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Research Article

Preliminary Research on Rotating Icing Test Scaling Law

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Abstract: A rotating icing scaling law used for parameter selection for tests in an icing wind tunnel is established using the basic physical process of icing. The method of selecting parameters for a scale model of rotating components is also discussed. A dimensionless quantity, called the rotation number, is derived from the water film momentum equation in the rotating coordinate system. This parameter must be matched between the reference and the scale model. Water collection properties and ice accretion are numerical calculated through the similarity law established in this study to evaluate the effectiveness of the rotating icing similarity law. Results show that when the rotating speed of the full size cone is 1000 or 3000 r/min, nearly identical droplets collection features and ice shape can be obtained for the half scale model. Thus, the established rotating icing similarity law is effective and can be used as the theoretical guidance for parameter selection for ice wind tunnel tests.

Keywords: Ice shape, rotating icing scaling law, rotation number, water collection property

INTRODUCTION

In-flight icing can result when an aircraft passes through a low temperature cloud layer and super-cooled water freezes upon impact with the aircraft surfaces. The resulting ice accretions can have dangerous effects on the aircraft, such as worsened flight performance, loss of maneuverability and a lack of stability. Ice formation on the rotating cone of the engine inlet can lead to the most deleterious effects because icing disrupts the essential streamline shape (Qiuyue, 2010). This can lead to airflow distortion at the engine inlet. Furthermore, when shed ice from the rotating cone is ingested, compressor blades can be damaged. Therefore, research on engine cone icing is particularly important. Completing tests in real weather conditions that lead to aircraft icing is the most ideal method for researching engine cone icing. However such testing is expensive and can only be done when correct atmospheric icing conditions exist. Furthermore, the time consuming process of finding in nature the extremes in the cloud liquid-water content envelope and drop size required for data collection severely limits such a method. Instead, use of an icing wind tunnel can reduce costs to study aircraft icing by simulating natural icing with water spray and providing control of cloud conditions, airspeed and temperature. Completing freezing tests using an icing wind tunnel can help to elucidate the mechanism of icing, evaluate the effects of ice shape on the aircraft performance and lead to an improved icing simulation mathematical model (Ruff, 1986; Kind *et al*., 1998).

In order to make the results of icing wind tunnel tests consistent with icing under real conditions, it would be ideal to use a full-size model under natural freezing weather conditions. Due to size constraints of working with a relatively small icing wind tunnel, this full scale experiment cannot be achieved. In addition, the icing wind tunnel cannot fully simulate the wide range of icing weather parameters, for example; the diameter of the super-cooled water droplets can vary in size from a few microns to several hundred microns, a range too wide for icing wind tunnels to reproduce. To solve these challenges, a scaling method is used to determine the scaled test conditions needed to produce the same results as would be seen when exposing the reference model to the desired cloud conditions (Ruff, 1985).

Such an icing scaling method requires either the entire model to be scaled in size, or the test conditions to be correctly scaled. The Arnold Engineering Development Center (AEDC) established a series of similarity equations which have had a significant influence on improving the simulation ability of icing wind tunnel experiments (Ruff, 1985). Later, Bilanin (1991) examined all possible similarity parameters, drew conclusions and made suggestions to improve some similarity methods. Anderson further evaluated the effectiveness of some similarity laws through the NASA's icing wind tunnel IRT (Anderson, 1994, 1996; Anderson and Ruff, 1999). He found that for rime ice, the accepted similarity laws can give the desired similar icing and thus serve as a useful tool. But for glaze ice and mix ice the efficacy of the laws is reduced, with

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only some able to obtain similar ice. In recent years, the development of the icing similarity laws in China has been slow, though Yi (2007) somewhat recently put forward an improved set of similarity laws. A further question is the development of an icing similarity law of rotating parts. Few have researched this problem and there is yet to be put forward dimensionless quantities of the rotation similarity. In this study, a dimensionless quantity of the rotational similarity was derived and a scaling theory of icing on the rotating cone was put forward based on predecessors' research on non-rotating parts. Numerical methods were used to test the validity of the icing similarity law for rotating components, with results showing that the rotating icing similarity law, as the basis of parameter selection, is effective and can be usefully applied to ice wind tunnel tests.

METHODOLOGY

Rotating icing scaling law: Icing on the rotating cone is a complex physical process, an examination of which includes understanding the droplets trajectories in the flow field as well as the distribution of droplets and ice on the rotating components. Furthermore, the heat balance on the icing surface and centrifugal force acting on the components can affect icing. Also to be considered is that a rotating icing test similarity law is different from the similarity law for tests completed in a conventional wind tunnel. The similarity law for a conventional wind tunnel test can be obtained through establishing the non-dimensional equations of the fluid, but for icing test similarity laws, especially those including rotating parts, other factors in addition to the requirements of fluid mechanics should be considered.

The most significant difference between the icing similarity test of a rotating cone and the standard icing similarity test is the water stress change at the rotating cone surface as this causes the icing area and accretion shape to change. This is due to disruption of the flow field and the stress of the droplets or water film as they are affected by rotating. In essence, the development of a similarity law for a rotating cone calls for a comprehensive consideration of many factors.

Considering the main factors that influence icing, several aspects that should be included in the rotating icing similarity law are:

- Geometric similarity
- Flowfield similarity
- Drop trajectory and impact properties similarity
- Water catch similarity
- Icing rotating similarity
- Energy balance similarity

The similarity equations should then be established by considering various parameters that relate to ice, including velocity, pressure, temperature, liquid water content, water droplets diameter, freezing time and rotating angular velocity. The rotating icing similarity law will be discussed below and the definition of similarity parameters and the equations for calculating these parameters will be given.

Geometric similarity: This similarity is used to ensure that the reference (full-size) and scaled model are geometrically similar over the entire model volume. In particular for a rotating cone, the cone angle must be consistent. This basic requirement will be assumed satisfied in subsequent derivations for other similarity requirements.

Flowfield similarity: Similarity of the flowfield suggests that the Mach number and the Reynolds number for the scaled model should be matched to their respective full size values. However, to match the Mach number using a scale model half of the reference size, it is necessary for the scale velocity to be nearly the same as the reference value. In this case, to match the Reynolds number the scaled velocity must be double the reference. Therefore, the Mach number and Reynolds number cannot be matched simultaneously when the scale model is other than full size.

An approach was derived to address this problem. The basic analysis is that because the Mach number is low in most icing conditions, the effects of compressibility can be ignored. The effects of Reynolds number can be overlooked due to the fact that ice accretion happens mostly at the leading edge, where the boundary layer is thin (Paraschivoiu *et al*., 1994). Flowfield similarity shows that icing similarity cannot be achieved under some flow velocities, for example; tests of the wing Reynolds number must be greater than 2×10^5, which requires that the test wind speed not be too small. The maximum speed is derived by considering the supersonic flow around the object under the critical Mach number. Therefore, establishing the flowfield similarity in the impacting zone requires that the Mach number be greater than the Mach number calculated from Re = 2×10^5 and also be less than the critical Mach number (Pope, 1947).

Drop trajectory and impact properties similarity: To obtain the parameters of water droplets trajectory similarity, the non-dimensional drop momentum equation is used. The similarity parameter is the modified inertia K_0, for which the Langmuir and Blodgett's expression is (Irving and Katherine, 1946):

$$K_0=\frac{1}{8}+\frac{\lambda}{\lambda_{Stokes}}\left(K-\frac{1}{8}\right),\left(K>\frac{1}{8}\right) \tag{1}$$

where, the inertia parameter $K=\frac{1}{18}\frac{\rho_d d_0^2 U_\infty}{\mu_\alpha L}$, ρ_d is the water density, U_∞ is the air velocity, L is the characteristic dimension, μ_a is the air viscosity, d_0 is the water droplet diameter and λ/λ_{stokes} is the range parameter. The drop Reynolds number is defined below:

$$\mathrm{Re}_d = \frac{\rho_a d_0 U_\infty}{\mu_a} \tag{2}$$

The value of λ/λ_{stokes} was tabulated by Langmuir and Blodgett as a function of the drop Reynolds parameter, as shown below:

$$\frac{\lambda}{\lambda_{stokes}} = \frac{1}{0.8388 + 0.001483\,\mathrm{Re}_d + 0.1847\sqrt{\mathrm{Re}_d}} \tag{3}$$

The modified inertia parameter is forced to be equal for the reference and scale model in order to meet the requirement of water droplets trajectories and impact properties similarity, that is:

$$(K_0)_S = (K_0)_R \tag{4}$$

Water catch similarity: The accumulation parameter Ac is used to insure properly scaled ice thickness across the entirety of the model. The definition of Ac is as follows:

$$A_c = \frac{LWC \bullet U_\infty t}{\rho_i L} \tag{5}$$

where, LWC is the liquid-water content of the cloud, t is the icing time and ρ_i is the ice density. The water similarity must be equal for the reference and scale model for the catch accumulation parameter Ac, that is:

$$(A_c)_S = (A_c)_R \tag{6}$$

Icing rotating similarity: To date, the icing scaling laws have not involved the parameters required to account for rotating parts, which are necessary for defining rotating icing similarity for icing on the rotating cone. The parameters mentioned above are not sufficient to satisfy scaling for a rotating model, therefore more work must be done. In this study, a dimensionless quantity was derived using the water film momentum equation under the rotating frame. The rotating speed relationship of the scaled model and full size reference were obtained through calculating the dimensionless value. The water film momentum equation of rotation coordinate system was derived from Newton's second law to give the following equation:

$$\begin{aligned} & u\frac{\partial v}{\partial x} - \Omega u\frac{\partial r_z}{\partial x} + v\frac{\partial v}{\partial y} - \Omega r_z\frac{\partial v}{\partial y} - \Omega v\frac{\partial r_z}{\partial y} \\ & + \Omega^2 r_z\frac{\partial r_z}{\partial y} + w\frac{\partial v}{\partial z} - w\Omega\frac{\partial r_z}{\partial z} = \upsilon\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \\ & - \Omega\upsilon\left(\frac{\partial^2 r_z}{\partial x^2} + \frac{\partial^2 r_z}{\partial y^2} + \frac{\partial^2 r_z}{\partial z^2}\right) + \Omega^2 r_y + 2\Omega v_r \end{aligned} \tag{7}$$

where, Ω is the rotating angular velocity and u, v and w are the velocities in the x, y and z directions, respectively. This was further simplified through dimensional analysis to give:

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = \upsilon\left(\frac{\partial^2 v}{\partial z^2}\right) + \Omega^2 r_y + 2\Omega v_r \tag{8}$$

With the tensor form:

$$u_j\frac{\partial u_i}{\partial x_j} = \upsilon\frac{\partial^2 u_i}{\partial x_i \partial x_j} + \Omega^2 r + 2\Omega u_i \tag{9}$$

Next, letting $x_i^0 = x_i/L_0$, $\upsilon^0 = \upsilon/\upsilon_0$, $u_i^0 = u_i/V_0$, $\Omega^0 = \Omega/\Omega_0$, $r^0 = r/r_0$ and dividing by V_0^2/L_0, allows the following to be obtained:

$$\begin{aligned} u_j^0\frac{\partial u_i^0}{\partial x_j^0} = {} & \frac{\upsilon_0}{L_0 V_0} \bullet \upsilon^0\frac{\partial^2 u_i^0}{\partial x_i^0 \partial x_j^0} + \frac{\Omega_0^2 L_0^2}{V_0^2} \bullet \Omega^{02} r^{02} \\ & + 2\frac{\Omega_0 L_0}{V_0} \bullet \Omega^0 u_j^0 \end{aligned} \tag{10}$$

The dimensionless value, $\frac{\Omega L}{V}$, should be equal between the reference and scale model due to the larger effect of the coriolis force and the centrifugal force. The value $\frac{\Omega L}{V}$ is named rotation number and represents the ratio of the coriolis force and the overall inertia force expressed by r_o. The icing rotating similarity law needs to match the rotation number across the full size and scale models except to match the parameters that are mentioned above, that is:

$$(r_o)_S = (r_o)_R \tag{11}$$

Energy balance similarity: Energy balance similarity is often called energy equation similarity. The icing types, surface characteristics and ice density of the scaled model should be similar with the full size. Similarity parameters in this section include freezing fraction, n; drop energy transfer, φ; and air energy transfer, θ according to the following expressions (Ruff, 1985):

$$n = \frac{c_{p,w}}{h_f}\left(\phi + \frac{\theta}{b}\right) \tag{12}$$

where,
b = The relative heat factor
h_f = Latent heat of freezing

$$\phi = T_0 - T_\infty - \frac{U_\infty^2}{2c_{p,w}} \tag{13}$$

where,
T_0 = The temperature at the freezing point of water
T_∞ = The static temperature

$$\theta = T_{sur} - T_\infty - \frac{U_\infty^2}{2c_{p,a}} + \frac{m_e h_v}{h_c} \tag{14}$$

where, T_{sur} is the surface temperature, h_v is the latent heat of vaporization and h_c is the convective heat transfer coefficient. The energy balance similarity must meet the following conditions:

$$(n)_S = (n)_R,\ (\phi)_S = (\phi)_R,\ (\theta)_S = (\theta)_R \tag{15}$$

Similarity equations: The dimensionless parameters needed to establish the icing rotating similarity law were obtained following which the rotating similarity equations were derived:

$$\begin{aligned}&(K_0)_S = (K_0)_R,\ A_{cS} = A_{cR},\ (n_0)_S = (n_0)_R\\&(\phi)_S = (\phi)_R,\ (\theta)_S = (\theta)_R,\ (r_o)_S = (r_o)_R\end{aligned} \tag{16}$$

There are six constraint equations for the rotating similarity law so that when the scaled size is given only one parameter can be freely selected. As a general rule, this parameter is velocity. Other parameters of the test could be obtained by calculating constraint equations. The order and method of this scaling process are:

$L_S = [\textit{selected by user}]$
$U_{\infty S} = [\textit{selected by user}]$
$T_S = [\textit{numerical solution from equation}(\phi_S = \phi_R)]$
$p_S = [\textit{numerical solution from equation}(\theta_S = \theta_R)]$
$(LWC)_s = [\textit{numerical solution from equation}(n_S = n_R)]$
$d_s = [\textit{numerical solution from equation}(K_{0,S} = K_{0,R})]$
$t_s = [\textit{iterative solution from equation}(A_{C,S} = A_{C,R})]$
$\Omega_S = [\textit{numerical solution from equation}(r_{o,S} = r_{o,R})]$

VALIDATION OF ICING ROTATING SIMILARITY LAW

In this research the numerical method was used to evaluate the effectiveness of the rotating icing similarity law due to a lack of experimental facilities. The thought is that for the numerical evaluation one can implement the icing calculation both on the full size and the scaled model. The parameters for the scaled model are selected by using the rotating icing similarity law. If the ratios of icing shapes are equal with the geometric proportion, the similarity law and the similarity equations established in this study would be considered effective. To numerically test whether the rotating icing similarity law is reasonable, the full size rotating cone was selected as a reference, as shown in Fig. 1 (units of mm) and the scaled model was half of the reference size. To make the test realistic, the rotation speeds for the full size reference were chosen to be 1000 and 3000 r/min and the parameters for the scaled model were obtained through the similarity law established in this study. Furthermore, two cases were calculated in this study to further validate the method. The computational domain and boundary conditions are shown in Fig. 2 and the working conditions were shown in Table 1 and 2. In both cases the conditions of the scale model were calculated by the equations given in the law.

Flow field calculation: The fluid is correctly described by Newton's law of viscous fluid and the incompressible Reynolds average Navier-Stokes equations were obtained through the mass conservation equation, the momentum equation and the energy conservation equation. The flow field calculation is the basis and premise of calculating droplet impact characteristics and ice accretion. The fluid continuity equation and momentum equation are as follows:

$$\frac{\partial \rho_a}{\partial t} + \vec{\nabla} \bullet (\rho_a \vec{v}_a) = 0 \tag{17}$$

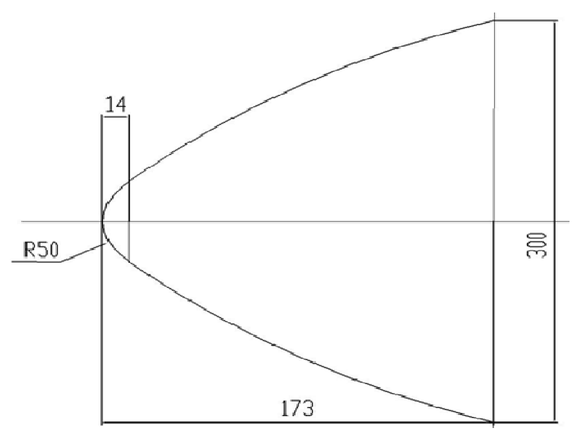


Fig. 1: Full size of the rotation cone

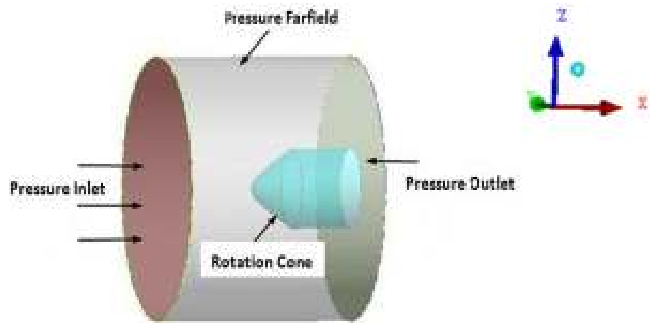


Fig. 2: Computational domain of the rotation cone

Table 1: Working conditions for case 1

Size	Rotation speed/ (r/min)	Characteristic length/m	Static temperature/K	Velocity/ (m/sec)	Drop diameter/μm	LWC/ (g/m^3)	t/sec
Full size	1000 (3000)	0.1730	262.0	89.4	40.00	1.000	200
Scale size	2000 (6000)	0.0865	259.6	89.4	26.08	1.414	70.8

Table 2: Working conditions for case 2

Size	Rotation speed/ (r/min)	Characteristic length/m	Static temperature/K	Velocity/ (m/sec)	Drop diameter/μm	LWC/ (g/m^3)	t/sec
Full size	3000	0.1730	262.00	89.4	40.00	1.000	200
Scale size	5033	0.0865	262.54	75.0	30.34	1.544	77.2

$$\frac{\partial \rho_a \vec{v}_a}{\partial t} + \vec{\nabla} \bullet \left(\rho_a \vec{v}_a \vec{v}_a \right) = \vec{\nabla} \bullet \sigma^{ij} + \rho_a \vec{g} \tag{18}$$

where, σ^{ij} is the viscous stress. In this research, pressure is used as the primary dependent variable and the SIMPLE algorithm is used to simulate the 3-dimensional turbulent flow. The Spalart-Allmaras turbulence model was also used in this study. The one-equation model and S-A model are calculated by experience and the dimensional analysis and the final control equation is derived from a simple flow. Compared with the two equation model, this has the advantages of fewer calculations and greater stability, making it the best choice.

Water droplets impact characteristics calculation: Once the air flow equation is solved the droplet motion equation can then be solved. The influence of gas on droplets was considered, but the function of droplets on air was not considered. The air flow parameters were used to calculate the droplet movement equation, allowing the droplet trajectories and parameters to be calculated. In the rotating case, the water droplets continuity equation and the equation of motion are as: follows:

$$\frac{\partial \alpha}{\partial t} + \vec{\nabla} \bullet \left(\alpha \vec{v}_d \right) = 0 \tag{19}$$

$$\frac{\partial \left(\alpha \vec{v}_d \right)}{\partial t} + \vec{\nabla} \left[\alpha \vec{v}_d \times \vec{v}_d \right] = \frac{C_D \operatorname{Re}_d}{24K} \alpha \left(\vec{v}_a - \vec{v}_d \right) + \alpha \left(1 - \frac{\rho_a}{\rho_d} \right) \frac{1}{Fr^2} \vec{g} \tag{20}$$

where, the variables α and V_d are mean field values of the water volume fraction and droplet velocity, respectively. The first term on the right-hand-side of the momentum equation represents the drag acting on droplets of mean diameter d. The second term represents buoyancy and gravity forces and is proportional to the local Froude number:

$$F_r = \frac{U_\infty}{\sqrt{Lg}} \tag{21}$$

Once the water droplets speed distribution was determined, the water collection coefficient could be calculated. Generally, collection efficiency in the vicinity of stagnation is greater than that in impingement limitation. This generalization is very important to correctly simulating ice accretion. In this research, collection efficiency is defined as follows:

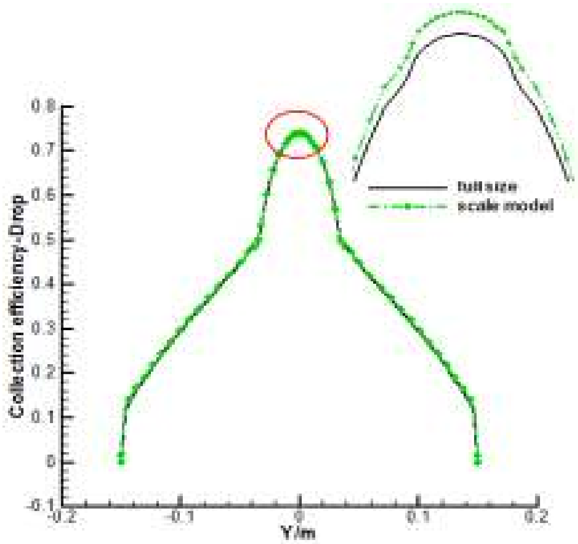
$$\beta = \frac{R_{accretion}}{R_{accretion,\max}} = \frac{R_{accretion}}{LWC \cdot V_\infty} \tag{22}$$

where,

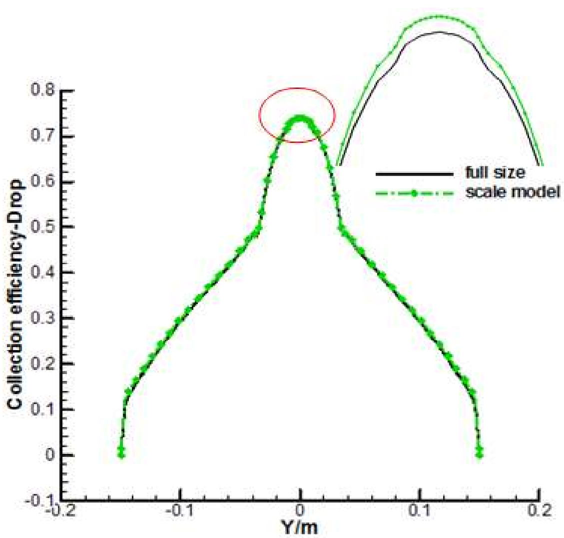
$R_{accretion}$ = The local accreted mass flux, with the unit is kg/sec

$R_{accretion,\ max}$ = The probable maximum local accreted mass flux and on the basis of incoming airflow, $R_{accretion,\ max} = LWC \cdot V_\infty$

The water droplets collection coefficient curve of Case 1 for the cone middle section (z = 0) is shown in Fig. 3, where the x axis is perpendicular to the flow velocity direction and the zero point is located in the



(a) Water collection coefficient (1000 r/min)



(b) Water collection coefficient (3000 r/min)

Fig. 3: Comparison of water collection coefficients

cone vertex. It can be seen that the water collection coefficient is greater at the stagnation point. Once the horizontal coordinate of the scaled model was normalized in geometry, it was found that the water collection coefficient of scale model is larger than that of the full size, though the difference is small, as shown in Fig. 3a and b with the rotating speed of the full size reference equal to 1000 and 3000 r/min. The largest error in the water collection coefficient of the two models is 2.7%, which is relatively small and can be ignored. The droplets impact limitation of full size and scale model are also similar in Fig. 3. From this analysis it can be concluded that the parameters calculated by the icing rotating similarity law meet the similarity requirement at both high and low speeds.

Ice accretion: Icing accretion is a complicated process that includes heat and mass transfer. The essence of solving for icing similarity is to calculate the mass conservation equation and the energy conservation equation. Centrifugal and Coriolis source terms are included in the governing equations for ice accretion in rotating components. Static walls within rotating domains experience a time-varying history because the movement of rotating components causes periodic variations in the flow field and particle impingement. Therefore, the instantaneous variation of these variables needs to be circumferentially averaged to account for their time variation. In this study, the Messinger model was used (Messinger, 1953; Qiu and Han, 1985). Jacobi pointed out that the equation to calculate the heat-transfer coefficient of a plate can be used on the cone (Qiu and Han, 1985). Boundary layer thickness of cone is 1/√3 times that of the plate, so for laminar flow of the cone, the equation for the local heat-transfer coefficient is:

$$h = 0.1568\sqrt{\frac{\rho V_l}{S}}T_t^{0.52} \tag{23}$$

For turbulent flow, the local heat-transfer coefficient is:

$$h = 0.923\left(\rho V_l\right)^{0.8} T_f^{0.292} S^{-0.2} \tag{24}$$

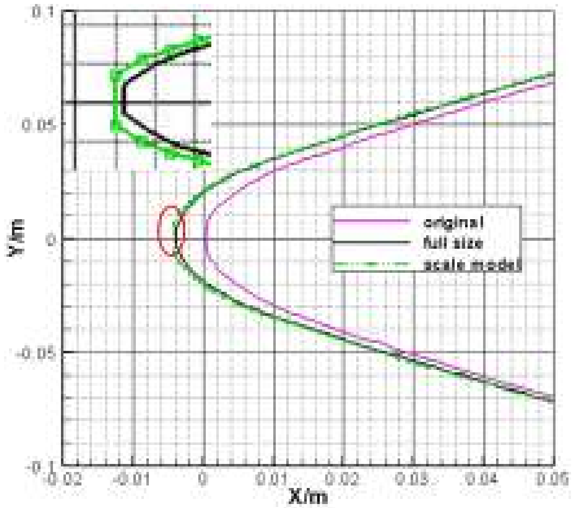
where, S is the distance from the top of the cone.

In this study, the thermodynamic model for icing is derived from the first law of thermodynamics to include the energy balance with the impingement model within the control volume. The energy balance is established as follows:

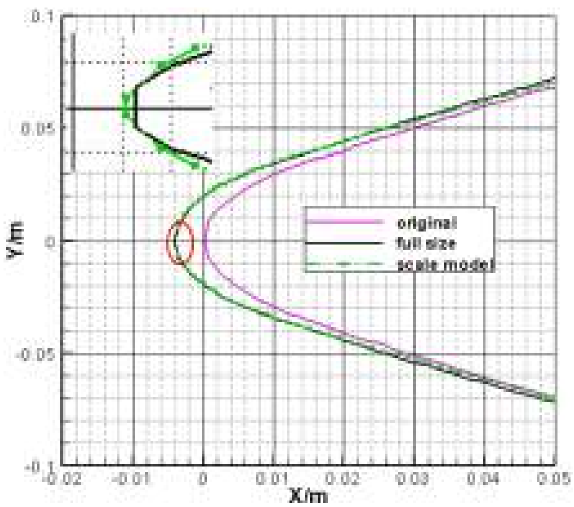
$$E_{imp,w} + E_{in} + E_f + E_{anti} = E_{out} + E_{ev} - E_{ice} + E_{conv} \tag{25}$$

With the terms on the left hand side giving energy increase and those on the right hand side giving energy loss.

Once the scaled model of Case 1 was normalized in geometry and the two were plotted together as shown in Fig. 4, it can be seen that the ice shapes of full size and scaled model are nearly identical. Enlargement of the plot near the point of stagnation shows that the ice thickness of the scaled model is larger than that of the full sized reference. This illustrates that the reduction of droplet size due to rotation is less than the geometric proportion of the full size and scale model. The largest error of ice thickness is 5.3%, a relatively small value which can be ignored. Through this analysis it can be concluded that the rotating icing similarity law established in this study is both feasible and effective.



(a) Ice shape (1000 r/min)



(b) Ice shape (3000 r/min)

Fig. 4: Ice shape comparison

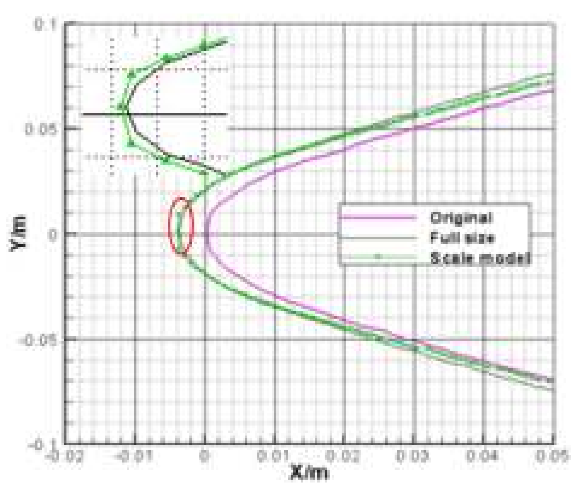


Fig. 5: Ice shape comparison

To test the universality of this rotating icing similarity law, the condition of case 2 was chosen and computed. The method to complete this evaluation was the same as described in the above sections. The ice shape of both the full size and scaled model are shown in Fig. 5. The results show that these still agree well under different speed conditions.

CONCLUSION

A rotating icing scaling law was established and the equations of the similarity parameters are given in this research. The water droplets collection coefficient and ice accretion for both full size and scaled model under different conditions and different speeds were calculated to evaluate the effectiveness of the law. Conclusions are as follows:

- It is feasible to calculate the rotation number, a dimensionless value derived in this study, as a parameter that must be matched across the full size and scale model in the rotating icing similarity law.
- Water impact properties and ice accretion can be numerical calculated through the similarity law established in this study and a similar ice shape can be obtained both for the full size and half scaled model under different speed conditions. This illustrates that the similarity law is effective and can be used as the theoretical guidance for parameters selection for ice wind tunnel tests.
- When the desired experimental conditions cannot be achieved the numerical method can be used to evaluate the effectiveness of the similarity law. Due to inaccuracies inherent in using a numerical method as opposed to real conditions, future work is needed to further verify the effectiveness of the derived law for the icing wind tunnel tests.

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