Journal of Human Movement Science (2024)
Clausius Scientific Press, Canada
DOI: 10.23977/jhms.2024.050305
ISSN 2523-5850 Vol. 5 Num. 3

Numerical Study of the Aerodynamic Characteristics in Ski Jumping

Huachen Cui

Affiliated Middle School of Peking University, A82 Daniwan Road, Haidian District, Beijing, China

Keywords: Ski jumping; aerodynamic analysis; computational fluid dynamics (cfd); posture optimization, athlete performance

Abstract: Ski jumping, a sport blending athleticism and aerodynamics, has evolved significantly over the past century, with a focus on achieving longer jump distances through optimal aerial posture. This paper delves into the aerodynamic principles governing ski jumping and investigates the historical evolution of jump postures. By employing computational fluid dynamics (CFD), our research aims to provide valuable insights into optimizing the aerial posture of ski jumpers. The literature review showcases the progression of ski jump postures from the early 20th century to contemporary techniques, emphasizing the crucial role of posture maximizing jump distances. Previous studies have elucidated the aerodynamic advantages of the "V" posture, highlighting its ability to minimize resistance and enhance lift, thereby enabling longer flight times and greater distances. Our research methodology involves utilizing CFD simulations to analyze the aerodynamic performance of athletes during ski jumping. By capturing airflow patterns and pressure distributions around the body, we aim to identify key factors influencing jump performance and propose strategies for optimizing posture. Comparing wind tunnel experiments with CFD simulations, we highlight the advantages of the latter in terms of cost-effectiveness, efficiency, and safety. CFD provides a versatile platform for studying fluid dynamics, allowing for precise adjustments of parameters and yielding reliable numerical results. The scope of our research encompasses fundamental fluid mechanics principles, methodology, and practical applications. Through a comprehensive analysis of aerodynamic phenomena and athlete performance, we seek to contribute to the ongoing development of ski-jumping techniques and enhance athletes' competitive edge on the global stage.

1. Introduction

1.1. Background

Skiing is a competitive sport where athletes place their skis on the soles of their boots to perform speed, jumping, and downhill on the snow. Over time, skiing has gradually evolved into various forms. The content of competition is not only based on speed as a criterion, but economic sports events such as ski jumping, which have dual considerations for sliding distance and aerial posture, have gradually entered our vision. Since the listing of ski jumping as a Winter Olympics event in

1924, ski jumping has developed rapidly over the past 100 years. Most countries, mainly Nordic countries, have started to develop ski jumping, and their participation in ski jumping has increased exponentially compared to a hundred years ago. At the Winter Olympics, ski jumping has also become a popular competition, with a large number of spectators actively paying attention to the development of ski jumping around the world. Therefore, our research will study the aerial posture of ski jumping from an aerodynamic perspective, and provide aerial technical support for ski jumping athletes to ensure that they can maximize their physical functions and achieve longer jumping distances, thus promoting the development of ski jumping.

1.2. Literature review

In 1934, Bigger ruud, Sigmund Rudd's younger brother, adopted an upper body forward tilt and extended arms posture, further raising the world record to 92 meters[1]. In the mid-1950s, Swedish athlete Andreas Daescher invented a new gliding posture: his body further leaned forward and his arms pressed back against his side. In 1985, Swedish athlete Jan Boklov was the first to separate the tips of two skis outward in a "V" shape during gliding. From the historical development of ski jumping, we can see that the distance of ski jumping largely depends on the posture of the action. Different postures determine the distance of jumping. Therefore, we analyze the aerial posture of ski jumpers through aerodynamics, and combine the traditional "V" posture to calculate the optimal tilt angle and body posture of ski jumpers in the air, in order to help them improve their performance in competitions. With the development of technology, people have begun to use scientific analysis to further improve the aerial posture of ski jumping, in order to achieve the goal of increasing the jumping distance of ski jumping. In previous studies, scientific theoretical support has been provided for the previous V-shaped attitude through aerodynamic theory. The V-shaped posture will keep the body and snowboard as parallel as possible to the ground. In order to enable athletes to reach a stable flight position as soon as possible in the early flight phase, it is necessary to ensure small resistance and complete backward and forward rotation angular momentum to achieve complete balance[2]. Garden et al. found through CFD simulation methods that in the early stages of flight, the influence of speed on the coefficient of force and drag is minimal, while the opposite is true: changes in the windward angle have a significant impact on the lift and drag of the athlete's body. With further wind tunnel experiments studying the dynamic characteristics of snowboards, it can be seen that the force increases with the increase of micro angles. A large V-shaped posture with zero edge angles can improve the negative impact of edge angles on physiological coefficients, while maximizing the upward lifting force of the air, also known as lift. Using this lift force can enable athletes to fly for longer periods of time, thereby achieving longer leap distances[3].

1.3. Scope of current research

Our research aims to use computational fluid dynamics as the primary research method by observing the aerodynamic phenomena of athletes, and to study the practice of aerodynamic theory by ski jumpers in the air through the analysis of their aerodynamic performance. The rest of paper is organized as follows: section2 methodology and fundamental of fluid mechanics Section 3 present the result and the discussion. Finally, the conclusion and the future work in section 4.

2. Methodology

2.1. Approaches to investigate the ski jumping problem

There are two main ways to study fluid mechanics, the first is through wind tunnel experiments, and the second is through computational fluid dynamics. Wind tunnels are artificially generated and controlled to simulate the flow of air around flying or solid objects. They are the most commonly used and effective tools for conducting aerodynamic experiments. In a simple sense, a wind tunnel can be understood as a process in which objects move while air remains stationary in real motion, or a wind tunnel where air moves while objects remain stationary[4]. Then the aerodynamic characteristics generated was simulated by the mutual motion between air and objects. The use of wind can obtain parameters such as force velocity, angle, and rotational speed during movement, and then analyze or determine the optimal posture of equipment control and body. The latest analytical trajectory flight distance of athletes was calculated based on the data measured through wind experiments and the analysis of the shape and size of the jump platform section. Therefore, an attitude control method was proposed through the theory of multi body system dynamics. However, at the same time, there are also some shortcomings in wind tunnel experiments that have led to deviations in the experimental results[5]. Firstly, there is the boundary effect. In real flight, the stationary atmosphere has no boundary, while the airflow in the wind tunnel has a boundary. Therefore, the existence of the boundary limits the curvature of the streamline near the boundary, making the wind tunnel flow field different from the real flow field. From another perspective, wind tunnel experiments require a large amount of space, highly precise experimental instruments, and precise control, which will consume a lot of manpower and resources. Repeated experiments also require a significant amount of time and cost, which has no positive impact on research efficiency. In response to the shortcomings of wind tunnel experiments, we propose a second approach to studying fluid mechanics. Computational fluid dynamics (CFD) is used to simulate and simulate actual fluid flow situations. The basic principle is to numerically solve the differential equation that controls fluid motion, obtain the discrete distribution of the fluid field in a continuous region, and approximate the simulation of fluid flow. Based on the application of Computational Free Dynamics in skiing, researchers used human posture 3D scanning technology to model the flight posture of ski jumpers. Computer simulation was used to obtain information on the athlete's body flow and air pressure of various parts of the body. By analyzing the flow and resistance of the human body under different conditions, the main reasons that affect sports performance can be identified. This provides a quantitative reference for optimizing technical actions. Compared with wind tunnel experiments, computational fluid dynamic experiments have lower costs and save time and resources. At the same time, it is convenient to adjust parameters, allowing researchers to adjust equipment parameters to study fluid behavior, thereby optimizing design and making use more stable and efficient. Finally, computational fluid dynamics has high security and can reduce the safety risks of experimental personnel and equipment. The results are accurate and can provide reliable numerical results, allowing researchers to understand physical phenomena and the actual situation of flow[6].

2.2. Fluid dynamics principle

In this section, governing equations controlling the fluid motions were presented to help explain the mechanism of Fluid and to reason why it is considered to be useful in drag reduction. These equations were also be utilized in the simulation part as a tool to simulate the behavior of fluid motion. Therefore, it is necessary to display how these equations are deduced and utilized in the simulation.

2.2.1. Governing equation of mass conservation

The mass conservation states that for an arbitrary control volume, the net rate of mass increase within the volume is equal to the net mass flux into the volume. For example, in the infinitesimal control volume, the rate of mass increase is $\frac{\partial(\rho dxdydz)}{\partial t}$. The net mass flux into the volume in x direction is the inflow rate minus the outflow rate, i.e.,

$$\rho v_x dydz - (\rho v_x dydz) + \frac{\partial(\rho v_x dydz)}{\partial x} dx = -\frac{\partial(\rho v_x)}{\partial x} dxdydz, \tag{1}$$

And similarly, the net mass flux into the volume in y and z directions are

$$\text{y direction:} \ -\frac{\partial(\rho v_y)}{\partial y} dxdydz \tag{2}$$

$$\text{z direction:} \ -\frac{\partial(\rho v_z)}{\partial z} dxdydz \tag{3}$$

x direction:
Inflow

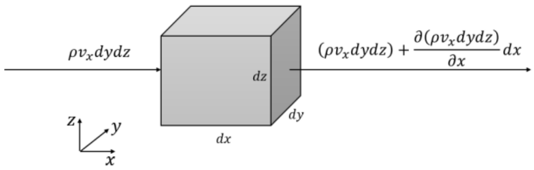


Figure 1: Taking x direction as an example showing mass conservation in the infinitesimal control volume

Summing the net mass fluxes into the volume in three directions (i.e, Equations 1, 2 and 3) introduces the total net mass fluxes, which equals to the rate of mass increase in the control volume, i.e,

$$-\frac{\partial(\rho v_x)}{\partial x} dxdydz - \frac{\partial(\rho v_y)}{\partial y} dxdydz - \frac{\partial(\rho v_z)}{\partial z} dxdydz = \frac{\partial \rho}{\partial t} dxdydz \tag{4}$$

by removing the term $dxdydz$, it comes,

$$-\left[\frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z}\right] = \frac{\partial \rho}{\partial t} \tag{5}$$

For the general incompressible fluid flow, which is the case of my study, the density of the fluid is a constant value, i.e., $\rho = const$, which means the rate of mass increase $\frac{\partial \rho}{\partial t} = 0$, thus that the mass conservation can be expressed as,

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \tag{6}$$

2.2.2. Governing equation of momentum conservation

The law of momentum conservation, which is namely a stretch of the Newton's 2nd Law, can be deduced by expanding the equation of continuity along with the Newton's 2nd law. As this is a vector relation, it can be separated into forces on each of the three dimensions. In general, the forces that anticipate, including viscosity, pressure and gravity, can be demonstrated in the following equations:

$$F = ma \tag{7}$$

$$\text{x direction: } \rho\left(\frac{\partial v_x}{\partial t} + v_x\frac{\partial v_x}{\partial x} + v_y\frac{\partial v_x}{\partial y} + v_z\frac{\partial v_x}{\partial z}\right) = \mu\left[\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}\right] - \frac{\partial p}{\partial x} \tag{8}$$

$$\text{y direction: } \rho\left(\frac{\partial v_y}{\partial t} + v_x\frac{\partial v_y}{\partial x} + v_y\frac{\partial v_y}{\partial y} + v_z\frac{\partial v_y}{\partial z}\right) = \mu\left[\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2}\right] - \frac{\partial p}{\partial y} + \rho g_y \tag{9}$$

$$\text{z direction: } \rho\left(\frac{\partial v_z}{\partial t} + v_x\frac{\partial v_z}{\partial x} + v_y\frac{\partial v_z}{\partial y} + v_z\frac{\partial v_z}{\partial z}\right) = \mu\left[\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right] - \frac{\partial p}{\partial z} \tag{10}$$

These equations are called the Navier–Stokes equations, which named after French physicist Claude-Louis Navier and Anglo-Irish physicist George Gabriel Stokes.

2.3. Drag coefficient

In fluid dynamics, drag (sometimes called resistance, a type of friction, or fluid resistance) is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid. This can exist between two fluid layers (or surfaces) or a fluid and a solid surface. The drag coefficient (commonly denoted as C_d) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment [7]. It is used in the drag equation in which a lower drag coefficient indicates the object will have less aerodynamic or hydrodynamic drag. The drag coefficient of any object comprises the effects of the two basic contributors to fluid dynamic drag: skin friction and form drag. In this study, the hydrophobic surface does not have a structured roughness shape and thus no form drag involved, so I mainly focused on the skin friction drag of solid surfaces. The drag coefficient can be expressed as:

$$C_d = \frac{\tau_w}{\frac{1}{2}\rho u^2} \tag{12}$$

Here, C_d stands for drag coefficient, τ_w stands for the shear force at the wall, ρ the density of the fluid, and u the reference velocity while the bulk velocity is used in this report.

2.4. Software use

Solid Works is a fully parameterized feature modeling software based on the Windows platform, which can easily achieve complex 3D part solid modeling, complex assembly, and generate engineering drawings. In our study, we established three-dimensional human models with different poses in the air, and simulated different poses in the air by adjusting different angles of attack. The model is simulated to understand the airflow model around the human body, without the need to establish a specific calculation method to draw the airflow trajectory and cutting diagram, in order to explore the lift, resistance, force, speed and pressure experienced by the skier in different air posture, and provide the best air posture[8].

3. Result and Discussion

3.1. Model Development

We used solid works software to model the human body of skiers in 3D, simulating their different body angles in the air.

In the process of modeling (see Figure 1), we first complete the initial 0 degrees modeling, which is also the most basic human body modeling process. When modeling the human body, we used skiers with a standard height of 180cm. We proportionally selected a normal male head height of 23cm and a male shoulder width of 40cm, with a distance from shoulder to waist of 64cm, a lower thigh length of 55.5cm, and a calf length of 37.5cm. The length of the upper arm is 40cm, and the length of the lower arm is 30cm. Based on this body data as the basis for modeling, we first use a three-dimensional rotation tool to form a complete sphere of the head, and divide the entire human body into four main parts. Firstly, the torso is idealized as a cylindrical shape with a bottom area of 793.01cm^2 and a height of 64cm. In the entire human body model, it plays an important role in the trunk, with the second main part being the legs, which are the thighs and calves. During the modeling process, stretching tools are used to achieve lengths of 55.5cm and 37.5cm for the thighs and calves, respectively[9]. The cylindrical base area proposed for the thighs is 231.8cm^2, and the cylindrical base area proposed for the calves is 126.67cm^2. The last part is a cylinder with arms separated on the left and right sides of the torso, which is divided into two parts: the upper arm and the lower arm. The upper arm is 40cm long and the lower arm is 30cm long. The bottom area of the large arm idealized as a cylinder is 71.47cm^2, and the bottom area of the small arm cylinder is 45.84cm^2. Finally, the various parts of the body during the modeling process are combined, and when moving and splicing tools and adding small cubes as connections, the entire human body becomes a whole to simulate the body of an aerial athlete and facilitate subsequent flow simulations[10].

After completing the human body modeling at a 0 degrees angle, we will adjust the angle of the completed human body modeling using the Move/Copy body tool. Firstly, we will replicate six identical 0 degrees models, and then use the rotation angle tool to adjust the tilt angle of the x-axis to form a forward leaning posture for your model. The forward leaning angles are 15 degrees, 30 degrees, 45 degrees, 60 degrees, 75 degrees, and 90 degrees, totaling seven different posture models. After that, the completed human body modeling is saved in layers, and they are stored in different documents respectively, so as to facilitate the flow simulation of a single model later[11].

Adjusting the angle of the human body model is beneficial for us to more accurately simulate the different body postures and inclinations of ski jumpers in the air, and to study the differences in pressure field velocity, growth force, and resistance under different postures and angles, as well as the relationships between them. Seven different situations are used to reflect the actual force situation, speed, and pressure under different postures in the air. By comparing postures, it is easier for us to infer the optimal posture of skiers in the air.

3.2. Model Development

The flow pattern is the characteristic flow pattern of a fluid under specific conditions. The classification of flow patterns can be based on various factors, such as velocity distribution, turbulence level, etc. In fluid mechanics experiments, flow pattern analysis helps to understand fluid behavior and provide quantitative data to validate numerical simulation results[12].

Combining the aerial posture of ski jumpers for flow simulation will be carried out through the following steps. The 0 °model will be used as an example to demonstrate the process of completing flow simulation.

(1) Stating the flow simulation

(2) Determine the unit system: I select SI unit system as the unit system for this flow simulation.

(3) Choose different analysis types: Since we are studying the flow simulation of air around skiers, we should choose the external type.

(4) Defining fluid property: Because the athlete skiing in the air so that we choose the air as the fluid.

(5) Defining the parameters for the velocity and direction of the fluid: z-direction and 20m/s.

(6) Defining computational domain: before any CFD analysis calculation, the first need is to define and construct the geometry of the flow region (i.e., the CFD computational domain). The creation of a geometric model is the basis for computational fluid simulation and analysis, and a

well-built geometric model can both accurately reflect the physical object under study and facilitate the next meshing step.

(7) Inserting the boundary conditions: before CFD simulation, it is necessary to define the boundary conditions between the surface of the object and the surrounding air, i.e. to determine the boundary conditions. Boundary conditions include parameters such as velocity, density, pressure, etc. The simulation process can be effectively controlled by setting boundary conditions. To be specific, here, human body is defined as real wall to represent the no slip boundary condition [13].

(8) Inserting the global goal: I insert the global goals to monitor the forces in three directions so that we can study the lift and drag forces on the object.

(9) Generating mash: A global mash was performed on the computational domain and adjust the global mash settings to 4. The division of the established geometric model into a finite number of meshes is called meshing. Because the CFD solution needs to be discretized, the two-dimensional or three-dimensional geometric model is discretized into grids, each of which has its own physical quantities and numerical solutions.

(10) Run the program: the results of the simulation are analyzed and evaluated, including the distribution of velocity, pressure, temperature and other parameters of the logistics field. Based on the analysis results, the performance of the object can be evaluated and optimized.

3.3. Result and Discussion

In this section, I first present the velocity field and pressure field, then the focusing on the lift and drug forces, the relation between the fluid field and the aerodynamic performance is discussed.

3.3.1. Velocity field

Velocity Field is a physical field consisting of velocity vectors at each moment and at each point. In the case of a fluid, for example, the velocity field is the distribution of vector velocities along the fluid flow front. The state of the fluid velocity vector distribution at all points in space at the same moment.

It shows the velocity field of simulation in all different cases, with the contour showing the magnitude of the velocity and the arrows showing the flow direction [14].

The first observation is that with the increasing of the angle, the low velocity region (also called wake region) after the skier's body decreases in both magnitude and size.

Further examine the arrows, after the human body, I found that a strong vertex structure in the small angles model.

3.3.2. Pressure field

Pressure field, a region of space where fluid pressure is distributed. It exists in the interior of solids, liquids, gases, or at the interface between a fluid and a solid wall, or between a solid and a so

In all the panels, the pressure shows a high value region (the red color) in front of human body and low value region (the blue color) closely after the human body, with a medium value region (orange region) in some distance.

While the high value region in front of the human body is similar, the low value region that highly depend on the angle of the skiers because this region always parallel with the human body angle.

Further observation found that the medium region (orange color) which is, right after the low value region, the shape of the medium region change with the angle.

4. Conclusion

(1) In this research, the CFD simulation was used to investigate how does the angle of the skiers influence the aerodynamic performance around the skiers.

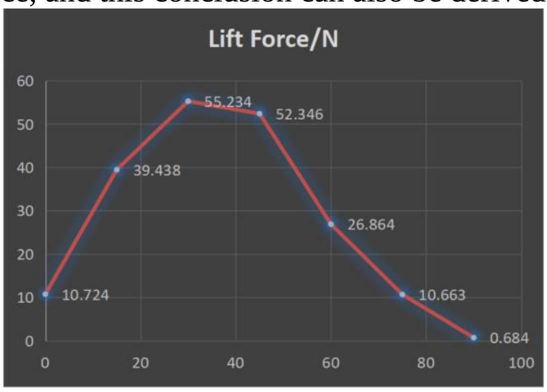
(2) Conclusion of velocity field and pressure field

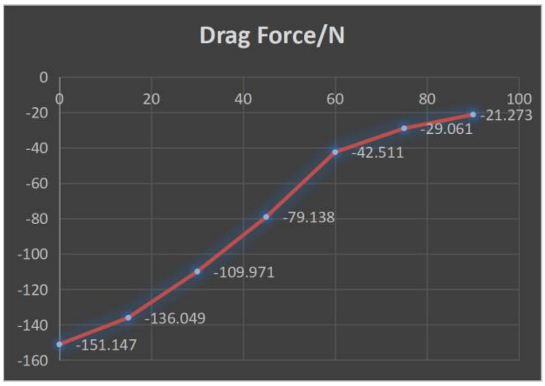
Specific 0 degrees to 90 the velocity field pressure field are obtained from the simulation. The velocity field and pressure field can tell me how the fluid moves and the magnitude and direction of the pressure received when the skier is in different positions in the air. From 3.1 it can be seen that the velocity decreases dramatically in the area near the back of the athlete's body, and in combination with the pressure field we can see that the fluid receives less pressure where it flows less, which can be seen in the image of the pressure field from high pressure to low pressure to high pressure. In conclusion, the athlete's body drastically reduces the pressure received by the back of the body [15]. Similarly, as the tilt angle increases, the region of low pressure on the back decreases, while the size of the pressure received at the front of the body facing the wind increases, and the shape of the region changes from a regular circle to an irregular shape, and gradually changes back to a regular circle as the angle increases to about 75°. In summary, the angle greatly affects the pressure and fluid velocity in different areas of the body.

(3) Conclusion of lift force and drag force

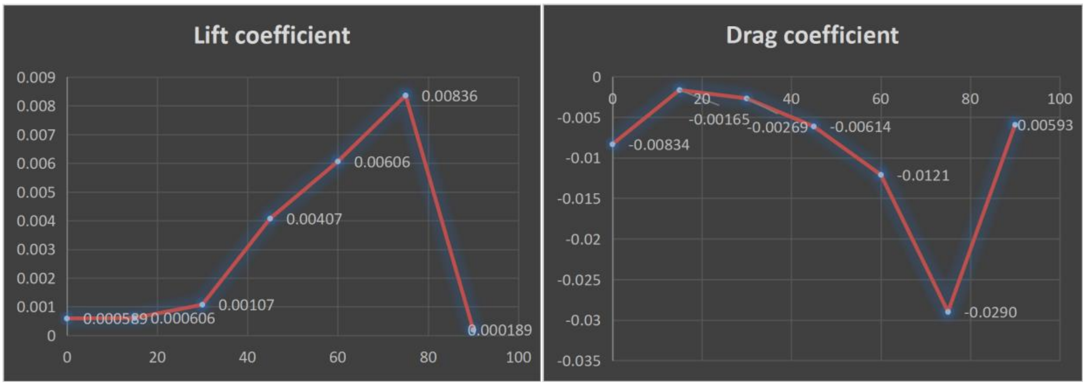
Based on the flow simulation we can derive a data table and four data graphs that include a representation of the trends in lift and drag as well as lift and drag coefficients (see Figure 2). First of all, I will analyze the lift and drag from the subject. The lift curve is increasing and then decreasing, and the lift reaches its maximum value when the athlete's body posture is 30°, and then decreases gradually. From this, we can find that the human body can be subjected to the maximum upward lift at 30°, which can increase the height of the athlete in the air, thus increasing the time in the air, and thus increasing the gliding distance of the athlete.

The resistance image shows that the magnitude of the resistance is decreasing, and the rate of decrease of the magnitude of the resistance is relatively stable until the athlete's body is presented at 60°, after which the rate of decrease of the resistance slows down significantly. From here we can see that the projected area brought about by the angle of inclination greatly affects the magnitude of the resistance received, and the reduction of the projected area also leads to the reduction of the resistance, and this conclusion can also be derived from the formula of the resistance.





(a) Lift Force (b) Drag Force



(c) Lift Coefficient (d) Drag Coefficient

Figure 2: Flow simulation graphs

5. Conclusion and Future work

The lift coefficient is the ratio of the lift force on an object to the product of the kinetic pressure of the airflow and the reference area. In our analysis of the coefficient of lift, the coefficient of lift increases and then decreases and reaches a maximum at 75°, growing faster throughout, and then decreasing rapidly at a very fast rate after reaching 75°before almost reaching a minimum.

The drag coefficient is the ratio of the drag force on an object (e.g., an airplane, a missile) to the product of the kinetic pressure of the air stream and the reference area. Based on the image we can observe that the magnitude of the drag coefficient shows an overall accelerating trend and also reaches its maximum at an elevation angle of 75°of the athlete's body. After that, the magnitude of the drag coefficient decreases at a very fast rate and reaches a value close to the minimum.

From here we can see that the trends of the coefficient of lift and the coefficient of drag are almost very similar, which also proves that the coefficient of lift and the coefficient of drag are not affecting purely lift or drag, but a single coefficient has a great impact on both forces, and the magnitude of the coefficients increases, and the lift and the drag both increase.

5.1. Future work

At present, we have completed the simulation of different postures of skiers in the air using CFD, as well as the data results and data graphs of lift, drag, lift coefficient, and drag coefficient obtained from flow simulation. From the perspective of flow simulation, I hope to further incorporate the form of skis, adding different postures of skis other than the human body, as a new research perspective, making research life more accurate and relevant to real life. Considering the simulation of the combination of two object forms at the same time will be more complex, and it can also further understand the impact of aerodynamics on ski jumpers. In the future, for further practical research, I hope to conduct real wind tunnel experiments to simulate the posture of athletes, and obtain data results that consider multiple influencing factors in real situations. I will compare this data result with the data obtained by CFD, and further study more suitable aerial postures for skiing athletes based on the two types of data.

References

[1] Brownlie L. Aerodynamic drag reduction in winter sports: The quest for "free speed." Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. 2021; 235(4):365-404.
[2] Anderson J D. Computational fluid dynamics: The basics with applications. McGraw-Hill Education. 2015.
[3] Asaoka Y, Shimoyama K. Aerodynamic performance of ski jumper's posture in wind tunnel experiment. Sports

Engineering, 2019, 22(4), 307-313.
[4] Brønstad E, Kjeldstad B. The biomechanics of ski jumping: A review. Sports Medicine-Open, 2018, 4(1), 22.
[5] Hyytinen T, Kivekäs J. Influence of ski jumper's posture on aerodynamic forces in a wind tunnel. Procedia Engineering, 2017, 200, 156-161.
[6] Ito S, Shibuya K. Computational fluid dynamics simulation of ski jumper posture for lift force optimization. Procedia Engineering, 2016, 147, 669-674.
[7] Javurek M, Slavik R. Analysis of ski jumper's aerodynamics during flight. Procedia Engineering, 2019, 186, 452-459.
[8] Kallio T, Smolander J. Aerodynamics of ski jumping flight. Procedia Engineering, 2018, 227, 44-50.
[9] Kazmierczak B J, Kozlowski K. Aerodynamic analysis of ski jumper's body posture in a V-flight position. Procedia Engineering, 2017, 186, 487-493.
[10] Kwiecien M, Rozycki P. Ski jumper's postures aerodynamic optimization based on the computational fluid dynamics simulation. Journal of Physics: Conference Series, 2019, 1267(1), 012009.
[11] Lee S, Kim H. Numerical analysis of ski jumpers' flight posture. Procedia Engineering, 2016, 147, 1137-1142.
[12] Luetkemeier M J, Harms T M. Aerodynamics of a ski jumper during takeoff and flight. Journal of Sports Sciences, 2018, 36(22), 2585-2592.
[13] Sammonds G M, Thompson M C. Aerodynamic analysis of ski jumping techniques. Procedia Engineering, 2017, 200, 148-155.
[14] Schindler M, Wendel J. Aerodynamic analysis of ski jumper's posture in flight. Procedia Engineering, 2019, 186, 406-413.
[15] Thiyagarajan P R, Narayanan V A. Aerodynamics of ski jumping: A CFD approach. Journal of Mechanical Engineering Science, 2016, 230(9), 1481-1493.