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A Statistical Study on Reduction of Drag Force for Golf Balls

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The most effective method to reduce the drag force of a sphere is to make dimples on its surface. In this paper, to investigate the flow in the dimple, the flow in a groove on a cylinder surface was visualized instead of the flow in a dimple of sphere. And the effective dimensions of the groove for reduction of drag force was verified. Moreover, since it can be considered that the flow in a dimple is similar to the flow in a groove, a statistical method to diagnose the optimum arrangement of dimples was investigated by applying the result of the groove flow.

1. Introduction

Many investigators have investigated a hydrodynamic problem on the drag force for a blunt body like a sphere or a cylinder for a long time. The drag of a slender body or a streamline body has been almost proved by using the boundary layer theory, while the drag problem of a blunt body has been behind that of a slender body. One of the reasons is that the blunt body drag is caused by not only friction but also separation of the flow. Especially, the pressure drag force due to the separation is much larger than the friction drag. Therefore it is important to study the phenomena of separation for the drag force.

The theoretical study of the drag force has been studied by many investigators since the d'Alembert's paradox, but the analytical theory of separation has not yet solved even at present.

The experimental studies on the reduction of drag force have been developed by several methods. One of the most effective techniques is to disturb the flow past the body surface. A tripping wire settled on the body surface changes the laminar boundary layer in the upstream into the turbulent one in the downstream. This turbulence has a remarkable effect to prevent the reverse flow in the boundary layer. And as a result of this, it is considered that the separation point of the boundary layer retreats the range of wake flow is getting narrower, and the drag force becomes less. Instead of the tripping wire, the roughness of the body surface shows the same effect, too. Weiselberger et al(1) has found out the fact that the drag force extremely decreases at a certain Reynolds number in the experiment of a sphere with smooth surface, where the cause of the drag reduction is apparently different from the turbulent separation effect.

Due to the experiments of Bearman and Harvey(2), an apparent difference between the characteristic curve of the drag coefficient of a ball with rough surface and that of a ball with dimples has been observed. The experimental result shows that the drag of a ball with dimples is less than that of a ball with rough surface. Considering this fact, the disturbance in a stream by the rough surface is not a

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sufficient explanation for the flow past the surface of a body made by dimples.

Kimura and Tsutahara[3] carried out the experimental study on the flow in grooves on a cylinder body instead of dimples of a golf ball, and ascertained that the drag reduction of the cylinder with grooves is caused by the separation bubble (vortex flow) in the groove. This means that the effect of a groove differs from the effect of roughness of the body surface, and also that the effect of the groove for the cylinder is the same as the one of dimples for a golf ball. In this experiment, a vortex flow in a groove was visualized by the hydrogen bubble method and the dye injection technique. And it is verified that the effective position of the groove is at 78° from the center of the cylinder.

The separation babble in the groove has the following two effects to retreat the separation point. The first is not to make the boundary layer into a reverse flow by the vortex in the groove, and the second has the effect to make the flow, which once separated from the surface, attach again towards the body surface.

The investigation on the groove or the dimple until now has been to verify qualitatively the explanation on the reduction of drag force for a blunt body and to find out the effective position of the groove on the cylinder. However, the relation between the size of the groove and Reynolds number is not found out. Moreover, in case of a rotating golf ball, the investigation on optimum arrangement of dimples has not been carried out.

In this paper, we research the statistically the arrangement of dimples, because a real golf ball flies with rotating. Without rotation, the effective position of dimples is at 78° above mentioned. In case of rotating golf ball, the more dimples are near 78° in probability, the better drag performance can be obtained. The purpose of this investigation is as follows; the first purpose is to verify the relation between Reynolds number and the effective groove size where a perfect separation bubble (vortex flow) occurs. The second purpose is to find out statistically the highest probability that the optimum arrangement of dimples occurs.

2. Experiments of Vortex Flow in Grooves

Experiments have been carried out using a shallow water tunnel made of acrylate resin as shown in Fig.1. There are two reservoir tanks at the upstream and downstream side, which are connected by an observation channel. These make a closed circuit being joined with two pumps, whose capacities are 140 ℓ/min and 80 ℓ/min. The pumps make a flow circulate from the upstream tank to the downstream tank through the test section. The test section is 120 mm in width, 465 mm in length, and 120 mm in depth. In order to rectify the circulated flow, two net screens settled at intervals of 20 mm, an aluminum rectifying lattice and a perforated plate with 6 mm in diameter are inserted at the upstream of the test section. By adjusting the revolution speed of pumps, the flow velocity can be varied from 0 to 20 cm/s.

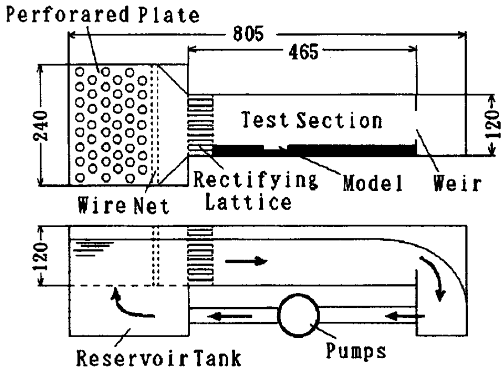


Fig.1 Shallow Water Tunnel

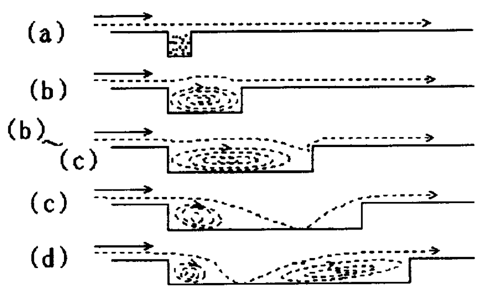


Fig.2 Types of Vortices

Two kinds of groove models ,a rectangular type and a trapezoid type whose oblique angle is 45° ,are used in this experiment. The depths of both grooves are 1, 3 and 5 mm, and the length is variable from 0 to 100 mm. Reynolds number is 80 ~ 750, which are the almost same as that of a real golf ball dimples.

The vortex in a groove is visualized by the surface floating tracer method and the dye injection technique. Fig.2 shows the several patterns of vortices. (a) no vortex exists in a groove because of too narrow groove length, (b) a perfect vortex exists in a groove, (b) to (c) the streamline of the main flow attacks at the trailing edge of a groove as the length becomes longer, (c) the vortex length becomes too small and the main flow enters into the bottom of the groove, (d) the size of vortex attaching to the front edge does not vary any further though the groove length becomes larger than the range (c).

In the visualizing experiments, blue ink is used for the dye injection method as shown in Fig 3, which shows a perfect vortex case of pattern (b) in a rectangular groove. The depth d=5 mm, the length ℓ =15 mm and Reynolds number Re=450. In the surface floating method, silver powder is used for the tracer as shown in Fig 4, which shows a perfect vortex case of pattern (b) in a trapezoid groove. The depth d=5 mm, the length ℓ =40 mm and Reynolds number Re=410.

Fig.5 shows the experimental results of the rectangular groove and the trapezoid groove. Both results of the two grooves are very similar. In the region (a), d/ℓ is larger than unity, d/ℓ is between 1 and 0.2 in the region (b), d/ℓ is between 0.2 and 0.1 in the region (c) and d/ℓ becomes smaller than 0.1 in the region (d).

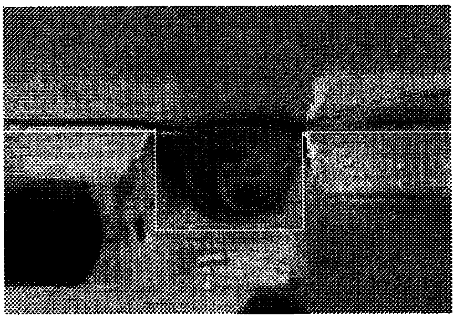


Fig.3 Vortex in Rectangular Groove

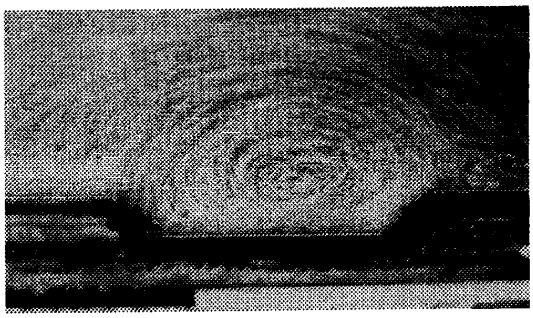


Fig.4 Vortex in Trapezoid Groove

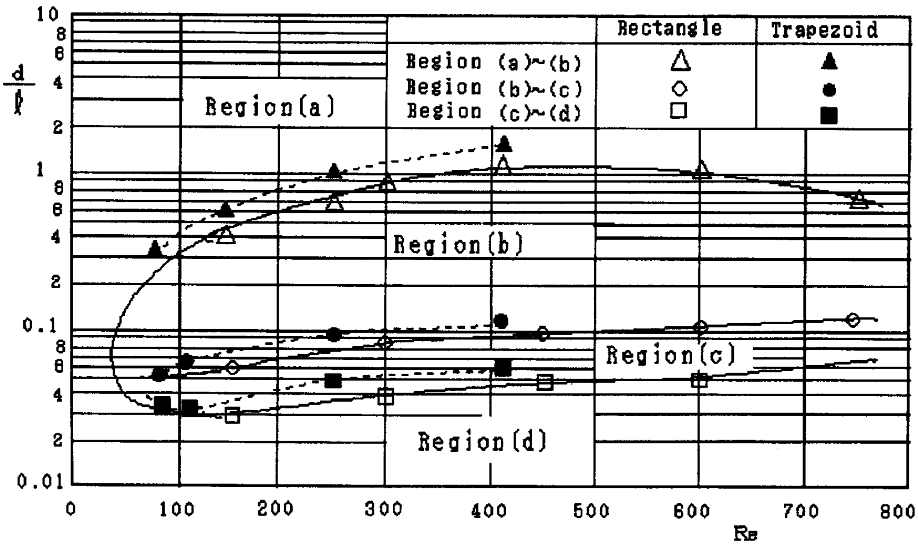


Fig.5 Experimental Result of Vortex Patterns in Groove

3. Measurement of Drag Coefficient of Sphere

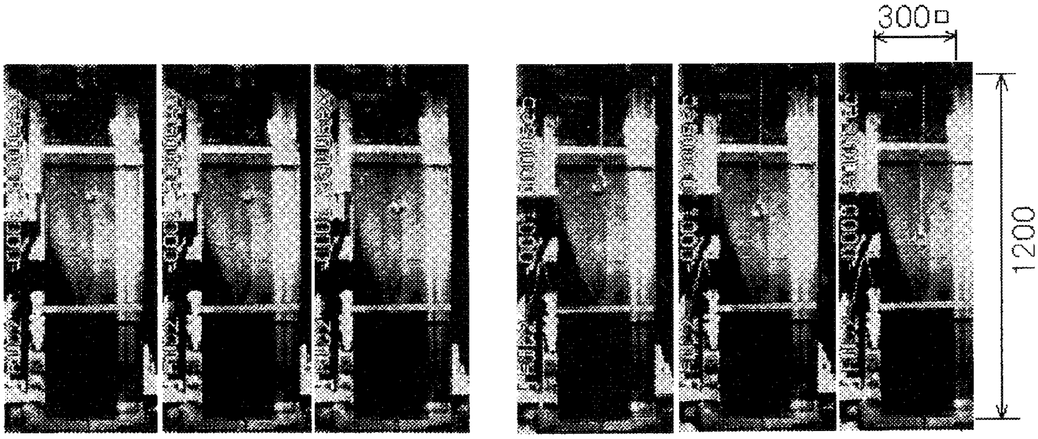
A real golf ball flies at the speed of over 200 km/hr, where Reynolds number is order of 10^5. In order to carry out experiments of a golf ball, we need a high-speed wind tunnel of 70 m/s or a water tunnel of 5 m/s. Since it is very difficult to use these high-speed equipments, a water tank for the falling test was used in this paper. The tank is made of acrylate resin, whose height is 1200 mm and cross-section area is 300 $\times$300 mm^2 as shown in Fig.6. To assure the accuracy of the measurements, a smooth ball was used for preliminary test. The equation of motion is as follows,

$$m\frac{d^2y}{dt^2} = mg - D - B \qquad (1)$$

where m is the mass of a smooth ball, D the drag force and B the buoyancy. The buoyancy $B = \rho g \pi d^3/6$, where d is the diameter of the smooth ball, ρ is density of water, and g is the gravity acceleration. The drag force D is proportional to velocity v when Reynolds number is small (i.e. at the Stokes flow, while D is proportional to v^2 as the velocity becomes larger. This means that it is difficult to integrate the equation (1). Therefore we integrate numerically by using well-known experimental data of the drag coefficient C_D for a smooth sphere. The drag coefficient C_D is given by the next equation.

$$C_D = \frac{D}{\frac{1}{2}\rho v^2 \frac{\pi d^2}{4}} \qquad (2)$$

The experiment was carried out by using a smooth ball made of acrylate resin whose diameter is 39.8 mm and the mass is 0.0391 kg. A high-speed camera was used for taking photographs, and one of the results is shown in Fig.6 (a).



(a) Smooth Ball (b) Smooth Ball with a Bar

Fig.6 Falling Test of Golf Ball (Photographed by High Speed Camera)

The comparison of a calculating result (solid line) and experimental one (dot mark) is shown in Fig.7. The both results agree very well, and it has been assured that this falling test can be used for the drag experiment of spheres and golf balls. However, the falling velocity reaches a constant value (limiting velocity) at the distance of 500 mm from the top, and then Reynolds number is only 1.8×10^4, which is not sufficient for measuring the drag of golf balls. This occurred for the reason why the smooth ball's weight was too light. Therefore, to make the ball weight heavier, a copper bar (4 mm in diameter, 1080 mm in length and 40 g in mass) was attached to the sphere as shown in Fig.6 (b).

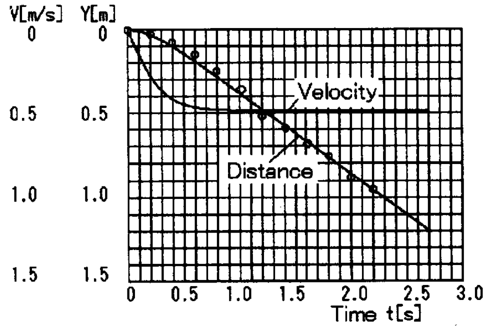


Fig.7 Result of Falling Test

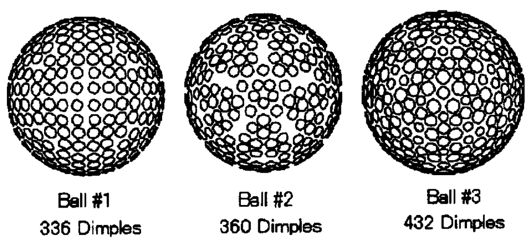


Fig.8 Golf Balls for Falling Test

Three kinds of golf balls were used for the falling test as shown in Fig.8. Ball #1, Ball #2 and Ball #3 are 41.15 mm, 42.67 mm and 42.67 mm in diameter; 44.14 g, 45.79 g and 45.47 g in mass and the dimple numbers are 336, 360 and 432, respectively. Each line in Fig.9 quoted the data from reference (2) shows the drag coefficients of a smooth ball, a golf ball and rough balls, in which k means the root mean square of roughness height and d shows the diameter of a golf ball.

The experimental results are shown by dot marks in the figure, and agree very well with Bearman's results and. At larger Reynolds number of 10^5, the drag coefficient of Ball #2 is the smallest no matter how Ball #3 has the largest number of dimples.

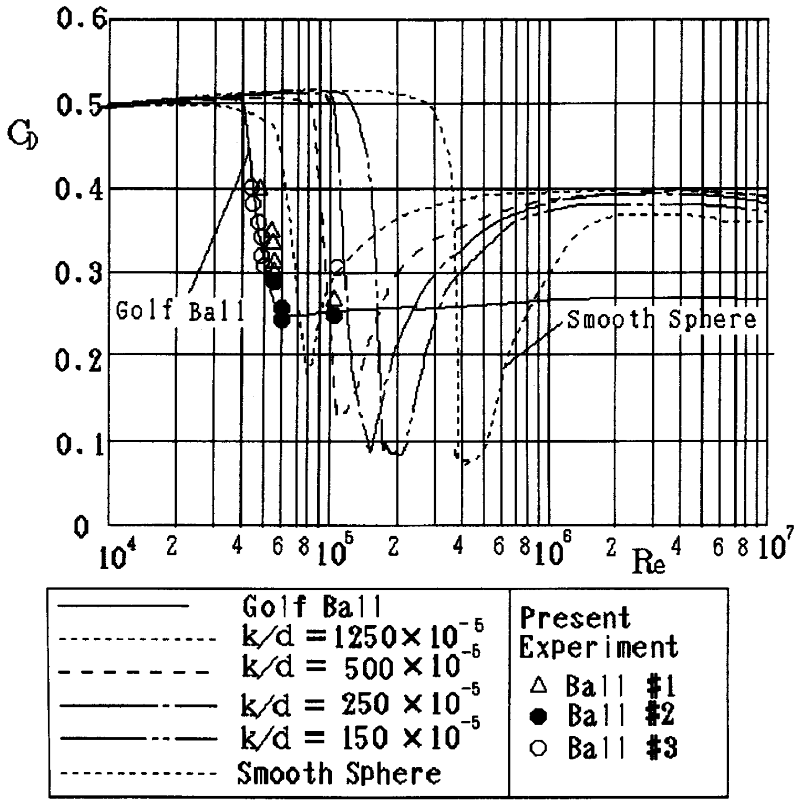


Fig.9 Curves of Drag Coefficients for Golf Balls and Experimental Results

4. Statistics on Arrangement of Dimples

To make the drag of a sphere reduce, the dimples made over the sphere surface is the most effective method. In case of two-dimensional body such as a cylinder, the groove made on its surface is the same effect as the dimples for three-dimensional case. Kimura and Tsutahara (3) were carried out the experiment on the effect of grooves. Three types of grooves were studied and a smooth circular cylinder without grooves was also used for comparison. The cylinders used in the experiment were 100 mm in diameter. All the chord length of these three grooves was 8 mm. The depth of the type 1 groove is 1.7 mm, one of type 2 is 1.2 mm and type 3 is 0.7 mm in depth.

The experimental result is shown in table 1. The attack angle θ means an angle from the foremost point of the cylinder to the leading edge of a groove as shown in fig.10. The groove has no effect when the position is less than 70°. As for all these grooves, the most effective angle is 78°.

The optimum position of a dimple is 78 ° without rotation as mentioned above. However, when a golf ball is rotating, we must consider about the probability that the leading edge of dimples comes to at 78 °.

Dimples are defined as "Sea" and the surface except dimples is defined as "Land" as shown in Fig.10. S and L are the width of the sea and the land along a peripheral line of cross-section (equator) as shown in Fig.11. Several pairs of the land and sea exist along the equator. For a pair of the land and sea, every ratio L/S is called the wavelength of spectrum, and M is defined as the magnitude of spectrum. Band widths of the spectrum L/S are as follows: For $0<L/S<1$, the band width is 0.1. For $1<L/S<10$, the band width is 1.0. For $10<L/S<100$, the band width is 10.0 and for $L/S>100$, the value of L/S becomes 100. If S=0 (there is no dimple around a circumference), L/S is defined as 100.

Table 1 Position of Attack Angle and Separation Points [deg]

Type \ θ	45	55	65	70	75	78	80	85
Smooth	92.5							
Type 1	92.0	91.0	93.0	93.0	94.0	94.5	94.0	85.5
Type 2	91.5	91.5	92.5	93.0	94.0	94.5	93.5	85.5
Type 3	92.0	91.5	92.0	92.5	92.5	94.0	93.0	85.5

An example of the spectrum graph for Ball #2 is shown in Fig.12, in which the horizontal axis shows the spectrum band value and the ordinate axis shows the frequency of L/S (in arbitrary scale). The calculating number of times is 100, which means that the number of L/S band is counted along 100 arbitrary equators. When the sea length is too small, it is considered that the dimple effect vanishes. The critical sea length at vanishing the dimple effect is defined as S_{crit}. M_0 shows the magnitude in case that the sea length is smaller than S_{crit}. In this paper, we assume that the critical sea length is 1.5 mm from the results of groove experiment as shown in Fig.5. Consequently, $M-M_0$ means the effective value of the magnitude.

Fig.13, 14 and 15 show the graph of $M-M_0$ for Ball #1, #2 and #3, respectively. In these graphs, too large L/S means that the dimple effect becomes small. At limiting case of $L/S=\infty$, there is no dimple along the line, and this is equivalent to a smooth ball. Consequently, the upper limit of L/S at vanishing the dimple effect is defined as $(L/S)_{high}$, which is called high critical value of L/S.

On the other hand, too small L/S means that the approaching distance of flow to a dimple edge is very short as the land length is too small. This means that the boundary layer does not develop, the flow collides the inner wall of a dimple and the flow separation is apt to occur. The limiting case of L/S=0 is equivalent to a rough golf ball. The lower limit of L/S at vanishing the dimple effect is defined as $(L/S)_{low}$, which is called low critical value of L/S.

At present, these critical values are not decided accurately. We assumed that $(L/S)_{high}=1.0$ and $(L/S)_{low}=0.1$. This reaches a conclusion that the ball #2 is superior to the others by comparing the magnitudes of spectrum between S/L=0.1 and S/L=1.0.

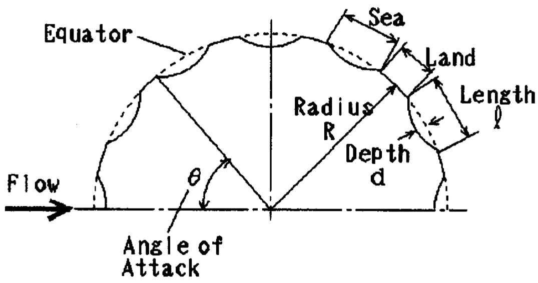


Fig.10 Land and Sea of Golf Ball

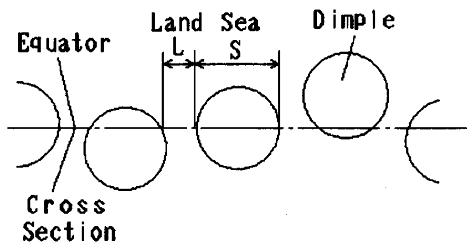


Fig.11 L/S Ratio around Cross-Section

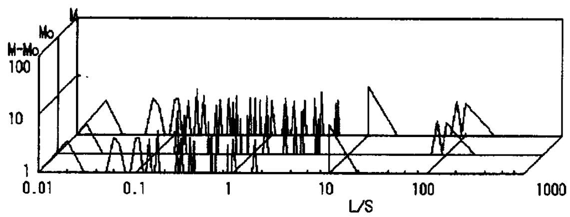


Fig.12 Spectrum Graph of Golf Ball #2

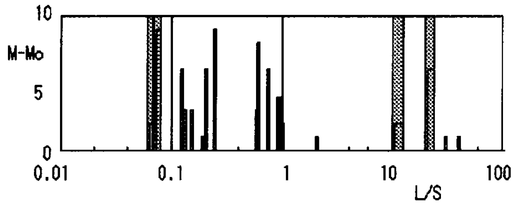


Fig.13 L/S Frequency of Ball #1

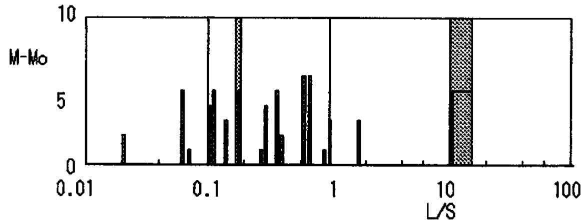


Fig.14 L/S Frequency of Ball #2

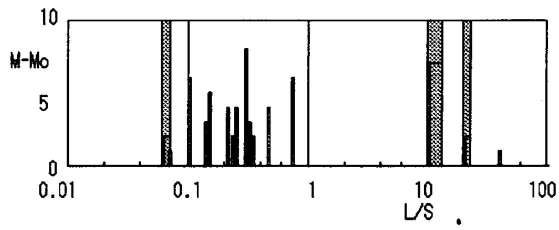


Fig.15 L/S Frequency of Ball #3

5. Conclusion

In this paper, to investigate the flow in the dimple, the flow in a groove on a cylinder surface was visualized instead of the flow in a dimple of sphere. And the effective dimensions of the groove for reduction of drag force was verified. When the ratio of depth to length of a groove d/ℓ is between 0.2 and 0.1, a perfect vortex occurred in the groove over a wide range of Reynolds number.

Moreover, since it can be considered that the flow in a dimple is similar to the flow in a groove, a statistical method to diagnose the optimum arrangement of dimples was investigated by applying the result of the groove flow. The result shows that the optimum arrangement of dimples can be obtained when the ratio of the sea to land S/L exists between 0.1 and 1.

References

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