Experimental study on the convection heat transfer of air across wires in the icing environmental conditions

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***Abstract**:* Atmospheric ice accretion on wires occurs frequently, it has becoming an urgent problem in power industry. In this paper, an experiment is designed to get the heat transfer coefficient. The experiment has been carried out in an icing wind tunnel operating in icing environmental conditions.Through analysis the heat balance equation of the heated wires and the different characteristics of the heat transfer process in the ice accretion process on overhead transmission wires,the theoretical formula of heat transfer coefficient is obtained.The parameters of the formula including current, resistivity, LWC, collection coefficient and temperature are measured by the experiment.The measurement of convective heat transfer coefficient is based on the theoretical formula and obtained by calculating. The icing wind tunnel experiments simulates the atmospheric icing environment. By changing the air temperature, the wind speed, the Liquid Water Content(LWC) and other weather parameters in the icing wind tunnel, the variation of the heat transfer coefficient can be found. The results show that the convective heat transfer coefficient is mainly affected by wind velocity. The current and the air temperature have a little effect on the convective heat transfer coefficient. The convective heat transfer coefficient increases with the increasing of wind velocity.This law can be used to provide theoretical support for anti-icing based on the Joule effect.

Keywords: convection heat transfer; ice accretion; atmospheric icing environment; icing wind tunnel

1. INTRODUCTION

In recent years, with the changes of the environment, the overhead electrical transmission lines icing occurs frequently. Ice accretion on power transmission lines affects a wide variety of wires in many countries. It is generally well known to occur in northern countries like Japan, Canada, England, Norway, French**,** American and China.Ice accretion is becoming an urgent problem in Power industry all over the world.

The research shows that transmission lines icing can occur only in a certain air temperature, humidity, wind speed and other conditions.In the natural environment, the icing form is not the same in different types of weather conditions. Even if the same weather conditions, the icing type is also different because of the different wire load [1].

Transmission lines icing is a complex process of heat transfer on the surface of the lines. The heat transfer process includes latent heat loss, radiation heat transfer, convection heat transfer, Joule heating and so on. The convection heat transfer is very important in the process, and the Local Heat Transfer Coefficient(LHTC) is essential in determining the ice shape of ice accretions. In 1984, Makkonen put forwarded the heat balance equation of icing on wires[2]. Makkonen has obtained the effect of the Heat Transfer Coefficient in the icing process by theoretical analysis. He established a mathematical model to predict the local heat transfer coefficient along the cylinder surface, based on the integral equations of the boundary layer. The value of the Heat Transfer Coefficient may be influenced even further by the geometry of the ice accretion and its surface roughness. In 2007, Zsolt Péter set up an icing wind tunnel to research the Heat Transfer Coefficient, he found the relationship between the Heat Transfer Coefficient and the Nusselt(Nu) and Reynolds(Re)number[3].

In this paper, the law of the heat transfer coefficient is obtained in the icing environmental conditions through experimental study. The results can be used to provide theoretical support for anti-icing based on the Joule effect and play a significant role in management atmospheric ice accretion on wires.

2. EXPERIMENTAL PRINCIPLES

Ice accretion on wire is a complex process of heat transfer on the surface of the lines.When not considering the formation of supercooled water droplets, only considering the ice growth process on the surface of wire, the transmission lines icing is the typical of heat and mass transfer process. The mainly heat transfer process of the transmission lines icing, as following [4]:

1, heat flux due to heating of wire by Joule heating: Φ_J

2, latent heat flux released during freezing: Φ_F

3, loss of sensible heat between the wire and the air stream by convection: Φ_C

4, heat loss due to evaporation: Φ_E

5, heat loss in warming the impinging water to the surface temperature: Φ_W

6, heat loss due to radiation, including the solar radiation to the wire: Φ_S

7, heat loss in warming the impinging ice crystals to the surface temperature: Φ_I

8, heat flux due to aerodynamic heating: Φ_V

9, heat flux due to the kinetic energy of the droplets and ice crystals: Φ_K

10, heat loss due to the water shed: Φ_R

In general, the terms Φ_V, Φ_K, Φ_I and the heat conduction through the wire are very small in regards to the magnitude of the other ones, and may be neglected. If the temperature of the water is equal to the wire's surface temperature, then Φ_R is zero. Under the role of critical current, Supercooled droplets on the surface of the wires can not be frozen, Φ_F is also neglected. So the heat balance equation for the icing surface is:

$$\Phi_J = \Phi_C + \Phi_E + \Phi_W + \Phi_S$$

（1）

here

$$\Phi_J = \mu I^2 / (\pi D)$$

（2）

Where I is the current intensity，μ the resistivity per unit of length and D the diameter of wire;

$$\Phi_C = h(T_s - T)$$

（3）

Where T_s and T are surface temperature and the air temperature respectively, h is the heat transfer coefficient;

$$\Phi_s = 4\sigma\varepsilon T^3 (T_s - T) \qquad （4）$$

Where ε is the emissivity of the wires, new line ε =0.23-0.43, old line ε =0.9, σ is the Stefan-Boltcomann constant;

$$\Phi_E = 0.662hL_V \left[P(T_s) - P(T)\right] / (C_a P)$$

（5）

Where h is the convection heat transfer coefficient, L_V is the latent heat of vaporization of Water, P is the pressure and $P(T)$ the saturation vapor pressure of moist air at temperature T, c_a the specific heat of air at constant pressure;

$$\Phi_W = (2/\pi) uEWc_w (T_s - T)$$

（6）

Where E is the total collection efficiency, u the air velocity, c_w the specific heat of water at constant pressure;

Finally, Eq(1) may be rewritten:

$$\mu I^2 / (\pi D) = (T - T_\infty)[h + 4\sigma\varepsilon T^3 + (2/\pi)uEWc_\omega] + 0.622hL_V \left[P(T) - P(T_\infty)\right] / (c_a P)$$

（7）

By calculation of the Eq(7), the expression of convection heat transfer coefficient is

$$h = \frac{\mu I^2 / (\pi D) - (T_s - T)[4\sigma\varepsilon T^3 + (2/\pi)uEWc_\omega]}{(T_s - T) + 0.622 L_V \left[P(T_s) - P(T)\right] / (c_a P)}$$

（8）

The Eq(8) is the experimental principle. In the experiment, the value of convective heat transfer coefficient is calculated by measuring various parameters.

3. EXPERIMENTAL PROCEDURE

A Experimental Setup

The experiment has been carried out in an icing wind tunnel.Cooling capacity required in the experiment provided by the consistent temperature and humidity room of Changsha University of Science and Technology and the temperature can be stabilized at –20℃.The wind tunnel surface was covered by insulation materials, guaranteed the temperature required for the experiment. The experimental setup was rigged with high amperage, low-voltage transformer allowing for Joule heating the test simulated wire by passing alternating current through it. The high amperage provided by rectifying power supply. The effective current was measured by a current transformer installed in the circuit. The simulated wire was installed in the test section of the icing wind tunnel, perpendicular to the direction of the air flow(Fig.1). Three thermocouples were welded on the inner surface of the wire and the temperature took the average of the three temperatures.The wires connections were kept outside the icing wind tunnel. Insulation materials were cooled down to required temperature before each experiment in order to keep the conductor connections as cold as possible and to reduce the thermal boundary layer in the wind tunnel test section and the radiative heat loss from the wires.

The cross-sectional dimensions of the icing wind tunnel test section are 320cm×320cm.The water droplets were injected into the refrigerated air stream by a nozzle. The distance between the spray bar (where the nozzle is fixed) and the test wire is 5m. The velocity field in the wind tunnel section under study was simulated for different free stream velocities and it showed a quite uniform distribution in both horizontal and vertical directions.

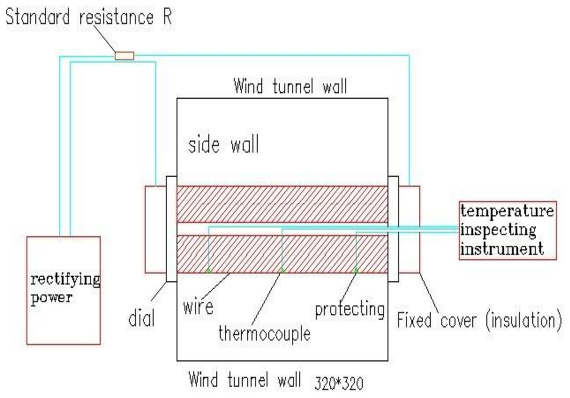

Fig.1: Schematic of experimental apparatus

B Parameters measurements

In the present study, most of the major parameters can be measured directly, including air speed and air temperature. Other parameters such as the Liquid Water Content (LWC) and the Collection Coefficient, however, cannot be accurately estimated until a specific test is under way. These parameters may be divided into two groups on the basis of the means applied to determine their values, as shown in Table 1.

Table 1: Experimental parameters

Group no.	Parameters
1 (to be measured)	Wind Speed, Air Temperature, Air Pressures, Diameter of test wire, The current intensity Surface Temperature of wire, Resistivity of wire
2 (to be test)	LWC, the Collection Coefficient

The wind speed was controlled by variable frequency fan and measured using a handheld anemometer in the test section. Air pressures was measured using a manometer, the air temperature and the surface temperature of wire is measured timely using a temperature inspecting instrument. The current intensity can be controlled by rectifying power supply. The diameter of test wire is 28.74mm, Simulation overhead transmission wires is made of the 304 stainless steel and its resistivity μ =0.73 $\Omega\cdot mm^2\cdot m^{-1}$.

The Liquid Water Content (LWC) and the Collection Coefficient measured by Yi Xian's method[5].Firstly, droplet trajectories are computed with a Lagrangian method to obtain the total collection coefficient of water droplet. The results show the collection coefficient is influenced mainly by the wind speed and the droplet diameter. Under the experimental condition, because the droplet diameter is the same, the total collection coefficient is 0.012, 0.02, 0.18when the wind speed is 2*m/s*, 4 *m/s*, 7 *m/s.* Secondly, ice mass is computed, and the curve relating LWC with ice mass is obtained. Lastly, the experimental results of ice mass are used to determine the value of LWC from the curve. In this experiment, the LWC value in the icing wind tunnel is 0.3g/m^3.Other related parameters can be found from the book of Heat Transfer[6]and Engineering Thermodynamics[7].

4. EXPERIMENTAL RESULTS AND ANALYSIS

In the present experimental study, by changing the air temperature, the wind velocity and other weather parameters, the results of the law of convective heat transfer coefficient are obtained in different meteorological parameters.

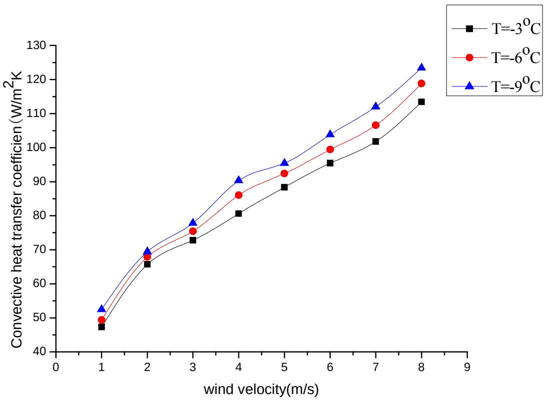

Fig.2: Effects of wind speed（I=20A）

Fig.2 shows experimental results between the convective heat transfer coefficient and wind speed. The results show that the convective heat transfer coefficient increased with the increasing of wind speed. When air across the simulation wires, the thermal boundary layer of the wire surface has changed with the wind velocity vary. At this kind of circumstance, the wind promotes the convective heat transfer of the wire surface. The experimental results are coincide with the theory analysis.

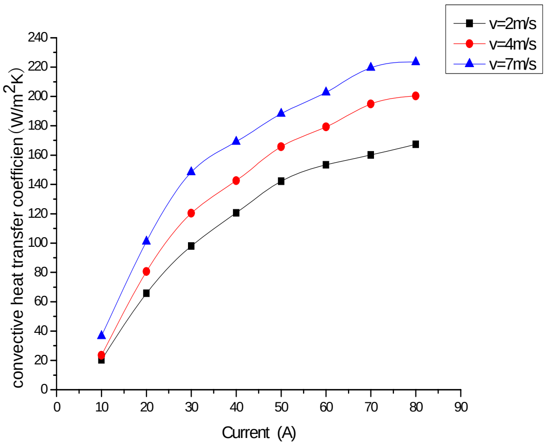

Fig.3: Effects of current（T=－3℃）

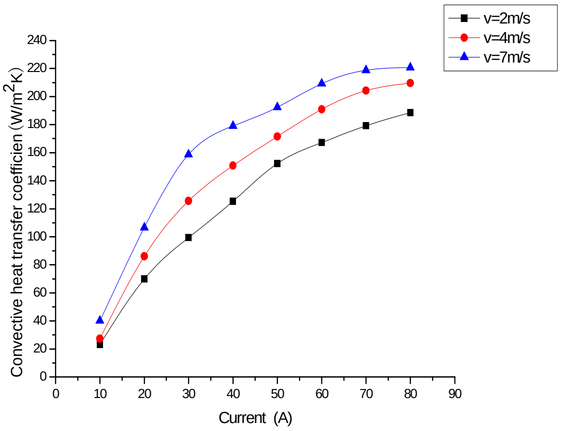

Fig.4: Effects of current（T=－6℃）

Fig.3 and fig.4 show the results that the convective heat transfer coefficient vary with current while the air temperature is－3 ℃ and－6 ℃.The results show that the convective heat transfer coefficient increases with the current. When the current flows through the wire, the temperature of the wire surface increased because of the Joule heating effect. Then the temperature between the wire and the environment become larger, the convective heat transfer is enhanced. So in the present study, the simulation wire was close to the actual wire only when the current is small._As can be seen from the fig.3and fig.4, the convective heat transfer has a little change when the current is 10－20A . This situation is consistent with the actual wire and the theory analysis.

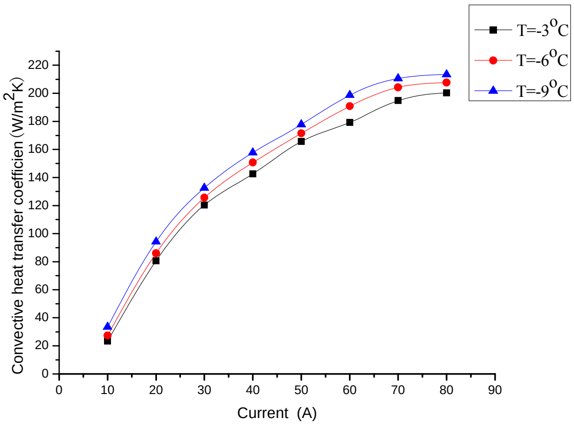

Fig.5:The convective heat transfer coefficient vary with current and air temperature（v=4 *m/s*）

The air temperature has little effect on the convection heat transfer coefficient，as illustrated in Fig.4. When the wind velocity is 4 *m/s* and the same current，the convection heat transfer coefficient has no evident difference. Fig.5 shows the results under the air temperature is －3℃，－6℃ and －9℃.

5. CONCLUSION

Through the experimental study and analysis, it can be concluded:

1）The convective heat transfer coefficient increased with the increasing of wind speed. Therefore, wind speed is the main factors of convective heat transfer on the wire surface.

2）The current and the air temperature have a little effect on the convective heat transfer coefficient，especially in the case of low current.

3）The experimental results of can be used to provide theoretical support for anti-icing based on the Joule effect.

4）The test bed can be used to measure the value of the local convective heat transfer coefficient，the experimental study will be presented on the next paper.

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