EXPERIMENTAL INVESTIGATION OF POOL BOILING HEAT TRANSFER ENHANCEMENT IN MICROGRAVITY IN THE PRESENCE OF ELECTRIC FIELDS

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1. INTRODUCTION

Boiling is an effective mode of heat transfer since high heat flux levels are possible driven by relatively small temperature differences. The high heat transfer coefficients associated with boiling have made the use of these processes increasingly attractive to aerospace engineering. Applications of this type include compact evaporators in the thermal control of aircraft avionics and spacecraft environments, heat pipes, and use of boiling to cool electronic equipment. In spite of its efficiency, cooling based on liquid-vapor phase change processes has not yet found wide application in aerospace engineering due to specific problems associated with the low gravity environment.

After a heated surface has reached the superheat required for the initiation of nucleate boiling, bubbles will start forming at nucleation sites along the solid interface by evaporation of the liquid. Bubbles in contact with the wall will continue growing by this mechanism until they detach. In terrestrial conditions, bubble detachment is determined by the competition between body forces (e.g. buoyancy) and surface tension forces that act to anchor the bubble along the three phase contact line. For a given body force potential and a balance of tensions along the three phase contact line, bubbles must reach a critical size before the body force can cause them to detach from the wall. In a low gravity environment the critical bubble size for detachment is much larger than under terrestrial conditions, since buoyancy is a less effective means of bubble removal (*Zell (1991), Ervin et al. (1992)*).

Active techniques of heat transfer enhancement in single phase and phase change processes by utilizing electric fields have been the subject of intensive research during recent years. The field of electrohydrodynamics (EHD) deals with the interactions between electric fields, flow fields and temperature fields. Previous studies *(Yabe et al. (1995))* indicate that in terrestrial applications nucleate boiling heat transfer can be increased by a factor of 50 as compared to values obtained for the same system without electric fields. Imposing an external electric field holds the promise to improve pool boiling heat transfer in low gravity, since a phase separation force other than gravity is introduced. The goal of our research is to experimentally investigate the potential of EHD and the mechanisms responsible for EHD heat transfer enhancement in boiling in low gravity conditions.

2. BACKGROUND

2.1 Boiling in low gravity environment

Numerous investigators have studied transient nucleate pool boiling both in earth gravity and microgravity. *Ervin et al. (1992)* used high-speed cameras to record two orthogonal views across and through the heating surface, and analyzed boiling spread across the heater surface. The heater surface was relatively large compared to the bubble dimensions at the onset of boiling and their experiments allowed the observation of six distinct categories of bubble dynamics as function of gravity for different surface orientations. In the absence of buoyancy, the initially stagnant fluid remains motionless while heated up to the onset of boiling. The high speed recordings of the boiling process indicate that bubbles grow larger under reduced gravity conditions, they begin to coalesce to a greater extent thus forming groups of larger bubbles *(Lee (1992))*. Coalescence increases with time and patterns are formed by small bubbles. The bubbles also increase in size at a certain distance from the heater *(Zell and Straub (1985), Zell (1991))*.

2.2 Influence of electric fields on heat transfer in boiling

A large amount of theoretical and experimental research has been done on EHD enhanced pool boiling in terrestrial conditions, that has potential applications in cryogenic engineering and heat exchangers *(Karayiannis et al. (1989), Ohadi (1991), Singh et al. (1993) and others ...)*. *Grassi and DiMarco (1992)* reviewed the effects of gravity and electric fields on pool boiling. They showed that the improved heat transfer performance is commonly related to the change in the boiling curve, as illustrated in Figure 1 by the dashed lines. As a result of the

superposition of the electric field, the natural convection and peak heat fluxes are increased, transition boiling can be suppressed, resulting in a more monotonous increase of the boiling curve. These authors emphasize that tests of EHD enhanced pool boiling in reduced gravity can also improve the comprehension of the basic underlying physics of boiling. To our knowledge, the effects of electric fields on boiling in microgravity have not yet been investigated experimentally.

The magnitude of the body force acting on the fluid in the presence of an electric field, $\vec{F_e}$ is obtained as

$$\vec{F_e} = \rho e \vec{E} - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left(E^2 \rho \left(\frac{\partial \varepsilon}{\partial \rho} \right) \right)$$

In this equation ρe is the electric charge density, obtained as the sum of the charges of positive and negative ions and the electrons in a unit volume, ε is the dielectric constant of the fluid and E the electric field strength. The first term on the right hand side of the equation represents the Coulomb force acting on the net charges, the second term describes the force caused by the spatial change of the dielectric constant ε, and the third component, called electrostriction, is the force caused by the inhomogeneity of the electric field strength.

To account for the influence of electric fields on the transport of momentum and heat, the body force term $\vec{F_e}$ has to be added to the external force term in the Navier-Stokes equations. Thus, the sets of equations · describing EHD phenomena consist of the continuity, momentum and energy equations accounting for flow and thermal phenomena, and the Maxwell equations (*Yabe et al., 1995*) that describe the influence of the electric field. The complexity of EHD phenomena is partly caused by the coupling of the governing equations. Examples of such coupling are the presence of the electric body force term in the Navier-Stokes equation as well as the presence of the fluid velocity in the term describing the convective component of the electric current.
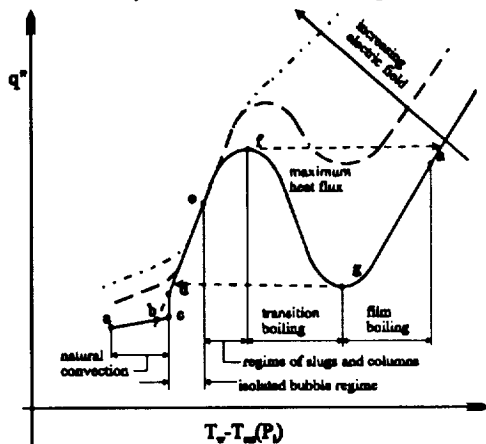

Figure 1. Pool boiling curve and changes due to the influence of the electric field

The presence of bubbles significantly increases the complexity of EHD phenomena, and causes dramatic changes of the boiling cycle, as discussed earlier (Figure 1). Several basic mechanisms involved in the boiling process, such as bubble growth on the wall and detachment, electric charging of bubbles, bubble buoyancy and rise velocity as well as the liquid vapor interface stability are expected to be influenced by the presence of electric forces. The process of EHD enhanced boiling in terrestrial conditions was analyzed experimentally using high-speed cinematography as well as by numerical simulation. One component of the force acting on a bubble in the presence of electric fields caused by the Maxwell stress is perpendicular to the surface and it presses the bubble against it. The radial component of the Maxwell stress parallel to the heated surface causes the motion of the bubble over the surface, characteristic for the presence of electric field.

3. METHOD OF STUDY

3.1 Visualization of temperature fields using real-time holographic interferometry

Holographic interferometry was introduced into heat transfer measurements some 30 years ago (*Hauf and Grigull (1970)*). It allows the visualization of complex steady and unsteady, two or three dimensional temperature fields (*Herman, Mewes, Mayinger, (1992)*) without disturbing the investigated physical process. In the past, some attempts were made to implement it in the investigation of phase change processes, such as boiling, melting and solidification of ice, as well as in sublimation processes. *Beer et al. (1977), Nordmann (1980)* and *Mayinger and Chen (1986)* investigated nucleate pool boiling using holographic interferometry combined with high-speed cinematography. The fringe patterns recorded in their experiments allowed the reconstruction of temperature fields around the bubbles, the analysis of bubble dynamics, and measurements of local heat transfer along the liquid--vapor interface. Due to the complexity of these highly unsteady heat transfer processes and the limitations of the equipment and techniques used in the evaluation of the visualization images, relatively little quantitative information was obtained from those studies. Although the first results of interferometric experiments were promising, measurements of boiling heat transfer by means of holographic interferometry were later abandoned, and nowadays bubble shape, size and frequency are commonly measured.

Holographic interferometry combined with high-speed cinematography, the measurement technique chosen for our study, has not yet been applied to analyze EHD processes in boiling an we expect that our research will yield a new quantitative and qualitative understanding of the phenomenon. Details of real-time holographic interferometry will not be discussed in this paper and the interested reader is referred to specialized literature (*Herman, Mewes, Mayinger (1992)*).

3.2 Thermochromatic liquid crystals

Thermochromatic liquid crystals respond to changes of temperature by changing color. When the heat transfer surface is coated with a layer of such crystals, the local surface temperature can be visualized and measured. This methodology was successfully applied to determine surface temperatures during the process of boiling by *Kenning (1992)*. In our laboratory the same technique was implemented to measure local surface temperatures during boiling. The visualized temperature fields were recorded on photographic film and the colors converted into temperatures by digital image processing techniques. Simultaneously, bubble distributions in the liquid phase were recorded with a second camera. Typical temperature patterns along the heated surface, reconstructed temperature fields as well as bubble distributions, recorded during our preliminary experiments, are shown in Figure 2. This approach will be used in our experimental study of EHD phenomena simultaneously with holographic interferometry.
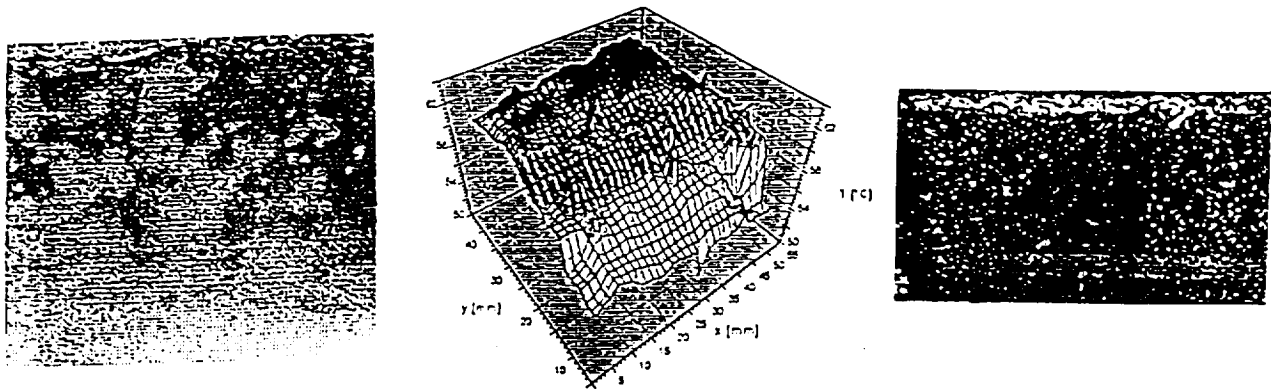
Figure 2. Temperature patterns along the heated surface, reconstructed temperature fields as well as bubble distribution in the liquid

3.3 Digital image processing

The availability of powerful computers and digital image processing techniques nowadays opens new possibilities in the study of high-speed heat transfer processes during boiling. A method for analyzing oscillating temperature fields in a sequence of images in communicating channels has been developed in our laboratory (*Herman (1992)*). By superimposing images after data reduction, the temporal development of an event can be reconstructed. This approach will be implemented to our studies of boiling.

4. EXPERIMENTS

We plan to conduct a systematic experimental investigation of pool boiling in microgravity to gain insight into the influence of electric fields on the boiling process and to perform a quantitative study of heat transfer enhancement in microgravity. We plan to simultaneously visualize and measure the temperature of the heated surface by coating it with thermochromatic liquid crystals and the temperature distribution in the liquid by holographic interferometry. A flat heater surface will be used in the experiments, because it resembles practical applications and it is convenient from the standpoint of optical visualization. This surface will simultaneously serve as one of the electrodes.

The experiments will be conducted in three phases characterized by increasing complexity of the boiling surface geometry. (i) In the first phase of our study the influence of the electric field on the behavior of a single bubble will be investigated. More details about these experiments are given in Section 4.1. (ii) In the second phase, a special heater surface allowing the forming of preferential nucleation sites at specified locations will be designed.
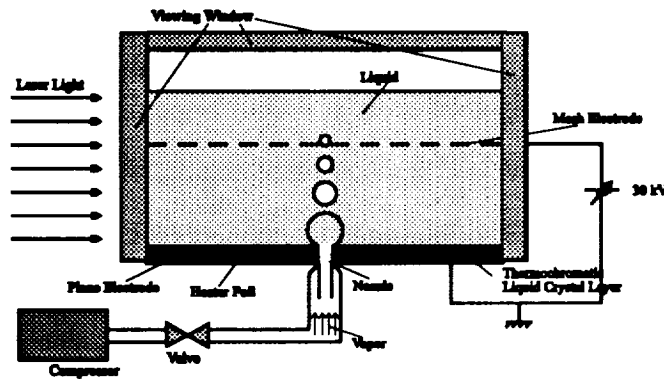
Figure 3. *Schematic of the experimental setup used to study the behavior of a single bubble*

Bubble generation on a heated surface in experimental studies corresponds well to general technical applications. The conditions in the thermal boundary layer along the heated surface and along the surface of the bubble are characterized by high temperature gradients and are difficult to evaluate and control. The exact location and time of bubble formation on a heated surface is generally not known and accurate alignment and focusing of the optical measurement equipment is difficult. As described by *Webb (1994)*, by puncturing the foil glued to a grooved surface at specified locations, reentrant cavities acting as preferential nucleation sites are formed on the heater. The surface with a controlled number of nucleation sites allows the study of boiling under more realistic conditions than nozzle injection and this approach was selected for the second phase of the research. The presence of a limited number of bubbles in the vessel allows the analysis of the interaction of bubbles with each other and the thermal boundary layer. (iii) In the third phase of the experimental research, smooth as well as enhanced boiling surfaces will be used. Since interferometric measurements are not possible when several bubbles are aligned along the path of the light beam, in the third phase data on bubble size, distribution and frequency can be obtained from high-speed visualization experiments.

4.1 Behavior of a single bubble

In the first series of experiments the influence of the electric field on a single bubble will be investigated. Pool boiling is simulated by injecting a single bubble through a nozzle into the subcooled liquid (heater off) or into the thermal boundary layer developed along the flat heater surface, as illustrated in Figure 3. Injection of individual bubbles into the liquid has been proven to be a technique suitable to simulate a physical situation similar to that in subcooled nucleate boiling, as discussed in several studies (*Nordmann (1980), Mayinger and Chen, (1986), Ogata and Yabe (1993)*). The advantage of this approach is that the conditions in the vicinity of the growing bubble can be controlled by the experimenter. Conversely to the situation on the heated surface, the conditions in the vicinity of the developing bubble are generally steady. The bubble grows in a uniformly subcooled liquid. Condensation begins immediately and it takes place over the whole perimeter of the bubble. Bubble growth will be possible as long as the amount of vapor introduced into the bubble through the nozzle is larger than the amount of vapor condensing on the bubble surface. When there is no superheated boundary layer present along the solid surface (heater off), Marangoni convection will be absent. The accurate location of bubble formation is known and thus the optical equipment can be aligned and focused accurately, which is an essential requirement for precision measurements of bubble shape, size and deformation, as well as visualization by holographic interferometry. The size of the bubble and the frequency of bubble departure can be controlled by suitable selection of nozzle diameter and mass flow rate of vapor. In this approach effects due to the presence of the electric field can be separated from effects caused by the temperature gradients in the thermal boundary layer initially, and the influence of the thermal boundary layer can be included after activating the heater at a later stage of the research. All these features of the experimental setup offer the advantage of yielding clear and unambiguous results depending on a limited number of controlled process parameters.

4.2 Experimental setup

The cross section of the experimental setup to be used in the first phase of the research is presented in Figure 3. Vapor is supplied to the bubble though the central cylinder of a coaxial nozzle. Vapor is also supplied to the outer annulus to prevent the cooling down of vapor when passing through the injection nozzle. The plane metal surface around the nozzle serves as one of the electrodes, and it is equipped with an electric heater that provides heating to the electrode, when required. The second brass mesh electrode is positioned above the heated surface and it is parallel to the first one. Later during the course of the project, the influence of the form of electrodes and the direction and form of electric field lines on the bubble motion and heat transfer enhancement will be

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investigated. Apart from the (i) parallel mesh wire electrode, we will use (ii) one and (iii) more cylindrical electrodes in these experiments as well.

4.3 Measurements

The temperature fields in the thermal boundary layer in the vicinity of the heated surface and around the growing bubble will be analyzed using holographic interferometry combined with high speed cinematography. Since typical time scales for boiling are of the order of ms, we will use a rotating prism high-speed 16 mm film camera that can achieve recording rates up to 6000 frames per second. This approach was successfully implemented to measure local Nusselt numbers along the perimeter of the growing bubble as function of position and time by *Nordmann (1980)*. We expect to be able to achieve similar or better accuracy, since Nordmann's evaluations were conducted manually. Local heat transfer along a heated wall and heat transfer enhancement will also be measured.

Investigations of bubble behavior in the vicinity of the heated surface by *Ogata and Yabe (1993)* indicated that bubbles were pressed against the heated electrode and moved violently around it, when either positive or negative voltage was applied. Such a behavior can initiate a whole range of interactions with the thermal boundary layer. The increased momentum transfer in the boundary layer due to bubble motion can yield an enhancement of heat transfer as result of the "massaging" of the thermal boundary layer, similar to that observed in barbotage. If the bubbles move close enough to the surface, heat transfer through the microlayer may be an important mechanism of enhancement. The bubbles "touching" the heater may generate additional nucleation sites and thus also contribute to the enhancement of heat transfer. These questions will be addressed in our study. The visualization of surface temperatures by thermochromatic liquid crystals will allow us to quantify these effects. In order to photograph the heated surface, the cover plate of the test section is manufactured of glass and the mesh electrode has to be semi-transparent as well.

We propose to vary the heater surface orientation from downward to upward. A properly applied electric field with downward facing heater geometry could allow one to obtain a region in the boiling liquid where the electric force approximately balances the gravity force. This experiment may answer the question regarding the possibility to achieve conditions of low gravity in earth -based experiments.

Precision measurements of bubble size during growth and after detachment, visualization of the local flow structure in the wake region by holographic interferometry, and the impact of the bubble on the thermal boundary layer in this simple and idealized situation will yield both qualitative insight and quantitative data.

4.4 Selection of the working fluid

Different substances, gases and liquids, as well as combinations of fluids have been used as working fluids in electrohydrodynamic studies. Dielectric liquids are required in electronic cooling applications. The commonly utilized refrigerants are suitable for our experiments, since their boiling point is achieved at relatively low temperatures, and thus power requirements on the heater are not excessive. An important property of a liquid that determines the magnitude of heat transfer enhancement in EHD applications is the relaxation time of electric charges, t_c, defined as $t_c = \varepsilon / \sigma_e$. In this definition, ε is the dielectric constant of the fluid and σ_e denotes its electrical conductivity. The relaxation time is the measure of the time period required to reach steady state in an electric field. The ratio of t_{EHD}, the time scale typical for the investigated EHD phenomenon, and the relaxation time determines if the fluid can be assumed to be a dielectric (for $t_{EHD} << t_c$) or an electrically conducting (for $t_{EHD} >> t_c$) substance. The EHD boiling heat transfer enhancement effect increases with increasing electrical conductivity of the liquid, as discussed by *Yabe et al. (1995)*. The effect is most pronounced when the relaxation time of electric charges in the liquid is less than the characteristic time for bubble detachment from the surface, which is known to be of the order of milliseconds. This criterion is satisfied by HCFC 123, mixtures of CFC 11 and ethanol, as well as other CFC alternatives. The orders of magnitude of the relaxation times are 1 s for insulating liquids, such as CFCs, 1ms for low conductivity liquids (HCFCs and HFCs) and 1 μ s for electrically conductive liquids, respectively. Apart from selecting one from the class of "semi-conducting" liquids, the final choice of the working fluid will also depend on the refractive index value, which has to be suitable for interferometric measurements.

5. CONCLUDING REMARKS

Heat transfer rates achieved in boiling under normal gravity and microgravity, as well as with and without electric fields, will be compared. System pressure will be varied as one of the parameters of the experiment. One of the expected results of this study will be the better understanding of the basic mechanisms of boiling and the dominating forces by separating the gravity dependent and gravity independent effects. Earlier studies of bubble growth, bubble dynamics, departure diameter and frequency under imposed electric fields of different intensities indicate that when high field intensities are reached, bubbles become smaller and move more violently around the heat transfer surface. This observation leads to the question if control of bubble diameter at detachment may be achieved in pool boiling under microgravity by controlling the intensity of the applied electric field. This hypothesis can be verified through our study. Another important question that remains to be answered is the possibility of the existence of steady state boiling and nucleate boiling under microgravity, as strong electric fields could prevent the coalescence of bubbles in low gravity conditions as well.

6. ACKNOWLEDGMENTS

7. REFERENCES

Beer, H., Burow, P, Best, R., 1977, Bubble Growth, Bubble Dynamics and Heat Transfer in Nucleate Boiling, Viewed with a Laser Interferometer, in Heat transfer in Boiling, eds. E. Hahne and U. Grigull, Hemisphere Publishing Corp., Washington, pp. 21-52.

Ervin, J. S., Merte, H., JR., Keller, R. B., Kirk, K, 1992, Transient Pool Boiling in Microgravity, Int. J. Heat Mass Transfer, Vol. 35, No. 3, pp. 659-674.

Grassi, W., Di Marco, P., 1992, Gravity and Electric Field Effects on Pool Boiling Heat Transfer, Proc. VIIIth European Symp. on Materiaaals and Fluid Sciences in Micrograavity, Brussels, ESA SP-333, pp. 783-788.

Hauf, W., Grigull, U., 1970, Optical Methods in Heat Transfer, in Advances in Heat Transfer, Vol. 6, Academic Press Inc., New York.

Herman, C., 1992, Heat Transfer in Single and Communicating Grooved Channels (in German), Dissertation.

Herman, C. V., Mewes, D., Mayinger, F., 1992, Optical Techniques in Transport Phenomena, Advances in Transport Processes VIII, Editors A. S. Mujumdar, R. A. Mashelkar, Elsevier Science Publishers, Amsterdam and New York, pp. 1-58.

Karayiannis, T.G, Collins M.W., Allen P.H.G, 1989, Electrohydrodynamic Enhancement of Nucleate Boiling Heat Transfer in Heat Exchangers, J. of Heat Technology, Vol. 7, No.2, pp. 263-274

Kenning, D. B. R., 1992, Wall Temperature Patterns in Nucleate Boiling, Int. J. Heat Mass Transfer, Vol. 35, No. 1, pp. 73-86.

Lee, D. J., 1992, Bubble Departure Radius under Microgravity, Chem. Eng. Comm., Vol. 117, pp. 175-189.

Mayinger, F., Chen, Y. M., 1986, Heat Transfer at the Phase Interface of Condensing Bubbles, Proc. 8 Int. Heat Transfer Conf., San Francisco, California, USA, pp. 1913-1918.

Nordmann, Dieter, 1980, Temperatur, Druck und Wärmetransport in der Umgebung kondensierender Blasen, Dissertation, Technische Universität München.

Ogata, J., Yabe, A., 1993, Augmantation of Boiling Heat Transfer by Utilizing the EHD Effect - EHD Behaviour of Boiling Bubbles and Heat Transfer Characteristics, Int. J. Heat Mass Transfer, Vol. 36, No. 3, pp. 783-791.

Ohadi, M. M., 1991, Heat Transfer Enhancement in Heat Exchangers, ASHRAE Journal, Dec., pp. 42-50.

Singh, A., Kumar, A., Dessiatoun, S., Faani, M. A., Ohadi, M. M., Ansari, A. I., 1993, Compound EHD-Enhanced Pool Boiling of R-123 in a Liquid-to-Refrigerant Heat Exchanger, ASME Paper - 93-WA/HT-40.

Yabe, A., Mori, Y. and Hijikata, K., 1995, Active Heat Transfer Enhancement by Utilizing Electric Fields, In : Annual Review of Heat Transfer, Vol. 7, Begell House Publishing.

Zell, M., 1991, Untersuchung des Siedevorgangs unter reduzierter Schwerkraft (Investigations of boiling under reduced gravity), Dissertation, Technische Universität München, Germany.

Zell, M., Straub J., 1985, Experimentelle Untersuchung des Warmeubergangs und seiner Transportmechanismen unter reduzierter Schwerkraft, Jahrbuch 1985 der Technischen Universit"at Munchen, Germany.

Webb, R. L., 1994, Principles of Enhanced Heat Transfer, John Wiley & Sons, New York.