CONVECTIVE HEAT TRANSFER EFFECTS IN AIRFOIL ICING

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Abstract. *Various classic icing codes have been developed and used by the aircraft manufacturers to predict the ice shapes evolution. These codes apply boundary layer integral analysis, based upon sand grain roughness, to estimate the convective heat transfer coefficient around the iced airfoil and uses abrupt transition between laminar and turbulent flow. In the present work, besides the integral analysis a smooth laminar-turbulent transition model, based upon the intermittency concept, is included. The transition onset position is either estimated by classical empirical correlations or simply imposed. The smooth transition model is included in the ONERA2D numerical code to predict ice shapes. The ice accretion on a NACA 0012 airfoil is simulated with the modified code and the results are compared to the ice shapes generated by ONERA2D original code and to experimental data. In addition, both the laminar-turbulent transition onset position and extension and sand grain roughness variation effects on the ice geometry are presented.*

Keywords: *aircraft icing, ice accretion, convective heat transfer, laminar-turbulent transition*

1. INTRODUCTION

The ice accretion on aircraft wings and stabilizers may cause aerodynamic performance degradation, weight increase, control and maneuver difficulties that may lead to an operational safety margin reduction. When the aircraft is flying through a supercooled water droplets cloud, which is in a meta-stable thermodynamic equilibrium, the ice accretion on some aerodynamic surfaces will occur if they are not adequately protected. In order to protect the airfoils and guarantee safe flight in icing conditions, commercial and some military aircraft have ice protection systems. An icing numerical tool may be used for wing or stabilizers design and ice protection system failure effects analysis. In addition, it is an important tool to help engineers decide whether the airfoils must be protected.

Convective heat transfer is important at glaze ice formation conditions, when liquid water is near freezing, because the heat convection is the main mechanism to remove the solidification enthalpy. On the other hand, convection has little influence when temperatures are far below freezing temperatures, since rime ice forms instantaneously as the droplets impact on the airfoil. Gent et al. (2000) pointed out that heat transfer coefficient is the most important and difficult parameter for accurate glaze ice shape prediction.

In the aerospace icing community, the mostly used heat transfer calculation procedure is the integral boundary-layer analysis based on sand grain roughness height k_s and abrupt laminar-turbulent transition. However, the k_s concept has some limitations, when applied to external boundary-layers, because it results from experimental data of flows inside rough pipes. In addition, there are experimental evidences (Havugimana et al., 2002; Kerho and Bragg, 1997; Pimenta, 1975) that sand grain-type integral analysis does not satisfactorily estimate the heat and momentum transfer of flows over rough surfaces. Another reason to revisit airfoil icing heat transfer derives from previous works about airfoil thermal anti-ice simulation, which were carried-out firstly by Silva (2002), summarized by Silva and Silvares (2002), published by Silva et al. (2003, 2005) and recently extended by Silva et al. (2006, 2007a,b). The main conclusions of which are the following: 1) the boundary-layer integral analysis can provide satisfactory results if its assumptions are reviewed and limitations are considered; 2) the laminar-turbulent transition affects the heat and mass transfer significantly and an abrupt transition may not represent the real phenomenum.

2. PREVIOUS WORKS

According to Pimenta (1975), the turbulent heat transfer over rough surfaces may depend on roughness size, shape and distribution. However, most classic works tried to identify the surfaces and to describe its performance with a single general parameter. The friction results of rough pipe flows have usually been extended to boundary-layer flows over plates. Basically, this was the approach of *Schlichting* and *Prandtl* in 1934 (Pimenta, 1975) when they conceived the sand grain roughness k_s concept. In sum, the k_s value can be a fraction of the actual roughness height because it must also represent the effects of roughness shape and distribution.

Some authors performed rough pipe flows experiments and proposed two-layer models to predict heat transfer: 1) the first layer is very thin, close to the wall and concentrates all the effects caused by the protuberances presence; 2) the second is located above the first and behaves as a "fully turbulent layer". These authors assumed Reynolds analogy validity, turbulent Prandtl number Pr_{turb} value or eddy-diffusivity distribution in order to match both layers. This procedure is applied by Dipperey and Sabersky (1963); Owen and Thomson (1963); and this approach is frequently used in icing literature.

Makkonnen (1985) proposed a calculation procedure for laminar, transitional and turbulent heat transfer between external flow and the rough surface of an iced cylinder. The author implemented a laminar boundary-layer conduction thickness Δ_4 evaluation with Smith and Spalding (1958) model. The turbulent Stanton number St_{turb} requires the friction coefficient C_f, which is obtained from momentum thickness $\delta_{2,turb}$, plus turbulent Prandtl number Pr_{turb} and experimental parameters. Therefore, the turbulent heat transfer coefficient h_{turb} evaluation is based on fully rough law of the wall, two layer model with empirical adjustments and sand-grain definition (Dipperey and Sabersky, 1963; Kays and Crawford, 1993; Owen and Thomson, 1963). Both laminar h_{lam} and turbulent h_{turb} coefficients are evaluated by the analogy between momentum and heat transfer, which assumes flow over a near isothermal surface without mass transfer. Makkonnen (1985) assumed the occurrence of an abrupt laminar-turbulent transition and that the momentum thickness has no discontinuity at transition point.

Based on experimental observations, Pimenta (1975) proposed a law of the wall and a mixing-length turbulence model to be used in finite difference boundary-layer code. The author noticed that the mixing-length theory results were closer to experimental data than classical correlations or integral methods to estimate the effect of roughness and transpiration on the turbulent flow and heat transfer.

Cebeci (1987, 1989) applied his own finite difference boundary-layer code to improve the heat and mass transfer prediction around airfoils contaminated by liquid water or ice. The *Cebeci-Smith* mixing-length turbulence model was adjusted to represent the flow over roughness. Shin et al. (1992) validated the turbulence model.

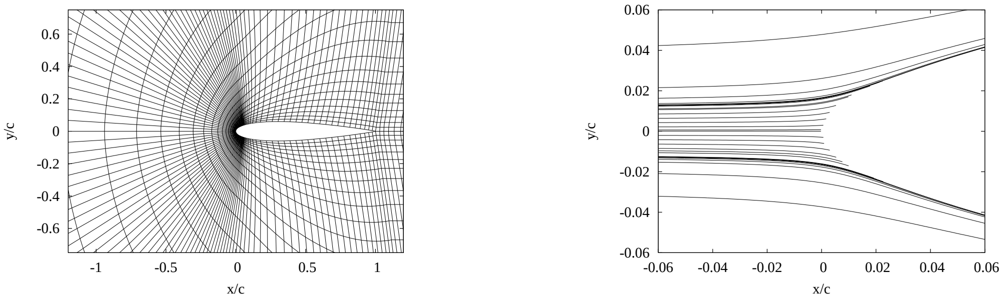
Havugimana et al. (2002) compared the skin friction and heat transfer over rough plates to some literature experimental data. The authors used a modified *Cebeci-Smith* mixing-length turbulence model that considered sand grain and discrete element roughness models. They concluded that classical boundary-layer integral analysis predicts the heat transfer when compared to experimental data and their results.

The classic icing codes LEWICE (Macarthur et al., 1982), TRAJICE2 (Cansdale and Gent, 1983) and ONERA2D (Guffond and Brunet, 1988) estimate ice shapes over non-protected airfoil surfaces. A comprehensive review of the mathematical models and a comparison of these codes prediction capabilities were published by Wright et al. (1997).

At British Royal Aircraft Establishment, Cansdale and Gent (1983) implemented one of the pioneering works regarding thermal balance around non-heated airfoils, under icing conditions, by extending Messinger (1953) mathematical model to compressible flow and water vapor local concentration. Gent (1990) implemented the numerical code TRAJICE2, which predicts two-dimensional ice shapes on airfoils. The author approximated the flow over the airfoil leading edge as one over the frontal part of a cylinder and, by scaling experimental results of heat transfer around rough cylinders, developed an empirical expression to evaluate convection heat transfer coefficient on airfoil surface. Alternatively, Gent (1990) implemented a boundary-layer integral analysis, which is similar to Makkonnen (1985), to evaluate the laminar and turbulent heat transfer coefficient over a near isothermal surface and without mass transfer effects. The laminar to turbulent transition is assumed to occur abruptly when *Reynolds* number on sand grain roughness is $Re_k = u_e \cdot k_s/\nu > 600$, where u_e is the velocity at the boundary layer top edge. As other classic icing codes, the heat transfer prediction is only valid for thin ice accretions, i.e., at the beginning of accretion process, in absence of flow separation(Gent et al., 2000).

LEWICE code, which has been developed by researchers (Macarthur et al., 1982; Ruff and Berkowitz, 1990; Wright, 1995) of the National Aeronautic and Space Administration - NASA, estimates the potential flow around the airfoil by panel method, the collection efficiency, the momentum and thermal boundary-layers as well as the ice shape. For convection heat transfer calculation, this code estimates the laminar boundary-layer conduction thickness $\Delta_{4,lam}$, assumes a transition criteria triggered by roughness $\mathrm{Re}_k = v_k \cdot k_s/\nu > 600$, where v_k is the velocity at the top of the roughness element, and estimates turbulent heat transfer coefficient $h_{\infty,turb}$ over a rough surface with similar assumptions and procedures adopted by Makkonnen (1985). The ice growth is predicted by the LEWICE's thermal module that adopts Messinger (1953) equations for freezing process over an adiabatic airfoil surface.

Guffond and Brunet (1988) developed ONERA2D code, at Office National D'Études et de Recherches Aérospatiales - ONERA, France, to estimate the ice geometry. Differently from LEWICE, it solves the full potential flow around the clean or iced airfoil in a C-type mesh by finite elements method (Bredif, 1983, 1985). With the pressure field, ONERA2D calculates the water droplets trajectories, collection efficiency, convective heat transfer coefficient and thermal balance (Messinger, 1953) in order to estimate the ice shape. Figure 1 shows samples of computational mesh and droplets trajec-



(a) Zoom in computational mesh (b) Droplets trajectories

Figure 1. ONERA2D application on a NACA0012 profile

tories calculated by ONERA2D around a NACA 0012 profile.

The ice growth modules of the classic icing codes have similar mathematical models and numerical implementation structure. Despite the limitations to predict glaze ice growth process, the numerical precision is well known and the ice shape results are accepted by the aerospace community.

There are several working groups that compared numerical results to experimental ice shapes. The most recent benchmarking work was performed by the Applied Vehicle Technology Panel, Research and Technology Organization, North Atlantic Treaty Organization - AVT-NATO-RTO (Kind, 2001), which made available experimental data from various ice tunnels and numerical results from mostly used codes by industry and academia.

3. OBJECTIVE

The objectives of the present paper are the following: 1) to review the application of heat transfer over rough surfaces in aircraft icing literature; 2) to assess the sensitivity of the ice geometry to variations in laminar-turbulent transition parameters and sand grain roughness.

4. ICING NUMERICAL CODE

The ONERA2D code, implemented by Guffond and Brunet (1988), was chosen as the icing numerical tool to predict ice shapes in the present paper. ONERA2D uses a predictor-corrector scheme that estimates the ice growth process in two runs. In the first run, the ice shape is predicted by considering a clean airfoil geometry and total duration. The second run uses first ice shape as the new airfoil surface to modify the pressure coefficient, local collection efficiency and heat transfer coefficient distributions at the same time. Other codes, such as LEWICE or TRAJICE2, simulate the icing process in several fixed time steps. Pressure, heat transfer and impingement change at each time step. According to Wright (1995), the increase of the number of time steps increase the accuracy for glaze ice prediction.

In the present paper, an additional mathematical model to run as the boundary-layer sub-program of ONERA2D is proposed. This is the same model developed by Makkonnen (1985) and used by Guffond and Brunet (1988); however, it has a new smooth, rather than abrupt, laminar-turbulent transition model. Neither the boundary-layer equations nor the icing growth process is modified.

Two laminar-turbulent transition models are used: 1) the abrupt one, which has the onset position predicted by empirical correlation and alters from laminar to turbulent regime at the transition point, as implemented in all classic icing codes; 2) the smooth one, which has no prediction for the onset position; it has an intermittency function that smoothly links the laminar and turbulent flows throughout a finite transition region.

5. BOUNDARY-LAYER MODEL

5.1 Momentum Boundary-Layer

The boundary-layer momentum integral equation may be conveniently expressed through a non-dimensional equation of momentum thickness (Kays and Crawford, 1993):

$$\frac{C_f}{2} = \frac{d\delta_2}{ds} + \delta_2 \cdot \left[\left(2 + \frac{\delta_1}{\delta_2} \right) \cdot \frac{1}{u_e} \cdot \frac{du_e}{ds} \right], \tag{1}$$

where s coordinate is the distance from the stagnation point measured over the airfoil surface.

Based on Thwaites (1949) approximation, Kays and Crawford (1993) integrated Eq. (1) in order to obtain the momentum thickness in laminar and turbulent flow regime:

$$\delta_{2,lam} = \frac{0.664 \cdot \nu_{air}^{1/2}}{u_e^{2.84}} \cdot \left(\int_{s_{stag}}^{s_o} u_e^{4.68} \, ds \right)^{1/2} \tag{2}$$

$$\delta_{2,turb} = \left[\frac{0.0156 \cdot \nu_{air}^{1/4}}{u_e^{4.11}} \cdot \int_{s_o}^{s} u_e^{3.86} \, ds + (\delta_{2,tr})^{5/4} \cdot (\frac{u_{e,tr}}{u_e})^{4.11} \right]^{4/5} \tag{3}$$

Equation (3) is evaluated with $\delta_{2,tr} = \delta_{2,lam} = \delta_{2,turb}$, i.e., the Eq. (2) provides the initial condition for the integral in Eq. (3) at transition onset position s_o.

5.2 Laminar Thermal Boundary-Layer

Similarly to Thwaites (1949), Smith and Spalding (1958) developed a procedure to evaluate the thermal boundary-layer over smooth and isothermal surfaces that considers constant Pr; neglects the effects of the boundary-layer shape and thickness; and assumes that boundary-layer thickness growth rate depends only on local conditions. The last assumption is crucial to the Smith and Spalding (1958) model, which assumes that wedge solutions are applicable to flows with variable pressure gradient.

Therefore, Smith and Spalding (1958) concluded that the conduction thickness Δ_4 can be represented as the following:

$$\frac{u_e}{\nu} \frac{d\Delta_4}{ds} = f \left(\frac{\Delta_4^2}{\nu} \frac{du_e}{ds} \right) \tag{4}$$

Where f is a function determined from wedge flow analytical solutions (Falkner-Skan family flows for several pressure gradients obtained by Eckert (1942)). Thus, Δ_4 can be approximated by:

$$\left[\frac{u_e^{2.87}}{\nu} \Delta_4^2 \right]_0^s = 11.68 \int_0^s u_e^{1.87} ds \tag{5}$$

At airfoil stagnation point, the local convective heat transfer h_{lam} is approximated by Smith and Spalding (1958) as:

$$\mathrm{Nu}_{stag} = \left[0.246 \cdot \mathrm{Re}_\infty \cdot \left. \frac{d\,(u_e/V_\infty)}{d\,(s/c)} \right|_{s=s_{stag}} \right]^{1/2} \tag{6}$$

5.3 Turbulent Thermal Boundary-Layer over Rough Surfaces

Kays and Crawford (1993) developed a mathematical model to predict Stanton number in turbulent regime St_{turb}:

$$\mathrm{St}_{turb} = \frac{C_{f,turb}/2}{\mathrm{Pr}_t + (C_{f,turb}/2)^{0.5} / \mathrm{St}_k} \tag{7}$$

The Stanton number based on roughness height St_k is defined as:

$$\mathrm{St}_k = C \cdot \mathrm{Re}_{ks}^{-0.2} \cdot \mathrm{Pr}^{-0.44} \tag{8a}$$
$$\mathrm{Re}_{ks} = (u_\tau \cdot k_s)/\nu \tag{8b}$$
$$u_\tau^2 = \tau_0/\rho = 0.0125 \cdot \mathrm{Re}_{\delta_2}^{-1/4} \cdot u_e^2 \tag{8c}$$

Where τ_0 is the shear stress at the wall; Re_{ks} is the Reynolds number based on shear velocity u_τ and roughness height k_s. Experimental data from Pimenta (1975), when roughness is composed by densely packed spheres, sets $C = 0.8$ when Pr=$\mathrm{Pr}_t = 0.9$.

By using the law of the wall for fully rough surfaces and making empirical adjustments, Kays and Crawford (1993) defined the turbulent friction coefficient $C_{f,turb}$ as the following:

$$\frac{C_{f,turb}}{2} = \frac{0.168}{\left[\ln \left(864 \cdot \delta_{2,turb}/k_s \right) \right]^2} \tag{9}$$

During the ONERA2D code implementation, Guffond and Brunet (1988) pursued Makkonnen (1985) calculation procedure, which applies Eq. (7),Eq. (8) and Eq. (9) to estimate respectively St_{turb} and $C_{f,turb}$. The procedure uses a different version of Eq. (8a) that has different exponent values (Dipperey and Sabersky, 1963; Owen and Thomson, 1963):

$$\mathrm{St}_k = C \cdot \mathrm{Re}_{ks}^{-0.45} \cdot \mathrm{Pr}^{-0.8} \tag{10}$$

Equation (10) is adopted with $\mathrm{Pr} = \mathrm{Pr}_t = 0.9$. According to Makkonnen (1985), the C parameter in Eq. (10) depends on the roughness geometry, however, a $C = 0.52$ value is an acceptable approximation when the geometry is unknown (Owen and Thomson, 1963).

5.4 Laminar-Turbulent Transition

It is difficult to predict the laminar-turbulent transition onset position and extension over irregular and rough surfaces because there is no general theory to describe the transition mechanisms. Therefore, all classic icing codes estimate transition onset position by empirical arguments.

For instance, ONERA2D (Guffond and Brunet, 1988) adopts a empirical classical criteria to determine the onset transition position s_o that is given by:

$$Re_k = \frac{u_e \cdot k_s}{\nu} > 600 \tag{11}$$

Most of the times, the classic icing codes assume that transition occurs abruptly in a position s_o. On the other hand, the present paper proposes to represent the transition as a region with defined length, where the flow goes from fully laminar to fully turbulent regime. The intermittency function is zero $\gamma = 0$ in the region upstream the initial position (onset) s_o of transition region; and it is almost unity $\gamma = 0.99$ at the end position of transition region, where the flow regime becomes fully turbulent. The intermittency γ depends on the formation and growth of the spots. Emmons (1951) derived an expression for γ given the probability distribution of the appearance of spots as a function of 2D coordinates and time, which was confirmed by the experiments of Schubauer and Klebanoff (1955). The intermittency function $\gamma(s)$ is defined as the fraction of time that flow is turbulent at certain position s. The Stanton number in transition region is evaluated by linear combination of the St_{lam} and St_{turb} weighted by intermittency function:

$$\mathrm{St}(s) = [1 - \gamma(s)] \cdot \mathrm{St}_{lam} + \gamma(s) \cdot \mathrm{St}_{turb} \tag{12}$$

Similarly, the linear combination procedure can also be applied to friction coefficient calculation C_f, i.e., the $\mathrm{St}(s)$ is replaced by $C_f(s)$ in Eq. (12).

Inspired by the intermittency concept and based in a comprehensive set of experimental data, Abu-Ghannam and Shaw (1980) defined the flow intermittency $\gamma(s)$ as:

$$\gamma(s) = 1 - \exp\left[-5 \cdot \left(\frac{s - s_o}{s_e - s_o}\right),\right] \tag{13}$$

where s_0 is the transition onset position from stagnation point, s_e is the end position of transition region. Thus, the difference $s_e - s_o$ gives the length of transition region.

As the study of the influence of roughness characteristics on the laminar flow stability is beyond the objective of the present paper, the values of s_o and s_e from Eq. (13) were arbitrarily defined and varied to verify the effects on the ice shape predicted by ONERA2D.

6. REFERENCE CASE

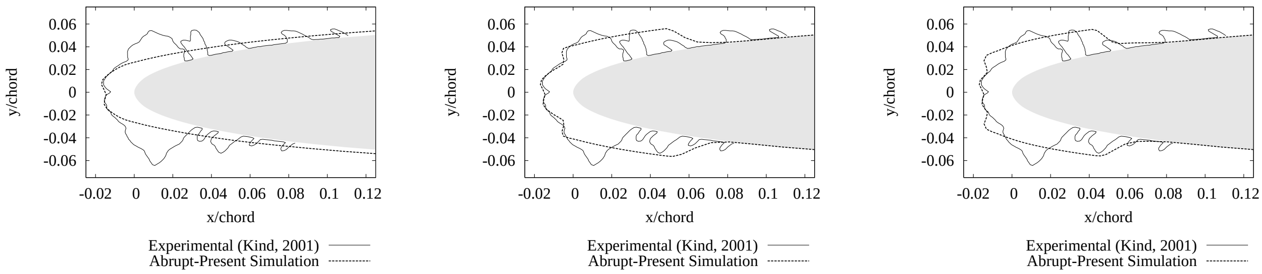
Table 1. Experimental Conditions

Flow Condition	**Value**	**Icing Condition**	**Value**
Angle of Attack (deg)	0.0	Liquid Water Content (g/m^3)	0.65
Freestream Velocity (m/s)	67	Median Volumetric Diameter (μm)	40
Freestream Static Pressure (Pa)	97147	Freestream Static Temperature (K)	264.4
NACA 0012 chord (m)	0.533	Duration (s)	672

Kind (2001) published results of a comprehensive comparison between icing codes and experimental data measured at several test conditions and icing tunnels around the world. In this work, the case C13 , performed with a NACA 0012 airfoil profile in the Icing Research Tunnel at NASA Glenn Research Center, was selected as the reference case to simulate the ice growth. The conditions of the tests are presented in the Table 1.

7. RESULTS

The items as follows show the results for several runs of the heat transfer model implemented in the present work coupled with the original modules of ONERA2D, which are the flow and droplets trajectories solver plus ice growth. The modeling uses abrupt and smooth laminar-turbulent transition. The former is the present authors implementation of the same mathematical model used in the original ONERA2D boundary layer module. The latter, used the same boundary layer model but with intermittency inclusion in laminar-turbulent transition. These options were tested and comparative results are presented. The ONERA2D best result for case C13, obtained and presented by Guffond at NATO-AGARD workshop (Kind, 2001), is also shown as baseline.

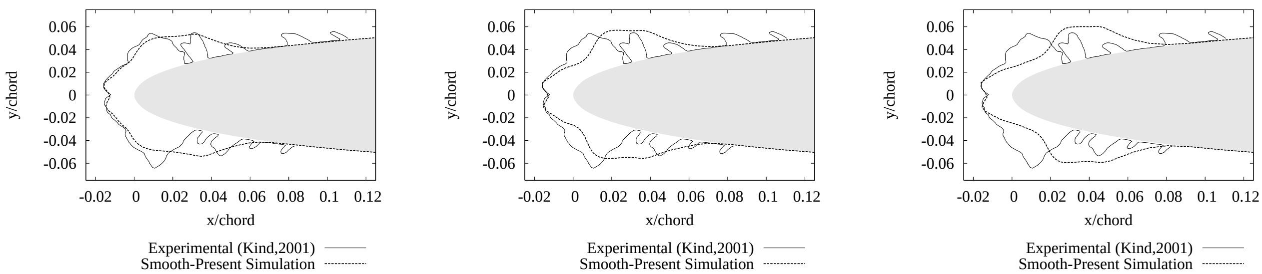


(a) ks=0.0001 (m) (b) ks=0.000125 (m) (c) ks=0.00015 (m)

Figure 2. Variation of Equivalent Sand Grain

The equivalent sand grain roughness k_s affects both convective heat transfer coefficient and the transition onset position. Several values of k_s were used to evaluate the effects in ice shape growth. The sensitivity study was performed considering the clean airfoil geometry; ONERA2D code was run once, because the validity of boundary layer integral analysis is limited to small and smooth ice formations, when no recirculation, strong pressure gradient, significant surface curvature and transition onset position variation are present.

The k_s that best fitted the frontal part of the experimental ice shape was then used in the further simulations. As shown in Fig. 2(b), the best fit was for $k_s = 0.000125$ [m]. Since the Re_k is affected by the value of k_s, it is expected that the onset position would vary with the variation of k_s. During the simulations it was observed that, for values of $k_s < 0.0001$, the ice shape was very similar to the one from Fig. 2(a), which depicts a uniform ice shape. In those cases, the laminar heat transfer coefficient distributions h_{lam} are very similar. Once k_s reaches a value that triggers the transition to turbulent flow regime, minor changes in the value imply in significant changes in the ice geometry. This result is shown in the Fig. 2(b) and Fig. 2(c).



(a) s_o/c=0.003/-0.001 (b) s_o/c=0.013/-0.011 (c) s_o/c=0.023/-0.021

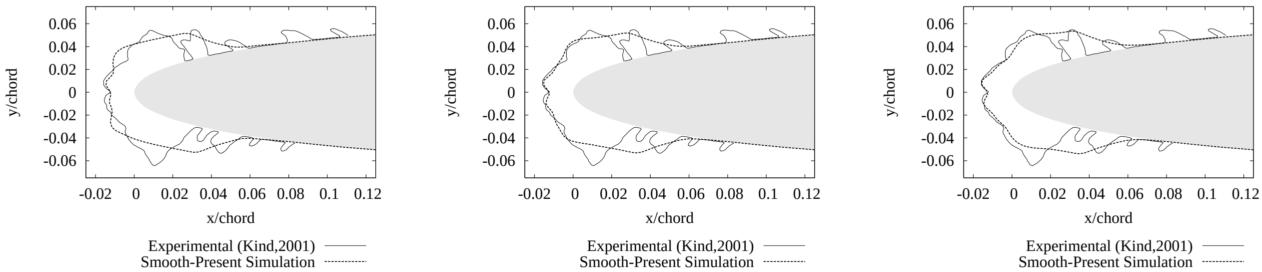
Figure 3. Variation Laminar-Turbulent Transition Onset Position

By adopting $k_s = 0.000125$, the abrupt transition onset position of the transition was manually varied in order to evaluate its influence on the ice shape. Due to integral analysis limitations, the ONERA2D code was run once. Figure 3 presents the results of this variation study. The positive values of onset position shown in Fig. 3 are located in upper surface and the negative in the lower surface of the airfoil in relation to stagnation point.

By comparing the figures, one may see that the ice shape moves in direction of the trailing edge together with the variation of the onset position. Near the onset position there is an elevation in the ice shape, which demonstrates that, at this point the convective heat transfer increased. The ice shape rate change near the onset position is similar for three figures because the transition length was zero length.

The sand grain roughness was $k_s = 0.000125$ and the onset positions were, during all simulation time, $s_o/c = 0.003$ in the airfoil upper surface and $s_o/c = -0.001$ in the airfoil lower surface. The position of the end of the transition was varied, which means the transition region length is different in each simulation. The intermittency function $\gamma(s)$ of

Eq. (13) was enabled to make a smooth transition between laminar to turbulent flow regime. Fig. 4 shows the results of the comparison.



(a) s_e/c=0.021/-0.017 (b) s_e/c=0.031/-0.027 (c) s_e/c=0.041/-0.037

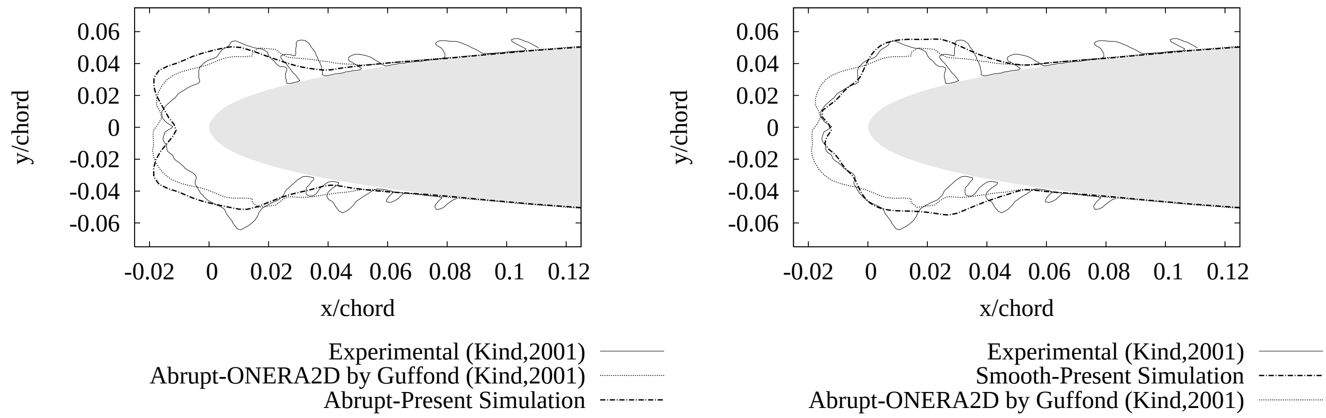
Figure 4. Variation of Laminar-Turbulent Transition Length $(s_e - s_o)$ with $s_o/c = 0.003/-0.001$

The variation in the transition region length affects the ice shape, since longer transitions make the ice shape smoother. As expected, short transition lengths make the ice similar to simulations results against abrupt transition models. The ice, in these cases, have horns near the onset position.

Table 2. Simulation Parameters

Parameter	**Upper Surface**	**Lower Surface**
onset position s_o/c	0.003	-0.001
end position s_e/c	0.041	-0.037
sand grain height k_s (m)	0.00023	

The onset position, end transition position and the sand grain were varied in order to find the simulated ice shape mostly similar to experimental one. The objective of this calibration is to show that these parameters influence the ice growth. Figure 5 presents simulation results, with abrupt and smooth model and Table 2 shows the parameters used in simulation. In Fig. 5(a), the results of present implementation of abrupt transition is compared to results of ONERA2D obtained by Guffond (Kind, 2001). Despite the two models have the same boundary layer and transition models as well as the same input data, the results are different due to different code implementations. At stagnation region, the present code used third order integration method. Otherwise, ONERA2D smoothes the heat transfer distribution to filter first order method numerical oscillations. In addition, Guffond (Kind, 2001) did not publish the k_s value used to run ONERA2D.

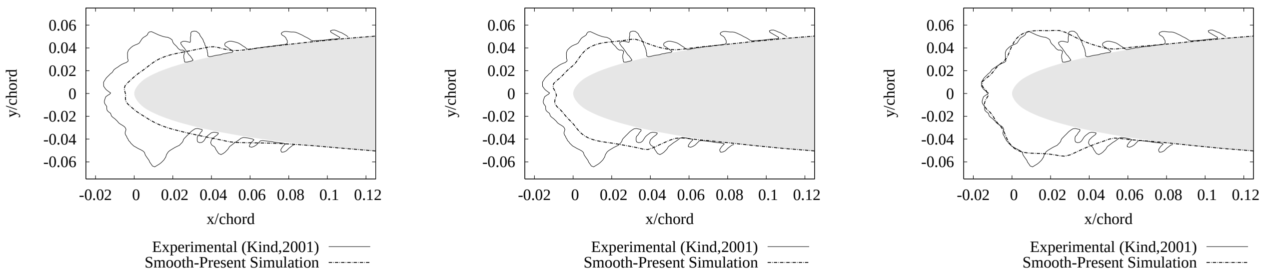


(a) Abrupt Transition (b) Smooth Transition

Figure 5. Present Simulation Results Compared to Baseline ONERA2D

Figure 5(b) demonstrates that an adequate prediction of the onset position, combined with a adequate model of transition development, can improve significantly the ice shape simulation. Figure 6 shows the ice growing process by adopting crescent time steps for same parameters of Table 2.

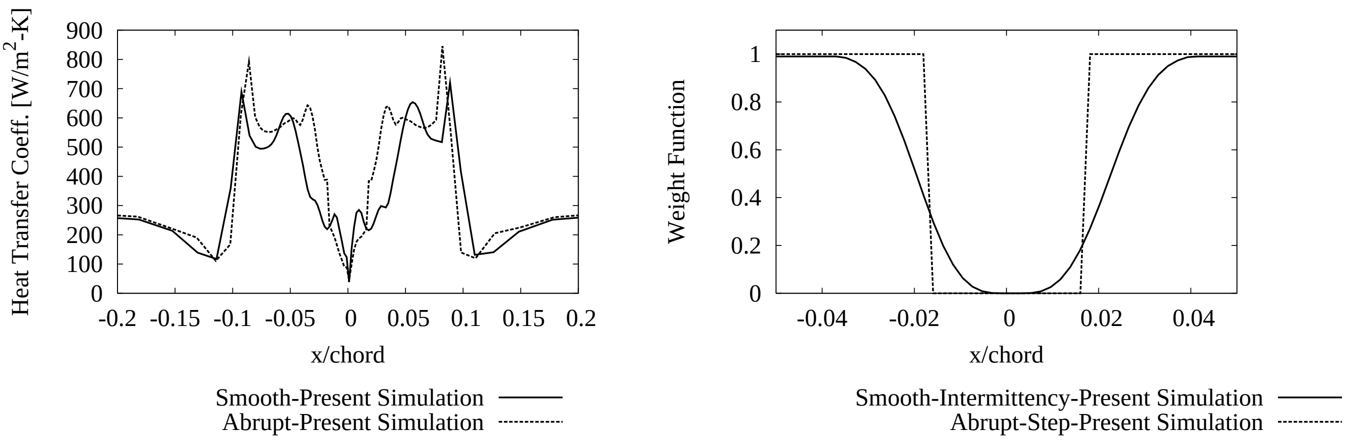
The ice growth module of ONERA2D was run by using the heat transfer model with a abrupt transition and automatic onset prediction, which is the original boundary layer and transition models of the code. In addition it was run using



(a) t=224(s) (b) t=448(s) (c) t=672(s)

Figure 6. Ice Growing Time Steps

the boundary layer and the modified smooth transition model, both implemented in the present paper, with the calibrated parameters. The comparison of the ice shapes with the two models is presented in Fig. 5, the heat transfer coefficient distribution is shown in Fig. 7(a), the intermittency (smooth model) and step (abrupt model) functions are presented in the Fig. 7(b). The transition onset location may change in the abrupt transition model because it depends on the critical Reynolds number $\mathrm{Re}_k > 600$ that varies with changes in the velocity distribution caused by ice formation. Otherwise, the smooth model has the transition parameters imposed by the user and fixed during the simulation time.



(a) Convective Heat Transfer Coefficient (b) Intermittency (smooth) and Step (abrupt) Functions

Figure 7. Present Simulation Results for Smooth and Abrupt Transition

8. CONCLUSION

A smooth transition model, based on flow intermittency concept, was implemented in ONERA2D code and the results were compared with experimental data. The intermittency application to boundary layer integral analysis, generated ice geometry results that better fitted the experimental ice shape than the results generated by the abrupt transition model of ONERA2D. In the ice frontal region, the deviations between present paper results and experimental data are satisfactory, while in the rear region, the deviations are accentuate, mainly due to the presence of recirculation, surface curvature and adverse pressure gradient.

The effects of variation of sand grain roughness, laminar-turbulent transition onset position and extension were assessed. All those parameters affected significantly the accreted ice geometry and changed the position, inclination and angle between ice horns as well thickness and shape irregularities distribution. The onset position variation towards trailing edge provokes the ice horns formation at more downstream positions. On the other hand, short transition regions caused sharper ice horns than long ones, which tended to smooth the ice surface irregularities.

From the results presented, it can be concluded that the use of a intermittency function make the convective heat transfer in the transition region more realistic. The use of an abrupt transition produced ice shapes with horn shapes near the onset position, which is not seen in experimental ice shapes. The analysis of the results of flow intermittency and step functions clearly shows that the two onset position are close but the extension and curve shape are not. This fact may have been caused by the improved fit between predicted and experimental ice shape when applying the smooth model implemented in the present paper.

In spite of the simple transition model used and the limitations imposed by the assumptions of integral approach, the presented results are encouraging and demonstrate that more detailed analysis are required about the subject.

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