Hydraulic Performance of Water Inlet Device in Ship Scoop Cooling System

Xingsheng Lao1*, Tianqi Dai2, Xian Gong3, Wei Zhang4, Bangming Li5, 
Wei Wang6

1Science and Technology on Thermal Energy and Power Laboratory, Wuhan Second Ship Design and Research Institute Wuhan, China
2Science and Technology on Thermal Energy and Power Laboratory, Wuhan Second Ship Design and Research Institute Wuhan, China
3Science and Technology on Thermal Energy and Power Laboratory, Wuhan Second Ship Design and Research Institute Wuhan, China
4Science and Technology on Thermal Energy and Power Laboratory, Wuhan Second Ship Design and Research Institute Wuhan, China
5Science and Technology on Thermal Energy and Power Laboratory, Wuhan Second Ship Design and Research Institute Wuhan, China
6Science and Technology on Thermal Energy and Power Laboratory, Wuhan Second Ship Design and Research Institute Wuhan, China

* Corresponding author: laoxingsheng@tsinghua.org.cn

Abstract—The scoop cooling system is widely used in advanced ships which usually requires a water inlet device protruding out of the board. The structure of the water inlet device not only determines the cooling water flow into the system, but also affects the additional resistance of the hull. The ratio of the static pressure difference between windward side of the device and the environment and the dynamic pressure head of the cooling water entering the flow channel is defined as the scoop lift head. The scoop lift head and additional resistance are used to describe the hydraulic performance of the water inlet device of the scoop cooling system, and a theoretical analysis method for the performance of the water inlet device of the scoop cooling system is proposed. The actual ship parameters are used to verify the scoop cooling capability and drag resistance characteristics of the water inlet device.

1. INTRODUCTION
Central cooling water system is one of the most important marine systems on ships, and it is of great significance to ensure the safety of ship power plants and other main auxiliary engines. Since the central cooling system has the largest flow and pipeline in the ship, the hydraulic characteristics of the system have a significant impact on the navigation safety and radiation noise of the ship.

The scoop cooling system has been widely used in advanced ship systems. It uses the dynamic pressure head of the ship to provide driving force for the central cooling system when sailing. The suction port of the gravity cooling water system needs to be designed with a water inlet device
protruding from the hull. The inlet of the device faces the direction of the submarine's navigation. In the future, the flow energy will be converted into the driving energy of the cooling water in the system to realize the spontaneous flow of the cooling system. The design of the water inlet device must be guaranteed. When the additional drag resistance of the ship is the smallest, the system has a reliable pressure head [1]. The external structure design of the water inlet device determines the flow supply capacity of the gravity-flow central cooling system. The ratio of the static pressure difference between the front surface of the device and the environment and the dynamic pressure head of the cooling water entering the system is defined as the flow head, which is a dimensionless quantity. The larger the flow head, the stronger the flow supplying ability. As a protruding structure of the hull, the diversion device will generate additional resistance to the moving hull. The application of scoop cooling system has been relatively extensive, and the matching design and control strategy of the system have also been studied [2,3], but there are few researches on the water inlet device of the scoop cooling system, and the main research carried out [4,5] Exhaustive optimization of the shape of the suction port and the discharge port has not formed a quantifiable design theory. In this paper, gravity head and additional resistance are used to describe the hydrodynamic performance of the water inlet device of the scoop cooling system, and a theoretical prediction method for the hydraulic performance of the water inlet device of the scoop cooling system is proposed, which can guide the design of the water inlet device of the scoop cooling system.

2. FLOW RATE CHARACTERISTIC OF THE SCOOP COOLING SYSTEM

2.1. Analysis of the head of the water inlet device

The water inlet device is generally composed of a protrusion and a diversion structure arranged outboard, as shown in figure 1.

![Figure 1: Schematic diagram of the shape of the water inlet device](image)

The ship’s speed is V, the ambient pressure is p, and the angle between the front flow surface of the water inlet device and the ship wall is φ, the difference between the front flow surface inlet pressure pw and the ambient pressure p is converted into the dynamic pressure head of the water inlet device, which is cooling. The driving force of the water system pipeline flow and the dynamic pressure head of the cooling water at the inlet of the system are the signs of the spontaneous driving flow ability of the water inlet device.

When the resistance coefficient in the pipeline is infinite, no cooling water enters on the front flow surface, which is approximately a solid wall. At this time, the pressure difference between the inlet pressure pw and the ambient pressure p is the largest. The flow is approximated as an inviscid flow. According to Newton’s collision law, the pressure value of the inclined solid wall can be obtained by the formula:

\[ p_{w} = p + \frac{\rho}{2}(V\sin\phi)^2 \]  

(1)

It can be seen from the above formula that when the inclination angle φ is 90°, the wall pressure is the largest, which is equal to the total pressure of the incoming flow. When the inclination angle φ is 0°, the wall pressure is the smallest, which is equal to the incoming static pressure.

Formula (1) is dimensionless, and the flow head is defined as the ratio of the difference between pw and p and the dynamic pressure head of the cooling water entering the scoop cooling system, and the dimensionless head is obtained as:
The dimensionless head in equation (2) is defined as the flow supply head, and the maximum flow supply head of the scoop cooling system is 1 when the front surface of the water inlet device is perpendicular to the incoming flow.

2.2. The impact of the hull boundary layer

When a ship is moving, there is a turbulent boundary layer near the hull. The boundary layer of the hull can be approximated by a flat turbulent boundary layer. According to the literature [6], in the boundary layer, the fluid velocity is lower than the boat speed and the dynamic pressure is small.

The thickness of the boundary layer is related to the Reynolds number and the flow direction size. For a flat plate without pressure gradient, when the flow is turbulent, equation (3) can be used in engineering design to estimate the boundary layer thickness [6]:

\[
\delta \approx 0.382 \left( \frac{\mu}{\rho U} \right)^{0.2} \times^{0.8}
\]

\[
\tilde{h} = \frac{p_w - p}{\rho V^2/2} = \sin\phi^2
\]

The minimum operating speed \( U \) of the scoop cooling system is taken as 2.5m/s, and the water intake of the water inlet device is about 100 meters away from the bow of the boat. According to formula (3), the thickness of the boundary layer is about 0.87 meters. Considering the thickened boundary layer of the blunt bow of the boat, the thickness of the boundary layer is taken as 1 meter. As the speed increases, the thickness of the fluid boundary layer decreases.

3. ADDITIONAL RESISTANCE OF WATER INLET DEVICE

3.1. Theoretical analysis of the additional resistance of the water inlet device

The function of the water inlet device is to divert water into the cooling water system. In order to increase the flow supply head, its suction port is generally perpendicular to the incoming flow, which will generate greater resistance.

The flow pattern near the water inlet device is shown in figure 2. The additional resistance of the water inlet device can be decomposed into the additional resistance caused by the diversion fluid and the suction port. The diversion fluid is streamlined and has low resistance. The suction port is a nozzle perpendicular to the incoming flow and is the main source of resistance of the water inlet device. The additional resistance is divided into two parts, one part is the resistance caused by the change of the velocity direction of the fluid entering the tube, and the other part is the resistance caused by the flow of the fluid not entering the tube.

![Figure 2: Schematic diagram of flow near the water inlet device](image)

The resistance in the tube is caused by the fluid in the tube changing the direction of movement. From the impulse theorem:

\[
\Delta(m\dot{V}) = \tilde{h} \Delta t
\]

The resistance component is:

\[
D = 2\alpha^2 (1 - \cos \beta) \frac{L^{N/A^2}}{2}
\]
Where is the dimensionless flow rate, which is the ratio of the inlet flow velocity in the water inlet device to the ambient flow velocity, is the angle between the inlet flow velocity in the water inlet device and the horizontal plane, and A is the cross-sectional area of the suction port.

The flow resistance is the resistance caused by the flow of the fluid outside the water inlet device, and its resistance component is:

$$D_z = \gamma(1-\alpha)^2 \frac{\rho V^2 A}{2}$$ \hspace{1cm} (7)

Among them is the undetermined flow resistance coefficient.

The total resistance and resistance coefficient of the suction inlet are:

$$D = [2\alpha^2(1-\cos \beta) + \gamma(1-\alpha)^2] \frac{\rho V^2 A}{2}$$ \hspace{1cm} (8)

$$C_D = 2\alpha^2(1-\cos \beta) + \gamma(1-\alpha)^2$$ \hspace{1cm} (9)

Comprehensive formulas (7), (8), (9), we can get

$$C_D = [2(1-\cos \beta) + \gamma]\alpha^2 - 2\gamma\alpha + \gamma$$ \hspace{1cm} (10)

It can be seen from equation (10) that the total resistance coefficient of the suction inlet has a parabolic relationship with the dimensionless flow rate, and there is a minimum value there $\alpha = \gamma / [2(1-\cos \beta) + \gamma]$.

3.2. Numerical simulation calculation

Use Fluent software to calculate the hydrodynamic force of the suction inlet device, and analyze its flow supply performance and resistance characteristics through CFD simulation. The calculation model and grid are shown in figure 3.

Irregular grids are used near the inlet of the gravity suction device and at the pipeline, while regular grids are used for most of the outer seawater area. The resistance generated by the resistance component is replaced by a pressure step surface in the middle of the pipeline, and the local resistance of the pressure step surface. The selection of the coefficient refers to the actual ship parameters. In the simulation process, the movement of seawater is used to replace the movement of the boat, and the outlet is set as a pressure outlet. There is a certain rotation and secondary flow in the water inlet device. In order to ensure that the Reynolds stress is consistent with the real turbulent flow, the turbulence model adopts the RNG k-\( \varepsilon \) model.

According to actual ship parameters, the water inlet device is 100 meters away from the bow, and its suction inlet is a rectangle of 750mm×230mm. According to the analysis results of section 1.2, the height of the water inlet device is designed to be 1m away from the hull so that it can be outside the hull boundary layer. Taking the common scoop cooling speed as the research condition, the suction port of the water inlet device in the model is perpendicular to the direction of the incoming flow, and the incoming flow speed is the same as the ship speed. After CFD simulation calculation, the velocity distribution of the flow field near the water inlet device is shown in figure 4.
Figure 4 Sectional velocity cloud diagram in the water inlet device

When the speed is constant, the resistance coefficient of the scoop cooling system takes a different value between 0 and 50. The average pressure of the suction inlet of the water inlet device in the simulation results is extracted, and the flow supply head is calculated according to formula (2). The flow channel in the water inlet device is extracted on the hull plane. The ratio of the average flow velocity to the ship speed is, and the relationship between the gravity head and the non-dimensional flow is calculated as shown in figure 5.

Figure 5 The relationship between gravity head and non-dimensional flow

The usual speed of the scoop cooling system is 3m/s. At this time, the relationship between the additional resistance coefficient of the water inlet device and the dimensionless flow is shown in table 1.

| Parameters | Flow velocity in pipe (m/s) | Resistance coefficient |
|------------|-----------------------------|------------------------|
| 1          | 3                           | 2                      |
| 0.7        | 2.1                         | 1.4375                 |
| 0.4        | 1.2                         | 1.1                    |
| 0.2        | 0.6                         | 1                      |
| 0.15       | 0.5                         | 0.9906                 |
| 0.1        | 0.333                       | 0.9875                 |
| 0.05       | 0.167                       | 0.9906                 |
| 0          | 0                           | 1.06                   |

From the calculation results, the relationship between the suction inlet resistance coefficient and the dimensionless flow is fitted into a quadratic relationship as follows:

\[ C_D = 1.25\alpha^2 - 0.25\alpha + 1 \]  \hspace{1cm} (11)

According to formula (11), there is 0.125, and the minimum value is obtained at and the value changes little when it is in the interval of 0~0.2. According to equations (5) and (6), the internal resistance and circumferential resistance components of the pipe are shown in figure 6.
Figure 6 Resistance in the pipe and the resistance component of the bypass flow

The relationship between the internal resistance and circumvention resistance and the dimensionless flow is shown in figure 5. The total resistance in the figure is relative value. It can be seen that when $= 0.25$, the flow resistance is equal to the resistance in the tube, and when $> 0.25$, the flow resistance is greater than the resistance in the tube and the difference increases significantly with increasing, and vice versa. It can also be seen from fig. 6 that at time, the total additional resistance increases with the increase of the dimensionless flow, and at time, the additional resistance increases by more than 10% compared to the lowest value.

In order to improve the flow supply ability, the dimensionless flow rate of the scoop cooling system should be designed to a lower value to obtain a larger flow head, and to reduce the additional resistance of the flow around the water inlet device, the dimensionless flow rate should be designed to a higher value.

The relationship between the cooling water flow that the gravity system can provide and the design demand flow at different speeds is shown in figure 7.

Figure 7 system's scoop cooling capacity

It can be seen that the system can be in the scoop cooling is achieved in a wide range at low speed. At medium and high speeds, the resistance of the water inlet device accounts for less than 3% of the total resistance of the actual ship, which has little impact on its maneuverability. When designing the system, it is affected by the resistance coefficients of the components in the scoop cooling system to comprehensively balance the flow supply capacity and additional resistance of the water inlet device. The dimensionless flow design interval of the scoop cooling system is more suitable to be set at 0.25-0.4.

4. CONCLUSION
This paper derives the theoretical analysis method of the water inlet device performance based on the fluid mechanics equation, and puts forward the guiding principles for the design of the water inlet device combined with three-dimensional numerical simulation calculation.
(1) In order to increase the gravity head, the suction port should be perpendicular to the incoming flow. In order to eliminate the influence of the boundary layer of the hull, the suction port of the water inlet device needs to be outside the thickness of the boundary layer.

(2) Scoop cooling system water inlet device flow head and flow resistance decrease with the increase of dimensionless flow, the total additional resistance does not change significantly when the dimensionless flow is not greater than a certain value, in order to balance the flow supply capacity and additional resistance diversion. The dimensionless flow rate of the device should be designed in a certain interval, which is 0.25~0.4 in the system described in this article.

(3) Substituting the water inlet device of the scoop cooling system proposed in this paper into the actual ship parameters for calculation, the results show that the scoop cooling capacity of the system can meet the cooling needs of medium and low speed navigation at this time, the additional resistance of the water inlet device accounts for less than 3% of the total resistance of the actual ship which has little impact on its mobility.

ACKNOWLEDGMENT
Project supported by the Hubei Province Natural Science Foundation of China (Grant No.2018CFB317).

REFERENCES
[1] Pang Fengge, Peng Minjun. Ship Nuclear Power Plant[M]. Harbin: Harbin Engineering University Press, 2000.
[2] Meng Qingzheng, Zhou Shaowei, Liu Junhua, et.al. Study on the Coordination of Marine Artesian Salt Water Circulation System[J] (in Chinese). Ship Engineering 2010, 32(2):151~154
[3] Sun Chang-jiang, Wu Wei, Zhang Xiao-yang et.al. Simulation Study on Automatic Flow Characteristics of Seawater Circulation Pump[J](in Chinese). Chinese Journal of Ship Research. 2011, 6(6):88~91
[4] Pei Jinliang. Numerical Investigation on Hydrodynamic Characteristic of Submarine Artesian Cooling System[D] (in Chinese). Harbin Institute of Technology, 2010
[5] Gao Wei, Miao Hui, Huang Shu-hong, et al. Optimization of the Types of Water Inlets in Marine Scoop Cooling Systems Based on CFD[J] (in Chinese). Journal of Engineering for Thermal Energy and Power. 2006, 21(3): 239~244.
[6] Zhuang Lixian, Yin Xieyuan, Ma Huiyang. Fluid mechanics[M]. Hefei: University of Science and Technology of China Press, 2009.
[7] M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.