Article

Analysis of the Influence of Convection Heat Transfer in Circular Tubes on Ships in a Polar Environment

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Abstract: Electric heat tracing is the main measure for cold protection of the polar transfer coefficient in marine engineering equipment, but thermal equilibrium is the key problem this technology faces. In this paper, the circular tube was the research object. We studied the influence of convective heat transfer by Fluent software and experiments with a wind speed of 0–40 m/s and temperature of −40–0 °C by constant heat flux heating. The results show that the convective heat transfer increases with increased wind speed and decreased temperature. When the temperature is below −30 °C, the effect of temperature is increased; when the wind speed is greater than 25 m/s and the temperature is lower than −20 °C, the effect of temperature on the convective heat transfer coefficient of the circular tube increases. Based on the simulation data, we established a prediction model, and the rationality of the prediction model was verified by tests. The model provides reference for the design of electric heat tracing of circular tubes on polar ships.

Keywords: polar region; circular tube; convective heat transfer; numerical simulation; experiment

1. Introduction

The abundant natural resources in the Arctic and the Arctic Passage, with economic importance and strategic value, are drawing attention to the Arctic region and the world [1]. In low-temperature environments, the formation of ice on ships and offshore platforms can create serious problems impacting the structural stability, material properties, and the economies of operation [2]. Circular tubes are widely used in polar engineering equipment such as handrails, pipes, rods, etc. for surface heating with electrical heat tracing (EHT) on vessels and platforms in arctic and polar environments [3].

EHT includes both working conditions of constant wall temperature and constant heat flux. EHT in circular tubes has a constant heat flux. Constant wall temperature is energy input by a body or a thermodynamic system during a constant temperature, and constant heat flux is energy input by a body or a thermodynamic system during constant heat. The heat loss is less than the input heat as the wall temperature continues to rise. The effect of convection heat transfer is affected by different methods. At present, the convective heat transfer of circular tubes is mainly studied at constant wall temperature. Forced convection from a heated circular cylinder and placed in a uniform cross flow of constant properties fluid has been investigated numerically. The two-dimensional governing equations of flow motion and energy were solved numerically, and the flow and thermal fields were mainly influenced by Reynolds number [4] (Mdallal, 2017). In the large-scale Reynolds number, different scale models are used to simulate the convection heat transfer across a single tube. The suitable numerical simulation methods were determined for different ranges of Re [5] (Zhou Bonan, 2018). The effect of forced convection heat transfer across a two-dimensional steadily rotating circular cylinder was numerically investigated, and the average Nusselt number is known to increase with the increment in the Reynolds number

without the gust condition, and the average Nusselt number is known to decrease with the rise in the Reynolds number with the gust effect [6] (Ikhtiar, 2016). A newly developed VLES (Very Large Eddy Simulation) method has been applied to investigate the unsteady flow and heat transfer mechanisms. DDES (Delayed Detached Eddy Simulation) and unsteady RANS (Reynolds-Averaged Navier-Stokes) methods have also been used in the simulations for comparisons. Two typical cases were selected and the results showed that the VLES predictions agreed well with the experiments for both the flow velocities and heat transfer [7] (Wan, 2020). Based on similarity theory, the laboratory physical model was established, and the convective heat transfer experiment and numerical simulations were carried out. The results showed that the influence of natural convection was stronger with the increase in tube diameter; at low Reynolds number, the influence of diameter on natural convection was more obvious. The experimental correlation formula of mixed convective heat transfer was obtained in [8] (Li Xiaochen, 2017).

At present, the convective heat transfer of circular tubes has been less studied at constant heat flux. A single comprehensive equation was developed for the rate of heat and mass transfer from a circular cylinder in crossflow, covering a complete range of Pr (or Sc) and the entire range of Reynolds numbers for which data are available [9] (Churchill, 1977). Unsteady flow and convective heat transfer over single and two tandem cylinders at constant heat flux condition in the subcritical range of Reynolds numbers was numerically investigated. The Nusselt number fluctuates with the small-scale vortex, and the Nusselt number in the separation flow region increases with the increased Reynolds number [10] (Dhiman, 2017).

To winterize vessels, EHT systems are often installed with constant heat flux. The variation law of convective heat transfer on a circular tube structure is not clear under a polar environment [11]. The loads may appear adequate, but they are minimum power capacity requirements and do not distinguish between anti-icing and de-icing. Additionally, lower ambient temperatures and higher wind speeds substantially increase heat losses. Therefore, we established a prediction model of the convective heat transfer coefficient of a circular tube to provide a reference to prevent the accumulation of snow and ice on ships. We used numerical simulation to analyze the change in the convective heat transfer coefficient of the circular tube with the wind speed range of 0–40 m/s and the temperature range of −40–0 °C. Temperature and wind speed ranges are determined by the guide to polar ships [12]. The temperature correlation formula of convective heat transfer was established, and the rationality of the model was verified by experimental tests. Finally, heat balance calculation software was developed by the predictive model, wherein rapid calculation of heat balance can be realized. This work provides a reference for the design of electric heat tracing for circular tubes on polar ships.

2. Method

In order to accurately measure the convective heat transfer coefficient of circular tubes under different wind speed and temperature conditions, an experimental platform for measuring the convective heat transfer coefficient of a circular tube was established according to Newton's law of cooling. The low temperature laboratory can control the minimum temperature of −50 °C and the maximum wind speed of 15 m/s (the design maximum for the test), which can essentially simulate a low-temperature polar environment.

2.1. Principle

According to Newton's law of cooling, the general definition of the heat transfer coefficient is:

$$h = \frac{q}{\left(t_w - t_f\right)} \tag{1}$$

where:

h: heat transfer coefficient, (W/(m^2 °C));

q: heat flux, W/m^2; i.e., thermal power per unit area;

t_f: temperature of the surrounding fluid, °C; and

t_w: temperature of the solid surface, °C.

EHT adopts a constant heat flux mode. When the t_w of a circular tube is stable, the heat output is consistent with the heat input by EHT during the experiment. According to Equation (1), the convective heat transfer coefficients of a circular tube at different wind speeds and temperatures can be calculated.

2.2. System

A test platform for measuring the convective heat transfer coefficient of circular tubes was set up in the cold laboratory, as shown in Figure 1. By adjusting the control box, the wind speed remained stable, satisfying the experimental requirements. The test tube was the handrail on board for the PC3 class icebreaker, which is made of Q235 smooth steel. The circular tube was placed on the support rack of the air duct, ensuring that the fluid passes evenly through the circular tube.
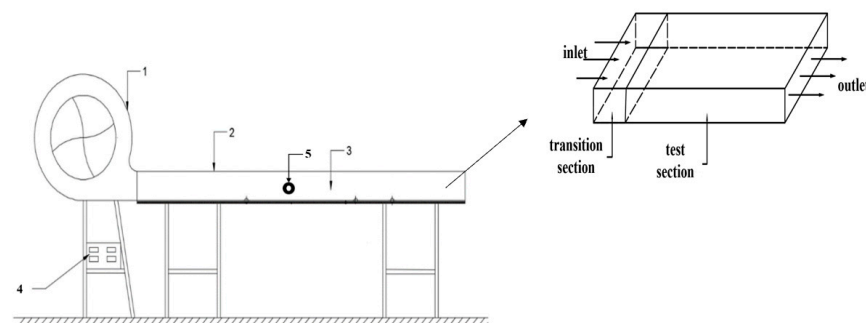

Figure 1. Experimental device for measuring the convective heat transfer coefficient. (1) Frequency conversion fan; (2) Air duct; (3) Air duct; (4) Control box; (5) Circular tube.

To reduce unnecessary heat loss, heating wires were evenly tied to the thermal insulation layer. Due to boundary layer separation caused by flow across the tube and the phenomenon of flow separation, the degree of convection heat transfer is different in different areas of the tube wall, and the temperature measurement points are arranged along the circumference. In the experiment, seven temperature measuring points were arranged every 30°, as shown in Figure 2.
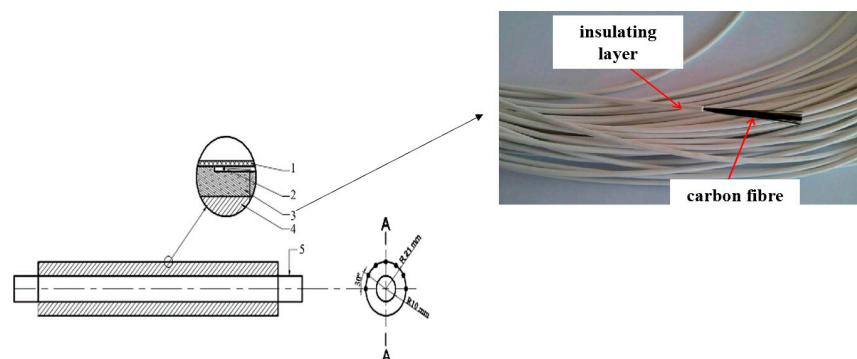

Figure 2. Arrangement of measurement locations. (1) Circular tube; (2) Thermoelement; (3) Heating wires; (4) Thermal insulation layer; (5) Wood.

The experimental measurement instrument parameters are shown in Table 1.

Table 1. Experimental measurement devices.

Experimental Test Apparatus	No.	Measuring Range	Precision
Temperature instrument	1	−50–220 (°C)	0.01 (°C)
K temperature thermocouple	7	−50–220 (°C)	1%
NK1000 anemometer	1	0.6–60 (m/s)	3%

3. Simulation

We used fluent software in this study and the two-dimensional mode. The physical model was established according to the experimental results of convection heat transfer in the EHT circular tube. Due to the irregular shape of the tube, we adopted unstructured finite element mesh division, considering that the flow field changes dramatically near and behind the tube. We improved mesh refinement around the tube, and the total number of grids was 107,583, as shown in Figure 3. We set the velocity inlet at the inflow boundary and the gauge pressure at the outflow boundary. EHT is even heating, so we set the no slip at the wall boundary; the simulation of convection heat transfer in tubes is under the second boundary condition, where the second boundary condition is the heat flux, that is, the boundary layer of normal component q_n:
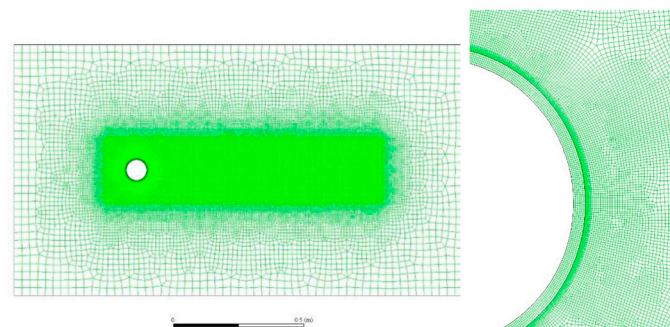
$$q_n = n \cdot q \tag{2}$$

where:

q: heat flux, W/m^2; and

n: the normal direction of heat flux.

The heat flux was 1801.86 W/m^2. Due to flow separation caused by flow across the tube, the boundary layer was affected by flow separation. The k–ε turbulent model and unsteady flow were solved by Fluent software. The wind speed was in the range of 0–40 m/s and the temperature was in the range of −40–0 °C.

Figure 3. Mesh generation of the convective heat transfer model for a circular tube.

3.1. Results and Discussion

Figures 4 and 5 show the variation in the convective heat transfer coefficient on circular tubes with wind speed and temperature. According to Figure 4, the convective heat transfer coefficient of circular tubes increases with the increase in wind speed and the decrease in temperature. In the temperature range of −30–−20 °C, the wind speed is greater than 25 m/s, and the influence of temperature on convective heat transfer coefficient increases. When the temperature is below −30 °C, the influence of temperature on the convective heat transfer coefficient still increases. According to Figure 4, when the temperature difference is constant, the convective heat transfer coefficient increases differently under different wind speeds. When the wind speed is greater than 25 m/s, the temperature ranges from −30 °C to −20 °C, and when the temperature is below −30 °C, the slope of the change curve of the convective heat transfer coefficient increases as the temperature decreases, indicating that the influence of temperature on the convective heat transfer coefficient increases. When the

wind speed is greater than 25 m/s, the starting point of flow separation moves backward, and the effect of disturbance strengthening heat transfer in the flow separation region is weakened. Therefore, the change rate in the convective heat transfer coefficient decreases with the increase in wind speed between −10 °C and −20 °C. When the temperature is below −20 °C, the decrease in air viscosity greatly enhances the convective heat transfer, and to some extent, offsets the influence of wind speed on heat transfer—it counteracts the heat transfer effect caused by wind speed.
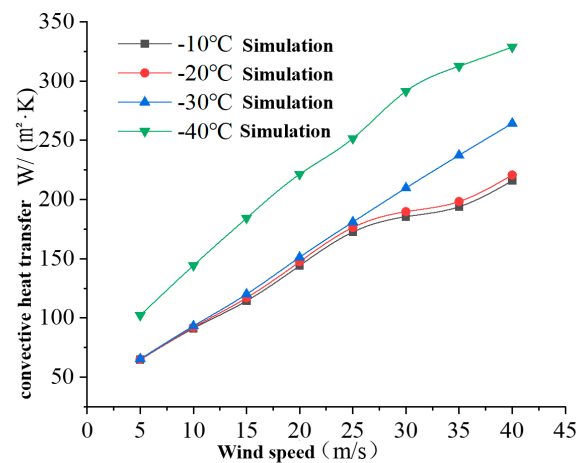

Figure 4. Variation in the convective heat transfer coefficient at temperature −40–0 °C with wind speed.
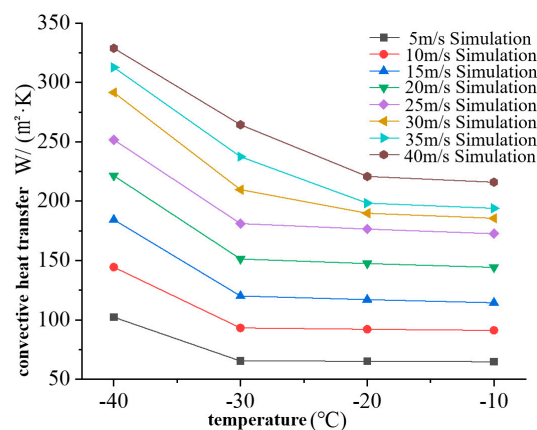

Figure 5. Change in the convective heat transfer coefficient at wind speed 0–40 m/s with temperature.

3.2. Prediction Model

The results of the empirical formula [13] for convective heat transfer of a circular tube under constant wall temperature show that the variation in convective heat transfer coefficient is obviously different with varying wind speeds and temperatures, a conclusion which is essentially consistent with our analysis. The results of the simulation analysis of the convective heat transfer coefficient on a circular tube in different temperatures, as shown in Table 2, indicate the following:

(1) Temperature −20–0 °C: When wind speed is less than 25 m/s, the convective heat transfer coefficient increases by 1.7% when the temperature decreases by 10 °C. The convective heat transfer coefficient increases by 21.2% when the wind speed increases by 5 m/s. When the wind speed is greater than 25 m/s, the convective heat transfer coefficient increases by 2.2% when the temperature decreases by 10 °C. The convective heat transfer coefficient increases by 7.8% when the wind speed increases by 5 m/s.

(2) Temperature −30–−20 °C: When wind speed is less than 25 m/s, the convective heat transfer coefficient increases by 1.9% when the temperature decreases by 10 °C. The

convective heat transfer coefficient increases by 22.4% when the wind speed increases by 5 m/s. When the wind speed is greater than 25 m/s, the convective heat transfer coefficient increases by 1.7% when the temperature decreases by 10 °C. The convective heat transfer coefficient increases by 13.5% when the wind speed increases by 5 m/s.

(3)　Temperature −40–−30 °C: When wind speed is less than 25 m/s, the convective heat transfer coefficient increases by 43.2% when the temperature decreases by 10 °C. The convective heat transfer coefficient increases by 23.6% when the wind speed increases by 5 m/s. When the wind speed is greater than 25 m/s, the convective heat transfer coefficient increases by 31.7% when the temperature decreases by 10 °C. The convective heat transfer coefficient increases by 9.4% when the wind speed increases by 5 m/s.

Table 2. Analysis results of the simulation data of the convective heat transfer coefficient.

Temperature	Wind Speed	Influence of Temperature on H Increase	Influence of Wind Speed on H Increase
−20–0 (°C)	<25 (m/s)	1.7 (%)	21.2 (%)
	>25 (m/s)	2.2 (%)	7.8 (%)
−30–−20 (°C)	<25 (m/s)	1.9 (%)	22.4 (%)
	>25 (m/s)	1.7 (%)	13.5 (%)
−40–−30 (°C)	<25 (m/s)	43.2 (%)	23.6 (%)
	>25 (m/s)	31.7 (%)	9.4 (%)

When the temperature is higher than −30 °C, the wind speed is the main factor of the convective heat transfer. When the temperature is lower than −30 °C, the effect of temperature increases significantly, and the effect of wind speed remains constant. Therefore, the prediction model of the convective heat transfer coefficient should consider the influence of different temperatures and wind speeds.

The variation in related parameters affected by temperature is shown in Table 3.

Table 3. Prandtl number Pr, thermal conductivity λ ranges.

Temperature	Prandtl Number	Thermal Conductivity
−30–0 (°C)	0.707–0.723	0.0220–0.0236 (W/(m·°C))
−40–−30 (°C)	0.723–0.728	0.0212–0.0220 (W/(m·°C))

The variation in related parameters is less affected by temperature. Prandtl number and thermal conductivity are regarded as constants in the process of convective heat transfer. Temperatures of −30–0 °C have a Prandtl number of 0.715 and thermal conductivity of 0.0228. Temperatures of −40–−30 °C have a Prandtl number of 0.726 and thermal conductivity of 0.0216. The prediction model of the convective heat transfer coefficient in different temperature can be expressed as:

$$h_m = C_1 \frac{\lambda}{d} Re^{m_1} Pr^{n_1}, \quad -30\text{–}0\,°C \tag{3}$$

$$h_m = C_2 \frac{\lambda}{d} Re^{m_2} Pr^{n_2}, \quad -40\text{–}-30\,°C \tag{4}$$

Based on Equations (3) and (4), the numerical simulation data were fitted, and the results are shown in Figure 6. In Equation (3), $C_1 = 0.490$, $m_1 = 0.659$, and $n_2 = 3.141$; in Equation (4), $C_2 = 0.191$, $m_2 = 0.599$, and $n_2 = 1.680$. The coefficient of determination was 98.0% for temperatures of −30–0 °C and 99.6% for temperatures of −40–−30 °C, indicating that the fitting results have high reliability.
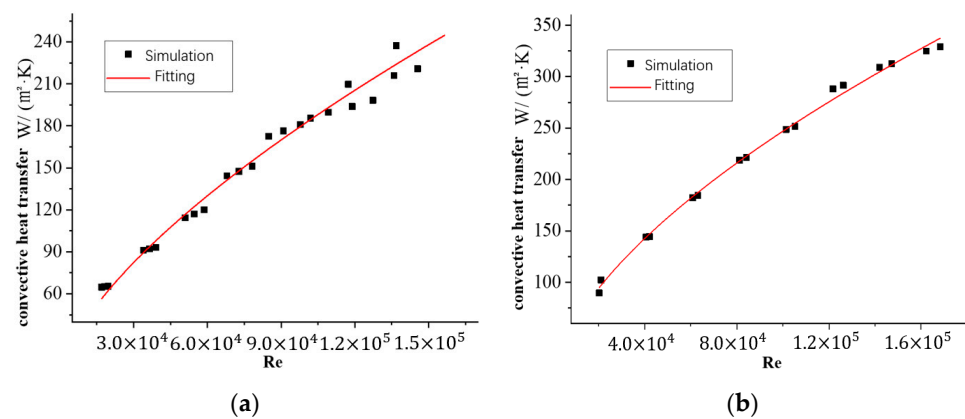
Figure 6. Fitted measured data of convective heat transfer coefficients. (**a**) Temperature −30–0 °C. (**b**) Temperature −40–30 °C.

4. Experimental Section

The test platform for measuring the convective heat transfer coefficient of a circular tube was set up in a cold laboratory. The convective heat transfer coefficient of the circular tube was measured under different wind speeds and temperatures. The experimental temperature control range was −5–−50 °C and wind speed ranged from 4 m/s to 13.7 m/s (the measured maximum for the test). The experimental circular tube was an actual handrail used on a polar ship. Its size parameters were an outer diameter of 0.042 m, inner diameter of 0.020 m, and length of 0.251 m.

4.1. Results and Discussion

Table 4 presents the test conditions and results of our experiment.

Table 4. Tests conditions and results.

No.	Temperature	Wind	Measured Convective Heat Transfer Coefficient
1	−5 (°C)	4.9 (m/s)	60.2 (W/(m² °C))
2	−5.1 (°C)	8.8 (m/s)	78.3 (W/(m² °C))
3	−4.7 (°C)	13.7 (m/s)	101.2 (W/(m² °C))
4	−10.0 (°C)	5.0 (m/s)	60.4 (W/(m² °C))
5	−10.0 (°C)	8.6 (m/s)	77.6 (W/(m² °C))
6	−10 (°C)	13.1 (m/s)	98.7 (W/(m² °C))
7	−15 (°C)	5.1 (m/s)	61.2 (W/(m² °C))
8	−14.8 (°C)	9.3 (m/s)	79.1 (W/(m² °C))
9	−14.8 (°C)	13.3 (m/s)	99.8 (W/(m² °C))
10	−20 (°C)	5.1 (m/s)	61.7 (W/(m² °C))
11	−19.9 (°C)	9.3 (m/s)	78.7 (W/(m² °C))
12	−19.4 (°C)	13.1 (m/s)	97.4 (W/(m² °C))
13	−25 (°C)	4.9 (m/s)	59.8 (W/(m² °C))
14	−25.1 (°C)	8.7 (m/s)	78.3 (W/(m² °C))
15	−24.3 (°C)	12.5 (m/s)	98.5 (W/(m² °C))
16	−30 (°C)	4.8 (m/s)	60.1 (W/(m² °C))
17	−29.9 (°C)	8.4 (m/s)	76.9 (W/(m² °C))
18	−29.3 (°C)	12.1 (m/s)	97.8 (W/(m² °C))
19	−34.9 (°C)	4.9 (m/s)	94.5 (W/(m² °C))
20	−35 (°C)	8.3 (m/s)	117.7 (W/(m² °C))
21	−34.3 (°C)	11.2 (m/s)	129.7 (W/(m² °C))
22	−39.6 (°C)	4.1 (m/s)	87.4 (W/(m² °C))
23	−39.7 (°C)	7.6 (m/s)	112.3 (W/(m² °C))
24	−40.3 (°C)	11.2 (m/s)	127.5 (W/(m² °C))

Experimental errors are normally classified into two categories:

(1)　The measuring temperature of the tube fluctuates periodically in this test; K temperature thermocouple accuracy is 1%; and

(2)　Each group of tests is conditioned three times; considering the influence of flow separation, the average value of each measuring point is taken as the average heat transfer coefficient.

In order to clarify the influence of temperature, the wind speed close to simulation was selected for analysis in the test; the result is shown in Figure 7. It can be seen from the figure that the simulation results were close to the test results. The mean error was 7.5%, and the correctness of the simulation model was verified. When the temperature was higher than −30 °C and the wind speed was constant, temperature had little effect on the convective heat transfer coefficient of the circular tube. When the temperature was lower than −30 °C, the effect of temperature on the convective heat transfer coefficient increased.
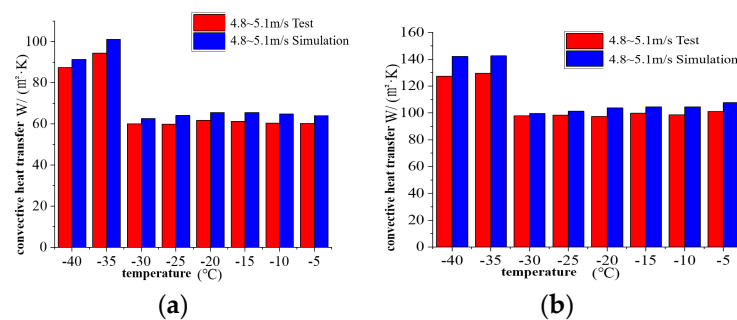

Figure 7. Convective heat transfer coefficient changes with temperature. (**a**) Wind speed 4.8–5.1 m/s. (**b**) Wind speed 12.1–13.7 m/s.

The temperature close to simulation was selected for analysis in the test; the result is shown in Figure 8. It can be seen from the figure that the simulation results were close to the test results. The mean error was 7.3%, and the correctness of the simulation model was verified. There was a small amount of heat loss in the test. When the temperature was constant, the convective heat transfer coefficient increased with the increase in wind speed.
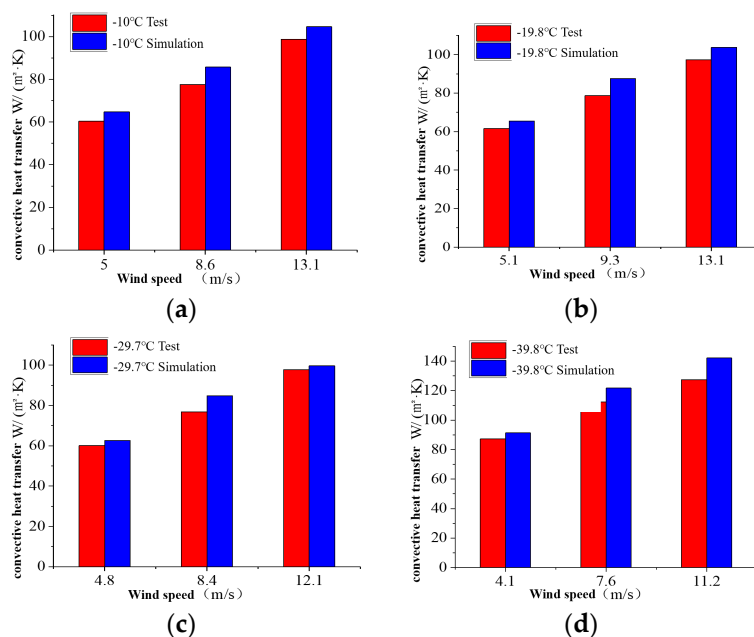

Figure 8. Convective heat transfer coefficient changes with wind speed. (**a**) Temperature −10 °C. (**b**) Temperature −19.8 °C. (**c**) Temperature −29.7 °C. (**d**) Temperature −39.8 °C.

4.2. Prediction Models

The test results and prediction model of the convective heat transfer coefficient in circular tubes are shown in Figure 9. When the wind speed was between 4.1 and 5.1 m/s, it can be seen from the figure that the fitting results were close to the test results, and the mean error was 2.6%. For a wind speed between 7.6 and 9.3 m/s, the test results were greater than the fitting results, and the mean error was 10.1%. When the wind speed was between 11.2 and 13.7 m/s, the test results were greater than the fitting results, and the mean error was 14.1%. In sum, the error was small between the fitting results and test results. Thus, the prediction model of the convective heat transfer coefficient in circular tubes can provide a reference for the design of polar ship engineering equipment.
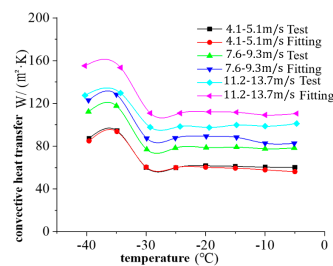

Figure 9. Comparison of the measured and fitted results.

5. Conclusions

In this paper, the influencing factors of environmental in the tube and polar regions were studied. The consideration given in the specification for heating lacking the environmental changes was supplemented. We used Fluent software to support our investigation of convective heat transfer in circular tubes. This was studied by numerical simulation under the second boundary condition, and the correctness of the simulation model was verified by testing with wind speeds of 0–40 m/s and temperatures of −40–0 °C so the variations in the convective heat transfer coefficient were found. The results illustrate the following conclusions:

(1) Convective heat transfer in circular tubes increases with the increase in wind speed and the decrease in temperature.
(2) When the temperature is lower than −30 °C, the effect of temperature on convective heat transfer is increased.
(3) When the wind speed is greater than 25 m/s and the temperature is lower than −20 °C, the effect of temperature on convective heat transfer is increased.
(4) Based on the simulation data, the prediction model of the convective heat transfer coefficient in circular tubes can be established.

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