Visualization and measurement of separation positions around rotating dimpled ball

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Abstract

Flow fields around balls used for ball games have very complicated and interesting physics because most of the balls fly near critical Reynolds number. However, the mechanism of separation flow around a dimpled ball including boundary layer transition has not been fully understood, especially when the ball is rotating, because the flow is three dimensional. In the present research, the authors visualized the separated flow using smoke wire and measured flow field using hot wire to clarify separation positions around a rotating dimpled ball. Furthermore, two experimental results are compared with each other and showed a good qualitative agreement on separation positions. In addition, the movement of separation positions depending on the conditions of uniform flow velocities and non dimensional spin parameters is clarified.

Keywords: Visualization; separation position; dimpled ball; smoke wire; rotation

1. Introduction

Flow fields around smooth sphere located stationary in the uniform flow usually can be divided into 3 regions according to the drag coefficient. In the subcritical flow region, the drag coefficient is nearly independent of the Reynolds number from 0.45 to 0.5. The next region, called critical flow, is where the Reynolds number is $3.5 \times 10^5 \sim 4.0 \times 10^5$ and drag coefficient has a rapid drop to the minimum value. With

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further increase of the Reynolds number, drag coefficient increases gradually at this supercritical flow region [1, 2]. Similarly, flow fields around a dimpled ball also can be divided with the relation between the Reynolds numbers and drag coefficients. However, in this case, it is known that critical range starts at the lower Reynolds number than a smooth sphere case [3, 4]. It is considered that near a dimpled ball surface dimpled surface triggers the boundary layer transition from laminar to turbulent flow at a relatively low Reynolds number, and with this boundary layer transition the turbulent separation occurs with small wake region, resulting in the reduced pressure drag. Furthermore, when the ball gains the rotation, the relative velocity between ball surface and uniform flow is changed. That means the characteristics of flow filed are also changed [5]. However, the mechanism of separation flow around a dimpled ball including boundary layer transition has not been fully understood, especially when the ball is rotating, because the flow is three-dimensional. In the present research, the experimental results visualized the separated flow using smoke wire and measured flow field using hot wire to clarify separation positions around a rotating dimpled ball are reported.

2. Experimental Apparatus and Method

2.1. Smoke Wire Visualization

A 100 mm diameter dimpled ball is located at the test section (220mm × 190mm) of a circulation type wind tunnel (see Fig. 1a). Smoke wire is used to visualize the flow fields. Separation points are identified by the photographs taken by a high speed camera (frame rate 2000fps, shutter speed 1/3000 sec). Dimple diameter is 9.53mm and dimple depth is 0.43mm. 312 dimples are distributed on a sphere. For the smoke wire, propylene glycol is applied to a thin wire and smoke is generated with turning on the electric power. The thin wire is made with 30 metallic fibers of 12μm diameter. For a light source, halogen lamp of 150W is used. Fig. 1 shows the experimental apparatus and coordinate system. The origin is set at the ball center, x direction is set to the uniform flow direction, y direction to the vertical direction and z direction to the span direction. The dimpled ball is rotated around z axis. φ is the angle from the xy plane and θ is the angle from the front stagnation point. The uniform velocity $U_c$ is set to 4, 6, 8, 10 m/s, and rotation is set to 0 rpm and 300 rpm.

2.2. Hot Wire Measurement

A 42.7 mm diameter dimpled ball (golf ball) is used for the flow velocity measurement (see Fig. 1b)). Flow velocity around ball is measured with the constant temperature type hot wire anemometer. Experimental conditions summarized with Reynolds number and the spin parameter (Sp=radius of ball * angular velocity / uniform flow velocity) are shown in table 1. In case of the 100mm diameter dimpled
ball without rotating, the boundary layer has a laminar separation when $U_p = 4 \text{m/s}$, transition from laminar to turbulent flow when $U_p = 6.8 \text{m/s}$ and a turbulent separation when $U_p = 10 \text{m/s}$.

Table 1. Conditions for experiments

| $U_p$ (m/s) | Re ($\times 10^4$) | Sp  |
|-------------|-------------------|-----|
| Visualization | 4                | 2.85 | 0.39 |
|              | 6                | 4.28 | 0.26 |
|              | 8                | 5.70 | 0.20 |
|              | 10               | 7.13 | 0.16 |
| Measurement  | 10               | 2.85 | 0.39 |
|              | 20               | 5.70 | 0.20 |

3. Results and Discussion

3.1. Smoke Wire Visualization

Fig. 2(a) shows a photograph at $U_p = 6 \text{ m/s}$, 0 rpm and $\varphi = 0^\circ$ plane. The separation point $\theta_s$ can be detected with the enlarged view of Fig. 2(a) (see Fig. 2(b)). For the emphasis of smoke, each photograph was taken from the difference between after and before smoke induced. It is seen that the upstream before separation position flows along the dimpled surface. However, the flow inside of dimple cannot be observed with slow shutter speed and low resolution. $\theta_s$ of Fig. 2 is $87.4^\circ$. The separation point was decided as the averaged value of 100 photographs. Fig. 2 is an instantaneous view when the averaged and instantaneous separation points are coincided with each other. Fig. 3 to Fig. 8 show the separation points of $\varphi = 0^\circ$, $15^\circ$, $30^\circ$, $150^\circ$, $165^\circ$, $180^\circ$ planes at 300rpm, i.e. Sp=0.26, respectively. Investigating those photographs, three dimensional and time averaged separation positions can be investigated.

Firstly, separation positions along the $\varphi = 0^\circ$ plane are considered. Compared with Fig. 2a ($\theta_s = 87.4^\circ$) and Fig. 3 ($\theta_s = 98.2^\circ$), where the rotating direction is the same with the uniform flow direction i.e. upside of ball, $\theta_s$ moves to downstream. On the other hand, compared with Fig. 2a ($\theta_s = 87.4^\circ$) and Fig. 8...
(θs=74.7°), where the rotating direction is opposite with the uniform flow direction i.e. downside of ball, θs moves to upstream. This means that θs moves to the rotating direction against the dimpled surface. This proves that the wake region is bended to the negative y direction, resulting in the lift force generation.

Secondly, three dimensional separation position distributions are considered. θs of φ=15° (see Fig. 4) and 165° (see Fig. 7) planes approximately agree with those of φ=0° and 180° planes, respectively. On the other hand, θs of φ=150° (see Fig. 6) plane has larger movement to downstream from that of φ=165° plane. However, θs of φ=30° (see Fig. 5) plane has a little movement to downstream from that of φ=15° plane.

With those results, when the ball is rotated, the movement of θs is varied depending on φ and it is considered that the three dimensionality of the boundary layer affects the separation specification. Therefore, the three dimensionality of the boundary layer is considered as following. The velocity distributions inside of the boundary layer at φ=0°, 180° can be regarded as two dimensional. However, except those positions, with the difference between the directions of shear force on the surface and the uniform flow, the boundary layer is twisted forming the three dimensional boundary layer.

Fig. 9 shows the relationship between the Reynolds number and θs on φ=0° and φ=180° planes. When 0 rpm and the subcritical Reynolds number region, θs is 82°, and this is almost the same with that of smooth sphere. On the other hand, at the supercritical range, θs is 99°, and this is smaller than that of smooth sphere of θs=120°. When the ball is rotated, θs moves to downstream at the upside of the ball and this movement is relatively insensible to the Reynolds number and at the downside of the ball, θs moves to the upstream largely.

θs on φ=0° and φ=180° planes at 0 rpm are shown in Fig. 10 with a bird’s eye view. As already discussed, θs moves to downstream as the uniform flow velocity increased.
Fig. 9. Relationship between the Reynolds number and $\theta$, on $\varphi=0^\circ$ and $\varphi=180^\circ$ planes

It is shown $\theta_s$ at 300 rpm in Fig. 11. Compared with 0 rpm, $\theta_s$ moves to downstream at the upside and to upstream at the downside. The uniform velocity range within this experiment, the movement of $\theta_s$ at upside is little. On the other hand, that at downstream is largely affected by the uniform velocity. With those results, it is considered that $\theta_s$ moves complicatedly with the relationship between the uniform flow velocity and the circumferential velocity.

3.2. Hot wire Measurement

The measurement results at $\varphi=0^\circ$ and $Re=2.96\times10^4$ are shown in Fig. 12. The results in Fig. 12 show the distributions of the averaged velocity and velocity fluctuation which are non-dimensionalized with $U_\infty$ at the 0.5 mm above the dimpled surface. In case of $Sp=0$ (0 rpm), the flow velocity is reduced at $\theta$ range of $90^\circ$ to $95^\circ$, and the flow fluctuation increased. This means that the measured point enters the separation region.

Using the averaged velocity distributions in Fig. 12, $\theta_s$ is conveniently defined by the intersection point with horizontal axis and the line having the biggest negative gradient which connected two adjacent measuring points. Fig. 13 shows $\theta_s$ on two conditions in table 1 with the results of Fig. 9. Although absolute values are different which is due to the difference of separation position definition, as can be seen in Fig. 13, $\theta_s$ moves to downstream at the upside of the ball and to the upstream at the upside of the
ball as the Reynolds number increased. This movement at the downside is larger than the upside, and qualitatively in good agreement with the visualization results on the whole.

4. Conclusion

The phenomenon of boundary layer separation on the dimpled surface of a ball was visualized with the smoke wire. As a result, when a dimpled ball rotated, the movement of the separation position was showed quantitatively. Furthermore, by the effect of the three dimensional boundary layer, it was also shown that the change of the separation position is due to the twisted boundary layer. Moreover, comparison with the results measured by hot wire was performed and it revealed that it was in a good qualitative agreement with the visualization results. For the future research, the visualization and the measurement will be conducted with the further various Reynolds number and the spin parameters, and the three dimensional separation will be investigated in more detail.

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