds to a different equivalent diameter of the drop. In the calculation, the thermophysical properties at the saturated state at atmospheric pressure were used for the liquid phase, and those at the film temperature were employed for the vapor phase.

The open circles in Figs. 6 and 7 show the heat fluxes obtained when no electrical potential was applied. The data points are distributed among the lines A and F, though not so randomly. Since the equivalent diameter of the liquid drop formed in this experiment was around 4 mm, the data marks should have fallen between the lines D and F. The cause of the slightly larger dispersion might be due to considerably large uncertainties in estimating the loss of heat from the heat transfer block.

In the cases of both R113 and ethanol, the heat fluxes increase as the applied voltage is increased. This means that the enhancement of evaporative heat transfer is achieved. However, the degree of enhancement is lower for R113 than for ethanol. A much higher voltage is needed to attain a certain enhancement ratio, because R113 is a non-polar liquid, whereas ethanol is a polar liquid. In the preceding studies [3–6] we found that the onset of instability at the vapor–liquid interface is observable under critical electric field intensities close to those for polar liquids, even for non-polar liquids which have relatively longer times for charge relaxation. However, this was not the case in the present experiment. The reason might be that the interfacial instability occurring in this experiment is so frequent that the relaxation of electric charge does not catch up with it in the case of non-polar liquids.

If Fig. 7 (for ethanol) is compared with Fig. 6 (for R113), it is noticed that enhancement of evaporation takes place at a lower voltage for ethanol than for R113. Increase of the heat flux with the voltage is much more prominent. The voltage above which enhancement of evaporation is observed is 70 V (open squares in Fig. 7), if the surface superheat is very high. Such a tendency coincides with the result confirmed in the previous reports [1, 2].

In contrast, the degree of enhancement was less in the low-superheat region in the case of R113. For example, substantially no enhancement was observed with R113 where the surface superheat was lower than 100 K. Observation with a high-speed video system supported this tendency because no liquid–solid contact was observed in the low superheat region, whereas it was recognized at a higher superheat. One of the most probable reasons for this may be, as mentioned above, a difference in the charge relaxation time of R113 from that of ethanol, as shown in Table 1. However, a more detailed discussion would be necessary to confirm this.

Figure 8 shows pictures taken by a high-speed video

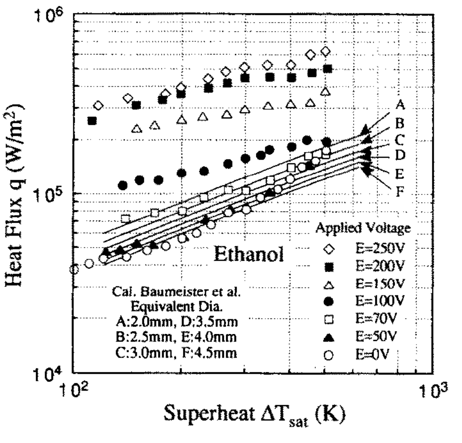
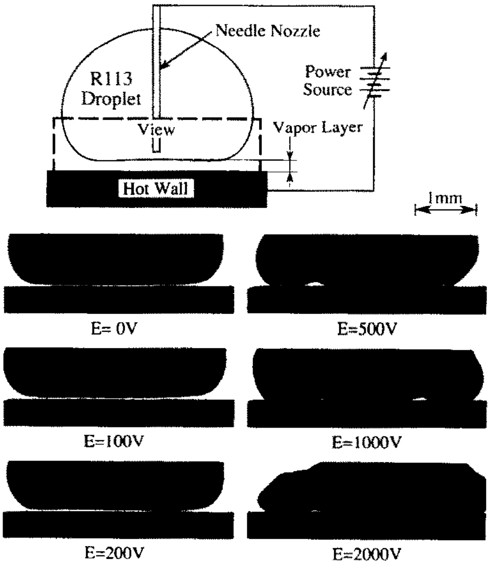


FIG. 7. Dependence of heat flux on surface superheat (ethanol).



Liquid: R113, Superheat ΔT_{sat}=400K, (1000frames/s)

FIG. 8. Pictures showing R113 droplets during evaporation under different voltages.

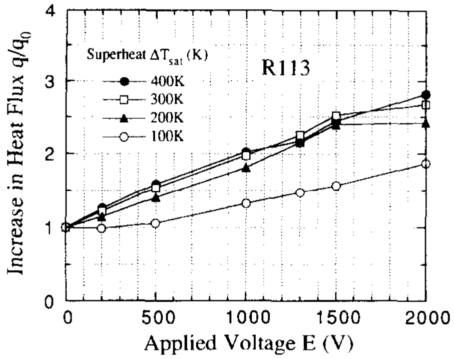


FIG. 9. Increase of heat flux with applied electric field (R113).

tape-recorder during evaporation of R113 drops under different electric voltages. When the applied voltage was 0 or 50 V, a clear gap was observed between the bottom of the drop and the surface, suggesting that the drop was evaporating stably in a spheroidal state. When the voltage exceeded 100 V, a column (or columns) of liquid appeared underneath the drop. As already mentioned, this is due to the occurrence of instability on the vapor–liquid interface. The instability leads to direct contact between the liquid and the heated surface, thus to enhancement of evaporation.

Figures 9 and 10 show the ratio of enhancement against the applied voltage. The surface superheat is taken as the parameter. These results are obtained from the plots shown in Figs. 6 and 7 by approximating them by appropriate smooth curves. The ratio of enhancement here is represented by the increase of heat flux under an electric field relative to the one without an electric field. In the case of R113 (Fig. 9) the heat flux ratios increase almost linearly with the applied voltage, although the gradient is small for the lowest superheat ($\Delta T_{sat} = 100$ K). In the case of ethanol (Fig. 10) the lower the applied voltage, the higher the enhancement ratio.

The effect of the electric field is not observed clearly at 50 V, but it becomes remarkable as the applied voltage is increased. However, the increase in the effect of the electric field seems to be dull at a higher voltage, in particular for lower superheat. The highest enhancement ratio obtained with ethanol is about 7.5 when 250 V is applied at a superheat of 120 K.

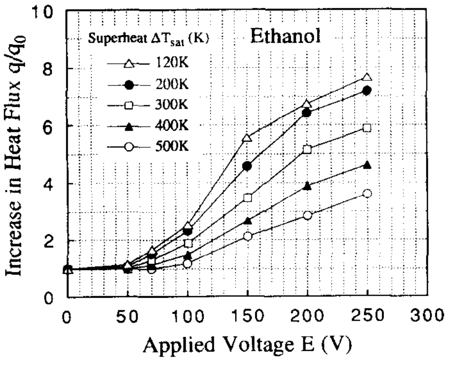


FIG. 10. Increase of heat flux with applied electric field (ethanol).

CONCLUDING REMARKS

A series of experimental and analytical studies have revealed that active enhancement of evaporative heat transfer using an electric field is very effective. A high enhancement ratio is obtained when a liquid drop evaporates on a hot surface in a spheroidal state. An additional experiment was carried out to measure the heat transfer coefficient during evaporation of R113 and ethanol drops. An effort was made to keep the volume of the drop and the heat flux steady during the measurement. The results are summarized as follows.

(1) Evaporation of R113 is enhanced by applying a considerably high voltage, although R113 is a nonpolar liquid.

(2) The effect of an electric field is remarkable for ethanol at low superheat region in particular. Such a tendency agrees qualitatively with the results obtained in the previous study [1,2].

(3) The maximum enhancement ratios attained in this study were 2.8 for R113 and 7.6 for ethanol.

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