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EFFECTS OF PRECISE ARRAYS OF PITS ON NUCLEATE BOILING*

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Abstract—A photographic method for the manufacture of precise arrays of artificial pits was applied to flat plate copper heat transfer surfaces. The surfaces were then used to boil Freon 113 at one atmosphere pressure. The resulting nucleate boiling data indicate that surface microgeometry has a profound effect on the location of both the nucleate boiling curve and the burnout point. Extremely shallow or jagged edged pits were found to be much more efficient than well formed pits. The heat transfer efficiency was found to increase with increasing pit density up to an upper limit above which increasing pit density does not affect the nucleate boiling behavior.

INTRODUCTION

A PHOTOGRAPHIC etching method [1, 2] was used to prepare precise arrays of artificial pits on copper surfaces. Briefly, the process involved applying a photo-sensitive coating, known as photo-resist, to the surface to be etched and then exposing that surface to light through a negative of the pattern of sites desired. After developing, the resist coating masked the surface everywhere except at points where pits were to be formed. The surface was then dipped into a corrosive chemical, causing pits to be etched while the remainder of the surface was protected by the mask. The mask was later stripped with solvent, leaving a flat surface perforated with a precise array of pits.

The experimental equipment included a pressure and condensing system, a heating element, and a temperature measuring system. Since the equipment has been described in detail [2] previously, that description will not be repeated here.

In order to insure that data could be meaningfully compared among surfaces, it was necessary to carefully prepare each before testing. The test surfaces were manually wet sanded using silicon carbide paper under flowing water. Four grits of paper, 240, 320, 400 and 600 (in order of decreasing roughness) were used. Additional mechanical polishing was done on the surfaces to achieve a nearly mirror-smooth finish. Each surface was scrubbed with acetone after polishing. The polishing proved to be more of an art than a science. An acceptable range for mirror surfaces boiling curves was thus adopted and surfaces not falling on that range were repolished before further testing.

The experimental data consisted of steady state measurements of surface, core, bath and ambient temperatures at various main heater power levels. Measurements of pit diameter and depth were also items of experimental data. The density (number of pits per unit area) of the etched arrays was known to be exactly that of the dot array negatives used. However, the pit diameters and depths had to be measured experimentally using a scanning electron microscope (SEM). Knowledge of the pit density permitted calibration of the SEM magnification. Micrographs of pits taken at an acute angle from the plane of each surface enabled the depth-to-diameter ratio to be determined geometrically [2]. The average diameter reported is considered to be accurate to $\pm 5\%$ but the accuracy of the depth measurement was only $\pm 20\%$ [2]. A summary of pit measurements is presented in Table 1. Representative micrographs of both good and bad etching results are presented in Fig. 1 for surfaces 9 and 10. The unpitted areas of both surfaces were somewhat rougher than most of the investigation.

EXPERIMENTAL OBSERVATIONS AND DISCUSSION

For low density arrays at low fluxes, the artificial pits were visually observed to be the active nucleation sites. For higher fluxes or dense arrays it was not clear where nucleation occurred because a curtain of bubbles obscured the surface. The bubbles from dense arrays were, nevertheless, smaller and in more regular patterns than those from other surfaces.

'Patchwise' boiling was often noted at low fluxes, especially on surfaces with dense arrays. These patches occurred at approximately the same locations on a given surface at a given flux, but the locations did not in general coincide with those of other surfaces.

Boiling from sandpaper finished surfaces exhibited a random distribution of sites. Patchwise boiling on

* The experimental work discussed in the paper was performed by Dr. Messina while he was a graduate student under Dr. Park at the University of Missouri-Rolla.

Table 1. Summary of pit measurements

Surface number	Density (pits/cm^2)	% Coverage	Average diameter (cm)	Depth-to-diameter ratio	Depth (10^{-5} cm)
6	280	9.65	0.0325	0.103	4.2
7	280	12.82	0.0374	0.064	2.4
8	140	12.46	0.0524	0.058	3.0
9	558	23.39	0.0358	0.030	1.1
10	558	21.86	0.0346	0.102	3.5
11	1120	21.17	0.0241	0.145	3.5
12	2232	46.08	0.0251	0.108	2.7
13	558	29.07	0.0398	0.051	2.0
14	280	6.28	0.0262	0.108	2.8
15	1120	43.79	0.0346	0.072	2.5
16	558	23.88	0.0362	0.053	1.9
17	140	9.67	0.0461	0.051	2.4
18	280	14.18	0.0394	0.106	4.2
20	2232	29.94	0.0203	0.094	1.9
21	1120	14.16	0.0197	0.086	1.7

sanded surfaces was not as clearly evident or widespread as on etched surfaces.

Visual observation of boiling from mirror surfaces revealed that relatively few sites were active at low fluxes. When nucleation did occur, the bubbles formed were flat and closely packed and no patchwise boiling was noted.

Vortices occurred on all surfaces studied, sweeping across the heat-transfer surface like small tornados leaving active nucleation sites in their wakes. However, such sites often did not remain active.

Poorly formed or very shallow pits such as those on surface 9 generally caused a significant increase in heat transfer. It was impossible to determine the causes for such poorly formed arrays. Variations in resist thickness or mirror surface roughness may account for the problem. However, a refined etching procedure could probably eliminate such problems.

Micrographs shown in Fig. 1 also illustrate the regularity of the etched arrays and reveal the microstructure of the material within the pits. As shown for surface 10, most surfaces contained 'boulders' within the artificial pits. It was impossible to determine the specific factors(s) which governed their existence. However, non-dispersive electron analysis revealed that the boulders consisted primarily of copper; but traces of iron and chlorine were also present, undoubtedly due to the ferric chloride etchant.

In general, the etching of mirror surfaces significantly increased the heat-transfer efficiency. Boiling curves generated from consecutive runs on a given surface were usually highly reproducible, with scatter apparent only at relatively low fluxes.

Introduction of similar pits into 600 grit sandpaper finished surfaces had very little effect on the nucleate boiling characteristics. Etching away large portions of the sanded surfaces caused marked decreases in efficiency, but the most inefficient transfer surfaces were still the mirror surfaces. Surfaces with very low pit coverages yielded data very close to those of mirror surfaces, particularly at high fluxes.

In general, it was possible to reproduce nucleate boiling results on separate surfaces containing nearly identical photographically etched artificial pits. Exceptions involved surfaces in which mutant pits were present. The reproducibility among all mirror surfaces was not as good. It was shown, however, that the scatter did not affect the etched surface results [2].

Comparison among the data for individual surfaces permitted the effects of pit density, diameter and coverage to be analyzed. Pit density was the predominant factor which determined the location of the nucleate curves. Five densities were studied: 140, 280, 558, 1120 and 2232 pits cm^2.

Representative curve fits for data at each pit density studied are compared in Fig. 2 with data for 600 and 240 grit sandpaper finished surfaces and all mirror control surfaces. An increase in pit density generally produced an increase in heat-transfer efficiency over the upper half of the nucleate region. The extent of the enhancement was considerable between 140 and 558 pits/cm^2. However, the improvement decreased with increasing density, and at high densities little further improvement was noted. An upper limit for the enhancement therefore existed.

All pitted surfaces were more efficient than mirror surfaces. However, sandpaper finished surfaces were even more efficient, with 240 grit more efficient than 600 grit. As sanded surfaces represent even larger site densities than 14400 sites/in.^{2}, all data of the investigation indicated that efficiency increased as the density of sites increased.

Many early investigators, including Kurihara and Meyers [3], studied boiling from sandpaper roughened surfaces and found similar trends for enhancement with increasing surface roughness. The cause of this difference in enhancement was not determined. Bubble interactions of pit geometries may have affected the limit, but more data are needed to explain the phenomena.

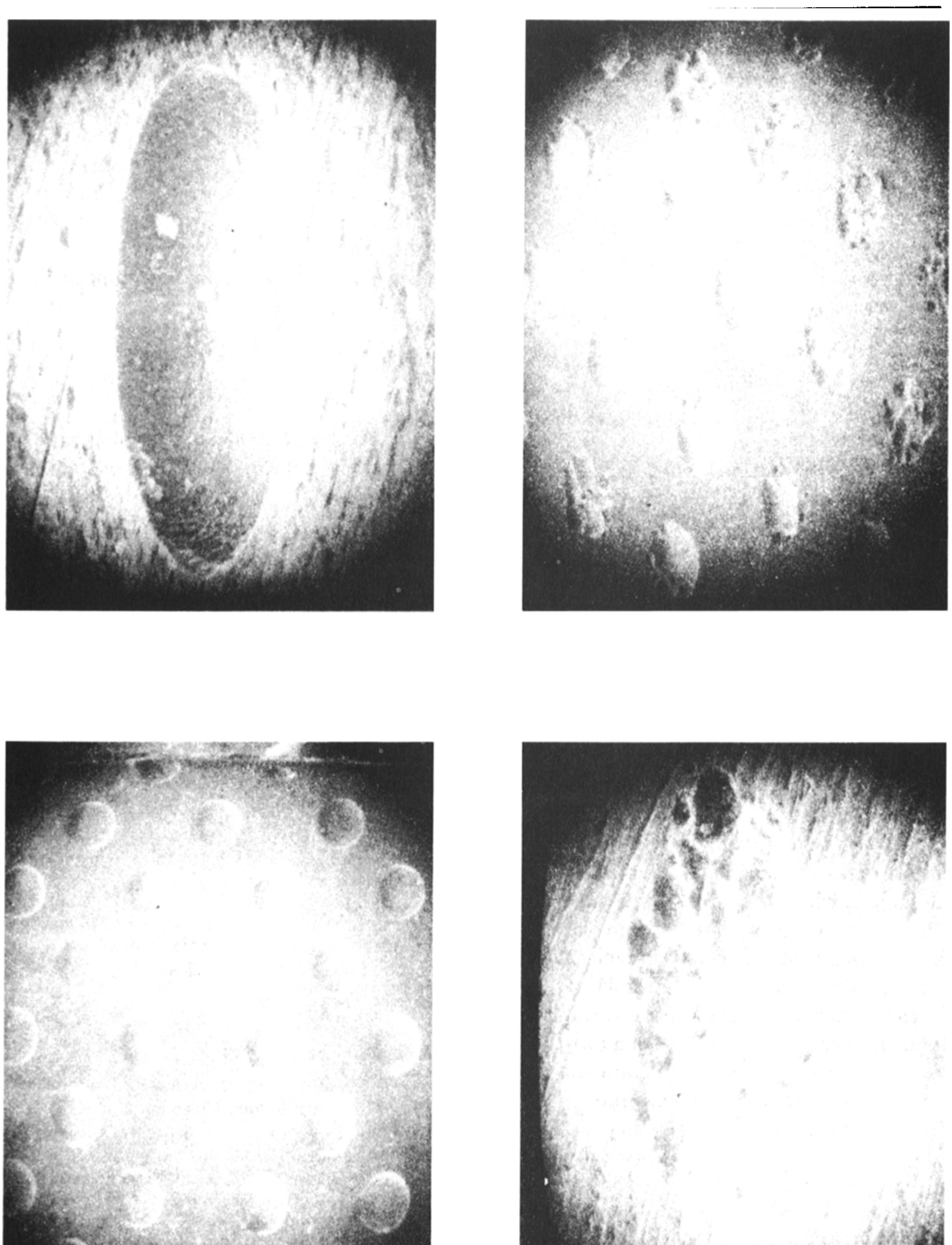

FIG. 1. Scanning electron micrographs of surface 9 (bottom row) and of surface 10 (top row).

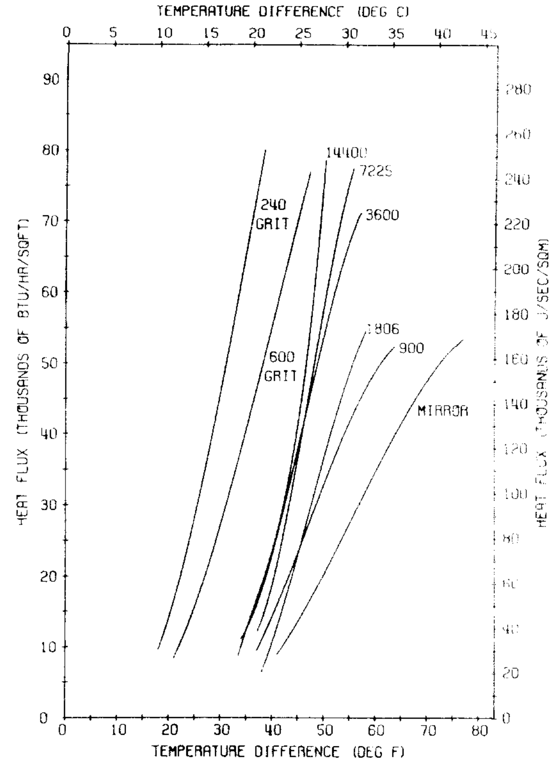

FIG. 2. Effect of pit density on the nucleate boiling curve (densities in pits/in.^{2}).

The fact that poorly formed pit arrays yielded seemingly anomalous results further highlights the important role of microstructure in boiling. It is significant that both jagged-edged pits such as those of surface 9, as well as very shallow pits yielded significantly higher heat transfer than other arrays. These data are not anomalous when considered in terms of the strong site density trend noted above. 'Cat prints', such as on surface 9, actually represented several pits at each etched site and thus provided a much larger density. The increased efficiency of surface 9 was thus consistent with the density trends of the investigation.

Build-ups of material were sometimes also present within the pits. It is possible that shallowness allowed particles within the pits to function as nucleation sites. These particles would have increased the effective nucleation site density and caused the enhanced heat transfer which was observed for shallow pitted surfaces.

No previous investigations have considered artificial pits as shallow as those of the present investigation to be efficient nucleation sites. It is nonetheless apparent, at least for the ranges of pit parameters and experimental conditions involved, that the pits acted as sources of bubble nuclei.

The substantial decreases in heat transfer rate which were noted when large portions of the 600 grit surfaces were etched away were expected since large scale etching essentially destroyed natural sites, decreasing the site density and thus also decreasing the heat transfer.

Inspection of the data also revealed that at approximately 75% of the critical flux sharp differences existed among curves representing constant pit densities. It is reasonable to assume that such changes represented a transition in the boiling mechanism, with the portion of the curve above the change being governed by a burnout mechanism of some type. Several previous investigators, e.g. [4] and [5] have postulated that distinct regions and mechanisms are required to explain nucleate boiling phenomena, basing their assumptions on the observation of bubble nucleation.

CONCLUSIONS

1. Surface microgeometry had a profound effect on the location of both the nucleate boiling curve and the burnout point.
2. Extremely shallow artificial pits with depth-to-diameter ratios as low as 0.030 functioned as nucleation sites on mirror surfaces.
3. Pit density dominated the location of the nucleate boiling curves. In general, the curve shifted to higher efficiency with increasing density. An upper limit also existed for this enhancement.
4. Extremely shallow or jagged edged pits were substantially more efficient for nucleate boiling than corresponding well-formed pits.
5. A transition in mechanism existed in the nucleate boiling region at approximately 75% of the critical heat flux.

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REFERENCES

1. A. D. Messina and E. L. Park, Jr., A new tool for nucleate boiling research, *Chem. Engng Commun.* **4**, 69 (1980).
2. A. D. Messina, Effects of precise arrays of pits on the nucleate boiling of Freon 113 from flat copper surfaces at one atmosphere pressure, Ph.D. Thesis, University of Missouri-Rolla, Rolla, Missouri (1978).
3. H. M. Kurihara and J. E. Myers, The effects of superheat and surface roughness on the boiling coefficient, *A.I.Ch.E. Jl* **6**, 83 (1960).
4. R. F. Gaertner, Photographic study of nucleate pool boiling on a horizontal surface. *J. Heat Transfer* **87**, 17 (1965).
5. R. Moissis and P. J. Berenson, On the hydrodynamic transitions in nucleate boiling, *J. Heat Transfer* **85**, 221 (1963).

EFFET DES RANGEES PRECISES DE PIQURES SUR L'EBULLITION NUCLEEE

Résumé—Une méthode photographique pour la fabrication précise de rangées de creux artificiels est appliquée sur des plaques planes en cuivre. Les surfaces sont utilisées pour l'ébullition de Fréon 113 à la pression atmosphérique. Les résultats sur l'ébullition nucléée montrent que la microgéométrie de la surface à une influence importante à la fois sur les positions de la courbe d'ébullition nucléée et du régime critique. Des piqûres extrêmement peu profondes ou à bords abrupts sont plus efficaces que des cavités bien formées. L'efficacité du transfert thermique augmente en même temps que la densité des piqûres jusqu'à une limite supérieure au dessus de laquelle un accroissement de la densité des piqûres n'affecte pas l'ébullition nucléée.

DER EINFLUSS REGELMÄSSIG ANGEORDNETER KEIMSTELLEN AUF DAS BLASENSIEDEN

Zusammenfassung — Mit einer fotografischen Methode wurden an waagerechten Oberflächen aus Kupfer regelmäßige Anordnungen künstlicher Keimstellen aufgebracht. An den Oberflächen wurde R113 bei atmosphärischem Druck verdampft. Die Ergebnisse der Siedeversuche zeigen einen starken Einfluß der Mikrogeometrie der Oberfläche auf die Lage der Siedekurve und den Burnout-Punkt. Die besonders flachen oder gezackten Keimstellen waren wirksamer als die gleichmäßig ausgebildeten. Die Intensität des Wärmeübergangs nahm bis zu einem oberen Grenzwert mit zunehmender Keimstellendichte zu. Über diesen Grenzwert hinaus beeinflußte die Keimstellendichte das Blasensieden nicht.

ВЛИЯНИЕ РАВНОМЕРНО РАСПРЕДЕЛЕННЫХ РЯДОВ ВПАДИН НА ПУЗЫРЬКОВОЕ КИПЕНИЕ

Аннотация — На поверхностях теплообмена в виде плоских медных пластин фотографическим методом вытравливались ряды впадин, равномерно распределенных по поверхности. Пластины затем использовались для исследования кипения фреона-113 при давлении в 1 атм. Полученные данные по пузырьковому кипению показывают, что микрогеометрия поверхности оказывает сильное влияние как на положение кривой пузырькового кипения, так и точки кризиса кипения. Найдено, что неглубокие впадины или впадины с зазубренными краями гораздо более эффективны, чем хорошо сформированные. Найдено также, что эффективность теплопереноса возрастает с увеличением плотности впадин, но до определенного предела, выше которого плотность впадин перестает влиять на поведение пузырькового кипения.