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Scaling for Icing Wind Tunnel Tests and Validation with Numerical Simulations

Gizem Özbek Yanmaz[*,**] *and Serkan Özgen*[**]
[*]*TUBITAK-SAGE PK.16 Mamak, 06261, Ankara, Turkey*
[**]*Middle East Technical University, Dept. Aerospace Eng., 06800, Ankara, Turkey*
gizem.ozbek@tubitak.gov.tr, serkan.ozgen@ae.metu.edu.tr

Abstract

Objective of this study is to develop a scaling method that produces scaled ice accretions over a range of test conditions and to validate it for icing wind tunnel tests. A method for size and test-condition scaling that is based on similitudes of geometry, flow field, droplet trajectory, water catch, energy balance and surface water dynamics is validated using ANSYS® Fluent 18.0 CFD tool and icing code FENSAP-ICE. The ice shapes obtained are verified with experimental data and the scaling method is tested for several Appendix-C conditions. Comparisons of the reference and scaled results show agreement.

Nomenclature

A_c	accumulation parameter, dimensionless
AOA	angle of attack, °
b	relative heat factor, dimensionless
c	airfoil chord, m
$c_{p,a}$	constant-pressure specific heat of air, cal/g K
$c_{p,ws}$	specific heat of water on model surface, cal/g K
D_v	diffusivity of water vapor in air, m^2/s
h_c	convective heat transfer coefficient, cal/ hr m^2 K
h_G	gas-phase mass transfer coefficient, g/m^2s
k	thermal conductivity, cal/ hr m K
K	inertia parameter, dimensionless
K_0	modified inertia parameter, dimensionless
L	characteristic length, m
LWC	liquid water content, g/m^3
M	Mach number, dimensionless
MVD	median volumetric diameter, µm
n	freezing fraction, dimensionless
n_0	freezing fraction at stagnation, dimensionless
P	pressure, Pa
P_w	vapor pressure of water over liquid water, Pa
P_{ww}	vapor pressure of water in the atmosphere, Pa
R_a	gas constant for air, N m/g K
Re	Reynolds number, dimensionless
T	static temperature, K
t_{exp}	icing time, s
V	free-stream velocity, m/s
We	Weber number, dimensionless
α	angle of attack, °
β	catch efficiency, dimensionless
β_0	catch efficiency at stagnation, dimensionless
γ	ratio of specific heats for air, 1.4

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θ	air energy transfer parameter, K
$\frac{\lambda}{\lambda_{Stokes}}$	drop range parameter, dimensionless
μ	viscosity, Pa s
ρ	density, kg/m^3
Λ_f	latent heat of freezing, cal/g
Λ_v	latent heat of sublimation, cal/g
σ_{wa}	surface tension of water against air, N/m
Φ	drop energy transfer parameter, K

Subscripts:

0	stagnation value
a	air
f	at the freezing point of water
R	reference conditions
s	at the surface
S	scale conditions
st	static
tot	total
w	water
δ	droplet

1. Introduction

Icing is one of the most dangerous hazards to be encountered by air vehicles in flight. The formation of ice on aircraft surfaces occurs during flight through supercooled droplets. Supercooling is the state in which water exists in liquid state at temperatures below 0°C. Cloud droplets may freeze instantaneously and form rime ice or run downstream and freeze later forming glaze ice structure. Ice accretion, particularly on control surfaces, wings and flight data sensors usually degrades both performance and operational safety of air vehicles. Thus, it has become important in the design and certification phases of system development to evaluate performance degradation because of icing. Test methods for evaluating the performance characteristics of aircraft in icing conditions are flight tests in natural icing conditions, simulated clouds produced by icing tankers and ground testing in icing wind tunnels. Icing wind tunnel testing is the most convenient method considering feasibility, cost and safety. However, when full-size model is too large for a given facility or when the desired test conditions are out of the operating capability of the facility, a scaling method that produces scaled ice accretions over a wide range of test conditions and that can be applied to a variety of icing testing situations is needed. The scaling method shall be validated before the icing wind tunnel testing for reliability and validity of the tests. This work illustrates a scaling method for size scaling and test-condition scaling that is based on similitudes of geometry, flow field, droplet trajectory, water catch, energy balance and surface water dynamics, [1, 2]. Icing analyses are performed for full-size and scaled conditions using a CFD tool ANSYS® Fluent 18.0 and in-flight icing code FENSAP-ICE. The ice accretions obtained by analyses are verified with experimental data available in the literature. Furthermore, the scaling method is tested for several Appendix-C icing conditions, especially at higher velocities compared to those currently present in the literature.

2. Icing similitude analysis

For in flight icing to occur, supercooled droplets must be present and ambient temperature must be below 0°C. Droplets may freeze instantaneously after impingement and form rime ice or some of the impinging droplets may freeze and some may run downstream and freeze later forming glaze ice. The freezing fraction is the ratio of the amount of water that freezes at impingement to the total amount of impinging water. Thus, the freezing fraction is unity for rime ice and it takes a value between 0 and 1 for glaze ice. The icing type changes the characteristics of ice formation and final ice shape. Rime ice is a dry, opaque ice which usually forms at low airspeed, low temperatures and low liquid water content icing environments, while glaze ice is a wet ice which forms at temperatures around 0°C, and high liquid water content icing environments.

A scaling method that produces similar ice accretions for scaled model size and/or test conditions requires the similitudes of geometry, flow field, droplet trajectory, water catch, energy balance and surface water dynamics [1, 2].

For rime ice, since all supercooled droplets that contact the surface freeze immediately and there is no water film layer, achieving energy balance and surface water dynamics similitudes is not necessary, first four similitudes are enough to achieve ice accretion similarity for rime ice.

2.1 Geometric similarity

The shape and material of scaled geometry and reference geometry should be similar for similar flow and icing physics.

2.2 Flow field similarity

Flight condition similitude is achieved by matching the Mach Number and Reynolds Number for reference and scaled conditions.

$$M = \frac{V}{\sqrt{\gamma R_a T}} \tag{1}$$

$$Re_a = \frac{V\,L\,\rho_a}{\mu_a} \tag{2}$$

However, matching these simultaneously is not feasible considering that the parameters constituting these numbers also constitute more critical scaling parameters regarding the droplet trajectory and ice accretion. Thus for most scaling analyses matching the Mach Number and Reynolds Number is not aimed. This assumption might be justified considering the fact that in majority of the icing conditions, the Mach number is relatively low and compressibility effects are negligible and ice accretion occurs near the stagnation regions, where the boundary layer is thin and viscous effects are rather small.

Therefore, the similarity of flow field is considered to be achieved when the Mach number and Reynolds number is in the interval of $M@Re = 2x10^5 < M < M_{critical}$ near the stagnation region, [1]. Lower limit corresponds to a Reynolds number that the velocity distribution is preserved up to stall and upper limit corresponds to critical Mach number where the supersonic flow is first seen on the geometry.

2.3 Droplet trajectory similarity

Droplet impingement zones and droplet trajectories should be matched for drop trajectory similitude. Modified inertia parameter, K_0, and collection efficiency, β_0, should be matched for droplet trajectory similarity.

$$K_{0,S} = K_{0,R} \tag{3}$$

$$K_0 = \frac{1}{8} + \frac{\lambda}{\lambda_{Stokes}}\left(K - \frac{1}{8}\right) \tag{4}$$

$$K = \frac{\rho_w (MVD)^2 V}{18\,L\,\mu_a} \tag{5}$$

$$\frac{\lambda}{\lambda_{Stokes}} = \frac{1}{0.8388 + 0.001483 Re_\delta + 0.1847\sqrt{Re_\delta}} \tag{6}$$

$$Re_\delta = \frac{V\,MVD\,\rho_a}{\mu_a} \tag{7}$$

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$$\beta_0 = \frac{1.40\left(K_0 - \frac{1}{8}\right)^{0.84}}{1 + 1.40\left(K_0 - \frac{1}{8}\right)^{0.84}} \tag{8}$$

2.4 Water catch similarity

The amount of ice accreted depends on the amount of water that impinges the surface. For ice accretion similitude, water catch parameters should match.

$$A_{c_{,S}} = A_{c_{,R}} \tag{9}$$

$$A_c = \frac{LWC\ V\ t_{exp}}{\rho_i L} \tag{10}$$

2.5 Energy balance similarity

Ice accretion occurs when the supercooled droplets hit the air vehicle surface and freezes immediately or a fraction of them freezes and remainder freeze downstream. For the first case, that is the formation of rime ice, there is no need for energy balance similitude since all impinging water freezes at the instant of impingement, at impinging point.

Ice accretes near stagnation point. Thus, without sacrificing accuracy much, energy balance can be calculated along stagnation line.

The energy balance is required for calculating the ratio of water that hits the surface and freezes, which is defined as freezing factor, n_0. For rime ice the freezing factor is unity. For glaze ice, freezing factor is less than 1, and it is a parameter to be matched for ice accretion similitude.

$$n_{0_{,S}} = n_{0_{,R}} \tag{11}$$

$$n_0 = \left(\frac{c_{p,ws}}{\Lambda_f}\right)\left(\phi + \frac{\theta}{b}\right) \tag{12}$$

$$b = \frac{LWC\ V\ \beta_0\ c_{p,ws}}{h_c} \tag{13}$$

$$\phi = T_f - T_{st} - \frac{V^2}{2c_{p,ws}} \tag{14}$$

$$\theta = T_s - T_{st} - \frac{V^2}{2c_{p,a}} + \frac{h_G}{h_c}\Lambda_v\left(\frac{\frac{P_{ww}}{T_{st}} - \frac{P_{tot}}{T_{tot}}\frac{P_w}{P_{st}}}{\frac{1}{0.622}\frac{P_{tot}}{T_{tot}} - \frac{P_{ww}}{T_{st}}}\right) \tag{15}$$

2.6 Surface-water dynamics similarity

For glaze ice a water film is present. The surface water dynamics affects the accreted ice shape. Weber number for reference and scaled conditions should be matched for surface-water dynamic similarity. The Weber number for characteristic length of the geometry is used for the current study. The characteristic length corresponds to the leading-edge radius which is proportional to the chord.

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$$We_L = \frac{V^2 L \rho_a}{\sigma_{w/a}} \tag{16}$$

3. Methodology

In the analysis, flow field solution, droplet trajectories, accumulation efficiencies and ice accretion are calculated for each flow condition. The cases that have long icing time, are analyzed using multi-shot method that is dividing the icing time into smaller time steps. The solution is updated according to the ice shape formed after each step and the flow is resolved again with the current displaced mesh. This cycle is repeated until the total icing time is reached and the final ice shape is obtained.

3.1 Flow solution

CFD analysis is performed using ANSYS® Fluent v18.0 software. Assumptions and settings during analysis are given below:

- The simplifications required for the designed geometric models are made by using ANSYS Design Modeler v18.0 software and the mesh is created in the ANSYS v18.0 Meshing interface. A denser mesh is applied in the regions where ice accretion is expected.
- Pressure-based Navier-Stokes equations are solved in the Fluent Solver and ideal gas assumption is made.
- The temperature-dependent change of the viscosity of the air is formulated with the Sutherland approach.
- On finite volumes, transport equations are discretized using the second order upwind method.
- k-ω SST is used as the turbulence model.

For all analyses, the pressure and the specified temperature are provided as input to the velocity inlet or pressure-far-field type boundary condition. In addition, Mach number value and air flow direction are given as input to the same boundary condition. The surface is defined as the isothermal wall boundary condition. The use of the isothermal wall boundary condition is required by FENSAP-ICE to calculate heat transfer from the surface of water and ice. In order to make this calculation, it is stated that the surface temperature value should be several degrees above the stagnation temperature of the air and it is recommended in reference [3] to specify the surface temperature value as 10 degrees higher than the total temperature.

3.2 Droplet trajectories and ice formation

Droplet trajectories and ice accretion are calculated with ANSYS FENSAP-ICE software. The assumptions made for the calculations of droplet trajectories and ice formation are as follows:

- The droplet distribution is monodispersed with a diameter of 20 microns.
- Surface roughness is an important parameter for ice formation. Surface roughness values are calculated in the Fluent Solver by NASA correlation. Then beading method is employed in FENSAP-ICE solver [3].

In order for FENSAP-ICE to use surface roughness output provided by Fluent, during the Fluent flow solution, the high roughness (icing) option should be used as the surface roughness model under the wall boundary condition [3]. The NASA correlation method used as a calculation method; characteristic length, free flow rate and temperature, LWC and surface roughness constant (taken as 0.5 according to Reference [3]).

3.3 Similitude Method

Assuming that the geometry and flow similarity are achieved, the droplet trajectory similarity, the similarity of the total mass of liquid water hitting the surface, the energy balance similarity and surface-water dynamics similarity shall be ensured for ice accretion similitude. To provide that, modified inertia parameter (K_0), accumulation efficiency (β_0), accumulation parameter (A_c), freezing rate (n_0), and droplet energy transfer parameter (ϕ) and Weber number (We) are to be matched.

4. Results and discussion

The purpose of the method is to be able to obtain the conditions that can be provided in an icing wind tunnel when the full-scale reference values are not feasible to maintain. Thus, the analyses performed are also chosen to serve this purpose. The main focus is on the size scaling and the velocity scaling considering the constrains of the test sections and limited range of test velocity.

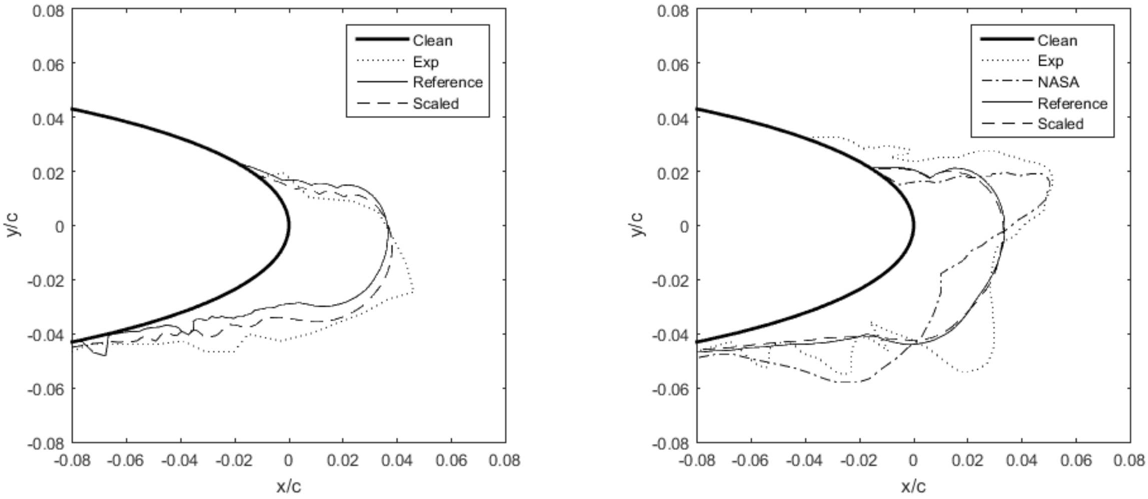
The similitude method is employed for several cases that are present in literature. The resulted ice shapes obtained from the analyses performed by FENSAP-ICE are compared with experimental data in literature for both reference and scaled ice geometries. Size and velocity scaling for rime and glaze ice are performed and agreement of ice accretions and final ice geometries are checked.

The cases given for NACA0012 airfoil are for size scaling. The size is reduced so that the scaled geometry shall be placed in a test section of an icing wind tunnel. The velocity for scaled geometry is increasing to match the surface-water dynamics, Weber number. The MVD and the exposure time decreases to compensate the shrinkage of the geometry and to match the total water catch. The rest of the parameters are balanced by the relations of scaling equations.

Table 1: Scaling conditions for geometry scaling. NACA0012 airfoil; Case 1 at 4° AOA data taken from reference [4] Case 27, Case 2 at 4° AOA data taken from reference [4] Case 34, Case 3 at 0° AOA conditions taken from reference [2] examples of size scaling with Ruff method Case 1.

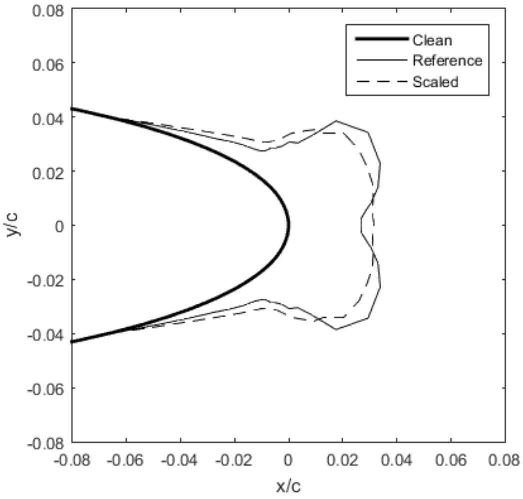
Case	**Type**	**c , m**	**T_{st} , °C**	**V, m/s**	**MVD, μm**	**LWC, g/m3**	**t_{exp} , s**	**K_0**	**β_0, %**	**Ac**	**n_0**	**b**	**Φ, °K**	**θ , °K**	**Re_a, 10^4**	**We_L, 10^6**
1	Ref.	0.530	-28.0	58.10	20.0	1.30	480	1.807	0.684	2.361	1.125	0.555	27.550	34.073	8.39	0.87
	Scaled	0.265	-28.4	82.17	11.4	1.48	150	1.807	0.684	2.361	1.129	0.530	27.550	32.697	5.93	0.87
2	Ref.	0.530	-16.8	93.89	20.0	1.05	372	2.423	0.738	2.388	0.572	0.636	15.705	18.768	12.05	2.27
	Scaled	0.265	-17.8	132.78	11.3	1.01	136	2.423	0.738	2.388	0.572	0.525	15.705	15.489	8.29	2.27
3	Ref.	0.914	-14.6	67.06	40.0	1.00	906	3.351	0.789	2.293	0.503	0.703	14.023	18.110	15.41	15.41
	Scaled	0.267	-15.9	124.16	14.4	1.03	138	3.351	0.789	2.293	0.504	0.552	14.023	14.241	7.81	7.81

The resulting ice shapes for NACA0012 cases are compatible. Especially for the Case 1, rime ice is well predicted by both reference geometry and scaled geometry. For the Case 2, the agreement with experimental and numerical data in literature are satisfying; although the horns are under predicted. The agreement between the reference and scaled ice shapes are acceptable. For Case 3 the agreement between the reference and scaled results are well correlated.



(a) Case 1

(b) Case 2



(c) Case 3

Figure 1: Scaling results for geometry scaling. NACA0012 airfoil; (a) Case 1 at 4° AOA data taken from reference [4] Case 27, (b) Case 2 at 4° AOA data taken from reference [4] Case 34, (c) Case 3 at 0° AOA conditions taken from reference [2] examples of size scaling with Ruff method Case 1.

The cases given for SA13112 airfoil focus on velocity scaling. The velocity is reduced so that the required velocity shall be provided by an icing wind tunnel. The size for scaled geometry is increasing to match the surface-water dynamics, Weber number. The MVD and the exposure time increases to compensate the growth of the geometry and to match the total water catch. The rest of the parameters are balanced by the relations of scaling equations.

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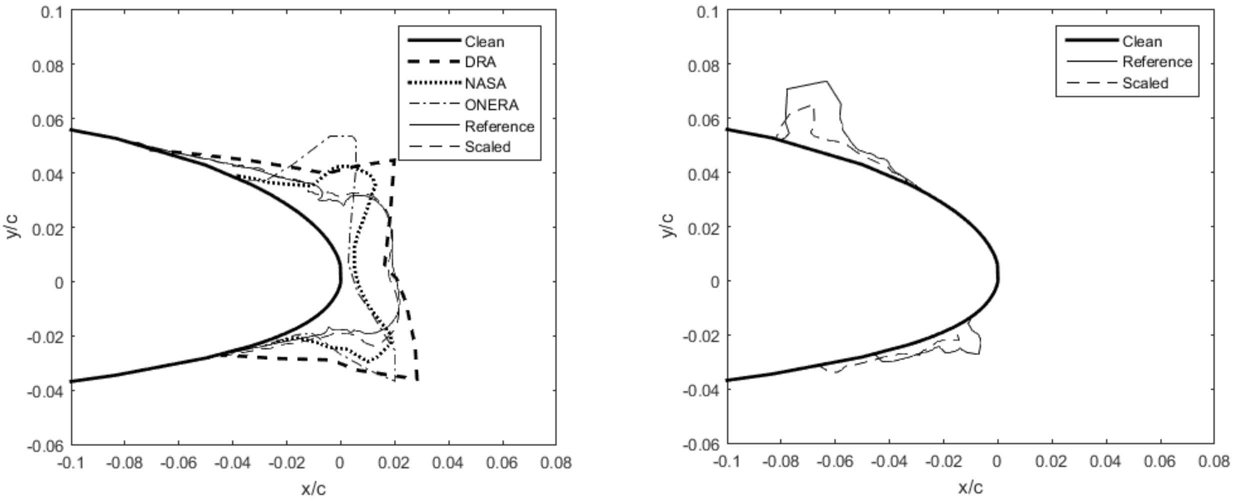
Table 2: Scaling conditions for velocity scaling. SA13112 airfoil; Case 4 at 0° AOA data taken from reference [4] Case 42, Case 5 at 0° AOA.

Case	**Type**	**c , m**	**T_{st} , °C**	**V, m/s**	**MVD, µm**	**LWC, g/m3**	**texp , s**	**K_0**	**β_0, %**	**Ac**	**n_0**	**b**	**Φ, °K**	**θ , °K**	**Re_a, 10^4**	**We_L, 10^6**
4	Ref.	0.600	-30.2	249.90	20.0	0.50	180	3.919	0.811	1.294	0.413	0.610	22.747	6.053	34.53	18.22
	Scaled	1.200	-26.4	176.71	35.7	0.96	266	3.919	0.811	1.294	0.458	1.387	22.747	18.703	48.28	18.22
5	Ref.	0.533	-10.0	243.90	20.0	0.12	900	5.112	0.844	1.705	-1.038	0.176	2.948	-14.915	17.92	15.41
	Scaled	0.800	-7.6	199.08	30.9	0.08	2519	5.111	0.844	1.705	-1.026	0.108	2.948	-9.042	30.63	15.41

The resulting ice shapes for SA13112 cases are also compatible. Especially for the Case 4, rime ice is well predicted by both reference geometry and scaled geometry. For the Case 5 the agreement with experimental and numerical data in literature is satisfying; although the horns are under predicted. The agreement between the reference and scaled ice shapes are acceptable.



(a) Case 4

(b) Case 5

Figure 2: Scaling results for velocity scaling. SA13112 airfoil; (a) Case 4 at 0° AOA data taken from reference [4] Case 42, (b) Case 5 at 0° AOA.

5. Conclusions

This study presents a scaling method and resulting ice geometries obtained by numerical analyses employing the scaling method and comparison of these ice geometries among reference and scaled results evaluating the performance of the method and with experimental and numerical data in literature.

The agreement of resultant ice shapes with experimental data is satisfying but the results of FENSAP-ICE software usually underestimates the ice accretion. Especially for the glaze ice case the horns are more smoothed than the experimental and numerical data in literature. For rime ice cases the agreement of ice shapes is well. Thus, the overall agreement is fair considering the ice accretion limits on geometries and maximum ice thickness.

The scaling method that is outlined will also be checked with an in-house ice accretion prediction tool in order to validate both that computational tool and the current methodology.

The scaling method works well considering the agreement of the results for reference and scaled ice geometries. However, it should be kept in mind that there could be phenomena for 3D case that may disrupt the correlation.

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