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Research paper

Cooling Effect Efficiency Prediction of Aluminum Dimples Block using DOE Technique

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Abstract

The main aim of the present work is to study the effect of heat enhancement method on the cooling process of a spherical dimple profile. It was prominently known that introducing dimples configuration causes an enhancement in heat transfer over a surface. In this project, an experimental investigation was carried out to examine the cooling effect of the spherical dimple profile during steady laminar flow in a wind tunnel. Seventeen different sets of parameters related to dimple diameter (mm), dimple orientation (angle) and air stream velocity (m/s) were studied. The Box-Behnken of Response Surface Methodology (RSM) was used as design of experiments (DoE) tool to evaluate these parameters on cooling time. This work deals with the analysis of variance (ANOVA) in order to establish the significant effect of input parameters. The result reveals that an increase in dimple diameter and air stream velocity increase heat dissipation. The shortest cooling time of 7 minutes can be achieved when the dimple diameter is 12 mm; the dimple orientation is 60° and air flow velocity at 18 m/s. The mathematical model has been rendered where the model has been experimentally validated with the average error of 6%.

Keywords: *Air Stream Velocity; Cooling Time; Dimples Structure; Heat Transfer Enhancement; Response Surface Methodology.*

1. Introduction

The conventional heat transfer augmentation technique increases either the coefficient of heat transfer or the fluid stream turbulence. The heat transfer enhancement method has gained attention in various industrial applications like aerospace industry, automotive and electronics industry. Paramount studies have been conducted on thermal performance problems. Heat transfer enhancement method can be grouped into three main ones; namely, active heat transfer improvement method, passive heat transfer improvement method and compound heat transfer improvement method [1].

The active method involves energy or power from an external source involving usage such as magnetic fields and pulse induction through plungers. The passive method requires surface modification like extended surfaces and modifications in geometric for heat transfer enhancement. The suggested passive methods for heat transfer enhancement are pin array, dimples, rib turbulators and fins [2]. The compound technique is a combination of active and passive methods to improve the heat transfer. But the passive method is more compatible as compared with other methods because the geometric modifications can be easily employed [3]. The flow separation and flow attachment region are further improved with passive method, spherical dimples as compared to other techniques [4]. Ample of efforts have been taken to develop new ideas for heat transfer improvement. Recently, dimples have pulled more attention because of the importance of the enhancement in heat transfer [5]. Many researchers have extensively conducted experimental and numerical studies for the use of dimples to enhance heat transfer.

An experimental investigation of dimple effects on drag reduction was conducted by Bearman and Harvey [6]. The study shows that dimple profiles create a boundary layer transition without the drag penalties related to sand roughness. The dimpled ball curve remains almost constant at critical Reynolds numbers. As a conclusion, dimple profile surface greatly impacts the drag reduction and laminar-turbulent transition than sand roughness. A study on spherical dimples influences on total heat transfer rate and pressure drop of flat surface of a turbulent flow was carried out in 1993. The result of the study shows that there is no change in pressure drop but the overall heat transfer rate improved to about 30% to 40% [7]. So, dimple profile gives vital effects on heat transfer rate without pressure drop. Beves et al. [8] evaluated that the application of dimple contour on a smooth surface augments the overall heat transfer rate with least pressure drop. Dimple profile not only fastened the heat transfer but it also lowers the pressure drop penalties [9].

Dimple profile increases the coefficient of heat transfer. This is because of the boundary layer of the mainstream was separated during air flow parallel to dimple block. The mainstream separated at the dimple entrance and recirculation zone is created in the upstream side of the dimples. The separated mainstream flow reattaches in the downstream side of the dimple surface and the reattached flow forms a twin vortex. [10-12].The other benefit of dimple profile it is less costly and the overall weight of the product is lighter due to the material removal [13].

As compared to other methods, the dimple method proves as the most significant method in improving thermal performance. Workpiece with staggered dimple arrangements have a great heat transfer coefficient of about 26 % as compared to workpiece with smooth surface. The improvement in heat transfer rate fastened the cooling process [14]. From previous studies, dimple profiled surface exhibits a greater performance in heat transfer. However, the influence of heat transfer towards cooling time has no report in the literature. In addition, the effects of dimple diameter on the heat transfer have not been reported as well. Therefore, the prime objective of this study is to observe the lower cooling time of a dimple surface with different diameters. Meanwhile, the effect of dimple arrangement and air stream velocity will be included in this work. The results of this research aim to serve the heat transfer application.

2. Methodology

The experimental setup for the cooling process is as shown in Figure 1. The experimental study was conducted in a subsonic wind tunnel with a steady laminar flow. Air was used as the fluid in this study and generated by an air blower at room temperature. The air stream was flowed from effuser to test section, where the workpiece was placed at the test section. The velocity of air stream was controlled by frequency inverter to ensure a steady laminar flow. The dimple profile was created on a workpiece according to the dimple parameter as detailed in Table 1. The workpiece material that was used in this experiment was aluminum 6061 with a final dimension of 135 × 100 × 30 mm (L × W × H) as shown in Figure 2. For this study, there are 9 workpieces that were used with various dimple parameters to investigate the heat dissipation. The dimple workpieces were heated over a hot plate heater at the test section of wind tunnel. Once the workpiece achieved the preferred initial temperature (60°C), the air stream started to flow over the workpiece in parallel direction. As the air stream flew over, the heat energy from the dimple workpiece started to dissipate. The changes in the temperature were monitored and measured through T-type thermocouple. The workpiece was connected with 4 cables of thermocouple data logger and linked to a high-performance personal computer. The temperature drop was measured every 1 minute interval until the workpiece achieved room temperature. The temperature drop was plotted in a graph and table through PicoLog Recorder Software as shown in Figure 3. This experimental step was conducted for 9 workpieces with a total experiment number of 17 run. Analysis of variance (ANOVA) was used to evaluate the relative significance of the dimple parameters with regards to the heat dissipation.

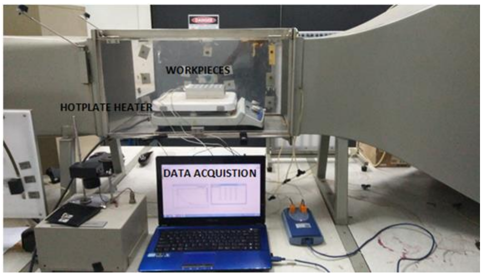

Fig. 1: Photograph of the experimental setup in a wind tunnel

Table 1: Parameters of dimple geometry

Dimple Features	Measurement
Diameter of dimple (mm)	14-10
Orientation of dimple (ϴ°)	90-60
Dimple Density (number)	36-32

Fig. 2: Dimpled profile workpiece under study with dimension

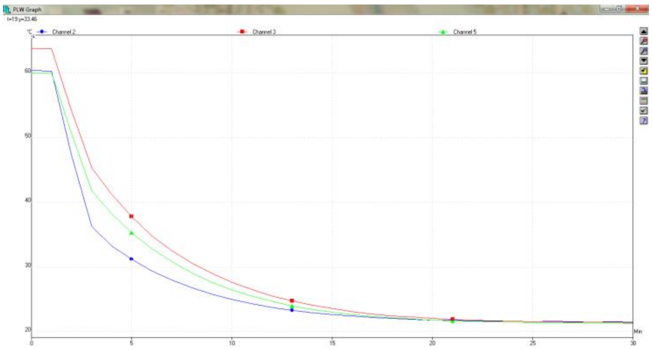

Fig. 3: Temperature drop during cooling process over time(d=14 mm, ϴ=75 °, V=16 m/s)

3. Results and Discussions

Figure 4 shows the observations of cooling time for every experiment run. Experiment no 2 of parameters d: 12 mm, ϴ: 60° and V: 18 m/s produces the lowest cooling time of dimple block, which is 7 minutes. The lower the value of the cooling time expressed, the higher the heat transfer. Experiments no 12 and no 13 present the highest cooling time of about 13 minutes. In both experiments, the diameter of dimple and velocity are the same at 10 mm and 17 m/s, respectively, while the dimple orientation were set at 90° and 60° for respective experiments no 12 and no 13. Therefore, from the observation, it can be concluded that the dimple diameter and air flow velocity are most affecting factor of the heat transfer rate. This is due to the increase in airflow velocity at the inlet, which causes the Reynolds number to be higher. When the airflow velocity increases the collision between air particles is greater, which promotes maximum vortex generation [15].

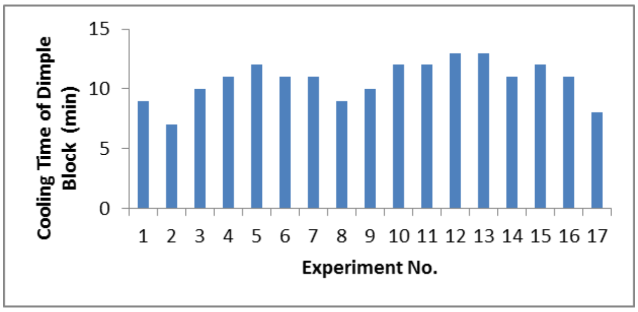

Fig. 4: Graph of cooling time throughout the experiment

In this experimental study, the performance of the dimple surface was evaluated through response surface methodology (RSM). Box Behnken design method is applied with 3 input parameters; namely, dimple diameter (mm) (A), dimple orientation (°) (B) and air stream velocity (m/s) (C) over the output response as overall cooling time of a dimple workpiece. The range of input parameters is shown in Table 2. In RSM, minimum value denotes as -1, whereas +1 represents the maximum value of each input parameters.

Table 2: Actual and Coded values for different parameters

Factor	Type	Low Actual	High Actual	Low Coded	High Coded
A	Numeric	10	14	-1	+1
B	Numeric	60	90	-1	+1
C	Numeric	16	18	-1	+1

Table 3 shows the analysis of variance (ANOVA) of the cooling time of dimple block. The significant factors that affect the response can be identified when the P-value is less than 0.05. Based on ANOVA analysis done by using Design Expert software, the dimple diameter (A) and air stream velocity (C) posed significant effects than the dimple orientation (B). Even though Factor B was an insignificant factor, it cannot separate from ANOVA. This is caused by the interaction of factor B with significant factors namely B2 and BC. In addition, term A2 and C2 also presented some significant effects on the cooling efficiency.

Table 3: Analysis Variance of cooling time of dimple block

Source	Sum of Squares	DF	Mean Square	F value	Prob > F	
Model	44.08	9	4.90	23.64	0.0002	Significant
A	6.12	1	6.12	29.57	0.00010	Significant
B	0.13	1	0.13	0.60	0.4627	
C	2.00	1	2.00	9.66	0.0171	Significant
A^2	8.55	1	8.55	41.28	0.0004	Significant
B^2	1.39	1	1.39	6.72	0.0358	Significant
C^2	22.76	1	22.76	109.88	<0.0001	Significant
AB	0.25	1	0.25	1.21	0.3083	
AC	0.000	1	0.000	0.000	1.0000	
BC	4.00	1	4.00	19.31	0.0032	Significant
Residual	1.45	7	0.21			
R^2	0.9682					

The prediction of the cooling time (CT) is given by Equation 1 as follows:-

$$CT=-517.98-9.61\times(d)-0.84\times(\Theta)+73.55\times(V)+0.36\times(d^2)-2.55\times10^{-3}\times(\Theta^2)-2.33\times(V^2)+8.33\times10^{-3}\times(d)\times(\Theta)-8.16\times10^{-15}\times(d)\times(V)+0.07\times(d)\times(V) \quad (1)$$

Based on the ANOVA, the R2 of the model is 0.9682, showing that the model fits the data. Figure 5 shows the comparison of mathematical model of calculated and observed data of actual experiment. The error between experimental result and statistical prediction calculation was in 1.1% - 5.3% range. Run no. 11 shows the lowest cooling time of 6.87 min (d=14 mm, Ɵ= 60° and V=18 m/s).

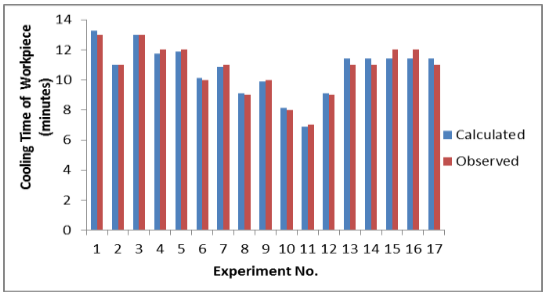

Fig. 5: Comparison between calculated and observed data

The validation of the model was done by comparing the combination of parameter which is not in data set with mathematical model. The cooling process of dimple block was conducted as per selected parameters, as shown in Table 4. The output, which is the cooling time of these parameters, is 9 minutes and 11 minutes. By substituting the parameter values into the mathematical model, the predicted cooling time obtained were 9.43 minutes and 10.2 minutes. This explains that there is a difference between the predicted and the actual value. The error of both experiment sets were 4 and 7.8%. The error is at an unacceptable range, which is below than 10% [16].

Table 4: Validation of prediction model

Experiment No.	A: Dimple Diameter,D (mm)	B: Dimple Orientation, Ɵ (°)	C: Air Fow Velocity,V (m/s)	Cooling Time,C_T (min)	Difference / %
1	10	60	18	9	4
2	14	60	16	11	7.8

Figure 6 shows the response of cooling time at different dimple diameters. From the graph, it is clear that the higher the dimple diameter, the lower the cooling time. As the dimple diameter is getting bigger, the total surface area of a workpiece also gets bigger. Hence, the air stream was exposed to a large surface area when it flew over the dimple block. This will enhance the heat dissipation from a great air motion. Therefore, this presented the shortest time needed for a workpiece to cool down. From the graph, at one point (after 13 mm), the cooling time started to increase even though the dimple diameter is bigger. This is due to the dimple radius to dimple depth ratio. As the diameter of dimple increases, the depth of dimple similarly increases. This deeper depth of dimple causes the vortex generation to take place in a longer time as compared to shallower dimple [17]. So, the dissipation of heat energy from deeper dimple is very difficult. In short, the diameter of a dimple shouldn't be too small or too big. The recommended dimple diameter range as a result from this study is 12 mm to 13 mm. This is in line with findings by other researchers [18].

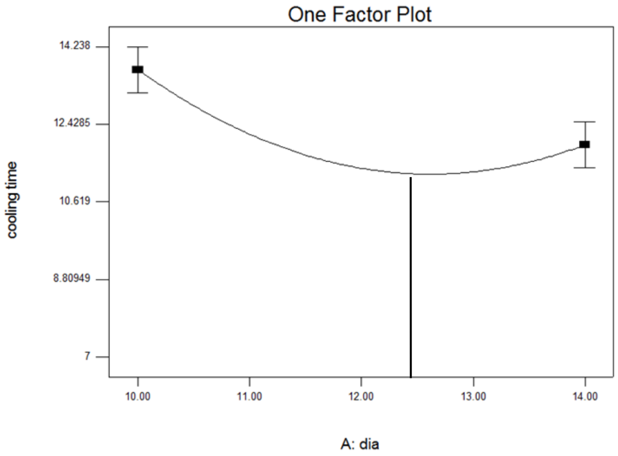

Fig. 6: Graph of dimple diameter against cooling time

The plot of the cooling time against dimple orientation is shown in Figure 7 It can be observed that the cooling time decreases when the dimple orientation in staggered arrangement (60°) as compared to inline arrangement, which is in 90° orientation. However, this graph is insignificant. This study found that the shaded region (Ɵ=70° - 80°) from the graph should be avoided in order to improve the heat transfer. The 75° dimple orientation which falls between inline and staggered arrangement does not carry any significant effects towards heat dissipation of the overall block. Dimpled profile surface has a much better heat transfer coefficients of about 26 % as compared to flat surface with staggered arrangement, whereas for inline arrangement of dimple, the heat transfer coefficients are about 25% as compared to flat surface [14]. At low angle of dimple orientation, the heat transfer coefficient yields higher values [19]. The heat dissipation will enhance when the coefficient of heat transfer is higher. Therefore, the dimple with staggered orientation (60°) dissipates heat energy faster from the dimple block as compared to the dimple with 90° orientation.

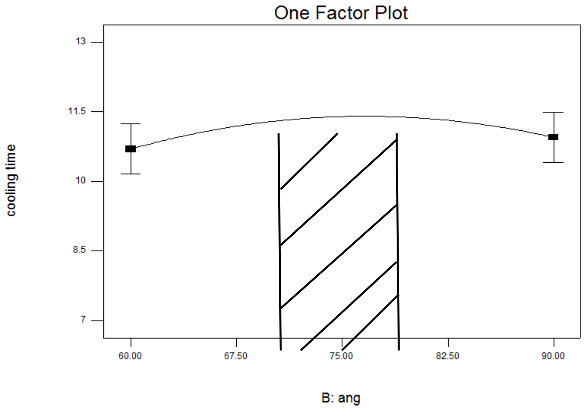

Fig. 7: Graph of dimple orientation against cooling time

The effect of air stream velocity towards cooling time is shown in Figure 8. When the velocity of air stream increased from 16 m/s to 17 m/s, the time taken for the workpiece to cool down also increased from 9.5 minutes to 11.5 minutes. However, the cooling time of workpiece decreased from 11.5 minutes to 8.7 minutes when the velocity of the air stream started to increase from 17 m/s to 18 m/s. As a result, the marked area in the graph (V= 16.50 – 17.25 m/s) promoted poor heat transfer. Consequently, it increased the time taken of the workpiece to cool down. Therefore, the shortest cooling time obtained is at 18m/s velocity.

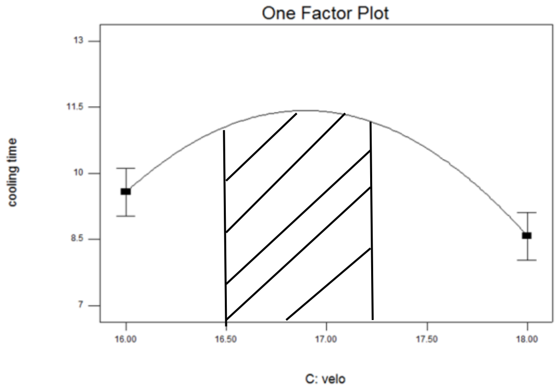

Fig. 8: Graph of air stream velocity against cooling time

4. Conclusion

Dimple diameter and the air stream velocity are significant factors that affect the cooling time of dimple workpiece. However, the orientation of dimple does not seem to have any significant effects on the same. The dimple diameter is the most significant factor that affects the heat dissipation of dimple block, followed by the air stream velocity. The best set of the parameters was in the case that the dimple diameter is 12 mm, the dimple orientation is 60° and the air stream velocity is 18m/s, in order to generate a low cooling time of about 7 minutes.

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