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Full Length Research Paper

An optimal parametric design to improve pool boiling heat transfer of sintered surfaces

Mao-Yu Wen[1]*, Ching-Yen Ho[2] and kuen-Jang Jang[1]

[1]Department of Mechanical Engineering, Cheng Shiu University, Kaohsiung 833, ROC, Taiwan.
[2]Department of Mechanical Engineering, Hwa Hsia Institute of Technology, Taipei 235, ROC, Taiwan.

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This study investigated the effect of design parameters on pool boiling heat transfer on the sintered surfaces of a tube. The pool boiling experiments were conducted in saturated, deionized and degassed water. Data were taken at an atmospherical pressure and a fixed heat flux of 41,000 $\mathrm{W/m^2}$. In the experimentation, the effects of the sintering pressure, sintering time, sintering temperature, heating rate, and particle size on the boiling heat-transfer coefficient of the sintered surface were investigated using the Taguchi method, and an $L_{15}(3^5)$ orthogonal array table was selected as an experimental plan for some parameters earlier mentioned. Based on the results of SN (signal/noise) ratio and ANOVA (analysis of variance), the optimal conditions of specifications of parameters will be provided. It was found that all the chosen sintering factors have significant effects on the pool boiling heat transfer coefficient. Flow visualization is also used to investigate the behavior of the pool boiling phenomena of the present sintered surfaces. Optimum pool boiling heat transfer coefficient of 5.29 $\mathrm{kW/m^2\,K}$ was achieved with a sintering pressure of 2 atmospheres, a sintering time of 2 h, a sintering temperature of 900°C, a heating rate of 5°C/min and a particle size of 0.35 mm in a nitrogen container.

Key words: Pool boiling, heat transfer coefficient, sintered surface, Taguchi method.

INTRODUCTION

A great amount of applications in a variety of industries such as electronic chip cooling, electric power generation, chemical thermal processes, and refrigeration and heat pump systems, rely on nucleate boiling to remove high heat fluxes from heated surfaces. Several typical approaches have been considered to enhance pool boiling and critical heat flux, including: (a) oxidation or selective fouling of a heater surface to increase the wettability of the liquid; (b) vibration of heaters to promote the departure of bubbles from a heater surface; (c) coating or extending of heater surface to increase the heat transfer area; (d) heater rotation to promote bubble departure from and liquid deposition onto the heater surface; (e) fluid vibration to promote bubble departure and liquid supply; and (f) the application of electric fields to promote bubble departure from the surface by dielectrophoretic force to increase liquid renewal (Chang and Baek, 2003). In addition to these methods, heater surfaces with thin porous layers of particles have been used in the attempt to improve pool boiling heat transfer. A number of methods (Scurlock, 1995; Webb, 1981, 1994; Bergles and Chyu, 1982; Chyu and Bergles, 1982) have been used for producing nucleation sites artificially, either by mechanically treating the existing surface by scratching, scribing, knurling, etc., or by chemical treatments such as etching, coating, or by sintering the surface with a porous layer containing ready-made nucleation sites.

The most significant advances in enhanced heat transfer technology have been made with special surface geometries that promote high-performance nucleate boiling. From 1955 to 1965, fundamental advances were made in understanding the character of nucleation sites and the shape necessary to form stable vapor traps. In

*Corresponding author. E-mail: wmy@csu.edu.tw.

addition, Bankoff (1958) developed a dynamic model to predict the ability of a cavity to serve as a stable vapor trap. The analysis considered triangular and constant width circular cavities and grooves. Bankoff's suggestion that grooves may function as vapor traps provided motivation for later research on cavities with reentrant groove shapes. Moreover, Griffith and Wallis (1960) showed that cavity geometry is important in two ways: the mouth diameter determines the superheat needed to initiate boiling and its shape determines its stability once boiling has begun. Furthermore, Bergles and Webb (1980) also defined 12 enhancement techniques applicable to pool boiling and presented 258 references for work on enhanced pool boiling.

There is no detailed information about the optimum design parameters for pool boiling heat transfer on sintered surfaces available in previous studies. This is because vast numbers of experiments are required to obtain such information. The need for so many experiments increases the experimental cost and time period. This systematically analyzed the influence of various design parameters on the heat transfer characteristics of pool boiling on sintered surfaces. The Taguchi method (Zeng et al., 2010; Li et al., 2010; Taguchi et al., 1989; Tseng et al., 2007; Bilen et al., 2001), known to be a highly reasonable tool in parametric studies, is also applied in the present study. Tests were run by boiling saturated, deionized and degassed water at atmospheric pressure. The results provide main optimum factors which significantly influence the thermal hydraulic performance of pool boiling heat transfer on sintered surfaces in the design process. One of the advantages of the Taguchi method over conventional experimental methods is that in addition to reducing the experimental cost at the minimum level, it also minimizes the variability around the target when bringing the performance value to the target value. Its other advantage is that optimal working conditions, determined from the laboratory study, can also be reproduced in real applications. This study presents an investigation of the effect of design parameters on pool boiling heat transfer and the phenomena on the sintered surfaces of the tube. The effects of five design parameters for the sintered surfaces on the boiling heat-transfer characteristics were determined using the Taguchi method. Contribution ratios for each parameter on the heat transfer were also determined.

EXPERIMENTAL APPARATUS AND PROCEDURE

Instrumentation

Figure 1 is a schematic drawing of the test apparatus, identifying all major components. The tank has a glass view port (100X100 mm) which permits the viewing of the tubes and photographing. A horizontal test section with the sintered surface is shown in Figure 2. The sintered surface is on a copper (k=111 $\mathrm{W/m\ K}$) tube (135.8 X 18.9 X 16.6 mm) comprising the augmented surface. Heating was provided by conducting direct current through electric wire packed into the copper tube. A two-walled structure (MgO + quartz) was sandwiched between the copper tube and the electric wire as an electrical shield. Quartz was used as electrical insulation. MgO distributes the heat energy uniformly. The boiling surface of the test tube was sintered with multiple copper particles. Sintering was performed in various conditions, as shown in Table 1. Table 1 lists the sintering pressure, sintering time, sintering temperature, heating rate and particle size for the sintered surfaces investigated in this study. Tests were run by boiling deionized water at atmospheric pressure. The boiler vessel consisted of a thick-walled stainless steel container with a Plexiglas cover fitted with a rubber O-ring. The top cover had penetrations for four auxiliary cartridge heaters to allow the test liquid to be preboiled at saturation temperature throughout the run. The vapor was condensed and returned to the boiler by gravity from a Pyrex glass condenser using tap water for cooling. An additional thermocouple was placed above the boiling fluid to determine fluid vapor temperature, and two thermocouples were immersed in the fluid pool to monitor fluid bulk temperature. To measure the surface temperatures of the heated tube, the heated tube was instrumented with 5 E-type sheathed thermocouples outside the surface of the tube. Each thermocouple was brazed to the tube wall at an equal distance. To minimize end losses, the test tube was insulated with a mixture of polystyrene and Devcon five-minute epoxy. Calibrated Chromel-constantan thermocouples (E-type) were used to measure the surface of the sintered surface of the heated tube and pool temperatures. Power supplied to the test sections and the auxiliary heaters was controlled via separate powerstates. Test section power was measured by a wattmeter, providing heat flux accuracy of $\pm$80 $\mathrm{W/m^2}$ at 80000 $\mathrm{W/m^2}$. The data were logged by a recorder (180 mm hybrid recorder, AH 3000, chino). The wall thermocouple readings were averaged. In addition, experimental procedure is as follows. At the start of each run, the tube heater was used to vigorously boil the pool for one hour in order to degas the test liquid. The experiment system was started up with no power input. Then it was necessary to heat the pool at low power until it reached the saturation temperature. The power applied to the test section was then gradually increased by controlling the heater voltage. The voltage was increased in two to four volt increments until the initiation of boiling occurred, at which point ten volt increments were made up to the maximum attainable heat flux. The power was then decreased in the same fashion. At the current power setting, a comparison was made between the two average temperatures for each thermocouple after a heat flux decrement. The procedure was repeated until the temperature difference between the thermocouples was less than 0.1 K. The system was assumed to be at steady condition. It was permitted to stabilize for five minutes and the following data were recorded: heater voltage, vapor temperature, liquid pool temperature, and the temperatures on the sintered surface of the test heater.

Experimental parameters and plan

We used five experimental parameters of the sintered surface related to the characteristics of boiling heat transfer. The levels of each factor in the current study are shown in Table 1. The design parameters were named A, B, C, D, and E, for the sake of convenience. Five sintering factors were selected: sintering pressure (A, 1-2 atm), sintering time (B, 2-2.5 hr), sintering temperature (C, 850 to 900°C), heating rate (D, 5 to 20°C /min), and particle size (E, 0.25 to 0.85 mm) under a nitrogen sintering atmosphere. Numerical analyses were performed to optimize the boiling heat transfer on the sintered surface of the copper tube using the $L_{15}(3^5)$ orthogonal array table for the design points, as shown in Table 2. In order to observe the effect of error sources on the boiling heat transfer, each experiment was repeated twice under

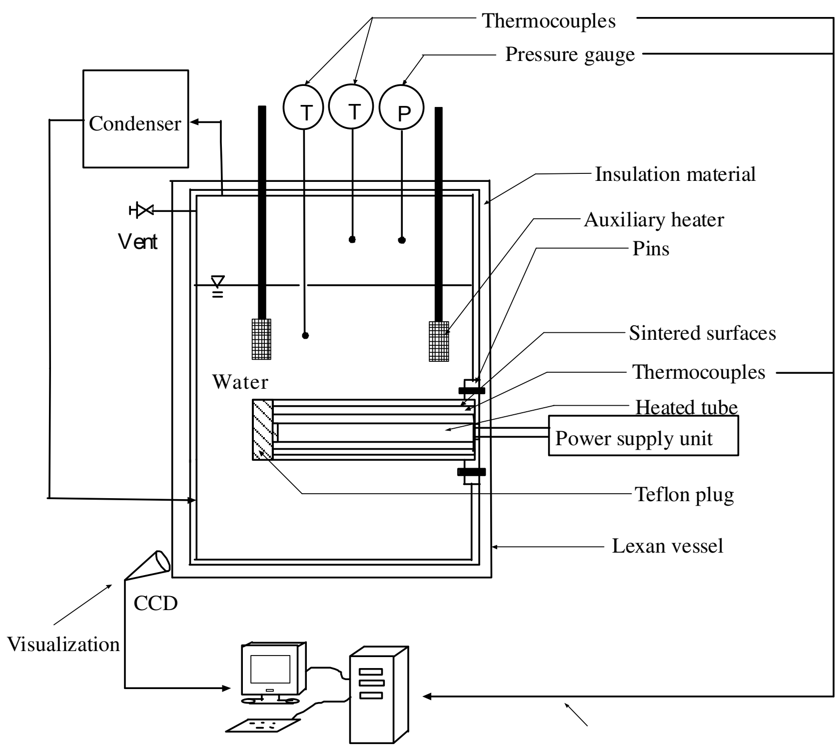

Figure 1. Schematic drawing of test apparatus.

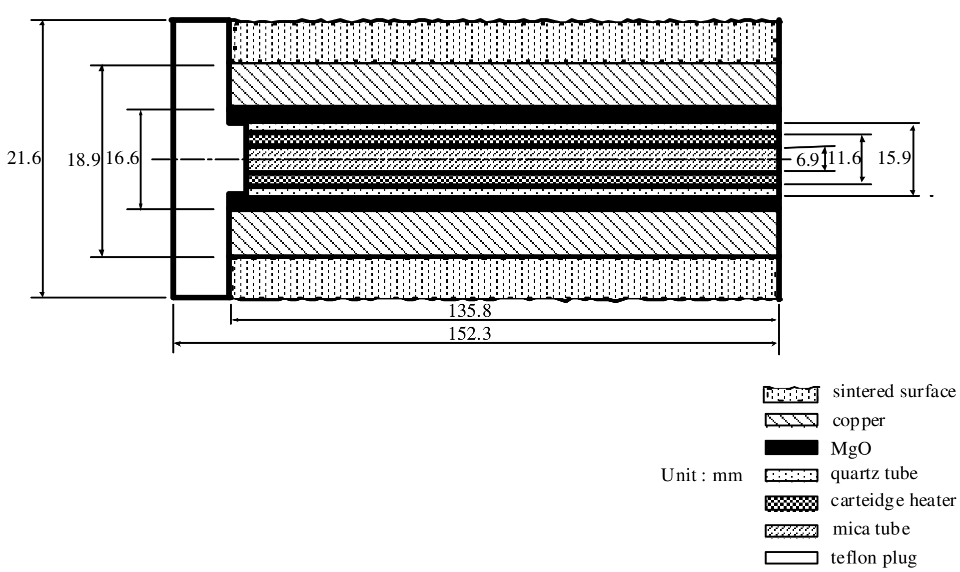

Figure 2. Schematic of test section.

the same conditions at different times. The SN (signal-to-noise) ratio can help designers to find out which levels of control factors are more efficient. The Taguchi method defines the SN ratio with the following equation:

$$SN = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \qquad (1)$$

for the *n* observations, Y_i in each trial. In the Taguchi method, the experiment corresponding to optimum working conditions may not have been carried out during the whole period of experimentation. In such a case, the performance value corresponding to optimum working conditions can be predicted by utilizing the balanced characteristic of the orthogonal array (OA). For this aim, the additive model may be used (Phadke et al., 1983):

Table 1. Three-level design parameters in this study.

Symbol	Parameter	Unit	Level 1	Level 2	Level 3
A	sintering pressure	atm	1	1.5	2
B	sintering time	hr	2	2.3	2.5
C	sintering temperature	℃	850	880	900
D	heating rate	℃ /min	5	10	20
E	particle size	mm	0.85	0.35	0.25

Table 2. L_{15} (3^5) orthogonal array table for the Taguchi method.

Number of test	Design parameter					SN ratio
	A	B	C	D	E	
1	1	1	1	1	1	14.733
2	1	2	1	1	1	6.566
3	1	3	1	1	1	6.060
4	1	3	1	1	2	7.501
5	1	3	1	1	3	13.355
6	2	1	2	2	1	6.762
7	2	2	2	2	1	15.396
8	2	3	2	2	1	9.904
9	2	3	2	2	2	6.397
10	2	3	2	2	3	8.741
11	3	1	3	3	1	11.906
12	3	2	3	3	1	7.732
13	3	3	3	3	1	6.679
14	3	3	3	3	2	7.887
15	3	3	3	3	3	8.924

$$Y_i = \mu + x_i + e_i \qquad (2)$$

Because Equation 2 is a point estimation calculated by using experimental data to determine whether the results of the confirmation experiments are meaningful or not, the confidence interval can be obtained using the following formula:

$$Y_i \pm \sqrt{F_{\alpha;1,df_e} Mss_e n_e^{-1}}\,, \qquad (3)$$

The general formula for the effective number of replications is as follows:

$$n_e = \frac{N}{1+\sum(ED)}\,, \qquad (4)$$

If the experimental results are in percentages (%), before evaluating Equations 2 to 4, first, the omega transformation of the percentage values should be applied using the following equation and then the interested values are determined by reverse transformation using the same equation (Taguchi, 1987),

$$\Omega = -10\log\left(\frac{1}{P}-1\right) \qquad (5)$$

The interactive effects of the parameters were not taken into account in the theoretical analysis because some of confirmation experiments performed at the optimum conditions showed that they could be neglected. This is mainly due to the significant and main effects of these experimental conditions (the sintering pressure, sintering time, sintering temperature, heating rate, and particle size) on the boiling heat-transfer coefficient of the sintered surface.

Uncertainties and data reductions

The uncertainty in the experimental data was estimated using a propagation of error analysis. The uncertainty in the average wall superheat was estimated by taking into account the uncertainty in the average wall temperature.

The parameters required to make measurements in these pool boiling experiments include boiling wall temperature, the voltage drop *E* across the test heater and the current *I*. The power input to the heated tube can be obtained from the relation:

$$q = I \times E / A \qquad (6)$$

The front surface superheat ΔT can be obtained by a data acquisition system. Then, the boiling heat transfer coefficient can be estimated with the measured heat flux and averaged wall superheat as:

$$h = \frac{q}{\Delta T} \qquad (7)$$

Table 3. Ranges of experiments and measurement uncertainties.

Parameter	Range	Uncertainty
Heat flux supplied to test section, q (W/m^2)	41000	$\pm 0.5\%$
Wall superheat, (℃)	0.74-0.89	$\pm 7.5\%$
Heat transfer coefficient, h ($kW/m^2\ K$)	4.60-5.51	$\pm 10.6\%$
Sintering pressure (atm)	1-2	$\pm 5.6\%$
Sintering time (h)	2-2.5	$\pm 0.05\%$
Sintering temperature (℃)	850-900	$\pm 7.5\%$
Heating rate(℃ /min)	5-20	$\pm 8.9\%$
Particle size (mm)	0.25-0.85	$\pm 0.1\%$

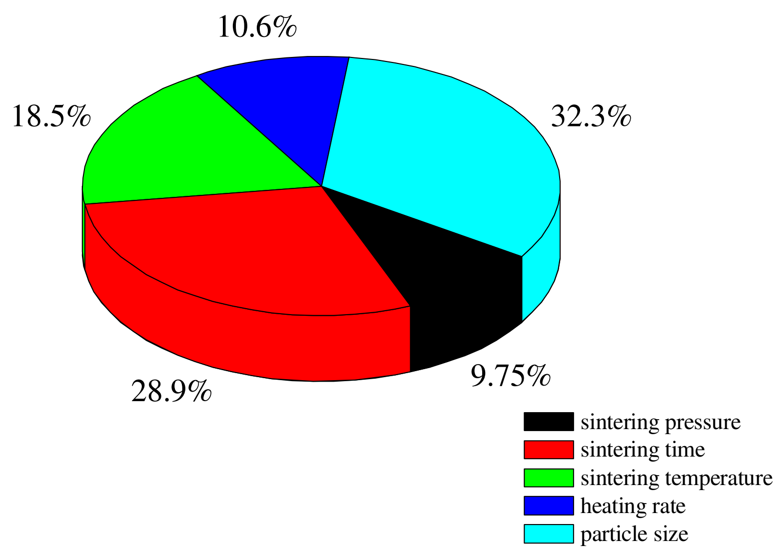

Figure 3. Contribution ratio on each factor.

RESULTS AND DISCUSSION

Repeated experiments showed that the data reproducibility was satisfactory. The ranges and measurement uncertainties for this study are listed in Table 3. Table 2 also shows the SN ratios calculated from the five tests. The effect of each sintering process parameter on the SN ratio at different levels can be separated out because the experimental design is orthogonal. Based on the results of SN ratio and ANOVA, the factorial effect and contribution ratio can be also calculated. The contribution ratio represents the effect of each factor on the boiling heat transfer coefficient. The percentage contribution is plotted in Figure 3. The effects of each factor on the boiling heat transfer coefficient are enumerated as 9.75 % for sintering pressure, 28.85% for sintering time, 18.47% for sintering temperature, 10.59% for heating rate, and 32.32% for particle size, as presented in Figure 3. Therefore, the particle size is seen to make the most major contribution to the overall performance.

Figure 4 shows the levels which provide optimal performance. The percentage contributions by each of the process parameters in the total sum of the squared deviations can be used to evaluate the importance of the process parameter change in relation to the quality characteristics. The numerical value of the maximum point of all levels on each factor marks the best value of that particular parameter, given in Table 4 for each parameter, and they resemble the optimum conditions in the range of the experimental conditions. Table 4 can be seen that an experiment corresponding to the optimum conditions is $A_3B_1C_3D_1E_2$. In addition, it should be noted that the heat transfer coefficient, 5.51 $kW/m^2\ K$, given in Table 4, is the result predicted by using Equation 2. The 98% significance level confidence interval of prediction is also given as 5.14-5.83 $kW/m^2\ K$ in Table 5, as predicted

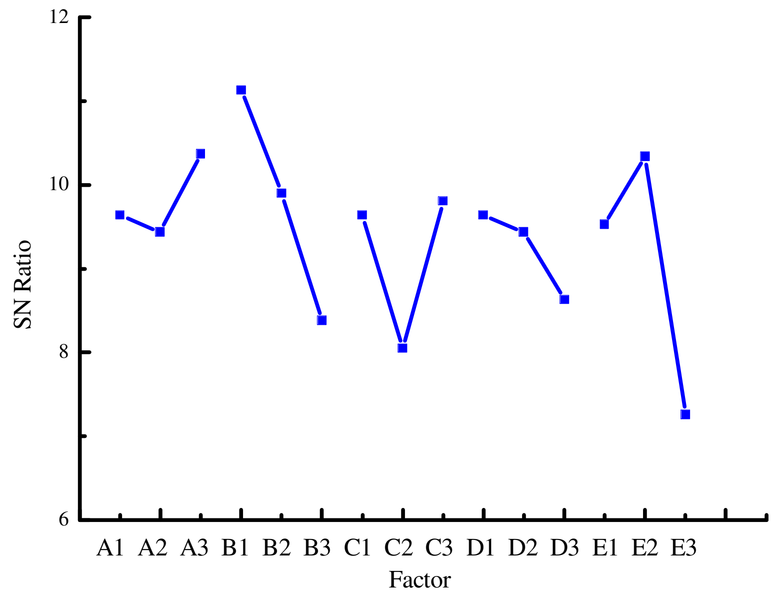

Figure 4. SN ratio on each factor.

Table 4. Optimum working conditions, and predicted and obtained values.

Parameter	Optimum conditions Optimum level	Optimum values
A	3	10.37
B	1	11.13
C	3	9.81
D	1	9.64
E	2	10.34

Predicted boiling heat transfer coefficient: 5.51 kW/m^2K; Predicted boiling heat transfer coefficient interval: 5.14-5.83 kW/m^2K; Obtained boiling heat transfer coefficient: 5.29 kW/m^2K.

by Equation 3. In order to test the predicted result, confirmation experiments were conducted twice at the optimum working conditions. Based on the fact that the heat transfer coefficients of 5.23 and 5.35 $kW/m^2\ K$, 5.29 $kW/m^2\ K$ are the averages obtained from the confirmation experiments at the same experimental conditions, as shown in Table 4, are well within the calculated confidence interval, it can be said that the experimental results are within ±4% in error. These results show that the interactive effects of the parameters are indeed negligible and also prove that the Taguchi method can be successfully applied to heat transfer experiments.

To expand the fundamental understanding of the pool boiling phenomena, flow visualization was made to observe the detailed fluid boiling characteristics of the present sintered surfaces. The flow visualization experiments were conducted using the strong-full light resource, a black background, a camcorder and a fast camera to record images of the pool boiling phenomena. The pictures are a small sample of that taken by the fast camera. The flow visualization showed how sintered surfaces affected the flow field and induced the boiling phenomena on the surface. Figure 5 shows typical photographs made by flow visualization of the present pool boiling on the sintered surfaces (Test 1, 3, 5, 7, 9, 11, 13, 15, and Test under the optimal condition) at a fixed heat flux of 41,000 W/m^2. The behavior of the unspecified other tests were similar. Starting from Figures 5 (b), (e), (g) and (h), one may find that bubbles rise from isolated nucleation sites. On the other hand, Figures 5 (a), (c), (d) and (f) indicate that because of the rough structure of the sintered surface, the active sites become very numerous due to plenty of additional tiny cavities in the sintered surfaces, especially for the test under the

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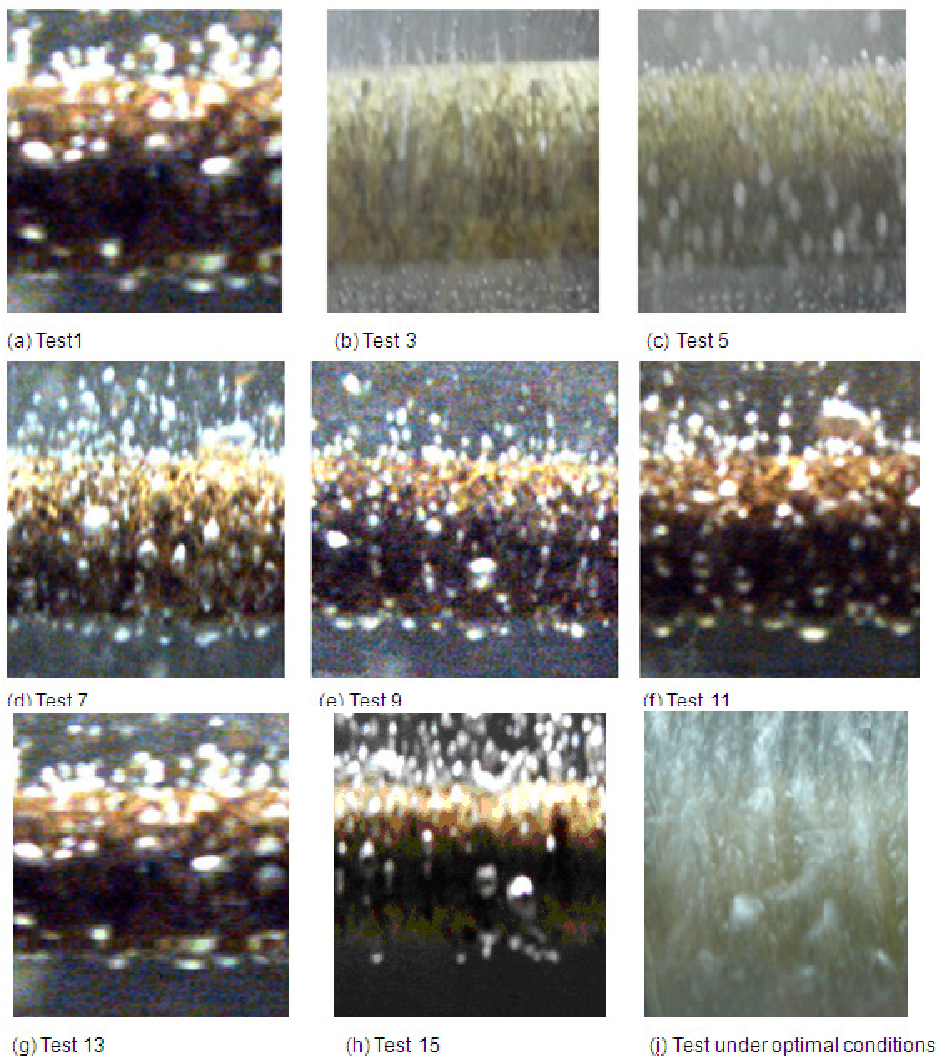

Figure 5. Photos of bubble formation in nucleate boiling under different test conditions, as shown in Table 1 and in the test under the optimal conditions.

optimal conditions (Figure 5 (i)). Looking at Figure 5 is apparent that the number of active nucleation sites generating bubbles is strongly influenced by the present surface condition. This indicates that the boiling phenomena of the sintered surface is of great importance and is responsible for improving the heat transfer performance. The results also contribute to our understanding of the best heat transfer effects for the sintered surface in the present study.

Conclusions

An optimized analysis for the experimental study of nucleate pool boiling heat transfer on sintered surfaces has been performed using the Taguchi approach. We proposed the optimum values of the design parameters for heat transfer from the sintered surface. In this study, the order of magnitude of the effects of each factor on the boiling heat transfer coefficient on the sintered surface is as follows: sintering pressure 9.75%, sintering time 28.85%, sintering temperature 18.47%, heating rate 10.59%, and particle size 32.32%. The results show that sintering time, sintering temperature, and particle size are the main factors that significantly influence the performance of the boiling heat-transfer surface discussed earlier. The contribution ratios of the sintering pressure and heating rate factors considered in this study also play important roles (about 10%) in the design process of a new boiling heat transfer surface. The optimum conditions of each factor are determined, and the reproducibility of these conditions has been verified by three analytical results. The flow visualization brought about a good understanding of the boiling phenomena for the present sintered surface. The findings of the present laboratory scale study will be useful for boiling heat transfer on sintered surfaces in heat–exchange processes used in a variety of industries.

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Nomenclature

A heat transfer surface area (m^2)
E electrical voltage (V)
ED effective number of degrees of freedom
e_i random error in *i*th experiment
F_α value of *F* table
h heat transfer coefficient ($\mathrm{kW/m^2\ K}$)
I electrical current (A)
MSS_e mean square error
N size of experiments
n_e effective number of replications
P percentage of product obtained experimentally
q heat flux ($\mathrm{W/m^2}$)
SN performance statistics
T temperature (K)
ΔT wall superheat, $\Delta T = T_w - T_{sat}$ (K)
Y_i performance value of *i*th experiment
x_i fixed effect of parameter level combination used in *i*th experiment
μ overall mean of performance value
Ω decibel value of percentage value subject to omega transformation (db)

Subscripts

df_e degrees of freedom at level of α
sat saturation
w wall

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