Analysis and Research on Cold Proof Design of Polar Marine Machinery

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Abstract: Polar marine machinery is an important equipment for China to participate in Arctic energy exploitation. The Arctic region is rich in natural resources and has a very important strategic position. As an important equipment for passage and exploitation of energy, its key technology is particularly important. As a special ship sailing in polar regions, polar ships generally adopt electric heat tracing measures due to the adverse environment in polar regions. The deck machinery and facilities shall be protected against cold. This paper mainly studies the convection of flat plate members under constant heat flow electric heating. The research results can be popularized and applied to the cold protection of most upper facilities of polar ships.

1. Introduction

At present, there are more than 40 kinds of deicing technologies applied and being studied at home and abroad. All kinds of cold prevention measures can be divided into antifreeze and deicing according to their nature. Antifreeze refers to preventing freezing or ice and snow accumulation on the surface of equipment and structures exposed to low temperature environment through heating, thermal insulation and covering, so as to ensure the normal and safe operation of equipment and systems; Deicing refers to the removal of ice on the surface of structures or equipment through various tools or deicing systems. Cold prevention measures can be divided into active measures and passive measures. The main feature of active measures is to consume external energy, while passive measures do not need to consume external energy.

L Zhang [1] studied the operation of ships in polar cold areas, analyzed the design points of anti-deicing electric heating system, the calculation method of heating power and relevant specifications, and put forward the design method of deicing system for polar navigation ship deck. Baen [2] studied the design and risk assessment of anti-icing system for exposed and uninsulated surfaces or equipment in harsh environment, and gave the minimum power capacity requirements; At the same time, the risk assessment given does not consider more factors, such as the criticality of the system and its drainage capacity under extreme conditions. WJ Chen [3] proposed a snow melting and deicing system using electric heat tracing to heat the deck step plate unit. The calculation method of heat required for heating is established, the working principle of constant power electric tracing band is introduced, and the installation of temperature control system and tracing band is analyzed.

Polar ships generally mean that considering their basic functions, combined with their ice navigation and relevant requirements, they have the ability to break ice or pass in ice through special ship type design and local structure reinforcement [4]. The key basic technologies involved in polar navigation ships mainly include ice breaking technology, cold prevention and deicing technology,
heating technology and low temperature resistance technology. These technologies are introduced below.

2. Convective Heat Transfer Theory

For the accurate measurement of convective heat transfer coefficient of superstructure components of polar ship, the laboratory has built a test platform for polar engineering environment. The polar low-temperature environment is simulated in the low-temperature laboratory. The variable-frequency fan provides adjustable and stable wind speed through the designed air duct. The characteristics of different components are fully considered in the design of heating system.

2.1 theoretical analysis

According to Newton's cooling formula, the local convective heat transfer coefficient of the flat plate can be expressed as:

$$q_s(x) = h_s (T_s - T_\infty)$$

In the formula, $q_s(x)$ is the heat flux density at the $x$ position of the plate; $h_s$ is the local heat transfer coefficient; $T_s$ is the wall temperature; $T_\infty$ is the air temperature. Under the condition of electric heating, the heat flux of the plate is a given rated amount, and the wall temperature distribution is $[5]$.

For laminar flow section

$$T_s(x) - T_\infty = \frac{0.623}{\lambda} Pr^{-\frac{1}{3}} Re^{-\frac{1}{6}} \int_0^1 \left[ 1 - \left( \frac{x}{\xi} \right)^{\frac{3}{4}} \right]^{\frac{7}{5}} q_s(\xi) d\xi$$

(2)

For turbulent section

$$T_s(x) - T_\infty = \frac{3.42}{\lambda} Pr^{-\frac{1}{3}} Re^{-\frac{1}{10}} \int_0^1 \left[ 1 - \left( \frac{x}{\xi} \right)^{\frac{3}{10}} \right]^{\frac{7}{5}} q_s(\xi) d\xi$$

(3)

In the formula, $Pr$ is the Prandtl number of air; $\lambda$ is the thermal conductivity of air; $Re$ is the local Reynolds number of the plate; $\xi$ is the length of the heating section from the leading edge of the plate. Since the electric heating is a constant heat flow heating mode, the integral in equations (2) and (3) is a constant, which can be converted into $\beta$. Further solution in the form of function. Combine equations (2), (3) and (1) to obtain:

Local surface heat transfer coefficient of laminar flow section: $h_s = 0.453 \frac{1}{x} (Re_x)^{\frac{1}{3}} (Pr)^{\frac{1}{3}}$  (4)

Local surface heat transfer coefficient in turbulent section: $h_s = 0.0308 \frac{1}{x} (Re_x)^{\frac{1}{3}} (Pr)^{\frac{1}{3}}$  (5)

It can be seen that the average convective heat transfer coefficient $h_m$ of the flat plate surface under the constant heat flow heating mode is:

$$h_m = \frac{\lambda}{l} \left[ 0.453 \left( \frac{u_\infty}{v} \right)^{\frac{1}{2}} \int_0^{x_c} \frac{dx}{x^{\frac{5}{3}}} + 0.0308 \left( \frac{u_\infty}{v} \right)^{\frac{1}{2}} \int_0^{x_c} \frac{dx}{x^{\frac{3}{2}}} \right] Pr^{\frac{1}{3}}$$

(6)

When the plate length is greater than the critical length, the heat transfer boundary layer can be regarded as composed of laminar flow section and turbulent section. The critical Reynolds number $Re_c$ is taken as $5 \times 10^5$, the above formula can be simplified as:

$$h_m = 0.0385 \frac{1}{l} \left[ Re^{\frac{1}{3}} + 754.6 \right] Pr^{\frac{1}{3}}$$

(7)

In the formula, $l$ is the length of the plate; $u_\infty$ is the air flow rate; $v$ is the air viscosity coefficient; $x_c$ is the length from laminar flow section to turbulent section.

When the length of the plate is determined, the average convective heat transfer coefficient and thermal conductivity of the electrically heated plate $\lambda$. There is a certain relationship between Reynolds number $Re$ and Prandtl number $Pr$. Where, parameter $\lambda$, and $Pr$ is related to temperature;
Reynolds number Re is greatly affected by wind speed. In the above theory, only the laminar flow section and turbulent section are considered, and the influence of transition section is ignored; In the theoretical derivation of convective heat transfer of heated plate, the critical Reynolds number is assumed, and its rationality needs to be further discussed. Therefore, it is urgent to study the convective heat transfer law of plate components on polar ships under different wind speeds and temperatures by means of numerical simulation and experimental testing.

2.2 Experimental principle

Convective heat transfer refers to the heat transfer process between various parts of fluid at different temperatures or between fluid and solid wall. There are many factors affecting convective heat transfer, such as the change of fluid phase state, the causes of flow, the flow form of fluid, the physical properties of fluid, the geometric factors of heat transfer, etc. The process of convective heat transfer is very complex. The study of convective heat transfer coefficient has great practical engineering significance. At present, the surface heat transfer coefficient in engineering design is mainly obtained through experiments, so the experimental research method is widely used in the study of convective heat transfer. The experimental study of convective heat transfer is essentially the measurement of convective heat transfer coefficient on the specimen surface under different experimental conditions.

In order to study the variation law of convective heat transfer of superstructure components of polar ship under electric heating mode, the convective heat transfer coefficients of different components under various specific working conditions were measured.

The convective heat transfer coefficient can be measured according to Newton’s cooling formula,

$$\dot{\varphi} = hA(t_w - t_f)$$  \hspace{1cm} (8)

Thus, it can be obtained:

$$h = \frac{\dot{\varphi}}{A(t_w - t_f)}$$  \hspace{1cm} (9)

Where, $h$ is the convective heat transfer coefficient, $w/(m^2\cdot K)$; $\dot{\varphi}$ is the heating amount of electric heating, $W$; $A$ is the area of heat exchange surface, $m^2$; $t_w$ and $t_f$ are the surface temperature and fluid temperature of the circular tube, respectively, $K$.

During the experiment, when the surface temperature $t_w$ of the specimen is stable, it is considered that the heat of the convective heat transfer zone is the same as the heat input by electric heating during the experiment $\dot{\varphi}$. The convective heat transfer coefficient under corresponding working conditions can be calculated by Newton cooling formula.

Equation (9) is only a definition of convective heat transfer surface heat transfer coefficient $h$, which does not explain the influence of physical parameters of external environment on surface heat transfer coefficient. The experimental study of convective heat transfer coefficient is to clarify the internal relationship and establish the calculation expression of surface heat transfer coefficient \[9\]. Due to the complexity of convective heat transfer process, the accurate expression of convective heat transfer coefficient cannot be obtained by theoretical calculation for most heat transfer cases. Through experimental research, the empirical expressions in a certain range of temperature and wind speed can be obtained.

3. Deicing and Anti-icing Technologies

Under extremely low ambient temperature, the surface of the ship's outdoor equipment is particularly easy to freeze, especially various ventilation devices, water systems, equipment air inlets, hatch covers and life-saving equipment. Special cold protection design is required for ship system, outdoor equipment and cabin environment \[7\]. The means to prevent icing are generally heat insulation, heat preservation and heating. The heat source can be steam, electricity, hot water, hot oil and other heat tracing media.

The anti-cold and de-icing measures for polar navigation ships are generally divided into active de-icing and passive anti-icing \[8\]. Literature \[8\] introduces the existing anti icing and de-icing methods and technologies at home and abroad, including active de-icing methods such as electric heating,
high-speed heat flow, infrared and ultrasonic guided wave, as well as passive de-icing methods such as super hydrophobic coating, sacrificial coating, water lubricated coating and low crosslink interface slip coating.

3.1 Traditional Deicing and Anti-icing Technologies

3.1.1 Thermal ice melting deicing method
Thermal ice melting is one of the earliest and most effective deicing technologies, which mainly uses Joule principle [9]. Applications on ships include heating cables, heating coils, steam pipelines, air heating, et al.

3.1.2 Mechanical deicing
Mechanical cold prevention and deicing refers to the destruction stress generated inside the ice through various machines to separate the ice from the hull surface to achieve the purpose of cold prevention. For example, steam deicer and high-pressure hot water deicing belong to common mechanical deicing. According to statistics, the energy consumption of mechanical deicing method is generally much lower than that of thermal ice melting and cold protection method, but this method needs to install corresponding mechanical parts and meet the resource requirements for installation and use.

3.1.3 Deicing Vehicle
The AIST-5TM deicing vehicle is refitted from the aero engine and wheels, and deicing is carried out through the huge heat and jet force generated by the aero engine. The warship will also consider the icing situation. Taking the support ship Svalbard of Norway as an example, there is no deck guard on the ship body, and the head windlass and other equipment are also protected by a smooth deck through a large number of vertical and inclined planes, to reduce the possibility of accumulated icing. However, it is worth noting that the damage caused by freezing to weapons and equipment is not limited to warships. In the NATO "Trident joint 2018" joint military exercise in 2019, the observation equipment of the German "leopard II" main station tank was frozen to strike, which will also affect the starting speed of the tank engine.

3.1.4 Other methods
In addition to the above cold prevention and deicing methods, there are also manual methods such as spreading antifreeze and shovel to achieve the purpose of deicing. At present, there are two kinds of antifreeze, one is salt snow melting agent and the other is environmental protection snow melting agent, which is cheap, but no matter which one has strong corrosion to deck, hull and coating. For manual deicing, salt water, steam and hot water are used to deice the passages, stairways and handrails.

In recent years, with the development of science and technology, some new ship cold protection and deicing technologies have emerged.

3.2 New anti-icing and deicing technology

3.2.1 Vibration resonance mechanical system
The impact pulse device is installed on the stress plane of the equipment and the design point of the fuselage to produce mechanical vibration in frequency and close to the resonance of these surfaces. The vibration destroys the metal adhesion strength of the shell and wing, and the rest is completed by the frontal air flow.

3.2.2 Ultra-high Frequency Heating
It is well known that eddy current will be generated in the conductor under the influence of
high-frequency magnetic field. Eddy current heats the metal of the shell, thereby reducing the adhesion between the shell and the shell. In turn, this makes manual ice drilling easier and, in combination with vibration, mechanizes the ice drilling process.

3.2.3 Microwave heating deicing
Most materials absorb microwave energy and generate heat under the action of microwave[10]. The microwave passes through the ice layer and acts on the material. After absorbing the microwave, the temperature of the material rises, melts the ice layer at the junction with the hull, and then combines the machinery or manpower for deicing, which greatly improves the deicing efficiency and has a broad application prospect in the field of ships.

3.2.4 Air Traction Circulating Temperature Rise and Antifreeze Technology[11]
The air traction circulating temperature rise and antifreeze technology uses the traction equipment to form a micro circulation of high and low temperature gas, so that the low temperature gas originally accumulated on the deck falls back to the sea surface, and at the same time, the gas with higher temperature is pulled back to the deck platform area, so as to achieve the purposes of temperature rise, antifreeze and deicing of the deck.

In addition, in 2019, researchers at the University of Houston developed a new anti-icing material-silicon polymer coating, which can prevent icing on any object surface. Our navy has developed a coating material similar to film, which is cheap and can be used on warships and aircraft at the same time to increase the anti-viscosity of weapons and equipment, reduce the coverage probability of ice and snow, and greatly reduce the impact of freezing on weapons and equipment. With the continuous emergence of new materials and technologies, the cold prevention and deicing technology is also constantly updated.

4. Conclusions
In this paper, the theory of convective heat transfer is analyzed, and it is known that the research on the convective heat transfer coefficient of flat plate mainly focuses on the heating mode of constant wall temperature. In order to realize the accurate measurement of convective heat transfer coefficient, the polar environment is simulated in the low temperature laboratory, the experimental platform for the measurement of convective heat transfer coefficient is designed and built, and the experimental principle, experimental system and measurement system are introduced in detail; Finally, several common cold prevention and deicing technologies are introduced, and it is concluded that the corresponding theory should be adopted for the cold prevention design of polar ships under different external environments.

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