EXPERIMENTAL INVESTIGATION ON COOLING EFFECT OF SPHERICAL DIMPLED PROFILE ALUMINUM BLOCK BY THE TAGUCHI METHOD

H. N. Ganesan[1], M.S. Kasim[1], J.S. Anand[1], Z. Abdullah[1], K.A. Zakaria[2], N.A. Masripan[2], H.E. Ab Maulod[3], M.A.M. Nawi[4], T. Ito[5]

[1]Faculty of Manufacturing Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 75450 Ayer Keroh, Melaka, Malaysia.

[3]Faculty of Engineering Technology,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 75450 Ayer Keroh, Melaka, Malaysia.

[4]Faculty of Engineering Technology,
Universiti Malaysia Perlis,
UniCITI Alam Campus, Sg. Chuchuh,
02100 Padang Besar, Perlis, Malaysia.

[5]Graduate School of Technology,
Industrial and Social Sciences,
Tokushima University, 2-1 Minami-Josanjima,
770-8506, Tokushima, Japan.

Corresponding Author's Email: [1]shahir@utem.edu.my

Article History: Received 18 January 2018; Revised 17 June 2018; Accepted 18 October 2018

ABSTRACT: Dimple profile plays a crucial role in enhancement of cooling process of various engineering application. This paper presents experimental investigation of convection heat transfer over spherical dimple on an aluminum block. In this study, an experimental investigation was carried out to observe the cooling effect under several conditions which are flow condition, dimple orientation, diameter of dimple, room temperature, air velocity, input of heat energy and condition of wind tunnel. A design of experiments technique was adopted in the form of orthogonal array L_8 (2^3), Taguchi 2-Level approach. A total of 4 types dimpled surface are studied. The ANOVA results shows the room temperature is the major contributing

factor towards rapid cooling process followed by wind tunnel condition, radius of dimple, air velocity, flow region and heat input. It was observed that the cooling time of 13 minutes can be achieved during laminar flow, 5 mm of dimple diameter, 60° angle of dimple orientation, 18 m/s of air velocity, 20 °C of room temperature.

KEYWORDS: *Spherical Dimple Aluminum Block; Cooling Time; Rapid Cooling Process; S/N Ratio*

1.0 INTRODUCTION

In automotive industry, due to the demand for more powerful products, power densities of automotive components have increased. The higher temperature of the engine system is one of the main factors that control the reliability of the engine mounting. Generally engine mounting receive high heat energy from engine during combustion process where it caused engine mounting to lose their mechanical strength and lead to short service life. Therefore it is important to lower the time taken to dissipate high heat from engine mounting.

Heat transfer rate can improve through many ways and passive method is one of the techniques. The passive heat transfer enhancement methods consist of use of roughened or extended surfaces and many other geometric modifications to improve convective heat transfer enhancement. There are numbers of heat transfer enhancement approaches either in the turbulent stream or heat transfer rate. One of the suggested techniques for heat transfer improvement is passive methods which are varied from pin array, dimples, rib turbulators and fins. However, increasing of fluid stream pressure drop must be put into consideration [1-2]. Introducing dimple feature on flat surface, promotes a good heat transfer rate and it will shorten the time taken of a cooling process. The dimple profile creates the flow separation on downstream of the profile to increase the heat transfer rate. Introducing dimple on a flat surface, it has not only fastened the cooling process while it also lower the pressure drop penalties [3]. The heat dissipation rate of a flat surface is improved through a dimple profile as compared to a smooth surface [4]. Another added advantage in dimple profile is the removal of material which reduces cost and weight of the equipment [5-6].

The improved heat transfer rate causes the rapid cooling process to take placed. This is due the dimple profile creates recirculation zone in the upstream side which separate the mainstream flow. The separated mainstream flow reattached as a twin vortex in the downstream side of the dimple surface. As the flow comes out of the dimple, it reattaches again at the downstream of the dimple [7-9]. Afanasyev [10] conducted a research on spherical dimples effects on total heat transfer rate of a flat surface. The results show that, there was a great increase in overall heat transfer rate between 30% to 40%. On the other hand, another research groups found that, adding dimple profile on flat surface enhances the heat transfer rate with minimum pressure drop [3]. Therefore dimples method considered as the most effective methods among the other methods.

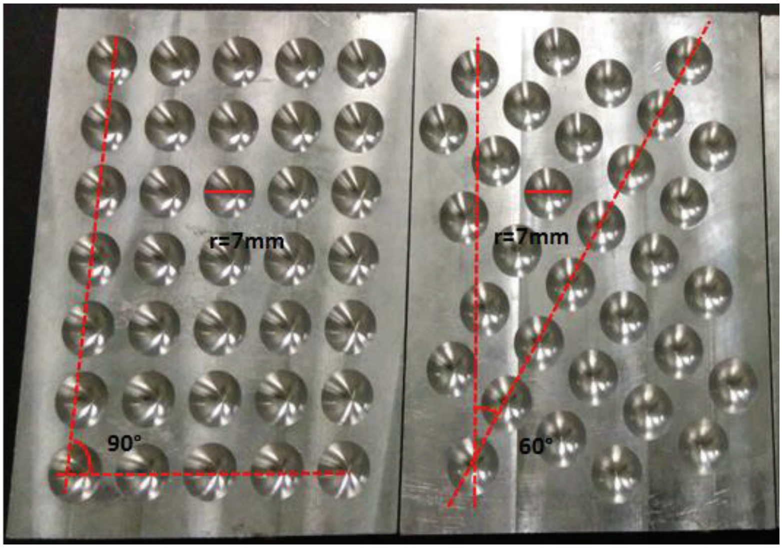
Katkhaw [11] indicated that dimpled profile surface have much better heat transfer coefficients approximately 26% as compared to flat surface with staggered arrangement. Chyu et al. [12] carried out an experimental investigation to study the heat transfer distribution over the channel. They compare and evaluate the hemispherical dimples and tear drop by using the transient liquid crystal imaging system. They observed a great improvement in the heat transfer rate for the dimples channel. In another study, Mahmood et al. [13], used the flow visualization method to study the dimples effect on heat transfer enhancement. They observed, the main factor that augments the heat transfer is the periodic nature of shedding off of vortices and is more noticeable at the dimple downstream rims.

Mahmood et al. [13] investigated the effect of Reynolds number, temperature ratio, aspect ratio, and flow structure over a dimple channel at one wall by using flow visualization method. They conclude the vortices that are shed off from the dimples become stronger. While the channel height to dimple diameter (H/D) ratio decreases and increases the local Nusselt number. Xie et al. [14] stated dimples have a simple geometry and well suited for blade tip cooling especially at low Reynolds numbers. The enhanced heat transfer rate promotes the rapid cooling process to take place. This dimple profile method can be applied in various applications for thermal issues such as in automotive and aerospace industry.

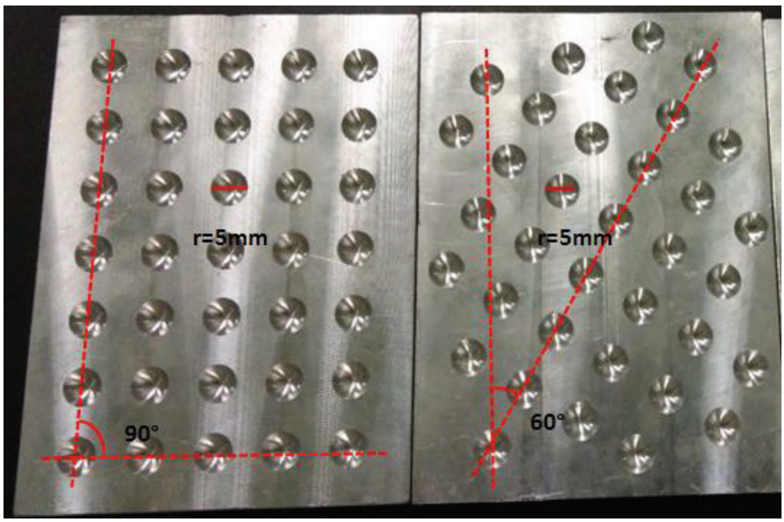
Based on the previous literature, it can be concluded that, the dimples profile have great possibility to improve the heat transfer. However, most of them used spherical dimples with uniform diameter and inline and staggered (60° & 90°) dimple arrangement for numerical or experimental work. Moreover, most of the investigations are restricted to flow in a channel or wind tunnel with internal flow, and very limited studies reported on the external flow [11-12]. Hence there is less study on room temperature effects on heat transfer. In addition, the effect of wind tunnel condition and air velocity on heat transfer rate is hardly found in the literature. Therefore the main aim of this study is to experimentally investigate the significant parameters that effect on heat transfer enhancement which improve the cooling time. In this study, a summary of experimental design was present first through Taguchi method. One of the screening and optimization techniques with a small number of experimental runs. Then the dimple effect towards cooling time during cooling process of spherical dimple Aluminum block in wind tunnel analyzed statistically to determine significant parameter for rapid cooing process.

2.0 EXPERIMENTAL SETUP AND PROCEDURE

The workpiece material that used in this experiment was aluminum 6061 with a final dimension of 135 × 100 × 30 mm (L × W × H). There are total 4 number of workpieces with various dimple profile were used. Characterization of the specimen was staggered into dimple radius of 5 – 7 mm and different orientation of 60° - 90° (Figure 1). The temperature of workpiece was set from 60 – 90 °C. The blocks were heated up by hot plate heater to reach the desired temperature. The temperature of inlet stream was controlled ranging from 20 – 26 °C. Then the aluminum block allow to cooling down through air flow in wind tunnel where the velocity of the air is set to be 15 to 18 m/s. The air velocity was measured through anemometer with ± 0.1 m/s accuracy. Figure 2 show, the setup of experiment in wind tunnel where the test section is set to be in closed and open condition. The purpose of this setting is to evaluate the effect of controlled and uncontrolled air flow. The temperature during cooling period of specimen blocks were measured and recorded by the data acquisition. 4 channels of K-type thermocouple with the accuracy of ±0.5°C was used during the experiment to record temperature every 1 minute interval.



(a) (b)



(c) (d)

Figure 1: Spherical dimple aluminum block: (a) Dimple radius is 7 mm with 60° angle orientation, (b) Dimple radius is 7 mm with 90° angle orientation, (c) Dimple radius is 5 mm with 90° angle orientation and (d) Dimple radius is 5 mm with 60° angle orientation

Figure 2: The setup of experiment in wind tunnel

Taguchi was selected due to robustness of this technique in evaluating the effects of parameter input to the output. Table 1 shows the detail of L8 orthogonal array with eight rows and seven columns. Based on orthogonal array (OA) of experiment with eight parameters and two levels, 8 numbers of runs were conducted throughout this experiment. Table 2 lists the details of the test matrix. The output of the experiment will be analyzed through analysis of variance (ANOVA) to evaluate the relative significance of the dimple parameters with regards to the cooling time.

Table 1: Level and parameters used in Taguchi method

Factors	Flow region	Dimple rad.	Angle	Room temp.	Air vel.	Heat input (°C)	Wind tunnel cond.
L1	Laminar	5 mm	60 °	20 °C	17 m/s	60 °C	Closed
L2	Turbulent	7 mm	90 °	26 °C	18 m/s	90 °C	Open

Table 2: Parameters of the cooling process

Exp. no	Flow region	Dimple rad. (mm)	Dimple orientation (deg)	Room temp. (°C)	Air vel. (m/s)	Heat input (°C)	Wind tunnel cond.
1	Laminar	5	60	20	17	60	Closed
2	Laminar	7	90	20	17	90	Open
3	Turbulent	7	60	20	18	90	Closed
4	Turbulent	5	90	20	18	60	Open
5	Laminar	7	90	26	18	60	Closed
6	Laminar	5	60	26	18	90	Open
7	Turbulent	5	90	26	17	90	Closed
8	Turbulent	7	60	26	17	60	Open

3.0 RESULTS AND DISCUSSION

The obtained experimental results for rapid cooling process are detailed in Table 3. It was notified that the data ranged from 13 – 40 minutes. From the observation, generally cooling time found to be faster at low room temperature compared to high room temperature.

Table 3: Results obtained from experimentation

No	Flow region	Dimple rad. (mm)	Dimple orientation (deg)	Room temp. (°C)	Air vel. (m/s)	Heat input (°C)	Wind tunnel cond.	Cooling time (min)
1	Laminar	5	60	20	17	60	Closed	13
2	Laminar	7	90	20	17	90	Open	19
3	Turbulent	7	60	20	18	90	Closed	15
4	Turbulent	5	90	20	18	60	Open	17
5	Laminar	7	90	26	18	60	Closed	29
6	Laminar	5	60	26	18	90	Open	27
7	Turbulent	5	90	26	17	90	Closed	32
8	Turbulent	7	60	26	17	60	Open	40

The details of the effects on room temperature were detailed in Figure 3. This parameter was associated with other parameters (dimple radius and orientation). It shows that the cooling time for specimen block with radius of 5 mm and orientation of 60° is 13 minutes at room temperature of 20°C whereas at room temperature of 26°C, the time taken is 27 minutes. The time for specimen block with radius of 7 mm and orientation of 60° to cool down under room temperature of 20°C is 15 minutes while at room temperature of 26°C is 40 minutes. The cooling time of the 5mm block with orientation of 90° is 17minutes and 32 minutes at room temperature of 20°C and 26°C. Therefore it can conclude that room temperature is a main factor of cooling time. When the block is hot, the air molecules directly above it get hot as well. Then equilibrium condition was achieved after some time and there is a no heat transfer take place. By creating air flow with lower room temperature it will disturb the equilibrium state and cold air molecules replaced the hot air molecules above the block. The cold air molecules will cool down the hot block faster.

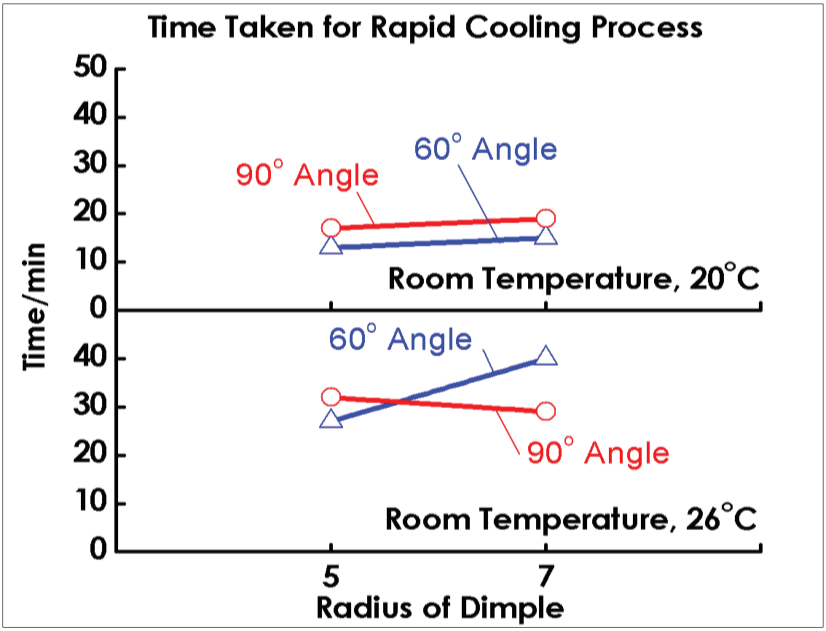


Figure 3: Graph of time taken versus radius of dimple at different room temperature

3.1 Signal/ Noise Ratio

The collected results were analyzed through Taguchi's method by using Minitab software. The results were analyzed by signal-to-noise ratio (S/N) and ANOVA. Signal to noise ratio (S/N) is used to measure the variations of the experimental design. S/N ratios provide the improvement of the measured control factors in term of quality characteristic. The quality improvement achieved over in variability reduction. S/N ratios characteristic can be categorized into three which are "Nominal is the best", "Larger is the better" and "Smaller is the better". The S/N ratio characteristic is choosing according to the experiment response. In this study, the response is shorter time taken for rapid cooling process of spherical dimpled aluminum block. Therefore "Smaller is the better" S/N ratio were selected and the S/N ratio were calculated through Equation (1) such as

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum y^2\right) \tag{1}$$

where n = number of observations and y = observed data, S/N = signal to noise ratio.

S/N ratio of cooling process explaining the most influencing factors which affects the process. Figure 4 and Table 4 show the S/N ratio results where the experimental factors ranked according to the significant effects towards the process response. The calculated S/N ratio for every experiment is in negative value. This is because of the experiment is not repeated or duplicated again. The positive S/N ratio value is obtained for repeated experiment only. From the S/N ratio analysis, can conclude that, all parameters were significantly effect on cooling time except initial block temperature (heat input). The most significant factor that affecting the rapid cooling process was ranked accordingly where it was dominated by the room temperature, followed by wind tunnel condition, radius of dimple, air velocity, flow region and dimple orientation. The least affecting factors is heat input.

From the Figure 4 also determine the trend of each factor. From this experiment, cooling time reduces as the dimple size, dimple orientation and room temperature decreases. However, increase in flow rate will increase cooling time. The aluminum block cools faster when the flow region is laminar and closed wind tunnel condition (controlled air stream). In laminar flow, the fluid particles flow in an orderly manner along path lines and energy are transferred across streamlines. As a result, there will be a great flow separation and creates the vortex formation which help to remove the heat energy from the block.

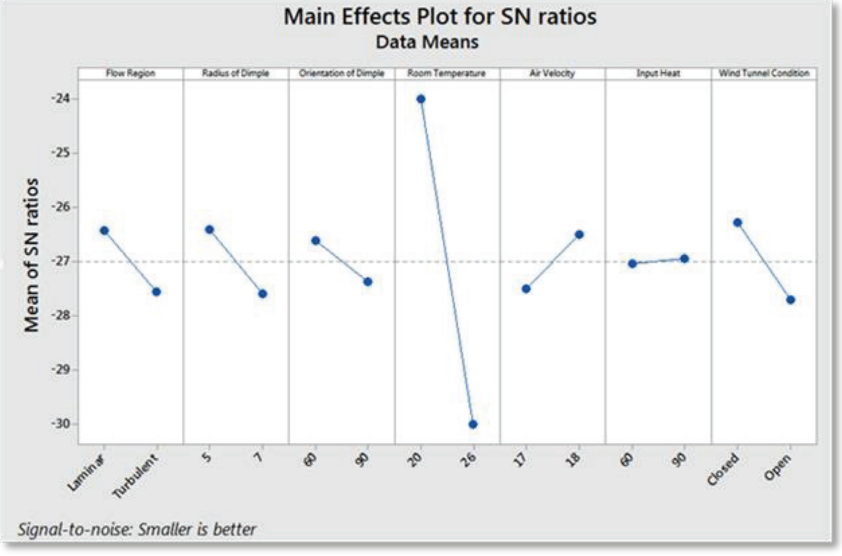


Figure 4: Main effect plot of S/N ratio of rapid cooling

Table 4: Response of S/N for rapid cooling process

Level	Flow region	Dimple rad.	Dimple orientation	Room temp.	Air vel.	Heat input	Wind tunnel cond.
1	-26.43	-26.40	-26.62	-24.00	-27.50	-27.04	-26.29
2	-27.57	-27.60	-27.38	-30.00	-26.50	-26.96	-27.71
Delta	1.14	1.19	0.77	6.01	1.00	0.09	1.43
Rank	4	3	6	1	5	7	2

3.2 Analysis of Variance (ANOVA)

Based on the result data set, the ANOVA is used to identify the factors that most influence the response. This analysis helps to alleviating the effects of experimental parameters on the output of the experiment. In this study, ANOVA was used to analyze the effects of flow region, radius of dimple, dimple orientation, room temperature, air velocity, heat input and condition of wind tunnel on rapid cooling of spherical dimple aluminum block. F value represents the ratio between the variances and is used to estimate how far the data are scattered from the mean. In this analysis, the F value cannot be calculated because of the model do not have sufficient degree of freedom for error where the condition known as asterisks [15]. Therefore the heat input parameter which ranked as the most insignificant factor in S/N ratio was removed to calculate the F value. Once the heat input factor removed the F value was calculated as shown in Table 5. However the sum of square and mean of square values are adjusted according to the degree of freedom. From the ANOVA results, factor room temperature had a dominating effect where the F value is 113.78 on the rapid cooling process of spherical dimpled aluminum block. Then the followed factors are air velocity and flow region with F value of 7.11 and radius of dimple and wind tunnel condition factors where the F value is 5.44. The least dominating factor is orientation of dimple with F value of 0.11.

Table 5: Result of ANOVA for rapid cooling process

Source	DF	Adj. SS	Adj. MS	F-Value
Regression	6	625.500	104.250	23.17
Radius of Dimple	1	24.500	24.500	5.44
Orientation of Dimple	1	0.500	0.500	0.11
Room Temperature	1	512.000	512.000	113.78
Air Velocity	1	32.000	32.000	7.11
Flow Region	1	32.000	32.000	7.11
Wind Tunnel Condition	1	24.500	24.500	5.44
Error	1	4.500	4.500	
Total	7	630.000		

4.0 CONCLUSION

As a conclusion, from Taguchi analysis of S/N ratio the room temperature, wind tunnel condition and radius of dimples are most significant factors that affect the rapid cooling process of spherical dimple aluminum block. However the heat input and dimple orientation does not seem to have any significant effects on the same. Faster cooling process can be achieved by laminar flow region, 5mm radius of dimple, 60° angle of dimple orientation, 20°C of room temperature, 18 m/s of air velocity, 60°C of heat input and the wind tunnel in closed condition.

ACKNOWLEDGMENTS

Authors would like to thank, Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka for assistant which is gratefully acknowledged. This research was supported by the Universiti Teknikal Malaysia Melaka through project no. PJP/2016/FKP/HI6/S01485.

REFERENCES

[1] H.C. Pisal and A.A. Ranaware, “Heat transfer enhancement by using dimpled surface”, *IOSR Journal of Mechanical and Civil Engineering*, vol. 6, no. 54, pp. 07-15, 2013.

[2] N. Vorayos, N. Katkhaw, T. Kiatsiriroat and A. Nuntaphan, “Heat transfer behavior of flat plate having spherical dimpled surfaces”, *Case Studies in Thermal Engineering*, vol. 8, pp. 370–377, 2016.

[3] D. Zhang, L. Zheng, G. Xie and Y. Xie, “An experimental study on heat transfer enhancement of non-newtonian fluid in a rectangular channel with dimples/protrusions”, *Journal of Electronic Packaging*, vol. 136, pp. 021005-1-021005-10, 2014.

[4] G.I. Mahmood, M.L. Hill, D.L. Nelson and P.M. Ligrani, “Local heat transfer and flow structure on and above a dimpled surface in a channel“, *Journal of Turbomachinery*, vol. 123, no. 1, pp. 115-123, 2001.

[5] C.C. Beves, T.J. Barber and E. Leonardi, “An investigation of flow over two-dimensional circular cavity,” in 15th Australasian Fluid Mechanics Conference, Sydney, 2004, pp. 13-17.

[6] G. Gadhave and P. Kumar, “Enhancement of forced convection heat transfer over dimple surface-review”, *International Multidisciplinary e – Journal*, vol. 1, no. 2, pp. 51-57, 2012.

[7] A. Khalatov, A. Byerley, D. Ochoa and M. Seong-Ki, "Flow characteristics within and downstream of spherical and cylindrical dimple on a flat plate at low Reynolds numbers," in ASME Turbo Expo: Power for Land, Sea, and Air, Vienna, 2004, pp. 589-602.

[8] P.M. Ligrani, J.L. Harrison, G.I. Mahmood and M.L. Hill, "Flow structure and local Nusselt number variations in a channel with dimples and protrusions on opposite walls", *International Journal of Heat and Mass Transfer*, vol. 44, no. 23, pp. 4413-4425, 2001.

[9] T S. Griffith, L. Al-Hadhrami and J.C. Han, "Heat transfer in rotating rectangular cooling channels (AR=4) with dimples", *Journal of Turbomachinery*, vol. 125, no. 3, pp. 555-563, 2003.

[10] V.N. Afanasyev, Y.P. Chudnovsky, A.I. Leontiev and P.S. Roganov, "Turbulent flow friction and heat transfer characteristics for spherical cavities on a flat plate", *Experimental Thermal and Fluid Science*, vol. 7, no. 1, pp. 1-8, 1993.

[11] N. Katkhaw, N. Vorayos, T. Kiatsiriroat, Y. Khunatorn, D. Bunturat and A. Nuntaphan, "Heat transfer behavior of flat plate having 45 ellipsoidal dimpled surfaces", *Case Studies in Thermal Engineering*, vol. 2, pp. 67-74, 2014.

[12] M.K. Chyu, Y.Yu, H. Ding, J.P. Downs and F.O. Soechting, "Concavity enhanced heat transfer in an internal cooling passage," in ASME International Gas Turbine and Aeroengine Congress and Exhibition, Orlando, Florida, 1997, pp. 437-444.

[13] G.I. Mahmood and P.M. Ligrani, "Heat transfer in a dimpled channel: combined influences of aspect ratio, temperature ratio, Reynolds number, and flow structure", *International Journal of Heat Mass Transfer*, vol. 45, no. 10, pp. 2011–2020, 2002.

[14] G.N. Xie, B. Sunden and W.H. Zhang, "Comparisons of pins/dimples protrusions cooling concepts for an internal blade tip-wall at high Reynolds numbers", *Journal of Heat Transfer*, vol. 133, no. 6, pp. 061902-1-061902-9, 2011.

[15] J.S. Lawson and J. Erjavec, *Modern Statistics for Engineering and Quality Improvement*. Pacific Grove: Duxbury Press, 2000.