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Verification and Validation of NASA LEWICE 2.2 Icing Software Code

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We present in this paper some results on the verification and validation of LEWICE 2.2 icing software code. The validation carried out a detailed analysis of ice accretion under a wide range of icing conditions. We performed a verification of the code options; analyzed and tested the LEWICE 2.2 code to ensure that no changes have been made to the previous validated ice shape simulation capability; and performed grid and time-step size sensitivity analysis, material properties and body dimensions sensitivity analysis, and validation of LEWICE 2.2 using thermal analysis. The validation tests have shown that the program is working properly. It is sending the right error messages; the output results are consistent, and the software is properly modeling the ice growth behavior. For the validation of LEWICE 2.2 using thermal analysis, the results show that the experimental data obtained with thermocouples do not compare well with the results of the numerical prediction. The error on the average temperature is too high (up to 60%) for all of the sections and for both the inside and outside surface.

Nomenclature

C = chord, m
Ma = Mach number
Re = Reynolds number
x = spanwise direction
y = normal direction

I. Introduction

ICE accretion is a phenomenon that takes place in many forms, depending on where it occurs. For example, the accretion of supercooled cloud droplets (liquid water below freezing temperature) leads to ice formation or growth on an aircraft that can affect its performance. To be allowed to fly in icing conditions, an aircraft must have a protection system that minimizes icing effects and enables it to maintain conditions sufficient for flying to the nearest airfield if protection systems fail. When a plane flies through a cloud of supercooled droplets, ice accretion occurs on the front of the wings, tail, and air intakes. Ice deposits can cause significant aerodynamic airfoil degradation or engine extinction as a result of ice ingestion coming from air intakes. To avoid icing, the pilot can employ a de-icing system, which protects against ice, or an anti-icing protection system, which prevents ice formation on the surface depending upon the type of system installed in the aircraft.

Several methods can be used to test the ability of the aircraft to fly under icing conditions: flight tests in icing conditions, icing tunnel studies, or numerical simulations. Two- and three-dimensional numerical codes were developed by NASA in order to simulate ice accretion.[1–6] The codes are used to determine the flowfield around the airfoil, water droplet trajectories, and ice formation and to compute the heat-transfer coefficient. After the computation of ice deposit on a profile, a de-icing or an electrothermal anti-icing system can be simulated.

NASA has developed a robust software code called LEWICE 2.0 to study ice formation and growth.[7] This code can reproduce results accurately for various spacing and time-step criteria across a computing platform.[8] LEWICE 2.0 is an ice-accretion prediction code that applies a time-stepping procedure to calculate the shape of an ice accretion. This code has been supported and maintained by the NASA Glenn Research Center.[9] A summary of the validation results of LEWICE 2.0 was presented by W. B. Wright.[8] The results show a comparison between LEWICE 2.0 and averaged experimental ice shape data as well as the comparison of individual experimental ice shapes against the averaged data. Spanwise variability and repeatability variability are presented as well as the variability caused by the technique used to trace the ice shape. The results of this comparison show the difference between the predicted ice shape from LEWICE 2.0, and the average of the experimental data was 7.2% while the variability of the experimental data was 2.5%. An investigation was also conducted by Riley and McDowal,[10] to study the effect of the number of time steps used by the ice-accretion code of LEWICE 2.0 in determining the ice shape. The investigation included a study of the LEWICE 2.0 validation database and approximately 30 additional LEWICE 2.0 runs. They tested the software code with constant time steps and also by using the automatic time-stepping feature. It was found that the accuracy of LEWICE 2.0 ice shapes does not improve when the time step is increased beyond a certain value. The authors recommended that LEWICE 2.0 users be warned against inputting too large a number of time steps.

Recently, NASA has developed a new version (LEWICE 2.2) of the icing software code. This version extends version 2.0 to include thermal analysis of anti- and de-icing systems. The thermal protection system simulation approach uses the LEWICE model for flowfield and trajectories and a two-dimensional unsteady heat-transfer model. The software features include composite body structures; electrothermal heater sequences with different power to each heater; gaps between heaters; a hot-gas anti-icing system; prediction of ice accretion, shedding, melting and refreezing; and water runback on surface.

The LEWICE 2.2 is a computer code written in FORTRAN 77 that runs on personal computers and Unix machines. The code determines the amount and shape of ice that will accumulate on a user-supplied geometric body, given the aerodynamic and cloud conditions specified by the user. The code has five modules: a potential flow aerodynamic calculation, a Lagrangian water droplet trajectory calculation, a lumped analysis control volume-based mass and energy balance, a routine that recalculates the geometry based on the amount of ice frozen for a given time step, and a finite difference heat-conduction calculation for the thermal analysis of anti- or de-icing. Testing and validating the LEWICE 2.2 software code are

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needed because of the new changes and capabilities added to the program.

The principal objective of this study is to verify and validate the ability of the LEWICE 2.2 code to perform the calculation specified accurately. The validation should carry out a detailed analysis of ice accretion under a wider range of icing conditions. The goal is to verify that the LEWICE 2.2 code operates in a reliable manner by performing the following activities:

1) The first is verification of code options: check and exercise each available input the software system will receive; all outputs the software system will produce; all functions the software system will perform; all performance requirements the software will meet (reliability, timing, etc.); the definition of all internal, external, and user interfaces; and all ranges, limits, defaults, and specific values the software will accept.

2) The second is verification of icing case: analyze and test the LEWICE 2.2 code to ensure that no changes have been made to the previous validated ice shape simulation capability (LEWICE 2.0).

3) Grid and time-step size sensitivity analysis is the third activity: study the sensitivity of the solution generated by LEWICE 2.2 to grid spacing and time-step size.

4) The fourth activity is parametric studies: study the sensitivity of the software to the difference in material properties and body dimensions.

5) The last is validation: conduct a thermal analysis study with LEWICE 2.2 using a set of 50 input conditions and comparison with experimental data

II. LEWICE 2.2 Software Code

The first step in the prediction using LEWICE 2.2 is the determination of the location, size, and shape of the ice that will form on the surface of interest. The computer code uses an analytical ice-accretion model that evaluates the thermodynamics of the freezing process that occurs when supercooled droplets impinge on a body. The atmospheric parameters of temperature, pressure, and velocity, and meteorological parameters of liquid water, droplet diameter, and relative humidity are specified and used to determine the shape of ice accretion.

The code has four major modules: 1) flowfield calculation, 2) the particle trajectory and impingement calculation, 3) the thermodynamic and ice growth calculation, and 4) the modification of the current geometry by adding the ice growth to it. The thermal module of LEWICE 2.2 can model any numbers of heaters, any heater chordwise length, and any heater gap desired. The heaters can be fired at the same time or can be cycled with periods independent of each other. The heater intensity can also be varied. In addition the user can specify any number of layers and thickness depthwise into the airfoil. There is a maximum flexibility in modeling virtually any electrothermal de-icer installed into the airfoil. In addition, the software code can also model a bleed of air that is temperature controlled.

The input information needed for the prediction of ice accretion and thermal analysis is as follows:

1) The main input file includes information about the time step, total time of icing, number of bodies to be simulated, the minimum size of control volume, the number of particle trajectories, density of water droplet, the particle size and distribution, and volume fraction of total liquid water contained in each drop size.

2) The meteorological and flight conditions file includes information about the chord, angle of attack, ambient velocity, liquid water contain in the air, ambient static temperature, pressure, and relative humidity.

3) The geometry input file contains (x, y) coordinate pair for the body geometry. A separate input file must be provided for each body being simulated.

4) The de-icer input file for thermal analysis is divided into five sections: a) description of the de-icer internal geometry and physical properties—number of layers in the y direction, number of heater sections in the x direction, the number of points in the layer and for each section, thickness of the layer and width of the section, thermal conductivity and thermal diffusivity, the anisotropy ratio, slope of thermal conductivity with temperature; b) definition of heater power and cycle time—heater on and off time or heater on and off temperature and the heater power; c) definition of boundary conditions—outside, inside, left or right boundaries, temperature, heat-transfer coefficients and wall heat fluxes at the four boundaries; d) definition of various flags that control different features; and e) time-step and input/output conditions—variable that are used to control the de-icer time step and the convergence of the solution. For the de-icing input file, the number of layers and sections is limited to 29, and the total number of points in the normal direction is limited to 290 points. There are two types of heater modes: 1) the heater can be given a specific wattage (kW/m^2), an ON time (s), an OFF time (s), and LAG time (s); and 2) temperature controlled, where in this mode we need to supply an initial wattage, an ON temperature, an OFF temperature, and the layer number that is used to control the heaters. The heater can be controlled by surface temperature instead of the heater temperature desired. The temperature-controlled heaters modeled in the software do not necessarily determine the optimum heat flux. Initially, it uses the wattages input until the temperature exceeds the ON temperature. It then turns off all heat until the temperature drops below the OFF temperature. Heat is then turned on, but at lower wattage. This process continues until the simulation time is reached. If the simulation time is sufficiently long and the wattage has not changed for a long time, then the wattage reported can be close to the optimum heat flux. Three models can be used for anti-icing and de-icing systems:

1) The first model is a one-dimensional steady-state anti-icer that can be run to generate an estimate of the heat required to keep the surface of the body free of ice based on an input surface temperature or based on an assumption that all of the impinging water evaporates. This can be achieved by supplying bleed air from a compressor or by supplying heat from an electrothermal heart pad inside the body geometry using one-dimensional steady-state heat-transfer analysis. Electrothermal pad can be used for either anti icing or de-icing system. Heaters are installed beneath the skin of the wing surface surrounding the leading edge. Thermal energy of the form of conduction heat destroys the adhesion force at the ice surface interface. Aerodynamic forces then sweep the ice from the surface. If enough heat is supplied, the water will not freeze on the surface, creating anti-icing conditions. The one-dimensional steady-state model for anti-icing systems produces an approximate solution. The surface temperature and heat-fluxes predictions are reasonable, but the heater and hot air temperatures are much higher than actual. The solution generated can be used as starting point for de-icing or anti-icing models.

2) The second model can be used to analyze two-dimensional transient icing with heater input. The model uses a standard heat-transfer coefficients assuming an ice-roughened surface. The boundary layer will turn turbulent because of the ice-roughened surface. This option is often preferable for de-icing simulation where significant ice is formed on the airfoil. This model is recommended for failed thermal cases with significant ice accretion.

3) The third model is also used to analyze two-dimensional transient icing with heater input, but the analysis performed uses a laminar heat-transfer coefficient that assumes a clean surface. This option is often preferable for de-icing simulation for cases that generate a small ice shape. This model provides better prediction for cases with clean leading edges; however, it is less conservative and has a tendency to overpredict temperatures for some cases. This model is used to calculate the temperature on a two-dimensional grid inside the body geometry using a given amount of heat from an electrothermal heater pad inside the body geometry. The equations for the temperature are discretized in two-dimensional grid with implicit central differencing (second-order accuracy of Taylor series) in the spatial direction and first order differencing in time. The internal geometry is defined using rectangular blocks in the computational domain. Each blocks contains grid spacing in the warp direction and the normal direction. The number of points defines the grid spacing in the normal direction for that layer. Each section will have the same grid spacing in the in the normal direction for a given layer.

Table 1 Input data ranges

Variable	Range
Time	2 to 45 min (120–2700 s)
C	13.9 to 78 in. (0.35–1.98 m)
AOA	−4 to 7 deg
VINF	56 to 146 m/s
Re	2.26 10^6 to 1.3 10^7
Ma	0.17 to 0.45
LWC	0.31 to 1.8 g/m^3
MVD	15 to 270 μm (15 10^{-6} to 270 10^{-6} m)
TINFS	−25.3°F to 26.7°F (−31.8 to −2.94°C)
TINFT	−15°F to 33°F (−26.11 to 0.55°C)

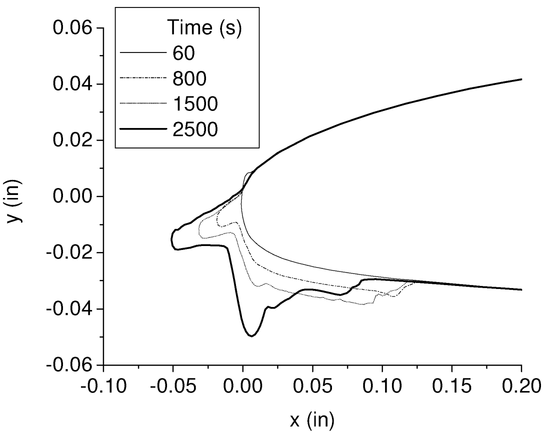

Fig. 1 Final ice shape for different total time of icing.

The output files from LEWICE 2.2 include information about the collection efficiency, ice density, ice shape, potential flow solution, mass fraction, mass flux, surface temperature output from the energy balance, and (x, y) droplet trajectories.

III. Results and Discussion

We present in this paper some results on the verification and validation of LEWICE 2.2 icing software code. For the verification of code options, we checked and exercised each available input the software system will receive; all outputs the software system will produce; all functions the software system will perform; all performance requirements the software will meet (reliability and timing); the definition of all internal, external, and user interfaces; and all ranges, limits, and specific values the software will accept. We checked the input files needed for ice-accretion prediction and the output files obtained using LEWICE 2.2. We checked and exercised each available input the software system will receive, the default input values, the main output files the software system will produce, and the warning error messages the software will send. For example, the error messages are obtained when the file is not typed correctly or is not in the directory, when the name list is out of order or missing, and input conditions are out of range. For the out-of-range tests, we checked if LEWICE 2.2 would produce data outside the input date ranges (see Table 1) and the kind of warnings that would be generated. We tested cases with different parameter out of ranges such as the total icing time (Time), size of control volume (DSMN), number of particle trajectories (NPL), size of water droplet (DPD), chord (C), angle of attack (AOA), flight speed (VINF), and ambient static temperature (TINFS). The program was working properly and was sending the right errors.

We checked also the functionality of the code and the consistency of the output results by changing the input conditions such as the time of icing, the water droplet size, and ambient temperature. The output results were consistent, and the software code LEWICE 2.2 was properly modeling the ice growth behavior. For example, by increasing the time of icing (see Fig. 1) or the size of the droplet or by decreasing the ambient temperature, the ice thickness increases.

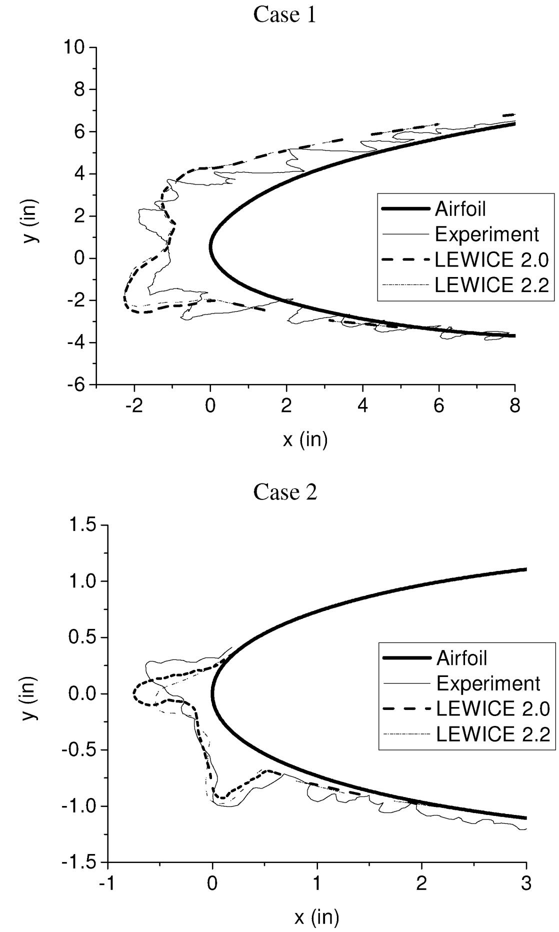

Fig. 2 Validation of ice shape simulation capability of LEWICE 2.2.

We tested the effect of bypassing the recommended operations procedures on the data. For example, we have bypassed the recommended operating procedure of LEWICE 2.2 by decreasing or increasing the point spacing past the recommended limits ($4 \times 10^{-4} < \mathrm{DSMN} < 8 \times 10^{-4}$). The effect on the ice shape prediction caused by an increase of point spacing ($\mathrm{DSMN} = 12 \times 10^{-4}$) is not big, but the difference is bigger with low point spacing ($\mathrm{DSMN} = 2 \times 10^{-4}$). The user should not choose point spacing out of the recommended limits.

For the ice shape validation, we checked and tested the code to ensure that no changes have been made to its previous validated ice shape simulation capability. We ran 200 cases using LEWICE 2.2 and LEWICE 2.0 for ice shape validation. The output results were compared to those obtained by LEWICE 2.0 and experimental data for the same input conditions. NASA has provided the input conditions, the geometry, and the experimental data for each case for the validation of ice shape. Seven different geometries have been used for this validation: 23014MOD, 4415MOD, NACA0012, NACA0015, NLF414, GLC305, and LTHS. Figure 2 shows comparison of the final ice shape for two cases obtained in the NASA Glenn Research Center wind tunnel (experiment) and predicted by LEWICE 2.0 and LEWICE 2.2. The results show a good agreement between the numerical and experimental data. The predicted ice shapes were obtained using a set of approximately 20 input conditions. The main input conditions for these two cases are summarized in Table 2. In general, the ice shape obtained with LEWICE 2.2 shows a small difference with the previously validated ice shape simulation capability. The difference between the two results depends on the input conditions and the body geometry used.

For the validation of thermal performance of LEWICE 2.2, we tested 100 cases using thermal analysis. We tested cases with different heater power level, heater zone on/off time, tunnel conditions or icing conditions, and de-icer models (de-ice, evaporative, and running wet). A comparison between the experimental data and the data obtained by the computer code LEWICE 2.2 is presented. The comparison included the outside and inside surface temperature at seven different sections (A, B, C, D, E, F, and G) for each time step and the average temperature difference. The sections A–G correspond to the positions of the heaters in the x direction. Section A is at the leading edge (parting strip); sections B and C are adjacent chordwise to section A, with B on the lower surface and C on the upper part of the airfoil; sections D and E are, respectively, adjacent to B and C; and sections F and G are, respectively, adjacent to D and E. Figures 3 and 4 show typical results of the predicted (with LEWICE 2.2) and experimental data of the outside and inside surface temperature of the airfoil for sections A and F. The de-icer input conditions for this case are summarized in Tables 3 and 4. The number of layers in the y direction is seven, and the ice is on the top of the airfoil. The number of heater sections in the x direction is seven (A to G). The heater level is between 12 and 16 W/in^2, and the on/off times are respectively 10 and 110 s. The two-dimensional transient icing model with laminar heat-transfer coefficient was used for this case. For the heater A, the results show an overprediction of the experiment results for both the inside and outside surfaces. The laminar heat-transfer coefficient assumes a clean surface or small ice shape. This overprediction is the result of the laminar assumption or the change in the heat-transfer coefficient caused by the evaporation of water above and beyond that which is already modeled. The predicted outside surface temperature compares well with the experiment results when the heater F turns on but does not show the correct cooling cycle for heater F after it turns off (see Fig. 4). This difference is attributed to the method by which LEWICE models shedding and runback water. The errors between the measured and predicted average temperature for all of the sections and for the inside and outside surfaces are shown in Fig. 5. The maximum error for the inside surface is about 30% and located on section C, and for the outside surface is about 49% and located on section D. The errors of the average temperature for the inside and outside surfaces and for all of the cases (3B to 91B) tested in this study are summarized in Figs. 6 and 7. For all of these cases the two-dimensional transient icing model with laminar heat-transfer coefficient was used. Either the icing parameters or the electrothermal ice protection system parameters have been changed from one case to another. Not

Table 2 Input conditions for the validation of ice shape

Variable	Case 1	Case 2
Time, s	360	690
IFLO[a]	6	11
DSMN	410^{-4}	410^{-4}
NPL	24	24
FLWC[b]	1	1
DPD, μm	20	20
C, m	4.5	0.534
AOA	4.5	3.5
VINF, m/s	90	102.8
LWC[c]	0.540	0.34
TINF, K	268.30	265.37
PINF[d]	10^5	10^5
RH[e]	100	100
Body geometry	4415MOD	NACA0012

[a]IFLO = time step for ice accretion. [b]FLWC = volume fraction of the total liquid water. [c]LWC = liquid water content of the air. [d]PINF = ambient static pressure. [e]RH = relative humidity.

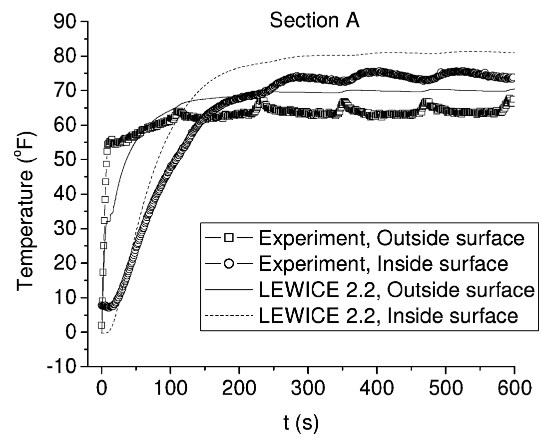

Fig. 3 Predicted and measured inside and outside temperatures for section A.

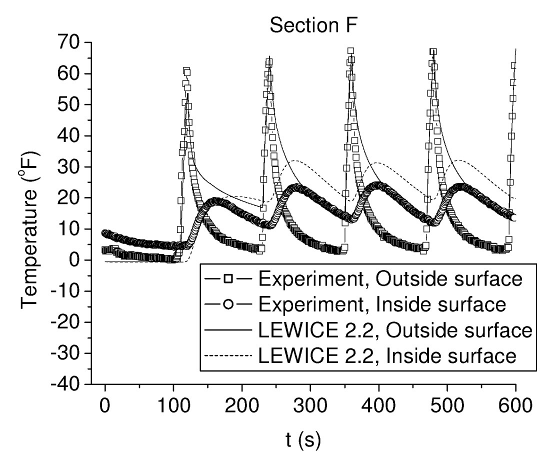

Fig. 4 Predicted and measured inside and outside temperatures for section F.

Table 3 De-icer input conditions

Variable	Substrate layer	Insulation layer	Insulation layer	Heater layer	Insulation layer	Abrasion shield layer	Ice layer
Number of nodes	15	8	18	7	18	8	21
Length, m	3.4310^{-3}	8.910^{-4}	2.810^{-4}	1.310^{-5}	2.810^{-4}	2.0310^{-4}	2.5410^{-3}
Conductivity, W/m.K	0.12	0.294	0.256	41	0.256	16.270	2.232
Diffusivity, m^2/s	1.65210^{-7}	1.04510^{-7}	1.4710^{-7}	1.1910^{-5}	1.4710^{-7}	4.0310^{-6}	1.1510^{-6}

Table 4 Title

Variable	Sec. A	Sec. B	Sec. C	Sec. D	Sec. E	Sec. F	Sec. G
Heater level, W/in.^{2}	12	16	16	15	15	15	15
Heater on/off time, s	10/110	10/110	10/110	10/110	10/110	10/110	10/110
Length, m	0.0254	0.01905	0.0254	0.0254	0.03175	0.0254	0.914
Conductivity, W/m.K	41	41	41	41	41	41	0.256
Diffusivity, m^2/s	1.19410^{-5}	1.19410^{-5}	1.19410^{-5}	1.19410^{-5}	1.19410^{-5}	1.19410^{-5}	1.6310^{-7}
Number of nodes	21	36	21	21	14	21	10

Table 5 Number of points at each section

Cases	NpS1	NpS2	NpS3	NpS4	NpS5	NpS6	NpS7	NpS8	NpS9	NpSt
1	05	06	12	12	15	09	09	07	04	79
2	10	14	21	21	36	21	21	14	10	168
3	20	25	36	36	50	37	37	24	22	287

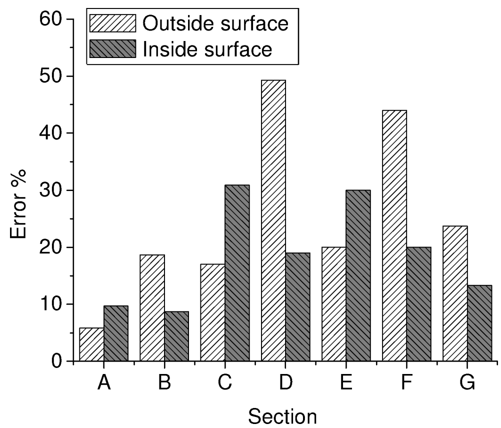

Fig. 5 Error of the average temperature for all of the sections.

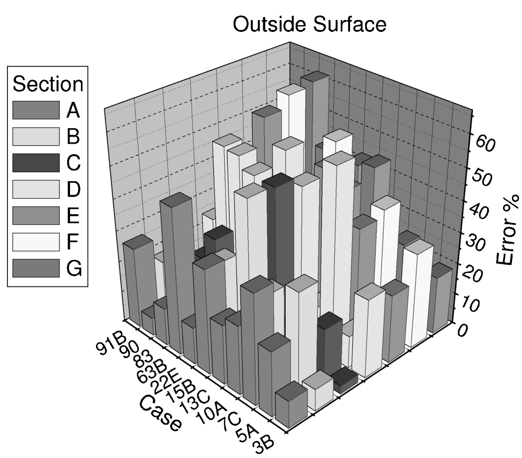

Fig. 6 Error of the average temperature at the outside surface.

all of these cases overpredict the experimental results even though they all used a laminar heat-transfer coefficient. There could be many factors that could cause this difference: 1) discrepancies between the actual and predicted heat-transfer coefficients, 2) improper modeling of the shedding/runback, and 3) effect of icing parameters such as the total ambient temperature. The errors of the average temperature for the inside and outside surfaces and for all of the cases are summarized in Figs. 6 and 7. The results show that the experimental data obtained with thermocouple do not compare well with the results of the numerical prediction using LEWICE 2.2. The error on the average temperature can reach up to 45 and 60% respectively for the inside and outside surfaces. The de-icing and anti-icing capabilities of LEWICE 2.2 are not performing the calculation accurately.

We also tested in this study the sensitivity of the solution generated by LEWICE 2.2 to grid spacing, time step, material properties, and body dimensions. For the grid spacing, we tested cases with the following 1) the number of layers for the body geometry is kept constant, and only the number of points in the normal direction for each layer has been changed; and 2) number of sections is kept constant, and only the number of points in the x direction for each section has been changed. Figure 8 shows a typical result of the temperature predicted in the middle of section 5 and at the top of layer 6. For this case the number of sections (9) is kept constant,

Table 6 Material properties for layer 6

Case	Material for layer 6	Conductivity, W/m/K	Diffusivity, m^2/s
1	Insulation	0.256	1.47×10^{-7}
2	Abrasion shield	16.27	4.03×10^{-6}
3	Abrasion shield	102	7.33×10^{-5}
4	Substrate (Al)	176.53	4.26×10^{-5}

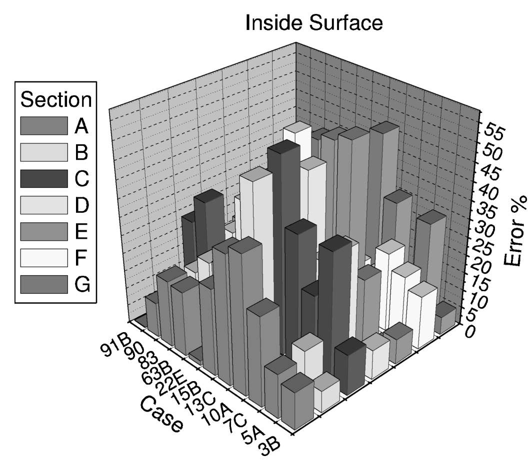

Fig. 7 Error of the average temperature at the inside surface.

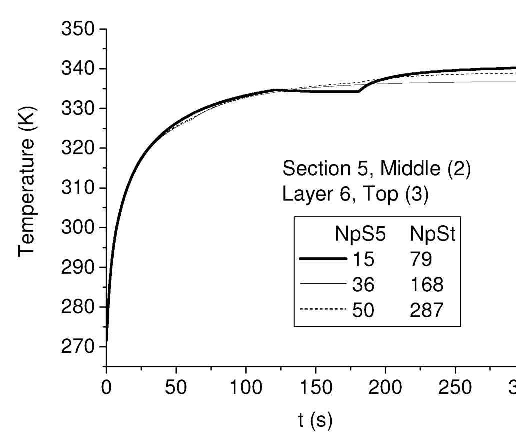

Fig. 8 Effect of grid spacing in x direction on the predicted temperature.

and only the numbers of nodes or points for each sections has been changed as shown in Table 5. For example, the number of nodes for section 5 has been changed from 15 to 50. The results of the tests show that the effect of grid spacing in the x and y directions on the predicted temperature is small or negligible. For time-step sensitivity analysis, the icing time step is kept constant, and only the de-icing time step has been changed. The de-icing time step is very small compared to the icing time step. Figure 9 shows the predicted temperature at the middle of section 4 and at the top of layer 6 with a de-icing time step (DTAUI) of 0.05, 0.1, 0.5, and 1 s. The results show that the error is very small (less than 3%). Also the effect of grid spacing and time step on the final ice shape is negligible. For the body geometry sensitivity test, we performed parametric studies using several body dimensions to assess the sensitivity of

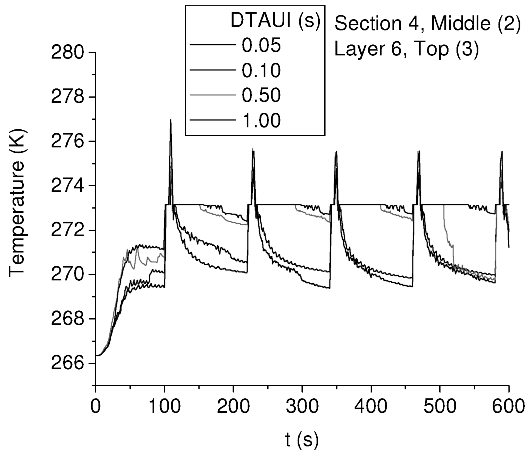

Fig. 9 Effect of de-icing time step on the predicted temperature.

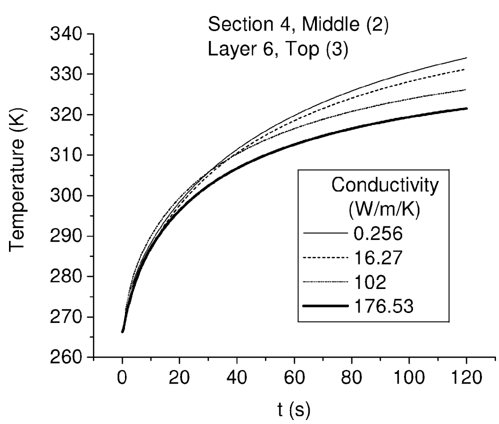

Fig. 10 Effect of material properties on the predicted temperature.

the software code to differences in body size (chord). For example, we tested one case where the value of the chord has been changed from 0.35 to 2.20 m. The effect of the body size or the chord on temperature for the heaters C, E, and D was negligible, but for heater A the error was about 8% between the low and high value of the chord. We also performed some tests to assess the sensitivity of the software code to differences in material properties (conductivity, diffusivity) as shown in Table 6. The results show no effect of the material properties on the final ice shape and a small difference (4%) on the predicted temperature (see Fig. 10).

IV. Conclusions

A verification and validation of LEWICE 2.2 icing software code was performed in this study. The tests included the verification of the code options; verification and validation of ice-accretion capability; grid and time step, body geometry and material properties sensitivity analysis; and the validation of the thermal performance of LEWICE2.2. The icing software code LEWICE 2.2 has been tested for hundreds of cases with different icing conditions and electrothermal ice protection system parameters. The software code LEWICE 2.2 is generally performing well for ice shape prediction, but it is not performing the calculation specified accurately for de-icing system. For the de-icing system, the two-dimensional transient icing model with laminar heat-transfer coefficient was used. The results obtained in this study show a difference between the predicted temperature using this model and those obtained experimentally using thermocouples. This difference can be explained by the discrepancies between the actual and predicted heat-transfer coefficients, improper modeling of the shedding/runback, and the effect of icing parameters such as the total ambient temperature. The thermal analysis shows a substantial difference between the mean temperatures measured and predicted by LEWICE 2.2. To improve the thermal capabilities of LEWICE 2.2, there is a need to improve the prediction of the heat-transfer coefficient and the criteria for water runback and ice/water shedding and to perform additional tests with more combinations of icing parameters and electro thermal ice protection system parameters.

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