

ICE ACCRETION PREDICTION WITH MIXED PHASE CLOUD PARTICLES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY



ERDEM AYAN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
AEROSPACE ENGINEERING

JUNE 2017

Approval of the thesis:

ICE ACCRETION PREDICTION WITH MIXED PHASE CLOUD PARTICLES

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ABSTRACT

ICE ACCRETION PREDICTION WITH MIXED PHASE CLOUD PARTICLES

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June 2017, 121 pages

Existence of ice crystals in convective clouds has become one of the major threats for flight safety. Several flight incidents have been reported in the last decades due to ice accretion around heated surfaces like air probes or on engine components. Ice accretion due to water droplets is a well studied issue. However, ice accretion due to ice particles is a relatively new aspect and the physics are not yet fully understood. Hence adequate models for representing the physical phenomena are very scarce. Within the recent years, several projects and groups have focused on this topic. High Altitude Ice Crystals (HAIC) project is one of them which has started in 2012 and completed in January 2017. HAIC FP7 European project is a large-scale integrated project and ice crystal accretion prediction is one of the issues within the scope of this project. It is observed in these studies that differing from water droplets, ice crystals generally pose a threat once they reach heated surfaces and either when they are partially melted or when water film is already accreted on the surface. Ice crystals can either melt completely during their trajectories by convection or melt upon impact on warmer components. Thus, the height of the liquid film on corresponding compo-

nents increases resulting in more ice crystals sticking. This scenario causes reduction in local surface temperature and enhances the probability of in-flight incidents by developing suitable conditions for ice accretion. Within the scope of this thesis, one aim is to enhance capabilities of an in-house developed tool TAICE by including models related to ice crystals accretion. Drag coefficient, heat transfer, phase change, impingement, erosion and accretion models have been implemented to TAICE. Some of them have been modified and further calibrated thanks to the available experimental results in literature. Another aim is to extend the two-layer ice accretion model (Extended Messinger Model) for mixed phase and glaciated icing conditions. In two-layer method, instead of predicting the equilibrium temperature in Original Messinger Model, temperature variation is modeled within the ice and water layers to improve accuracy of the prediction. Extension of the Messinger Model has not been performed up to now in the literature for ice crystal accretion and this motivates the study. All of the implemented models are detailed in theory part and validation of the tool has been performed by using NASA-NRC, COX and TUBS experiments. Moreover, some 2-D and 3-D industrial applications like ice accretion prediction on engine inlet and pitot-tube have been included in this thesis.

Keywords: in-flight icing, ice accretion prediction, ice crystals, solid cloud particles, mixed phase icing, TAICE

ÖZ

KARIŞIK FAZDAKİ BULUT PARTİKÜLLERİ İLE BUZ BİRİKİMİ TAHMİNİ

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Tez Yöneticisi : Prof. Dr. Serkan Özgen

Haziran 2017 , 121 sayfa

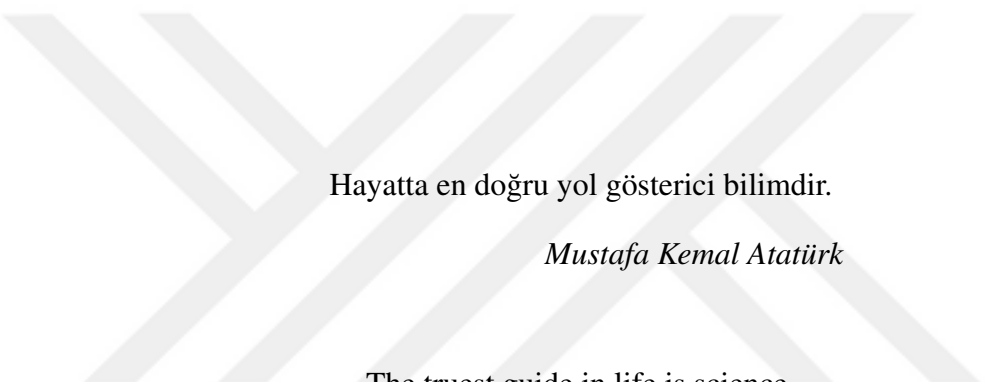
Taşıyıcı bulutlarda oluşan buz kristalleri uçuş güvenliği için başlıca tehditlerden biri haline gelmiş ve son yıllarda hava sensörleri, motor parçaları gibi ısıtılan veya sıcak yüzeyler etrafında oluşan buzlanmadan ötürü birçok problemlili uçuş olayı rapor edilmiştir. Sıvı damlacıklardan dolayı oluşan buzlanma iyi bilinen bir konu olmasına rağmen katı fazdaki buz parçacıklarından dolayı oluşan buzlanma göreceli olarak yeni araştırılmaya başlanmış bir konudur. Ayrıca buzlanmaya sebep olan fiziksel mekanizma tam olarak henüz anlaşılamamış ve doğru olarak modellenememiştir. Bu problemin anlaşılması ve çözümü için konuyla ilgili birçok proje başlatılmıştır. Yüksek irtifa buz kristalleri (HAIC) projesi bu amaçla oluşturulan projelerden bir tanesi olarak 2012 yılında başlatılmış ve çalışmalar 2017 yılı Ocak ayında tamamlanmıştır. HAIC projesi konuyla ilgili değişik çalışma gruplarını bir araya getiren büyük çaplı bir Avrupa Birliği 7. çerçeve programı projesidir. Projenin amaçlarından bir tanesi de buz kristalinden dolayı oluşan buzlanma tahmini için modeller geliştirmektir. Proje çalışmaları süresince buz kristallerinin su damlacığından farklı olarak ısıtılan yüzey-

lere yaklaştıklarında kısmi olarak eriyerek veya yüzey üzerinde su tabakası oluştuğunda bir tehdit unsuru haline geldikleri gözlemlenmiştir.

Buz kristalleri yörünge süresince veya yüzeye çarptıktan sonra eriyebilir. Bu sebepten ötürü yüzey üzerinde oluşan su tabakasının yüksekliğinin artması daha çok buz kristalinin yüzeye yapışmasına ve onların da erimesi durumunda su tabakasının yüksekliğinin daha çok artmasına ve yeterince soğuma sağlanırsa yüzey üzerinde buz oluşumuna sebep olmaktadır. Ayrıca proje süresince buz kristallerinin yüzeye çarpması ve yüzey üzerindeki buz birikimi üzerindeki erozyon etkisi için güvenilir modeller oluşturmak amacıyla bazı deneyler yapılmıştır.

Bu tez kapsamındaki amaçlardan bir tanesi öz kaynaklarla geliştirilmiş olan buzlanma tahmin aracı TAICE'ın buz kristallerinden dolayı oluşan buzlanmanın tahmini için gerekli modellerin eklenerek kabiliyetlerinin artırılmasıdır. Bu amaçla yazılıma sürüklenme katsayısı, ısı transferi, faz değişimi, çarpma, erozyon ve buz birikimi modelleri eklenmiştir. Eklenen bu modellerden bazıları literatürdeki deney sonuçları kullanılarak geliştirilmiş ve kalibrasyon yapılmıştır. Tez kapsamındaki bir başka amaç ise iki-tabaka buz oluşumu modelinin karışık faz durumlarına uygun olarak kullanılabilmesi için geliştirilmesidir. İki-tabaka modelinde klasik Messinger modelinden farklı olarak denge sıcaklığı tahmini yerine su ve buz tabakaları boyunca sıcaklık değişimleri modellenerek buzlanma tahminin doğruluğu arttırılmıştır fakat bugüne kadar karışık faz problemleri kullanımı için uygun hale getirilmemiştir. Bu tezde iki-tabaka modeli karışık faz problemlerine de uygun hale getirilmiş ve eklenen diğer modeller ile birlikte doğrulaması yapılmıştır. Kullanılan tüm modeller teori kısmında açıklanmış ve geliştirilen yazılımın doğrulaması için NASA-NRC ve COX deneyleri kullanılmıştır. Ayrıca endüstri uygulamalarına örnek olması için motor hava alığı ve pitot tüp gibi bazı 2-B ve 3-B parçalar üzerinde buz birikimi hesaplamaları da tez kapsamında ele alınmıştır.

Anahtar Kelimeler: Uçuş sırasında buzlanma, buz birikimi tahmini, buz kristalleri, katı fazdaki bulut parçacıkları, karışık fazlı buzlanma, TAICE



Hayatta en doğru yol gösterici bilimdir.

Mustafa Kemal Atatürk

The truest guide in life is science.

Mustafa Kemal Atatürk

ACKNOWLEDGEMENTS

Starting from the beginning of my PhD studies I had the pleasure to be supported by numerous friends, colleagues and my family. Here I would like to thank these people all. Without their help this work could not be possible.

First of all I want to thank my supervisor Prof. Dr. Serkan Özgen for his supervision, collaboration, and the hilarious discussions. It was a great honor for me to study with a well known scientist in icing field around the world. I have really enjoyed working under his supervision.

Thanks to each members of our monthly repeating last Thursday meetings: Eray Göksu, Onur Albostan, Ulaş Yaman, Ersin Öner and Emre Yalçın for fruitful discussions. Special thanks to Halil Kaya for scientific documentary sessions.

I would like to thank Murat Canıbek and Dr. Erhan Tarhan for giving me the opportunity of working at HAIC project at which I formed the basis of my thesis and for their support during the study. I also want to thank to Dr. Aykut Tamer for his recommendations and keen interest to the topic.

I enjoyed the time a lot at Turkish Aerospace Industries and that is why I want to sincerely thanks to flight sciences chief Senem Atalayer and my colleagues Fazıl Gömeç and Berrak Barun for their support and motivation. Thanks to Kenan Cengiz for accompanying me during the studies at the library.

Special thanks go to my family and friends who continuously supported and motivated me whenever needed and showed lots of patience.

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LIST OF ABBREVIATIONS

Abbreviations

<i>AIAC</i>	Ankara International Aerospace Conference
<i>CIRA</i>	Italian Aerospace Research Center
<i>CS</i>	Certification Specification
<i>EASA</i>	European Aviation Safety Agency
<i>EIWG</i>	Engine Icing Working Group
<i>FAA</i>	Federal Aviation Administration
<i>FAR</i>	Federal Aviation Regulation
<i>FP7</i>	Seventh Frame Project
<i>HAIC</i>	High Altitude Ice Crystals
<i>HIWC</i>	High Ice Water Content
<i>ICC</i>	Ice Crystal Icing Consortium
<i>IPHWG</i>	Ice Protection Harmonization Working Group
<i>IWC</i>	Ice Water Content
<i>LWC</i>	Liquid Water Content
<i>MVD</i>	Mean Volumetric Diameter
<i>MMD</i>	Mean Mass Diameter
<i>NRC</i>	National Research Council Canada
<i>NTI</i>	Newmerical Technologies International
<i>NACA</i>	National Advisory Committee for Aeronautics
<i>NASA</i>	National Aeronautics and Space Administration
<i>ONERA</i>	French Aerospace Research Center
<i>SP</i>	Sub-Projects
<i>SLD</i>	Supercooled Large Droplets
<i>TAI</i>	Turkish Aerospace Industry
<i>TRL</i>	Technology Readiness Level

Nomenclature

A_p	cross sectional area of particle
A_s	surface area of particle
$A_{\perp}$	projected area of the particle with respect to the flow
B, h	ice and water layer thicknesses
c	chord
C_D	drag coefficient of cloud particle
C_p	specific heat at constant pressure
d_p	particle diameter
D	diffusivity
$\mathbf{D}$	drag force of cloud particle
e	particle eccentricity
e_{σ}	surface energy per unit area
E	particle aspect ratio
g	gravitational acceleration
h_t	heat transfer coefficient
k	thermal conductivity
k_s	roughness height
L_f, L_v	latent heat of freezing and evaporation
L	ratio of the kinetic energy to surface energy
$\dot{m}$	mass flow rate
m_p	mass of cloud particle
M	molar masses
Nu	Nusselt number
$P_B P_D$	particle bouncing and deposition probabilities
P	pressure
Pr	Prandtl number
Q	heat terms in the interface conditions as explained in the text
Q_s	activation energy
r	sticking efficiency of cloud particle
r_p	particle radius
Re	Reynolds number
Re_k	roughness Reynolds number

RH	relative humidity
s	circumferential distance along the geometry surface
Sc	Schmidt number
Sh	Sherwood number
St	Stokes number
Sta	Stanton number
t	time
T	temperature in the ice layer
U_e	edge velocity
U_k	flow velocity at the roughness location
v_p	particle volume
V_{rel}	particle relative velocity
V_∞	freestream velocity
V_x, V_y	velocity vector components of the flow field
V	velocity magnitude of cloud particle with respect to the flow field
x, y	Cartesian coordinates
$\ddot{x}_p, \ddot{y}_p$	acceleration vector components of the cloud particle
$\dot{x}_p, \dot{y}_p$	velocity vector components of the cloud particle
x_p, y_p	position vector components of the cloud particle
y_v	vapor mass fraction

Greek Symbols

α_{melt}	melt ratio of ice crystals after impinging
β	local collection efficiency
γ	angle between velocity vectors of the cloud particle and flow field
δ	boundary layer thickness
ϵ_{er}	erosion rate
ϵ_s	particle sticking efficiency
ζ	particle restitution coefficient
η_{melt}	melt ratio of ice crystals before impinging
θ	temperature in the water layer or momentum thickness
λ	energy terms in the energy balance equation

μ	dynamic viscosity
ν	kinematic viscosity
χ	evaporation or sublimation coefficient
ϕ	particle sphericity
$\phi_{\perp}$	particle crosswise sphericity
ψ_c	impinging crystal mass to impinging total mass ratio
ψ_l	impinging droplet mass to impinging total mass ratio
ρ	density of air or liquid water content
σ_w	surface tension of water
τ	shear stress

Subscripts

a	air properties
c, l	quantities related to solid (crystal) or liquid (droplet) cloud particles
con	quantities related to convection
ct	constant
ev	quantities related to evaporation
f	quantities related to freezing
i	ice properties
imp	quantities related to impinging particles
in	quantities related to inflowing runback water
k	airflow properties at roughness height
lam	laminar flow
m	mixture properties
n	normal component
p	particle
r, g	quantities related to rime or glaze ice
rec	recovery
ref	reference
s	quantities related to sticking ice crystals
sat	saturated air properties
sta	static
sub	quantities related to sublimation

subs	substrate
t	tangential component
tot	total
tr	transition
turb	turbulent
v	vapor properties
w	water properties





CHAPTER 1

INTRODUCTION

1.1 Aircraft Icing

Ice accumulation on airplane components during flight is one of the most severe threats to flight safety. Ice can accumulate on wings, stabilizing surfaces, control surfaces, engine components and flight data sensors as shown in Figure 1.1. This may result in degradation of aerodynamic performance, alteration of stability and control characteristics often in an unpredictable manner, severe reduction in engine performance, false flight data readings and increase in weight. Thus, icing can be considered within the most serious hazards for air vehicles and generally it comes from the freezing of supercooled droplets which remain in liquid phase even at temperatures below freezing and due to ice crystals which exists generally in convective weather conditions in tropical regions.



(a) Icing on aircraft wing before take-off.



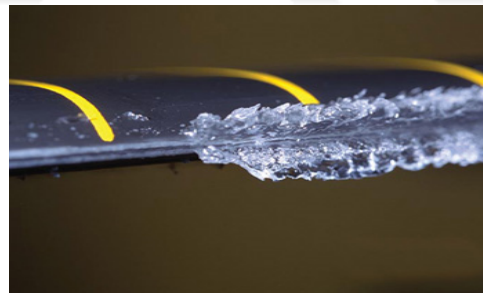
(b) Icing on aircraft propeller spinner.

Figure 1.1: Ice accretion on aircraft components [4].

Ice accretion is generally divided into two categories: rime ice and glaze ice which are shown in Figure 1.2. Cloud droplets may form rime ice upon impinging on unprotected surfaces, or may form glaze ice after running downstream. However, they differ in terms of shape. Rime ice is a dry, milky and opaque ice deposit which usually occurs at low airspeed, low temperature and low liquid water content. Characterized by instantaneous freezing of the incoming supercooled water droplets upon impact trapping the air inside. As a consequence, the shape of the surface is altered and it generates performance penalties due to the loss in the aerodynamic characteristics. Moreover, the added weight introduces an unbalance of the aircraft components during the flight. On the other hand, glaze is a wet growth ice formed at a temperature around 0°C and a high liquid water content. It has a clear appearance and a density closer to that of the cloud water. It occurs when a fraction of the water droplets freezes upon impact while the remainder droplets run back along the surface and freeze downstream. This ice accretion process produces different ice shape deposit: such as double horned, beak or a rounded ice. Glaze ice accretion dangerously affects and alters the shape of the original surface body producing aerodynamic penalties much more severe than rime ice accretion can cause.



(a) Rime ice accretion on aircraft wing.



(b) Glaze ice accretion on aircraft wing.

Figure 1.2: Icing types [1].

Icing is most severe when the ambient temperature is near 0°C but may be encountered at temperatures as low as -40°C and as high as 10°C . Ice can form on every exposed frontal surface of the airplane at 0°C or colder temperatures when liquid water is present, i.e. when flying through clouds. Ice accretion due to water droplets builds in flight where no heat can reach it. Heated surfaces, on the other hand, may face with ice accretion also due to ice crystals. Therefore, transport category aircraft

must demonstrate that they can fly safely in icing conditions by complying with airworthiness requirements issued by Certification Authorities. These conditions and related requirements are included in FAR-25 (FAA) and CS-25 (EASA).

1.2 Ice Crystal Icing

For a long time and until very recently, icing conditions and related requirements were covered by CS Appendix C, which takes into account only the icing conditions involving liquid phase clouds and where the cloud droplets are smaller than 50 microns. However, following the review of icing related events, Ice Protection Harmonization Working Group found accidents and incidents that were believed to have occurred in icing conditions that were not addressed by Appendix C. There have also been a number of power loss event reports during the last two decades, which have occurred in the presence of ice crystals and mixed phase conditions. Some of these events involved multi-engine power loss. Although the events did not result in accidents, they were considered as serious safety threats. Therefore it was proposed to amend CS-25 and FAR-25 to better protect large airplanes certified for flight in icing conditions [8]. As a result, both FAA [10] and EASA [9] have issued amendments to their respective certification regulations extending the icing envelopes to include Supercooled Large Droplets and mixed phase clouds in Appendix O and Appendix P (Appendix D in FAR-25), respectively. Moreover, differing from water droplets ice crystals do not have to be in spherical shape and they have variety of shapes within the clouds as depicted in Figure 1.3. Moreover, the maximum dimension of different ice particles varies between several microns and a few millimeters.

High water liquid content is mostly encountered within convective clouds which are often seen in tropical regions. Updraft cores of these clouds continuously transport humid air at low-level to higher altitudes, where water vapor is condensed as the temperature decreases. As shown in Figure 1.4 larger droplets begin to freeze spontaneously to ice crystals at around $-10\text{ }^{\circ}\text{C}$ and as droplets get smaller, colder temperatures are required to freeze them. By $-40\text{ }^{\circ}\text{C}$ virtually all droplets will have frozen. However, in between there may be regions in the clouds with very high ice crystal concentration and also where ice crystals and liquid water droplets may co-exist.

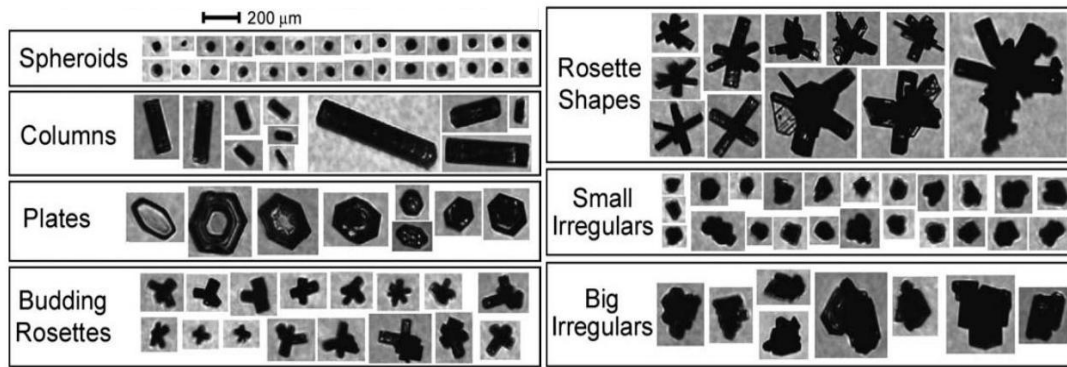


Figure 1.3: Ice crystal shapes observed within clouds. Pictures are taken from Lawson *et al* [38].

Ice accretion in such conditions involve phenomena that are significantly more complex than those in Appendix C icing conditions [73]. Some of these phenomena are trajectories of non-spherical ice crystals, heat transfer and melting in ice crystals, impingement of ice particles on a dry or wet surface, reemission of ice particles from the surface after impact and erosion. To increase the understanding the mechanisms of ice crystal accretion and to optimize aircraft safety in glaciated icing conditions, several projects and working groups focus on ice crystal icing research. Examples are the High Ice Water Content (HIWC) and High Altitude Ice Crystals (HAIC) projects as well as the Ice Crystal Icing Consortium (ICC) and the Engine Icing Working Group (EIWG).

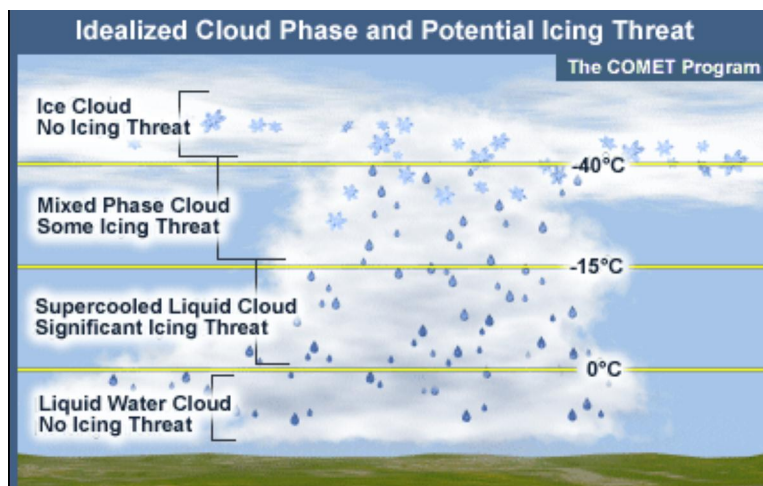


Figure 1.4: Cloud particles and icing risks at different altitudes [3].

Upon facing with some events related with mixed phase icing, researchers have focused on this issue. Such as Mason *et al* [42], describe an engine icing incidence. In their study ice crystals first melt upon contact with warm engine parts and a water film can be created. Subsequent ice particles are captured by the water film allowing ice accumulation to occur. The engine abnormalities then occur when this ice buildup sheds.

The study of Nilamdeen *et al* [53] is among the early numerical attempts to address mixed phase icing by solving the governing equations for multiphase flow. Emphasis has been given to ice crystal drag coefficient modeling and crystal bouncing. Four mixed phase ice accretions performed in the Cox icing tunnel were studied.

The study of Wright *et al* [76] extends the GlennICE numerical tool to model mixed-phase conditions. The study mentions the modifications that were made to GlennICE including those related to the particle trajectory algorithm, energy balance and erosion. The same four test cases as in Nilamdeen *et al*'s study have been investigated, together with an engine ice ingestion case.

A comprehensive account of mixed phase and glaciated icing conditions and their numerical modeling has been given by Villedieu *et al* [73] and Trontin *et al* [68]. These studies give a detailed account of models related to particle trajectories, heat transfer and phase change, impingement, accretion and erosion related to mixed phase accretion. Calibrations of model parameters are also explained in a detailed manner.

The experimental work of Al-Khalil *et al* [11] and the results therein have become benchmarks for the validation of computational results related to mixed phase icing. The authors present the results of wind tunnel tests under liquid phase and mixed phase conditions at the Cox wind tunnel. Four of these experimental cases have been extensively used by icing researchers developing numerical tools worldwide for validation. These cases are also studied in the present study for validating the results of the current computational tool.

More recent experimental efforts have been reported by Currie *et al* [25, 24, 23]. These references include databases obtained in the NRC wind tunnel and have been used to develop the models related to mixed phase icing.

1.3 Motivation

This thesis is focused on the numerical analysis of ice accretion in mixed phase conditions, where models related to mixed phase icing are implemented to TAICE. The numerical tool has four modules; a flow-field solution module that uses the Hess-Smith panel method, a module for computing droplet and ice crystal trajectories and collection efficiencies using the Lagrangian approach, a thermodynamical module, and an ice accretion module that utilizes the Extended Messinger Model. Extended Messinger Model has been introduced by Myers [47] as a significant improvement over the Original Messinger Model. A major improvement is the introduction of temperature gradients in the ice and water layers instead of fixed temperatures resulting in an unrealistic temperature discontinuity in the ice/water interface. In the Extended Messinger Model, transition from rime ice to glaze ice is smooth, whereas it is sudden in the original Messinger Model. These two improvements render the Extended Messinger Model a more faithful representation of the icing physics.

The Extended Messinger Model has been used extensively with the tool TAICE to study icing in liquid phase cloud conditions for airfoil, wing and intake geometries, and the obtained results have been validated [56, 57]. Nevertheless, no extension of such models to the mixed phase conditions have been proposed in the literature so far. Thus, this motivates us to fill the gap in mixed phase icing prediction studies. For this purpose, Extended Messinger Model has been modified further to include mixed phase effects together with the relevant models: drag coefficient models, heat transfer and phase change models for ice crystals and water droplets in trajectory calculations, impingement models and erosion models.

1.4 Trajectory Modeling Studies in Literature

Trajectory calculations take into consideration the particle motion starting from the release point, which is far away from aircraft body, till to the impinging point. Any issue, which effect this particle motion, is investigated under this topic. Drag force calculations, heat transfer with surrounding and phase change phenomena can be counted within these issues. There are numerous study in literature which investi-

gate drag force calculations of the particles. Most of these studies deal with spherical particles. Since ice crystals are not always pure spherical, the relations which are applicable to spherical particles can not be used for ice crystals. For spherical particles, several formula are available which are accurate for a large range of Reynolds numbers. For non-spherical ones, at least one or two additional parameters have to be introduced in the expression of the drag coefficient to account for the influence of the particle shape. Most commonly used geometrical parameters are the particle sphericity and crosswise sphericity which will be detailed later. A number of semi-empirical relations for drag force calculations have been proposed in literature including these geometrical parameters and Reynolds number. Analytic results fit well to the existing experimental results according to these studies in literature.

In case of solid or liquid non-deformable spherical particles embedded in a fluid, there exists a theoretical expression for the force exerted by the fluid on the particle. Several expressions have been proposed in the literature for the drag coefficient of a spherical particle. The most widely used is certainly the fit proposed by Clift and Gauvin [20]. On the other hand, for non-spherical particles Haider and Levenspiel suggest an expression for drag force coefficient in terms of sphericity and Reynolds number [29]. Moreover, well known another drag force coefficient model for non-spherical particles which takes crosswise sphericity into consideration also in addition to the sphericity and Reynolds number is the Ganser Model [27]. Finally, an alternative drag force coefficient model was proposed by Hölzer and Sommerfeld [35]. Their model includes the effect of orientation of the particle as in the Ganser Model. These three drag force coefficient models are selected among the models to be used in this thesis work. A comparison study has been done to evaluate their effect on particle trajectory and presented in AIAC in September 2015 [12].

Ranz-Marshall relation provides good accuracy for spherical particle heat transfer calculations. However, since this relation does not include any information related to geometrical shape of the body, it could not be used for non-spherical particles. Moreover, in literature there are several relations for Nusselt number calculations but again these relations only applicable for some regularly shaped particles. Within the scope of the HAIC project new equations have been proposed to be used for non-spherical particles also by including particle sphericity and crosswise sphericity.

Whitaker [75] was the first researcher who study at heat transfer calculations for non-spherical particles. He dealt with flat plates, circular cylinders and spheres. Later, Sparrow [66] performed numerical study for heat transfer around the particles having non-circular cross-sections. He summarized all his correlations which can be used as basis for non-spherical particles. More recently, Saha [64] proposed a numerical investigation of fluid flow and heat transfer around cubic shapes. Then, a general correlation based on the particle geometrical properties has been introduced by Richter *et al* [61] as a Nusselt Model. A sample result from his study is shown in Figure 1.5. By including sphericity and crosswise sphericity in their relation Richter Model can be applied to all particle shapes. However, for oblate particles where aspect ratio is less than 0.8 this relation gives unrealistic results and exhibits large deviation with respect to Comer numerical results [21]. This shows that Richter relation possess a limited range of validity. In order to overcome this problem, Villedieu *et al* [73] suggested a new relation for the Nusselt number of non-spherical particles computation. New relation fit well to the Richter's relation for the particles having high aspect ratios and much better than Richter's relation for the others.

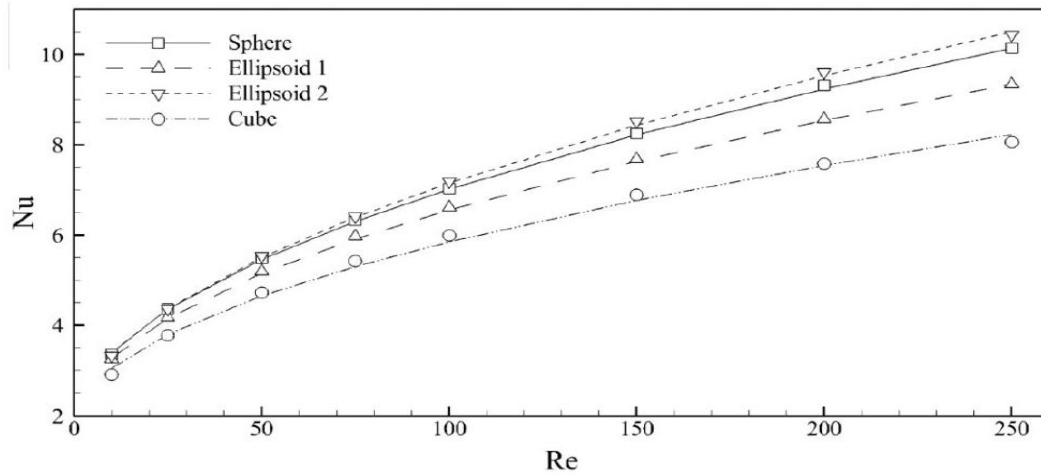


Figure 1.5: Computed and approximated Nusselt Number comparisons according to Richter. Symbols are used to show original data [61].

On the other hand, since ice crystals are solid particles and they may change phase during their trajectories, phase change relations should be taken into consideration also. Mason published a pioneering work [41] including modeling of solid ice crystals melting and evaporation phenomena. In his model particle starts to melt and

evaporate at melting point and temperature of the particle core is uniform. Ice core temperature remains constant and equal to melting temperature during all the melting process. Furthermore, ice core and the surrounding liquid film are assumed as spherical and concentric. There is no fluid motion in the liquid film and the heat transfer between ice core and liquid film is purely conductive. Ice particles do not shed their liquid water film during the melting phase. Later, Wright *et al* [76] also used similar assumptions for ice-crystal melting and evaporation relations. Rassmussen *et al* [60] proposed to improve Mason's phase change model including in their relation the influence of an internal circulation in the liquid layer and eccentric location of the ice core. However, according to their results only 10% reduction has been reached due to these two effects for ice crystals less than 500 μm . Thus, modeling these effects has been found as computationally expensive when compared with the other source of errors in ice crystal icing applications. The main limitation of these models is that they do not take into account the influence of the particle possible non-sphericity shape which is expected to reduce the total melting time. To overcome this limitation, Villedieu *et al* [73] developed an extension of Mason's model which accounts for the influence of the particle sphericity on the heat and mass transfer coefficients.

1.5 Impingement Modeling Studies in Literature

Since ice crystals are solid particles at least partially, they may bounce off the wall upon contact to the surface or they may split into smaller particles and some of the fragments may stick to the wall depending on the particle kinetic energy. These phenomena first observed in the experimental tests performed in the beginning of 2000s [11, 72, 30]. Restitution coefficient has been defined and adjusted thanks to the initial experiments to determine the fraction of the ice crystals that stick to the surface. However, modeling these phenomena was far from sufficient for ice crystals before HAIC project. Previous models which dealt with particle behavior from rebound to fragmentation and for the velocity and size distributions after impact were mainly based upon hail ball experimental data and only some of these models considered incidence angle of the ice particles. Furthermore, no model was available that regards the influence of the wall temperature on the impingement outcome, i.e. defines which

part of the particle will stick on the wall and which part will bounce off. Then, thanks to the HAIC experiments it is observed that impinging ice crystals on a surface may lead to three different scenarios which are sticking, bouncing and shattering.

Impact model which is discussed in this study is mainly based on these experiments and enhanced by Villedieu *et al* [73] and Trontin *et al* [68]. According to their studies, again in bouncing and sticking regimes particle size and shape do not change after impact. However, it may split into smaller particles in shattering regime. In bouncing regime, particles just bounce off from the wall and emitted to the flow. On the other hand, in sticking regime particle may adhere to the wall completely. A sample numerical modeling study of the particle collision is shown in Figure 1.6 The threshold between these regimes depends on the kinetic energy of the particle before impact and has been determined by using experimental data. Moreover, since bouncing ice crystal particles may cause trouble in downstream, ice crystals trajectory calculations are not finalized when they hit to the surface. TAICE trajectory calculation routines have been modified to follow each particle after impact for this purpose.

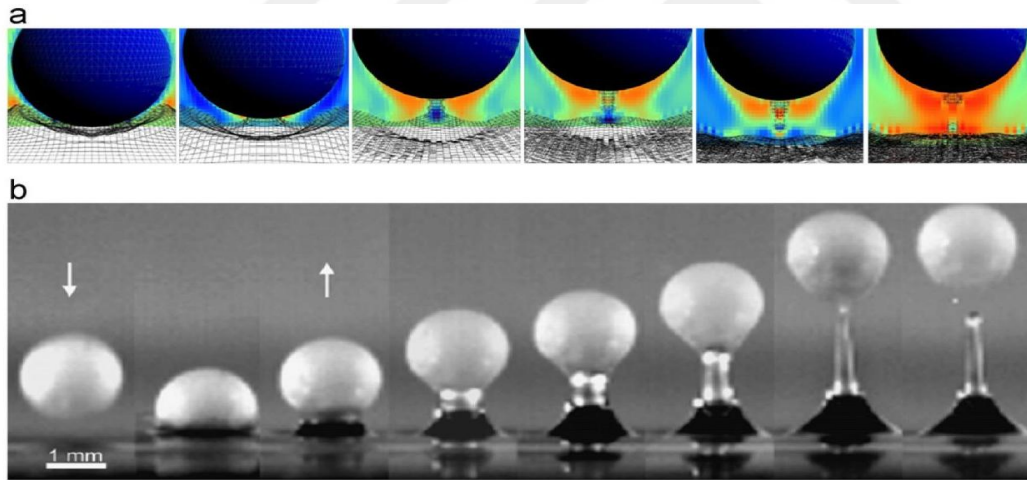


Figure 1.6: Numerical study of the particle collision to the surface covered with water film. Pictures are taken from Jain *et al* [37].

1.6 Erosion Modeling Studies in Literature

It is observed in the experiments that upcoming ice crystals cause reduction in the amount of ice which is already accreted on the surface. These phenomena was first

noted in Al-Khalil's *et al* [11] ice crystal accretion study. According to their study increase in IWC caused less amount of ice accretion. Later Wright *et al* [76] proposed a model to predict erosion effect on accreted ice in their study. IWC, ice crystal velocity and temperature of the surface effects are modeled in their relation. They calibrated the model by using available data. However, their model could not be validated yet due to the lack of experimental data. It should be noted that this model is further calibrated in this study to be consistent with the ice accretion prediction approach explained in this thesis study. Moreover, Trontin *et al* [68] extended this relation also by taking partially melted ice crystals into consideration. They included particle diameter, surface curvature, tangent and normal components of the particle velocity, impinging particle temperature and melting ratio of the particle in their relation. However, as in the Wright *et al* [76] case due to the lack of experimental data this model also could not be validated yet.

1.7 Accretion Modeling Studies in Literature

As recently proposed by Mason *et al* [42] and Veillard [71], ice crystals can penetrate into the engine core, when they cannot be deflected towards the by-pass duct as a result of having large momentum. Moreover, due to the increasing temperature ice crystals start melting on their paths within the aircraft engine. Thus, sticking mechanism works and forms a liquid film which, in turn, is able to capture further ice crystals. This scenario results in reduction of the local surface temperature and, hence, promotes ice accretion. Finally, ice blocks shedding from the forward components can seriously damage the subsequent compressor stages or be ingested into the combustion chamber, thus leading to surge and flame-outs.

Up to now two main approaches are encountered for ice accretion modeling due to water droplets, which are Messinger model and film-based models. In the first one the equilibrium temperature is calculated within the control volume and depending on the predicted temperature icing type and subsequent calculations are decided. Ice and water layers are not modeled separately and neither water film height nor its dynamics are studied. This model is extended to make it applicable for ice accretion prediction problems including ice crystals also. On the other hand, in the second approach

temperature variation within both ice and water layers are modeled. However, second model has not been extended to be used for ice crystal accretion cases up to now.

The pioneering work by Messinger provided a basic model which include energy and mass balance relations onto a surface covered by a water layer [44]. In its original form, the model represents a one-dimensional, equilibrium energy balance to evaluate the equilibrium temperature within the control volume on the surface which exposed to icing. In his approach surface is unheated and insulated. It is further assumed that analyses are based on steady-state computations and transient behavior of the ice accretion are not dealt with. Moreover, water film covering the surface can not break up or separate and residual water on the surface is not modeled, so they have to run towards downstream locations. Later, some improvements have been performed on this model. Compressibility heating has been included and model was modified to be used for anti-icing simulations.

Later, Nimladeen and Habashi [51, 52] have performed some preliminary works including ice crystals in their analyses also which can be counted as initial attempts for Extended Original Messinger Model. They developed a model for mixed phase conditions including water droplets, ice crystals and air. Moreover, Rios Pabòn uses Vidaurre's experiments [72] to implement a new model based on initial ice crystal shatter and melting over a stator blade surface. Due to the limited number of experimental tests, accuracy of the model predictions are questionable. Then, thanks to the visual observations performed by Al-Khalil [11] and Lozowski [40], ice crystal accretion phenomena have taken attraction of the icing researchers. Moreover, Villedieu *et al* [73] and Trontin *et al* [73] have used extended version of the Messinger model and made some improvements by modeling water and ice accumulation rates separately. The final extended ice crystal accretion model has been validated against experimental [11] and numerical [43] data on a NACA 0012 airfoil in COX tunnel facility and an unheated non rotating cylinder in NRC tunnel facility.

On the other hand, using lubrication theory in ice accretion prediction studies were first proposed by Bourgault *et al* [16]. Later, more comprehensive study accounting for heat conduction in both ice and water layers and modeling also gravity, pressure gradient on the surface, capillary forces and surface curvature have been introduced

by Myers [47] and then developed in a series of paper by him and several colleagues [48, 50, 49, 18]. Film models for ice accretion applications have also been widely focused on with a more theoretical point of view by Rothmayer and his colleagues [62, 69, 70, 55]. The extension to mixed phase of the two-layer model described above has not still been focused on and will be the main concern of this thesis.

1.8 Numerical Methods

Two different numerical approaches can be used while performing particle trajectory calculations. First one is named as Lagrangian and it deals with individual particles by evaluating forces and moments on the particle. Each particle which trajectory calculations starting from release point till to the impact on a wall is taken into account separately. On the other hand, second one is referred to as Eulerian and it deals with the particles passing through the control volume which can be fixed or moving. Mass and energy balance equations are solved for a set of conservative variables. Eulerian description is usually preferred in aerodynamics. Note, however, that the physical laws such as Newton's laws and the laws of conservation of mass and energy apply directly to particles and easier to deal with in a Lagrangian description. Selection of the method generally depends on the application. Usage of the both methods are very common in existing icing codes and both have advantageous and disadvantageous which will be discussed below in the separate parts. More information can be found in studies of Durst *et al* [26], Crowe *et al* [22], Loth [39] and Wachen *et al* [77].

1.8.1 Lagrangian Methods

Lagrangian method has been used for a large range of icing applications [58, 63, 46] and preferred in a lot of ice accretion prediction codes including TAICE. NASA tools, ONERA tools and CANICE can be count among these codes. Moreover, as Wright *et al* [76] noted in his study, being one of the ice crystal accretion prediction tools, Lagrangian method is used in GlennICE. Again according to Wright *et al* [76] due to small liquid and ice water content values, particle with air and particle with another particle interactions can be neglected. This makes Lagrangian icing tool to couple

with Eulerian flow solver easier. The only information that the icing code needs from flow solver are the flowfield variables to compute relative motion of the particle.

Trajectory calculations are easier when each particle is followed separately. At each time step net forces and moments are integrated to calculate the next location of the particle. Moreover, accurate trajectory prediction is possible with lower time steps and by taking into consideration the heat transfer between surrounding. Furthermore, turbulence effect on particle trajectories can be partly accounted by coupling with a Navier-Stokes solver. Thus, random fluctuating velocity components can be taken into consideration. However, it is not sufficient for correctly modeling of turbulence effects. Since in most of the icing applications particles are equally distributed in the flowfield, accuracy of the turbulence effect on particles are questionable.

On the other hand, when dispersed phase is dense and when the flow is complex, tracking each individual particle becomes computationally expensive and this can be counted in cons side of the method. Moreover, another disadvantage is that a large number of particles is needed to solve the mass balance equation to compute an appropriate density field everywhere.

1.8.2 Eulerian Methods

Eulerian approach is generally preferred for modeling fluid flows. However, they are not as common as Lagrangian tools in icing applications. Only few of the icing tools have used Eulerian Methods in their computations. NTI code [53] and CIRA code [36] can be counted among these tools. Moreover, ONERA has also Eulerian code in addition to the Lagrangian ones [45]. In an Eulerian approach, transport equations are solved for momentum and volume fractions and pressure, velocity, and all other flow properties are described as fields within the control volume. In other words, each property is expressed as a function of space and time. The Eulerian approach provides a description of the average of the properties of the dispersed phase inside an averaging volume. Thus, this could be an advantage for a dense dispersion and when solution requires a large number of particles. However, since it is not possible to deal with each particle separately, averaging the particle behaviors causes loss in accuracy. In icing applications when numerical schemes in 3D Eulerian droplet solvers are dealt

with, it is seen that mainly they are based on Finite Volume [67, 46] or Finite Element methods [17]. Moreover, some algorithms are proposed in the study of Tong *et al* [67] to solve well-known problems when particle behavior is focused on.

1.9 High Altitude Ice Crystals Project

High Altitude Ice Crystals is an integrated European union 7th framework program which aims at enhancing safer flights within mixed phase and glaciated icing conditions. Having identified the regulation changes according to these particular icing conditions, the HAIC project have provided the necessary acceptable means of Compliance and appropriate ice particle detection and awareness technologies to the Aeronautics industry for commercial aircrafts. The project is coordinated by AIRBUS and divided into 7 sub-projects as shown in Figure 1.7. The constructed consortium have 34 partners from 11 European countries including Turkey. Moreover, 5 international partners from the rest of the world have contributed the project as advisors. The project started in August 2012 and completed in January 2017 in 4.5 years [2].

One of the objectives of the HAIC project is to develop the acceptable means of Compliance through the understanding and modeling of the specific physical phenomena. Another objective is to use the enhanced models in icing applications in industry. Thus, aircraft and engine manufacturers including TAI is invited to the project to evaluate the developed models in industrial programs. The role of TAI is to contribute cross validation of the numerical tools by making use of performed experiments and generated models within SP6 work-package which is named as “high ice water content tools and simulation development”. Within this work-package several benchmark test cases have been solved to verify and validate numerical models developed for ice crystal trajectories, impingement and accretion. At the end of the project the activities within SP6 have reached 5th Technology Readiness Level (TRL) which means that resulting methods are validated in relevant environments. In addition to the models implementations, the unique aspect of this thesis study is to further extension of the Messinger Model which is out of scope of this project. Thus, it is aimed that improvements in the predictions which are discussed in this thesis will cause the other researchers to focus on this extended version of the Messinger Model [2].

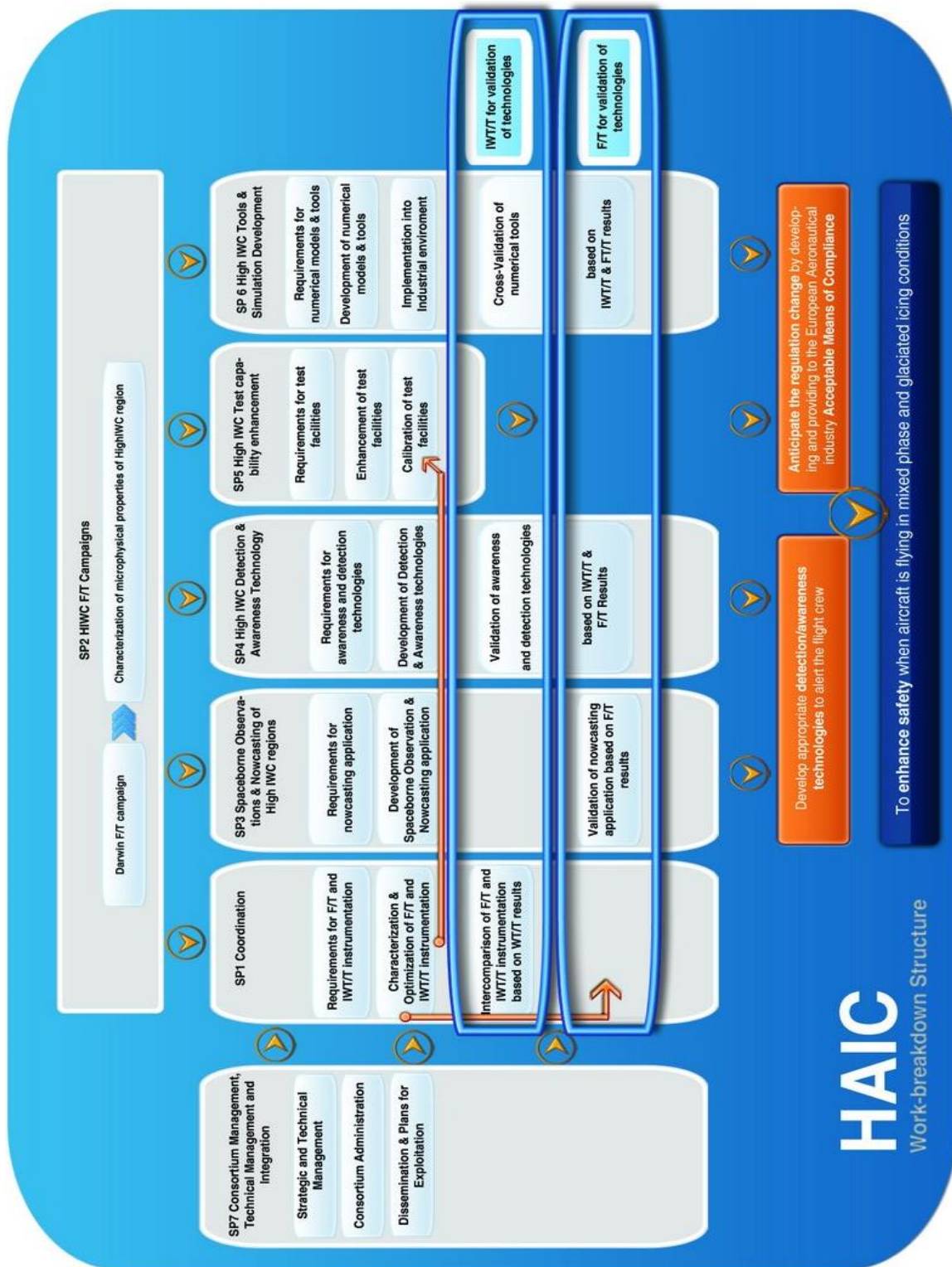


Figure 1.7: HAIC project work breakdown adopted from <http://www.haic.eu> [4].

CHAPTER 2

THEORY

In this section, the method which is used for solution of the flow variables is discussed first. Then, particle trajectory calculations are detailed for droplet and ice crystals separately. Having identified the ice crystal geometrical properties this part is completed by focusing on details of the each implemented models specific to ice crystal accretion. The flowchart of the developed computational tool is presented in Figure 2.1.

2.1 Flow Field Solution: Hess-Smith Panel Method

In this thesis Hess-Smith panel method is used to determine the flow velocity components required for droplet trajectory calculations and the velocity distribution around the airfoil for boundary-layer calculations. The ice accretion prediction code can be coupled with high fidelity flow field solver. However, it is reported that using such a solver does not improve accuracy and it causes enormous increase in computational time [19].

There are many choices for how to formulate a panel method (singularity solutions, variation within a panel, singularity strength and distribution, etc.) but in this study the body is divided into quadrilateral panels, each having a constant strength source singularity element plus a vortex singularity that is constant for all panels. The developed computer program uses N quadrilateral panels to solve for N singularity strengths using the flow tangency boundary condition at the collocation points of the panels. The collocation points are the centroids of each panel. Same approach is

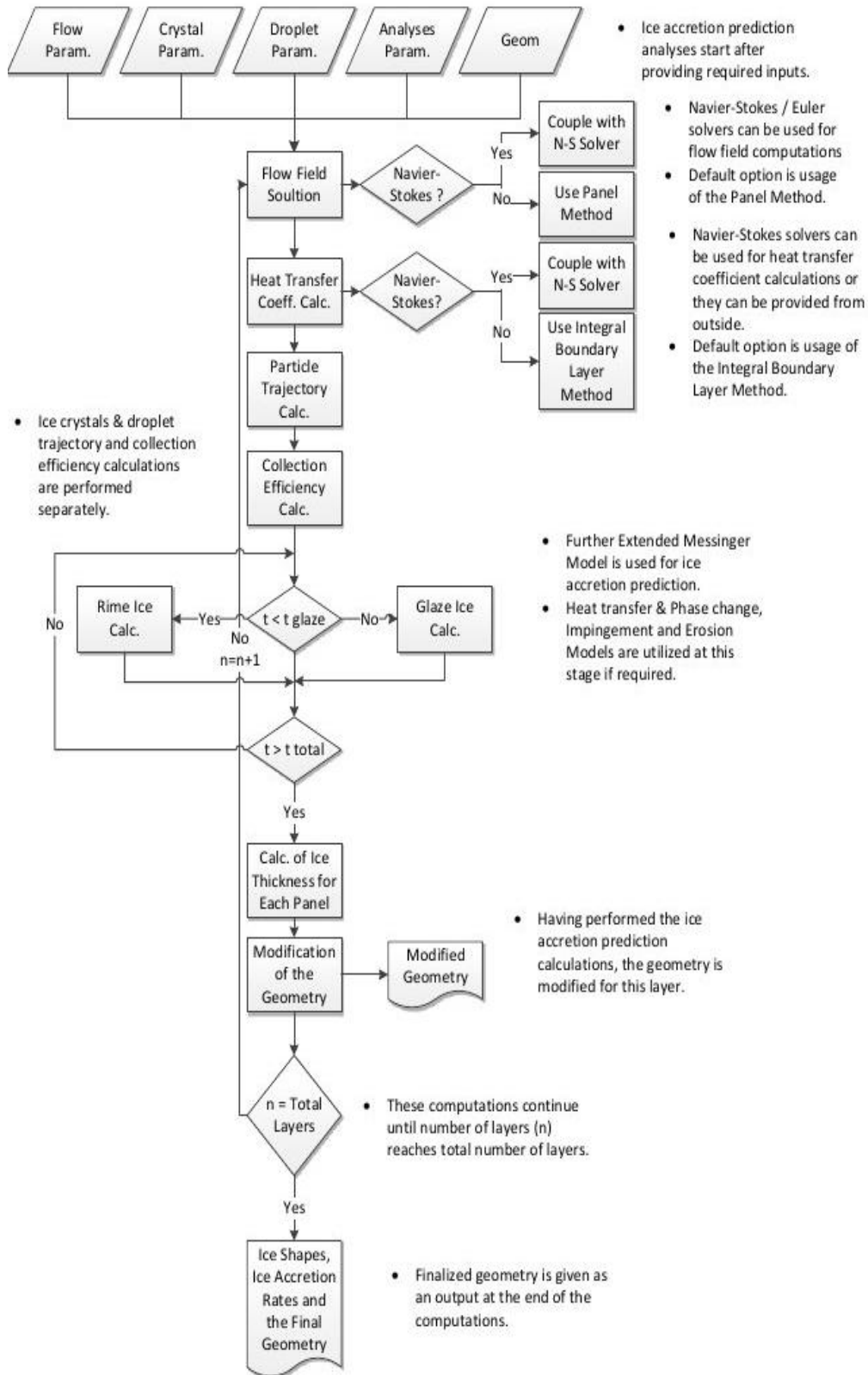


Figure 2.1: Flowchart of the mixed phase icing prediction computational tool, TAICE.

followed for both 2 and 3 dimensional codes. This provides the velocity potential at any point in the flow field. The derivatives of the velocity potential are the velocity components at a given point in the flow field. It should be added that there is no turbulence in the flow and for the upstream flow, inviscid assumption is made. Moreover, panel method is used also while calculating heat transfer coefficients for which velocity distribution around the body is required.

Pressure coefficient comparisons with experimental data for NACA 23012 airfoil at $\alpha = -0.27^\circ$ are shown in Figure 2.2 and the results are accepted as accurate enough for the purpose of this study [56].

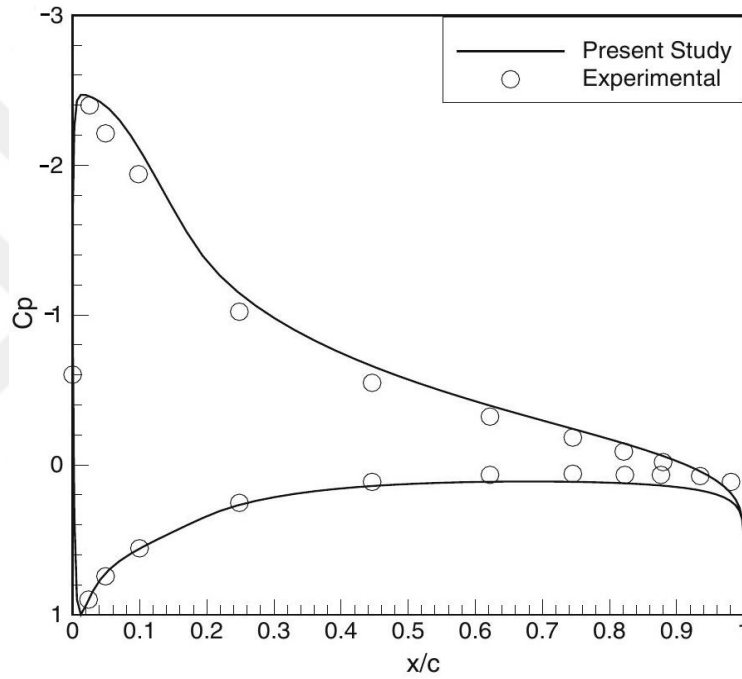


Figure 2.2: Comparison of pressure distributions obtained by Panel method and experimental data. NACA 23012 at $\alpha = -0.27^\circ$ [56].

2.2 Particle Trajectories and Collection Efficiencies

The equations governing droplet and crystal trajectories are identical. However, the models used for drag coefficients and heat transfer differs between liquid and solid cloud particles. The differences are pointed out below, where appropriate. The following assumptions are made for the particles:

- Droplet sizes are small and they remain spherical,
- The presence of cloud particles has no effect on the flow field,
- Gravity and aerodynamic drag are the only forces acting on the cloud particles.

Thus, the governing equations for particle motion in Cartesian coordinates are:

$$m_p \ddot{x} = -D \cos \gamma, \quad (2.1)$$

$$m_p \ddot{y} = -D \cos \gamma + mg, \quad (2.2)$$

$$\gamma = \arctan \frac{\dot{y}_p - V_y}{\dot{x}_p - V_x}, \quad (2.3)$$

$$D = \frac{1}{2} \rho V^2 C_D A_p, \quad (2.4)$$

$$V = \sqrt{(\dot{x}_p - V_x)^2 + (\dot{y}_p - V_y)^2}. \quad (2.5)$$

In above expressions C_D is drag force coefficient, V_x and V_y are velocity components of the particle.

2.2.1 Liquid Droplets

Drag force coefficient due to resistance the relative velocity of the droplets is calculated with the following model as Gent *et al* [28] suggested.

$$C_D = \left(\frac{1}{24} \right) \begin{cases} 1 + 0.197 Re_p^{0.63} + 2.6 \times 10^{-4} Re_p^{1.38}, & \text{if } Re_p \leq 3500 \\ (1.699 \times 10^{-5}) Re_p^{1.92}, & \text{if } Re_p > 3500 \end{cases} \quad (2.6)$$

$$Re_p = \frac{\rho_a d_p V_{rel}}{\mu} \quad (2.7)$$

where V_{rel} is the relative velocity of the particle and μ is the dynamic viscosity. Sutherland viscosity law is used for calculating this parameter.

2.2.2 Ice Crystals

Concerning ice particle trajectories, having in mind the scenario proposed by Mason *et al* [42], all aspects of the modeling problem are tried to be addressed in this chapter.

The influence of the shape on the efforts exerted by the carrier fluid on the particle is considered. Moreover, this study also focuses on heat exchange modeling by taking into consideration the influence of the particle shape on the Nusselt number and deals with phase change phenomena.

Ice crystals are formed generally within the tropical clouds and may have various shapes. They differ from droplets in terms of their shape and they do not have to be exact spherical. Thus, for accurate prediction of the trajectories, drag force coefficient, heat transfer and phase change models should be modified for non-spherical particles in order to be used for ice crystals. Required models are depicted along the trajectory in Figure 2.3. Before discussing these models in detail, geometrical properties of ice crystals will be given below.

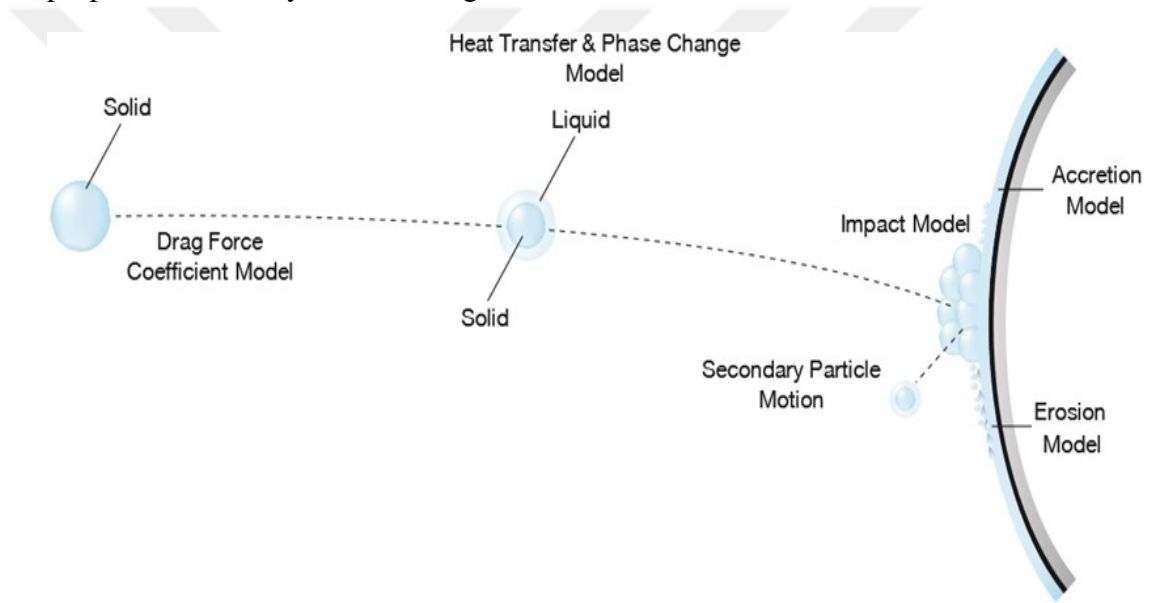


Figure 2.3: Models related to mixed phase icing starting from the release point till to the accretion on the surface.

2.2.2.1 Geometric properties of ice crystals

It is realized that ice crystals may have various and complex shapes. Thus, some geometrical parameters are required to define the shape of the particles. Volume equivalent diameter, d_p , is the most important one.

$$d_p = \sqrt[3]{\frac{6v_p}{\pi}} \quad (2.8)$$

where v_p is the volume of the ice crystal particle. Moreover, sphericity, which is a measure of how round an object should be introduced.

$$\phi = \frac{\pi d_p^2}{A_s} \quad (2.9)$$

In the above relation, A_s denotes the surface area of the particle and by definition $\phi \in [0, 1]$. Another parameter which is related with the orientation of the particle, is crosswise sphericity and can be specified as follows:

$$\phi_{\perp} = \frac{\pi r_p^2}{A_{\perp}} \quad (2.10)$$

where $A_{\perp}$ is the projected area of the particle with respect to the flow.

Calculation of sphericity and crosswise sphericity are generally given in terms of another two important parameters which are aspect ratio E and eccentricity e . They can be specified as follows:

$$E = \frac{d_1}{d_2} \quad (2.11)$$

$$e = \sqrt{1 - \min\left[\frac{d_1}{d_2}, \frac{d_2}{d_1}\right]^2} \quad (2.12)$$

where d_1 and d_2 are diameters of the particle parallel and perpendicular to the revolution axis, respectively. In these equations aspect ratio is used for classification of the spheroid geometry as oblate ($E < 1$) or prolate ($E > 1$). Sample shapes for both types are shown in Figure 2.4. Thus sphericity for oblate particles:

$$\phi = \frac{4E^{2/3}}{2 + E^2 e^{-1} \ln((1 + e)(1 - e)^{-1})} \quad (2.13)$$

and for prolate particles:

$$\phi = \frac{2E^{2/3}}{1 + Ee^{-1} \arcsin e} \quad (2.14)$$

During the trajectory of the particle, it is assumed that once they reach to a stable orientation they stay in this orientation. Thus, crosswise sphericity can be reduced to following relations for oblate and prolate particles respectively:

$$\phi_{\perp} = E^{2/3} \quad (2.15)$$

$$\phi_{\perp} = E^{-1/3} \quad (2.16)$$

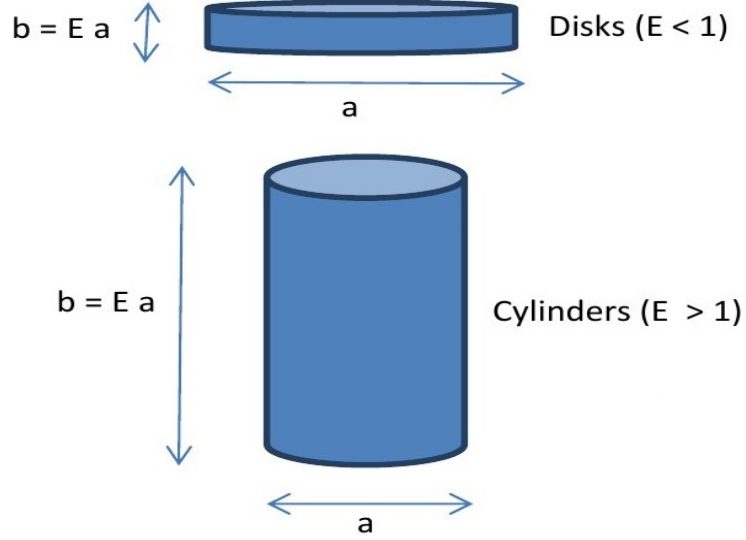


Figure 2.4: Oblate and prolate definitions which are used for classification of the non-spherical particles.

2.2.2.2 Drag force coefficient models

Since ice crystal particles may not have to be spherical, lift force can appear depending on the orientation of the particle. Moreover, particle may rotate and change its orientation during the trajectory. However, in order to reduce the computational cost of the analyses it is assumed that particle travels with fixed orientation without rotating. In literature it is possible to find several drag force coefficient models but only some of them are applicable to non-spherical particles. In this thesis only mostly used models will be discussed.

Haider and Levenspiel suggest a model in terms of ϕ and Re_p and it is supposed to be valid for the particles having crosswise sphericity around 1 [29]:

$$Re_p = \frac{\rho_a d_p V_{rel}}{\mu} \quad (2.17)$$

where ρ_a is air density and V_{rel} is the relative velocity of the particle and μ is the dynamic viscosity.

$$C_d = \left[\frac{24}{Re_p} \left[1 + a(Re_p^b) \right] \right] + \frac{c Re_p}{Re_p + d} \quad (2.18)$$

Following terms should be defined:

$$a = \exp(2.4486\phi^2 - 6.5481\phi + 2.3288) \quad (2.19)$$

$$b = 0.5565\phi + 0.0964 \quad (2.20)$$

$$c = \exp(-10.2599\phi^3 + 18.4222\phi^2 - 13.8944\phi + 4.905) \quad (2.21)$$

$$d = \exp(15.8855\phi^3 - 20.7322\phi^2 + 12.2584\phi + 1.4681) \quad (2.22)$$

In the previous relation, crosswise sphericity $\phi_\perp$ is not included. Thus, Ganser [27] has suggested another model which also takes crosswise sphericity into consideration.

$$C_d = \left[\left[(24/Re_p^*) (1 + 0.1118Re_p^{*0.6567}) \right] + \frac{0.4305Re_p^*}{Re_p^* + 3305} \right] C_{d,ct} \quad (2.23)$$

$$Re_p^* = \frac{Re_p}{\frac{2}{3}\phi^{-1/2} + \frac{1}{3}\phi_\perp^{-1/2}} C_{d,ct} \quad (2.24)$$

$$\log C_{d,ct} = 1.8148 (-\log \phi)^{0.5743} \quad (2.25)$$

Moreover, an additional drag model including $\phi_\perp$ is suggested by Hölzer and Sommerfeld [35]:

$$C_d = \frac{8}{Re_p} \frac{1}{\phi_\perp^{1/2}} + \frac{16}{Re_p} \frac{1}{\phi^{1/2}} + \frac{3}{Re_p^{1/2}} \frac{1}{\phi^{3/4}} \quad (2.26)$$

2.2.2.3 Heat transfer and phase change models

Temperature of the particles may change due to the heat transfer between particle and surrounding along the trajectory of the ice crystals. Moreover, if their temperature increases up to melting point, they may even change phase before impinging to the surface. Since this may lead to change in accumulated ice on the surface, it should be taken into consideration. Nusselt number which is a measure of the ratio between heat transfer by convection and heat transfer by conduction. In simplest form it can be calculated with the following relation[73]:

$$Nu = \frac{h_t d_p}{k_a} \quad (2.27)$$

Here h_t refers to the heat transfer coefficient and k_a refers to air heat conductivity. Moreover, general form of the heat transfer equation in the absence of phase change relations:

$$m_p c_p \frac{dT_{p,m}}{dt} = \pi d_p \frac{Nu}{\phi} k_a (T_a - T_{p,s}) \quad (2.28)$$

where m_p refers to particle mass, c_p is specific heat capacity, T_a is air temperature, $T_{p,m}$ is the mean particle temperature and $T_{p,s}$ is the particle surface temperature. On the other hand, the Nusselt number formulation can be defined in terms of ϕ , $\phi_\perp$, Re and Pr :

$$Nu = 1.76 + 0.55\phi Re_p^{1/3} Pr^{1/3} \phi_\perp^{3/400} + 0.014 Re_p^{1/3} Pr^{1/3} \left(\frac{\phi}{\phi_\perp} \right)^{36/5} \quad (2.29)$$

Moreover another important dimensionless parameter should be introduced here, which is Prandtl number. It is basically the ratio of diffusion of momentum to diffusion of heat in a fluid and can be calculated with the following relation:

$$Pr = \frac{\mu C_p}{k} \quad (2.30)$$

Theoretically Equation 2.29 can be applied to all particles. However, when aspect ratio is less than 0.8, this relation produces unrealistic results. Thus, Villedue *et al* [73] suggested an extension of the Frossling correlation and can be applied to all particles.

$$Nu = 2\phi^{1/2} + 0.55 Pr^{1/3} \phi^{1/4} Re_p^{1/2} \quad (2.31)$$

Heat transfer equations can be divided into three parts according to Mason's study [42]. Before passing to the relations, assumptions should be discussed.

1. Ice core temperature is constant during melting phase and equal to T_f .
2. Melting process begins when ice core temperature of the particle reaches T_f .
3. Ice core is spherical and concentric.
4. Heat transfer between ice core and surrounding liquid film is purely conductive.
5. The ice crystals do not shed their liquid film during the melting phase.

Starting from Mason's study many improvements have been performed on this model. Rasmussen *et al* [60] take eccentric location of the ice core and influence of an internal circulation into consideration. Furthermore, Villedue *et al* [73] include the effect of non-sphericity and noted decrease in the melting time.

- When $T_p < T_f$, ice crystal temperature increases up to melting temperature. Particle mass may change by sublimation in this step and can be calculated as follows:

$$\frac{dm_p}{dt} = -\pi d_p \frac{Sh}{\phi} \rho_a D_{v,a} (y_{v,s} - y_{a,s}) \quad (2.32)$$

In above relation $D_{v,a}$ is vapor diffusivity in the air and Sh is the Sherwood number and can be calculated with Chilton-Colburn analogy. Again in the same relation $y_{v,s}$ and $y_{a,s}$ are vapor mass fractions at particle surface and at free stream respectively.

$$D_{v,a} = 0.0000226 \left(\frac{T_p}{273.15} \right)^{1.81} \left(\frac{10000}{P_a} \right) \quad (2.33)$$

$$Sh = 2\phi^{1/2} + 0.55 Sc^{1/3} \phi^{1/4} Re_p^{1/2} \quad (2.34)$$

$$y_{v,s} = \frac{M_v}{M_m} \frac{P_{sat} T_{p,s}}{P_a} \quad (2.35)$$

$$y_{v,a} = \frac{M_v}{M_m} \frac{P_{sat} T_a RH}{P_a} \quad (2.36)$$

where M_v and M_m are molar masses of vapor and mixture respectively, RH is relative humidity, P_a is static air pressure, $P_{sat}(T_{p,s})$ is the saturated pressure on the particle surface and $P_{sat}(T_a)$ is the saturated air pressure at T_a . Moreover, Sc is Schmidt number and can be calculated with the following relation including kinetic viscosity, ν :

$$Sc = \frac{\nu}{D_{v,a}} \quad (2.37)$$

Moreover, saturated pressure relations in Pa over ice and over water are:

$$P_{sat,w}(T) = \exp(-6024.53T^{-1} + 29.32) \times \exp(1.06 \times 10^{-2}T - 1.32 \times 10^{-5}T^2 - 0.49 \ln T) \quad (2.38)$$

$$P_{sat,i}(T) = \exp(-6093.94T^{-1} + 24.10) \times \exp(2.71 \times 10^{-2}T + 1.67 \times 10^{-5}T^2 - 2.43 \ln T) \quad (2.39)$$

Thus, by assuming constant particle density ρ_p , the final heat transfer equation becomes:

$$\frac{\pi\rho_p d_p^3}{6} C_i \frac{dT_p}{dt} = \pi d_p \frac{Nu}{\phi} k_a (T_a - T_p) - \dot{m}_{sub} (L_f + L_v) \quad (2.40)$$

In above relation L_f and L_v are latent heat of fusion and latent heat of evaporation at particle temperature.

- When $T_p = T_f$, particle starts to melt at melting temperature and is surrounded with concentric water film. Moreover, particle mass may reduce due to evaporation and this step continues until ice particle is completely melted. At the end of this step particle becomes completely spherical. Thus, heat transfer relation is:

$$\pi d_p \frac{Nu}{\phi} k_a (T_a - T_f) = \dot{m}_{ev} L_v + \dot{m}_f L_f \quad (2.41)$$

where, $\dot{m}_{ev}$ is evaporation rate and can be calculated with the following relation:

$$\dot{m}_{ev} = -\frac{dm_p}{dt} = \pi d_p \frac{sh}{\phi} \rho_a D_{v,a} (y_{v,s} - y_{a,s}) \quad (2.42)$$

Reduction in the mass of ice may directly related with the melting rate as follows:

$$m_{p,i} = \frac{\pi\rho_{p,i} d_{p,i}^3}{6} \quad (2.43)$$

$$\dot{m}_f = -\frac{dm_{p,i}}{dt} \quad (2.44)$$

- In the final step, when $T_p > T_f$, particle is completely spherical and droplet temperature increases starting from melting point. In this step, mass of the particle may reduce by evaporation. Thus, when evaporation rate is considered in the heat transfer relation, the final equation will be as follows:

$$m_p C_w \frac{dT_p}{dt} = \pi d_p Nu k_a (T_a - T_p) - \dot{m}_{ev} L_v \quad (2.45)$$

2.3 Impingement Model for Ice Crystals

2.3.1 Calculation of Deposition Probability

Impinging ice crystals on a surface may lead to three different scenarios which are sticking, bouncing and shattering. Impact model which is discussed at this section is mainly based on HAIC experiments and literature data [11].

In bouncing and sticking regimes, particle size and shape do not change after impact. However, it may split into smaller particles in shattering regime. In bouncing regime, particles just bounce off from the wall and re-emitted to the flow. On the other hand, in sticking regime particle adheres to the wall completely.

As it is depicted in Figure 2.5, behavior of the ice crystals depends on the existence of water layer on wall and ice crystal surfaces. Increase in water film thickness height on wall surface or melting of the ice crystals during their trajectories enhances the sticking possibility of the particles. Initially when there is no ice or water accreted on the surface. Only water droplets and partially melted ice crystals may stick to the wall which is shown in the upper part of the figure. Then due to the impinging water droplets and partially melted ice crystals, ice accretion starts on the surface. This process, which is referred as rime ice condition, continues till the ice layer surface temperature reaches to melting temperature. Again pure solid ice crystals could not stick to wall during this process. However, once water starts to accumulate on top of ice layer, which is shown in lower right side figure as glaze ice condition, solid particles may stick to the wall as well.

This model is based on literature data, experimental results and many simplifying assumptions. Several adjustable parameters are used in order to compensate the lack of data and physical knowledge with respect to the most complex phenomena. The threshold between these regimes depends on the kinetic energy of the particle before impact. Below, a dimensionless number, L which is the ratio of the kinetic energy to the surface energy, is introduced.

$$L = \frac{1}{12} \frac{\pi \rho_p d p^3 v_{pn}^2}{\pi e_\sigma T_p d_p^2} = \frac{1}{12} \frac{\rho_p d_p v_{pn}^2}{e_\sigma T_p} \quad (2.46)$$

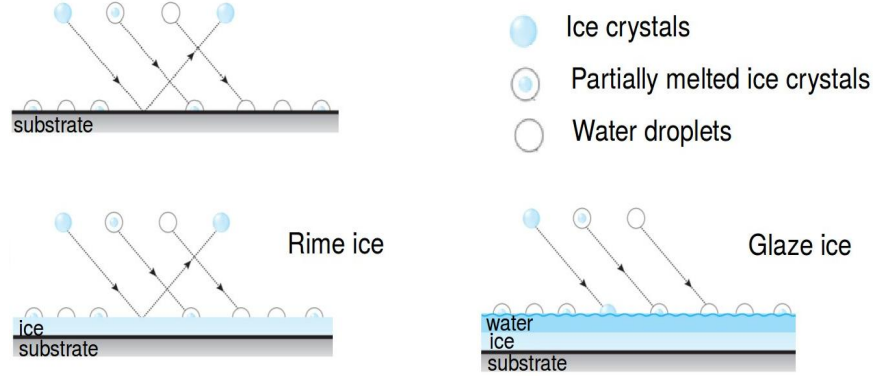


Figure 2.5: Behavior of the ice crystals after impact. Pure solid ones may stick to the wall when there is water film on the wall. Partially melted ones may stick to the wall in all cases.

In above equation, v_{pn} is normal velocity of the particle and e_σ is the surface energy per unit area and can be calculated with the following relation.

$$e_\sigma = e_{\sigma 0} \exp\left(\frac{Q_s}{RT} - \frac{Q_s}{RT_0}\right) \quad (2.47)$$

where Q_s is the activation energy. As it is given in Higa *et al* [34], $Q_s = 4.82 \times 10^4 \text{ J K}^{-1} \text{ mol}^{-1}$ and according to Vidaurre and Hallet [72] $e_{\sigma 0} = 0.12 \text{ J m}^{-2}$ at $T_0 = 253 \text{ K}$. Thus, when $L \geq 90$, high loss of kinetic energy and fragmentation, when $L \leq 0.5$, no fracturing is expected. On the other hand, when it is in between, inelastic bouncing with some particle fragmentation is expected but less kinetic energy loss will occur in this case. These values are determined based on both literature data and Hauk's experimental results[34, 72, 32].

Predicting sticking ratio is the challenging part of this model and simplest relation is suggested by Trontin *et al* [68]. In their study, sticking ratio depends only on the mean melt ratio of the impinging ice crystals and total water content of the flow in their study and they calibrated the model using the NASA-NRC experiments[25, 24, 23]. However, in this study a simplified form of their relation is used:

$$\epsilon_s = K_l \psi_l \quad (2.48)$$

In the above equation, sticking ratio is related with the dimensionless parameter which is K_l and the liquid ratio of the impinging particles. Moreover, according to Trontin

et al [68] in rime ice condition ice crystals do not stick on the surface and K_l should be equal to zero for consistency.

Impinging liquid ratio in total amount of impinging particles are given below.

$$\psi_l = \frac{\dot{m}_{imp,l}}{\dot{m}_{imp,c} + \dot{m}_{imp,l}} \quad (2.49)$$

Moreover, it is observed from the experiments that sticking ratio of the ice crystals increase with increasing ψ_l up to a point. However, further increase does not cause additional increase in the sticking ratio of the ice crystals. Thus, a limitation is introduced here for ψ_l for this purpose. Its value could not exceed 0.2, which is determined during the calibration study. The model which is discussed here considers the possibility for liquid film covering the wall and for the ice particle to be partially melted. The thicker the water film or higher the melting rate is, the larger the mass deposition rate is. In addition the model predicts behavior of secondary particles which are produced in case of bouncing or shattering regimes. The model is mainly empirical and most of the adjustable constants have been fitted thanks to literature and HAIC experimental data.

2.3.2 Prediction of Secondary Particle Behavior

Since bouncing ice crystal particles may cause trouble in downstream, ice crystals trajectory calculations are not finalized when they impact the surface. As it is discussed in the impact model part, in shattering and bouncing regimes particle may be re-emitted to the flow [68].

- Bouncing Regime when $L \leq 90$:
 - Particle bouncing probability is $P_B = 1 - \epsilon_s$
 - Mass flow rate is updated as $\dot{m}'_p = (1 - P_D)\dot{m}_p$
 - Ice core density remains constant, $\rho'_{p,i} = \rho_{p,i}$
 - Sphericity does not change, $\phi' = \phi$
 - Particle diameter does not change $d'_p = d_p$
 - No change in solid and liquid mass fractions $m'_{p,i}/m'_p = m_{p,i}/m_p$

- Secondary particle velocity is $v'_p = \zeta_t^B [v_p - (v_p \cdot \mathbf{n})] - \zeta_n^B (v_p \cdot \mathbf{n})$

In above computations ζ_t^B and ζ_n^B corresponds to the tangential and normal restitution coefficients for bouncing regime respectively. Below model was derived for restitution coefficients [31, 33]:

$$\zeta_t^B = 1 \quad (2.50)$$

$$\zeta_n^B = \begin{cases} 1, & \text{if } L \leq L_{c1} \\ (0.5/L)^{1/3}, & \text{if } L_{c1} \leq L \leq L_{c2} \end{cases} \quad (2.51)$$

- Shattering Regime when $L > 90$:

- Particle bouncing probability is $P_B = 1 - \epsilon_s$
- Mass flow rate is updated as $\dot{m}'_p = (1 - P_D)\dot{m}_p$
- Ice core density remains constant, $\rho'_{p,i} = \rho_{p,i}$
- Sphericity is chosen randomly from the range , $0.7 \leq \phi' \leq 0.9$
- Particle diameter is updated as: $d'_p = \nu d_{max}$

In the last equation ν is a random number between 0 and 1. In addition d_{max} is the largest particle diameter after fragmentation.

$$\frac{d_{max}}{d_p} = \left(\frac{90}{L} \right)^{2/11} \quad (2.52)$$

- No change in solid and liquid mass fractions $m'_{p,i}/m'_p = m_{p,i}/m_p$
- Secondary particle velocity is $v'_p = \zeta_t^F [v_p - (v_p \cdot \mathbf{n})] - (v_p \cdot \mathbf{n})(\zeta_{nt}^F \mathbf{t} + \zeta_{nn}^F \mathbf{n})$

In above computations ζ_t^F is tangential restitution coefficient and ζ_{nt}^F , ζ_{nn}^F are normal restitution coefficients for fragmentation regime respectively. Below model was derived for restitution coefficients:[31][33]

$$\zeta_t^F = 1 \quad (2.53)$$

$$\zeta_{nt}^F = 0.4 \left(1 - \sqrt{\frac{90}{L}} \right) \quad (2.54)$$

$$\zeta_{nn}^F = \left(\frac{0.5}{L} \right)^{1/3} \quad (2.55)$$

2.3.3 Erosion Model

It is observed in experiments that in mixed phase icing conditions upcoming solid particles cause reduction in the amount of accreted ice on the surface [11]. Generally this reduction is much more noticeable in glaze ice conditions. Wright *et al* proposed a model which is given below to predict erosion effect on accreted ice in their study [76]. However, their model has not been validated yet due to the lack of experimental data.

$$\epsilon_{er} = \epsilon_{ct} \left(\frac{d}{d_{ref}} \right)^3 \left(\frac{v_{tang}}{v_{ref}} \right)^{2.25} \left(\frac{IWC}{IWC_{ref}} \right)^{0.2} \left(\frac{\exp\left(14 - \frac{Q}{RT_{surf}}\right)}{\exp\left(14 - \frac{Q}{RT_{ref}}\right)} \right)^{1.25} \quad (2.56)$$

In above relation, ϵ_{er} is by definition refers to erosion rate and its value should be between 0 and 1, ϵ_{ct} is erosion constant, d_{ref} is particle reference diameter, v_{ref} is particle reference velocity, IWC_{ref} is reference ice water content and T_{ref} is reference equilibrium temperature of the panel. Q is activation energy ($Q = 69\,000 \text{ J mol}^{-1}$) and R is perfect gas constant ($R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$). According to the Wright *et al* and after calibration; $\epsilon_{ct} = 0.17$, $d_{ref} = 150 \mu\text{m}$, $v_{ref} = 51.44 \text{ m/s}$, $IWC_{ref} = 0.7 \text{ g/m}^3$ and $T_{ref} = 265.14 \text{ K}$. Inclusion of erosion efficiency in ice accretion calculation relations have been modified as Trontin *et al* [68] suggested for easy implementation and further calibrated in this study.

$$\dot{m}_{er} = \epsilon_{er} \dot{m}_{imp,c} \quad (2.57)$$

In above relation $\dot{m}_{er}$ is the amount of reduced mass rate due to erosion and can be calculated by multiplying erosion efficiency with impinging mass rate. This reduced mass includes both water and ice parts as it is shown below:

$$\dot{m}_{er} = \dot{m}_{er,i} + \dot{m}_{er,w} \quad (2.58)$$

where $\dot{m}_{er,i}$ and $\dot{m}_{er,w}$ are ice and water erosion mass rates respectively and they are related with the total erosion rate which will be detailed in the accretion part. Moreover, it should be noted that reduced mass due to erosion could not be greater than the mass of the impinging ice crystals.[68].

2.4 Convective Heat Transfer Coefficients: Integral Boundary Layer Method

The convective heat loss from the body surface is characterized by a heat transfer coefficient. Integral boundary layer method is used in TAICE for calculating heat transfer coefficients when they are not supplied from an external flowfield solution. Since equations which are used for calculating heat transfer coefficients depend on the flow being laminar or turbulent, transition prediction should be the initial step. According to the Von Doenhoff criterion, transition is fixed at the streamwise location where $Re_k = 600$ where Re_k is the roughness Reynolds number defined as shown below:

$$Re_k = \frac{\rho U_k k_s}{\mu} \quad (2.59)$$

where k_s is roughness height and U_k is local flow velocity at the roughness height location. Following relation can be used for calculating U_k :

$$\frac{U_k}{U_e} = 2 \frac{k_s}{\delta} - 2 \left(\frac{k_s}{\delta} \right)^3 + \left(\frac{k_s}{\delta} \right)^4 + \frac{1}{6} \frac{\delta^2}{\nu_a} \frac{dU_e}{ds} \frac{k_s}{\delta} \left(1 - \frac{k_s}{\delta} \right)^3 \quad (2.60)$$

In above equation s is the streamwise distance along the body with respect to stagnation point and U_e is the edge velocity which corresponds to flow velocity outside the boundary layer at the roughness location. Roughness height is calculated from[74]:

$$k_s = \left(\frac{4\sigma_w \mu_w}{\rho_w} F \tau \right)^{1/3} \quad (2.61)$$

where σ_w is surface tension. Fraction of the body surface that is wetted by water droplets is denoted by F , while τ denotes surface shear stress. Thus, boundary layer thickness is:

$$\delta = \frac{315}{37} \theta_{lam} \quad (2.62)$$

Thwaites formulation can be used for laminar momentum thickness calculation as follows[65]:

$$\frac{\theta_{lam}^2}{\nu} = \frac{0.45}{U_e^6} \int_0^s U_e^5 ds \quad (2.63)$$

According to the Smith and Spalding relation, heat transfer coefficients can be calculated for laminar flow where $Re_k \leq 600$ as follows [28]:

$$h_c = \frac{0.296kU_e^{1.435}}{\sqrt{\nu \int_0^s U_e^{1.87} ds}} \quad (2.64)$$

For turbulent flow, where $Re_k \geq 600$, Kays and Crawford formulation is used [28]:

$$h_c = St \rho U_e C_p \quad (2.65)$$

St is Stanton number and can be calculated as follows:

$$St = \frac{C_f/2}{Pr_{turb} + \sqrt{(C_f/2)/St_k}} \quad (2.66)$$

Where roughness Prandtl number, $Pr_{turb} = 0.9$ and roughness Stanton number St_k is:

$$St_k = 1.92Re_k^{-0.45}Pr_{lam}^{-0.8} \quad (2.67)$$

Where laminar Prandtl number, $Pr_{lam} = 0.72$ and by using the Makkonen relation:

$$\frac{C_f}{2} = \frac{0.1681}{[\ln(864\theta_{turb}/k_s + 2.568)]^2} \quad (2.68)$$

Finally turbulent momentum thickness is:

$$\theta_{turb} = \frac{0.036\nu^{0.2}}{U_e^{3.29}} \left(\int_{s_{tr}}^s U_e^{3.86} ds \right)^{0.8} + \theta_{tr} \quad (2.69)$$

Where θ_{tr} is laminar momentum thickness at transition point.

Heat transfer coefficient distributions are calculated and compared with the given data in LEWICE manual [5]. Corresponding comparisons are depicted in Figures 2.6 and 2.7. Calculations are performed on NACA 0012 airfoil at 129.46 m/s and -12.6°C . Flow angle of attack values are $\alpha = 4^\circ$ and $\alpha = 0^\circ$. It is seen in both comparison cases that although there is a slight difference at transition locations, the obtained data is evaluated as consistent with the given data in LEWICE manual for the purpose of this study.

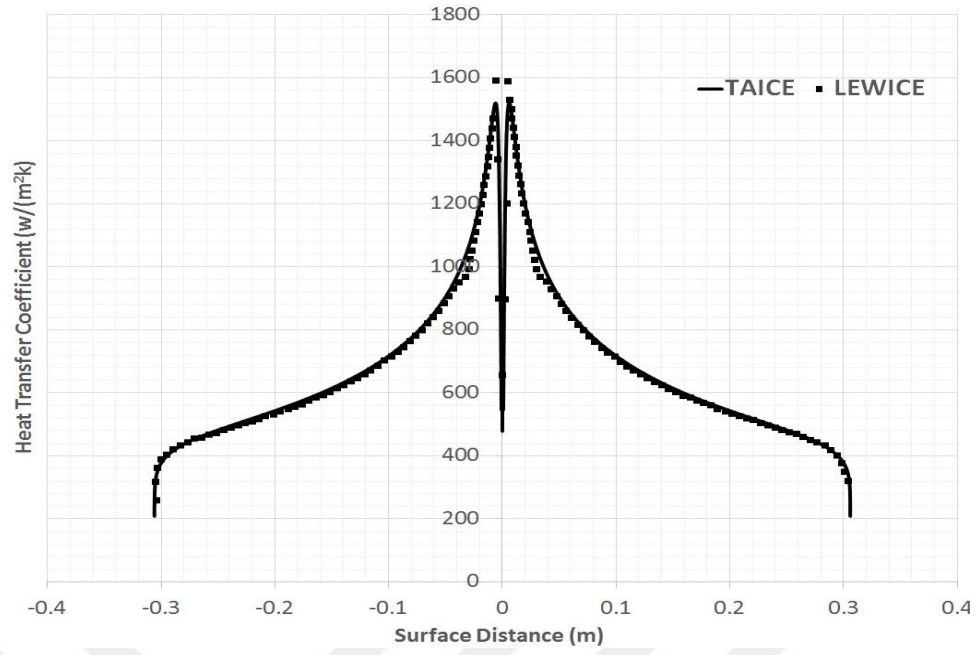


Figure 2.6: Comparison of heat transfer coefficients on NACA 0012 airfoil at $V = 129.46 \text{ m/s}$, $T = -12.6 \text{ }^{\circ}\text{C}$ and at $\alpha = 0^{\circ}$ [5].

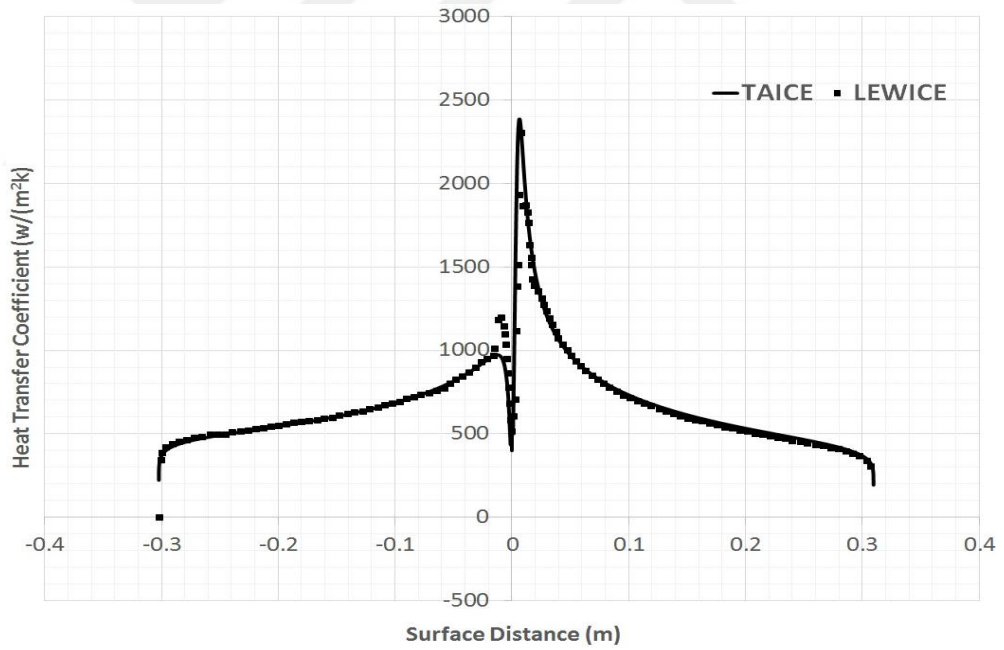


Figure 2.7: Comparison of heat transfer coefficients on NACA 0012 airfoil at $V = 129.46 \text{ m/s}$, $T = -12.6 \text{ }^{\circ}\text{C}$ and at $\alpha = 4^{\circ}$ [5].

2.5 Ice Accretion: Further Extension of the Messinger Model

The proposed extension mainly consisted of modifying the mass and energy balance equations to account for the presence of solid ice crystals among the impinging particles. In its original form, classical Messinger Model represents a one-dimensional, equilibrium energy balance to calculate the equilibrium temperature onto an insulated surface which exposed to icing. In practice, it is evaluated at discrete positions around the leading edge of the body under investigation by using a control volume approach. Main assumptions of the classical Messinger Model is itemized below.

- Ice and water layers are not separately modeled and temperature variation along the layers are ignored.
- Equilibrium temperature is calculated at each discrete panels.
- Water accretion is not predicted. Runback water flows directly downstream.
- Steady-state approach is used and ice accretion rate is constant.

The original model is based on two main equations: the mass and energy balance on the icing surface. The main idea is to find equilibrium temperature of the accreted ice or water layer on each panel. Icing types are determined according to the calculated layer equilibrium temperature. If it is less than melting temperature water could not accumulate on ice layer. Thus, for this case icing condition is accepted as rime. However, when it is equal to melting temperature, icing condition is referred as glaze icing due to the appearing water in addition to the accreted ice. On the other hand, when equilibrium temperature is greater than melting temperature only water can accumulate on the surface which later moves to downward panels. Calculations start with assuming a tentative temperature value and the freezing fraction is computed from the energy balance equation. If the calculated value is not compatible with the initial temperature, than another one is assumed and same calculations are performed until convergence is satisfied.

Later a more comprehensive model including the effect of surface curvature, capillary and pressure gradient has been introduced by Myers. He deal with heat conduction in

both ice and water layers in his model and further developed by himself with several co-workers. [47, 48, 49, 50].

The ice accretion problem is based on the phase change or Stefan problem. According to the Extended Messinger Model, the problem is governed by four equations: energy equations in the ice and water layers, mass conservation equation and the phase change condition at the ice/water interface [47]. Moreover, in this thesis study this model is further extended by including solid ice particles in computations.

$$\frac{\partial T}{\partial t} = \frac{k_i}{\rho_i C_{pi}} \frac{\partial^2 T}{\partial y^2}, \quad (2.70)$$

$$\frac{\partial \theta}{\partial t} = \frac{k_w}{\rho_w C_{pw}} \frac{\partial^2 \theta}{\partial y^2}, \quad (2.71)$$

$$\rho_i \frac{\partial B}{\partial t} + \rho_w \frac{\partial h}{\partial t} = r_l \rho_l \beta_l V_\infty + r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{e,s}, \quad (2.72)$$

$$\rho_i L_f \frac{\partial B}{\partial t} = k_i \frac{\partial T}{\partial y} - k_w \frac{\partial \theta}{\partial y}. \quad (2.73)$$

In equation 2.72, the ice density is assumed to have two distinct values for rime ρ_r and glaze ρ_g ice. Again in the same equation r_l and r_c are sticking ratios of droplets and crystals respectively where $r_c = \epsilon_s$. The coordinate y is perpendicular to the surface. Moreover, the Stefan condition 2.73 which exhibits an energy balance, states that the phase change boundary velocity is related with the temperature gradients across the boundary. In the next step, boundary and initial conditions are defined in order to calculate the temperature distributions in the ice and water layers, which eventually allows calculation of the ice layer and water layer thicknesses [47]:

- (i) It is assumed that ice is in perfect contact with the substrate ($y = 0$), which has high conductivity and a thermal mass much greater than ice. Thus, in this model temperature variation of the substrate is assumed as negligible and at the beginning it has a fixed and known value. Moreover, for ice accretion on the surface, the substrate temperature should not be greater than T_f . Otherwise, only water can accumulate on the surface.

$$T(0, t) = T_{subs} = \begin{cases} T_{rec}, & \text{if } T_{rec} \leq T_f \\ T_f, & \text{if } T_{rec} > T_f \end{cases} \quad (2.74)$$

- (ii) The temperature is continuous at the phase change boundary ($y = B$) and equal to the freezing temperature T_f . This condition is not imposed in rime ice conditions:

$$T(B, t) = \theta(B, t) = T_f. \quad (2.75)$$

- (iii) At the air/ice interface ($y = B$) in rime ice conditions, heat flux is determined by convection Q_{con} , sublimation Q_{sub} , cooling by incoming droplets Q_{cl} , cooling by incoming crystals Q_{cc} , kinetic energy of incoming droplets Q_{kl} , kinetic energy of incoming crystals Q_{kc} , aerodynamic heating Q_{aero} , latent heat release Q_{lat} and energy brought in by runback water Q_{in} :

$$\begin{aligned} -k_i \frac{\partial T}{\partial y} = & (Q_{con} + Q_{sub} + Q_{cl} + Q_{cc}) \\ & - (Q_{aero} + Q_{kl} + Q_{kc} + Q_{lat} + Q_{in}) \text{ at } y = B. \end{aligned} \quad (2.76)$$

In rime ice conditions, the heat terms are expressed as:

$$Q_{con} = h_c [T(B, t) - T_a], \quad (2.77)$$

$$Q_{sub} = \chi_{sub} \left[p_v(T(B, t)) \frac{T_o}{T(B, t)} \left(\frac{p_i}{p_o} \right)^{-1/\gamma} - (RH)p_v(T_a) \frac{p_o}{p_a} \right], \quad (2.78)$$

$$Q_{cl} = r_l \rho_l \beta_l V_\infty C_{pw} [T(B, t) - T_l], \quad (2.79)$$

$$Q_{ccs} = (1 - \eta_{melt}) r_c \rho_c \beta_c V_\infty C_{pi} [T(B, t) - T_c], \quad (2.80)$$

$$Q_{ccl} = \eta_{melt} r_c \rho_c \beta_c V_\infty C_{pw} [T(B, t) - T_c], \quad (2.81)$$

$$Q_{kl} = r_l \beta_l V_\infty \frac{V_{imp,l}^2}{2}, \quad (2.82)$$

$$Q_{kc} = r_c \beta_c V_\infty \frac{V_{imp,c}^2}{2}, \quad (2.83)$$

$$Q_{aero} = r h_c \frac{V_\infty^2}{2C_p}, \quad (2.84)$$

$$Q_{lat} = \rho_r L_f \frac{\partial B_l}{\partial t}, \quad (2.85)$$

$$Q_{in} = \dot{m}_{in} C_{pw} [T_f - \theta(B + h, t)]. \quad (2.86)$$

Some of the heat terms given in previous relations contribute to heat loss and some of them cause heat addition to the control volume as shown in Figure 2.8.

At the air/water interface ($y = B + h$) in glaze ice conditions, heat flux is determined by convection Q_{con} , evaporation Q_{ev} , cooling by incoming droplets

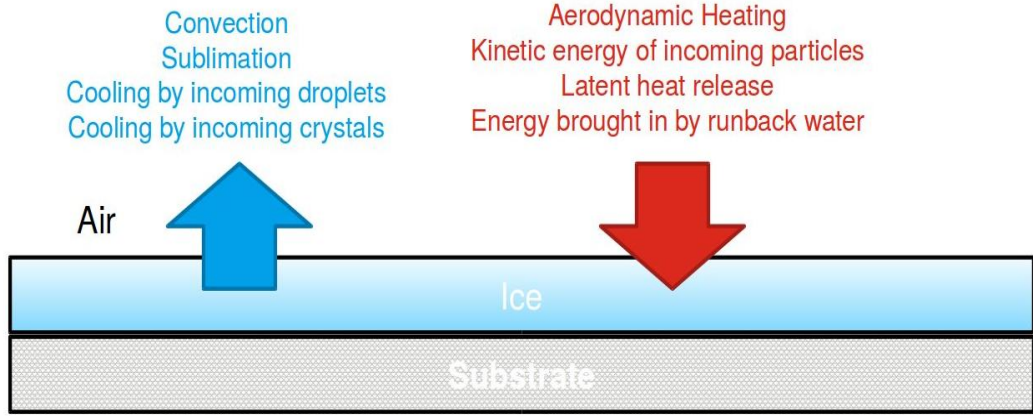


Figure 2.8: Heat loss and heat addition terms in rime ice condition

Q_{cl} , cooling by incoming crystals Q_{cc} , kinetic energy of incoming droplets Q_{kl} , kinetic energy of incoming crystals Q_{kc} , aerodynamic heating Q_{aero} and energy brought in by runback water Q_{in} :

$$-k_w \frac{\partial \theta}{\partial y} = (Q_{con} + Q_{ev} + Q_{cl} + Q_{cc}) - (Q_{aero} + Q_{kl} + Q_{kc} + Q_{in}) \quad \text{at } y = B + h. \quad (2.87)$$

In glaze ice conditions, the heat terms are expressed as:

$$Q_{con} = h_c [\theta(B + h, t) - T_a], \quad (2.88)$$

$$Q_{ev} = \chi_{ev} \left[p_v (\theta(B + h, t)) \frac{T_o}{\theta(B + h, t)} \left(\frac{p_i}{p_o} \right)^{-1/\gamma} - RH p_v(T_a) \frac{p_o}{p_a} \right], \quad (2.89)$$

$$Q_{cl} = r_l \rho_l \beta_l V_\infty C_{pw} [\theta(B + h, t) - T_l], \quad (2.90)$$

$$Q_{ccs} = (1 - \eta_{melt}) r_c \rho_c \beta_c V_\infty C_{pi} [\theta(B + h, t) - T_c], \quad (2.91)$$

$$Q_{ccl} = \eta_{melt} r_c \rho_c \beta_c V_\infty C_{pw} [\theta(B + h, t) - T_c], \quad (2.92)$$

$$Q_{kl} = r_l \beta_l V_\infty \frac{V_{imp,l}^2}{2}, \quad (2.93)$$

$$Q_{kc} = r_c \beta_c V_\infty \frac{V_{imp,c}^2}{2}, \quad (2.94)$$

$$Q_{aero} = r h_c \frac{V_\infty^2}{2 C_p}, \quad (2.95)$$

$$Q_{in} = \dot{m}_{in} C_{pw} [T_f - \theta(B + h, t)]. \quad (2.96)$$

Some of the heat terms given in previous relations contribute to heat loss and some of them cause heat addition to the control volume as in the rime ice case. The only difference is instead of sublimation, evaporation is included in this computation due to the accreted water above ice layer as shown in Figure 2.9.

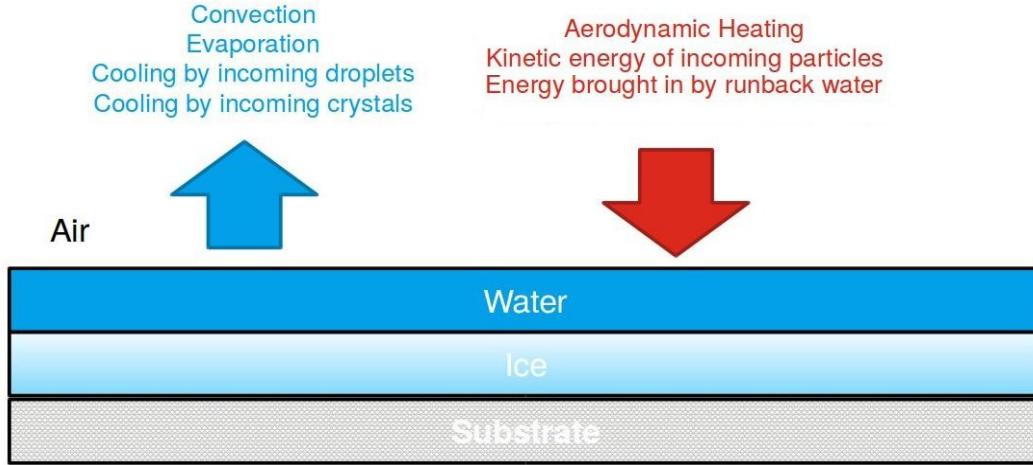


Figure 2.9: Heat loss and heat addition terms in glaze ice condition.

- (iv) Surface ($y = 0$) is initially ($t = 0$) devoid of ice and water:

$$B = h = 0 \quad \text{at} \quad t = 0. \quad (2.97)$$

- (v) Rime ice growth and temperature profile calculation:

In this part two important relations, which are rime ice growth rate and temperature profile variation, are derived. By setting $h=0$ in equation 2.72, ice thickness information at any time could be obtained:

$$B(t) = \frac{r_i \rho_i \beta_i V_\infty + r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}}{\rho_r} t \quad (2.98)$$

The temperature profile in the ice layer is assumed as linear.

$$\frac{\partial^2 T}{\partial y^2} = 0 \quad (2.99)$$

Integrating twice:

$$T(y, t) = a_1 y + a_2 \quad (2.100)$$

Applying equation 2.74 yields:

$$a_2 = T_{subs} \quad (2.101)$$

In order to find a_1 the equation 2.76 is employed.

$$\begin{aligned} -k_i a_1 = & (Q_{con} + Q_{sub} + Q_{cl} + Q_{cc}) \\ & - (Q_{aero} + Q_{kl} + Q_{kc} + Q_{lat} + Q_{in}) \quad \text{at} \quad y = B. \end{aligned} \quad (2.102)$$

Then using equations 2.77 to 2.86 :

$$a_1 = \frac{-h_c [\theta(B, t) - T_a] - r_l \rho_l \beta_l V_\infty C_{pw} [\theta(B, t) - T_l]}{k_i} + \frac{-r_c \rho_c \beta_c V_\infty [(1 - \eta_{melt}) C_{pi} \eta_{melt} C_{pw}] [\theta(B, t) - T_c]}{k_i} + \frac{(Q_{aero} + Q_{kl} + Q_{kc} + Q_{lat} - Q_{sub}) + \dot{m}_{in} C_{pw} [T_f - \theta(B, t)]}{k_i} \quad (2.103)$$

Evaluate equation 2.100 at $y = B$ and by substituting a_1 and a_2 from equations 2.101 and 2.103:

$$T(B, t) = \frac{-(a + b + c + e) T(B, t) + aT_a + bT_b + cT_c + eT_f + d}{k_i} B + T_{subs} \quad (2.104)$$

Solving for $T(B, t)$:

$$T(B, t) = \frac{k_i T_{subs} + (aT_a + bT_l + cT_c + eT_f + d)B}{k_i + (a + b + c + e)B} \quad (2.105)$$

For the calculation of Q_{sub} , vapor pressure needs to be calculated using equation 2.78. This is a function of $T(B, t)$, which is not linear. Therefore, $T(B, t)$ needs to be calculated through an iterative process until convergence in Q_{sub} is reached. Substituting $T(B, t)$ from equation 2.105 back into equation 2.103 yields:

$$a_1 = \left[\frac{-(a + b + c + e)}{k_i} \right] \left[\frac{k_i T_{subs} + (aT_a + bT_l + cT_c + eT_f + d)B}{k_i + (a + b + c + e)B} \right] + \frac{aT_a}{k_i} + \frac{bT_l}{k_i} + \frac{cT_c}{k_i} + \frac{eT_f}{k_i} + \frac{d}{k_i} \quad (2.106)$$

Then after performing some simplifications:

$$a_1 = \frac{[d + b(T_l - T_{subs}) + c(T_c - T_{subs}) + e(T_f - T_{subs})]}{k_i + (a + b + c + e)B} + \frac{-a(T_{subs} - T_a)}{k_i + (a + b + c + e)B} \quad (2.107)$$

Substituting a_1 from equation 2.107 and a_2 from equation 2.101 yields the temperature variation within the ice layer in rime ice condition:

$$T(y, t) = a_1 y + T_{subs} \quad (2.108)$$

(vi) Glaze ice growth ($\partial B_I / \partial t$) and temperature profile within the water layer ($\theta(y, t)$):

While calculating ice growth in the rime ice condition, since all upcoming water droplets and liquid parts of the partially melted ice crystals freeze, water layer does not appear above the ice surface. However, when the ice layer surface temperature reaches to melting point and when water starts to accumulate on the surface, the physical phase of ice crystals becomes a questionable. At this point three different scenarios may occur:

- Depending on the energy transfer between ice crystals and accreted ice and water layers, upcoming ice crystals may completely melt,
- Depending on the energy transfer between ice crystals and accreted ice and water layers, upcoming ice crystals may partially melt,
- If surface temperature is below melting temperature, they may remain solid.

Thus, the melting ratio is an additional unknown and can be predicted by solving energy balance equation. Energy and mass terms which are included in the control volume are depicted in Fig. 2.10.

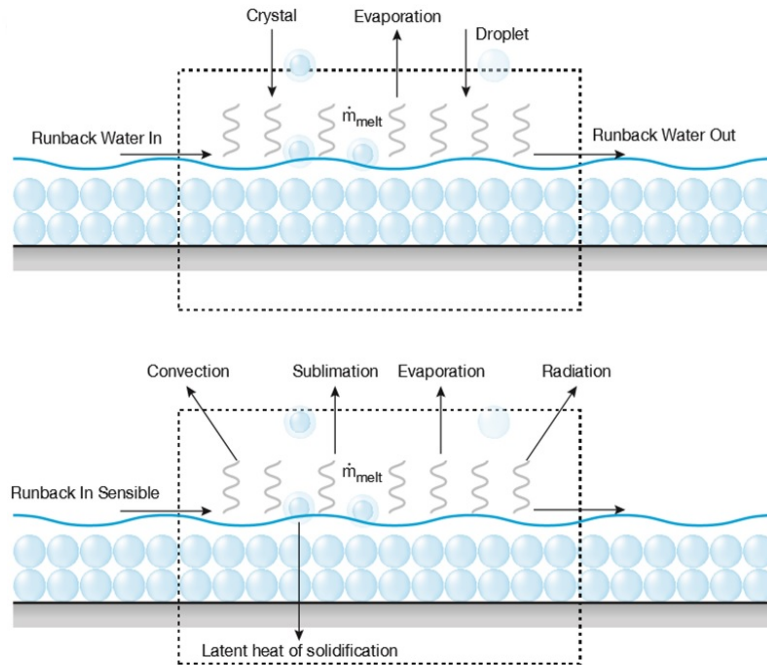


Figure 2.10: Mass and energy terms in the balance equations.

The energy terms that contribute to the energy balance are as follows:

$$\lambda_{h,w} = r_l \rho_l \beta_l V_\infty C_{pw} (T_f - T_l) + \dot{m}_{in} C_{pw} (T_f - T_{in}), \quad (2.109)$$

$$\lambda_{h,i} = (r_c \rho_c \beta_c V_\infty (1 - \eta_{melt}) C_{pi} + r_c \rho_c \beta_c V_\infty \eta_{melt} C_{pw}) (T_f - T_c), \quad (2.110)$$

$$\lambda_{in} = r_l \beta_l V_\infty \frac{V_{imp,l}^2}{2} + r_c \beta_c V_\infty \frac{V_{imp,c}^2}{2}, \quad (2.111)$$

$$\lambda_{out} = h_c (T_{rec} - T_f) + \dot{m}_{ev} L_{ev} \quad (2.112)$$

Inclusion of the heat loss by melting part of the incoming ice crystals causes an imbalance in the energy equation and this must be compensated by additional freezing or melting. Thus, at melting temperature, the remaining energy before computing the melting ratio can be calculated as follows:

$$\lambda_{net} = \lambda_{in} - \lambda_{out} - \lambda_{h,w} - \lambda_{h,i} \quad (2.113)$$

$$\alpha_{melt} = \frac{\lambda_{net}}{r_c \rho_c \beta_c V_\infty L_f} \quad (2.114)$$

Three different scenarios are possible after calculating remaining energy terms which are explained below and shown in 2.11:

- When $\lambda_{net} > 0$ and $\alpha_{melt} < 1$ some energy is available in the control volume and it will melt some part of the ice crystals. Surface temperature of the water layer will be equal to melting temperature.
- When $\lambda_{net} > 0$ and $\alpha_{melt} > 1$ some energy is available in the control volume and all ice crystals will melt. Remaining energy will increase the temperature of the water layer and the surface temperature of the water layer will be greater than melting temperature.
- When $\lambda_{net} < 0$ all upcoming ice crystals will stay as solid even after impact. Surface temperature of the water layer will be less than melting temperature.

Assume that the temperature profile in the ice layer is also linear:

$$\frac{\partial^2 T}{\partial y^2} = 0 \quad (2.115)$$

Integrating twice $T(y,t)$ can be obtained:

$$T(y, t) = a_3 y + a_4 \quad (2.116)$$

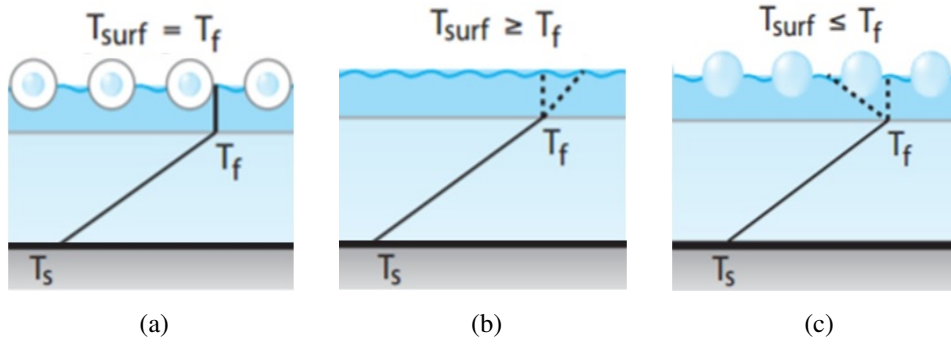


Figure 2.11: Melt ratio prediction scenarios (a) When $\lambda_{net} > 0$ and $\alpha_{melt} < 1$ (b) When $\lambda_{net} > 0$ and $\alpha_{melt} > 1$ (c) When $\lambda_{net} < 0$.

Employing the first condition as defined in 2.74 yields:

$$a_4 = T_{subs} \quad (2.117)$$

Thus, it yields:

$$T_f = a_3 B + T_{subs} \quad (2.118)$$

Assume that the temperature profile in the water layer is linear:

$$\frac{\partial^2 \theta}{\partial y^2} = 0 \quad (2.119)$$

Integrating twice:

$$\theta(y, t) = a_5 y + a_6 \quad (2.120)$$

Employing condition 2.70 yields:

$$T_f = a_5 B + a_6 \quad (2.121)$$

In equation 2.121, there is no need to calculate a_5 when the temperature of the water layer surface is equal to melting temperature which corresponds to $0 < \alpha_{melt} < 1$ case. However, for other cases, the condition defined in 2.74 needs to be imposed:

$$\begin{aligned} -k_w a_5 = & (Q_{con} + Q_{ev} + Q_{cl} + Q_{ccs} + Q_{ccl}) \\ & - (Q_{aero} + Q_{kl} + Q_{kc} + Q_{in}) \end{aligned} \quad (2.122)$$

Substituting Q_{con} , Q_{ev} , Q_{cl} , Q_{ccs} , Q_{ccl} and Q_{in} from equations 2.88 to 2.96:

$$\begin{aligned} k_w a_5 = & -r_c \rho_c \beta_c V_\infty \left[(1 - \eta_{melt}) C_{pi} + \eta_{melt} C_{pw} \right] [\theta(B + h, t) - T_c] \\ & - r_l \rho_l \beta_l V_\infty C_{pw} [\theta(B + h, t) - T_l] + (Q_{aero} + Q_{kl} + Q_{kc} - Q_{ev}) \\ & - h_c [\theta(B + h, t) - T_a] + \dot{m}_{in} C_{pw} [T_f - \theta(B + h, t)] \end{aligned} \quad (2.123)$$

then a_5 can be obtained as follows:

$$a_5 = \frac{-(a + b + c + e)\theta(B + h, t) + aT_a + bT_l + cT_c + eT_f + d}{k_w} \quad (2.124)$$

Evaluating equation 2.121 at $y=B+h$, substituting a_5 from equation 2.124:

$$\begin{aligned} \theta(B + h, t) = & T_f + \\ & \frac{-(a + b + c + e)\theta(B + h, t) + aT_a + bT_l + cT_c + eT_f + d}{k_w} h \end{aligned} \quad (2.125)$$

Solving for $\theta(B + h, t)$:

$$\theta(B + h, t) = \frac{k_w T_f + (aT_a + bT_l + cT_c + eT_f + d)h}{k_w + (a + b + c + e)h} \quad (2.126)$$

For the calculation of Q_{ev} , vapor pressure needs to be calculated using equation 2.89. This is a function of $\theta(B + h, t)$, which is not linear. Therefore, $\theta(B + h, t)$ needs to be calculated through an iterative process until convergence in Q_{ev} is reached.

Substituting $\theta(B + h, t)$ from equation 2.126 back into equation 2.123:

$$\begin{aligned} a_5 = & \frac{a(T_a - T_f) + b(T_l - T_f) + c(T_c - T_f) + d}{k_w + (a + b + c + e)h} \\ & + \frac{e(T_{in} - T_f) + f(T_a - T_f)}{k_w + (a + b + c + e)h} \end{aligned} \quad (2.127)$$

Therefore equation 2.120 could be calculated as follows which gives information about temperature variation within the water layer:

$$\theta(y, t) = a_5 y + T_f \quad (2.128)$$

By using equation a_5 from 2.127 and integrating equation 2.72 yields:

$$\begin{aligned} h = & \frac{r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \alpha_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{ev}}{\rho_w} (t - t_g) \\ & - \frac{\rho_g}{\rho_w} (B_l - B_g) \end{aligned} \quad (2.129)$$

This integration involves B_g and t_g constants which are the ice thickness and time at which water first appears. Substituting equation 2.98 and 2.129 into equation 2.73 yields:

$$\rho_g L_f \frac{\partial B_l}{\partial t} = k_i \frac{T_f - T_{subs}}{B_l} - k_w a_5 \quad (2.130)$$

Here a_5 can be calculated from equation 2.127 and h from equation 2.129. In order to find B_g (hence t_g), substitute $\partial B_l / \partial t$ from equation 2.98 into equation 2.130. However, by taking the ice thickness only due to liquid water coming from droplet freezing or liquid part of partially melted ice crystals into account:

$$\frac{\partial B_l}{\partial t} = \frac{r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}}{\rho_r} \quad (2.131)$$

$$L_f (r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}) = k_i \frac{T_f - T_{subs}}{B_g} - k_w a_5 \quad (2.132)$$

By rearranging the relation ice thickness (B_g) and the time (t_g) at which water first appears could be obtained:

$$B_g = \frac{K_i (T_f - T_{subs})}{(r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}) L_f + k_w a_5} \quad (2.133)$$

Note a_5 has to be calculated for $h = 0$ here because at $B = B_g$, $h = 0$

$$a_5 = \frac{a(T_a - T_f) + b(T_l - T_f) + c(T_c - T_f) + d}{k_w} \quad (2.134)$$

$$t_g = \frac{\rho_r}{r_l \rho_l \beta_l V_\infty + r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}} B_g \quad (2.135)$$

When we collect all unfrozen water in one term:

$$\dot{m}_w = \frac{\rho_w h}{t - t_g} \quad (2.136)$$

As discussed in the erosion model part, water and ice erosion rates can be related with the total erosion rates as follows:

$$\dot{m}_{er,i} = \dot{m}_{er} \frac{\dot{m}_i}{\dot{m}_i + \dot{m}_w} \quad (2.137)$$

$$\dot{m}_{er,w} = \dot{m}_{er} \frac{\dot{m}_w}{\dot{m}_i + \dot{m}_w} \quad (2.138)$$

Accumulated water and ice mass rates can be updated after having calculated the erosion rates:

$$\dot{m}_{i,upd} = \dot{m}_i - \dot{m}_{er,i} \quad (2.139)$$

$$\dot{m}_{w,upd} = \dot{m}_w - \dot{m}_{er,w} \quad (2.140)$$

Moreover, Trontin suggested that some of the accreted water does not run downstream and stay inside the accumulated ice layer [68].

$$\dot{m}_{out} = 2\zeta\dot{m}_{w,upd} \quad (2.141)$$

$$\zeta = \frac{\psi_l + \eta_{melt}\epsilon_s\psi_c}{\psi_l + \epsilon_s\psi_c} \quad (2.142)$$

Above relation is applicable only when $\zeta \leq 0.5$. Otherwise all the accreted water is assumed to run downstream.



CHAPTER 3

COMPARISON OF DRAG COEFFICIENT MODELS

3.1 Comparison Study Purpose

Purpose of this chapter is to discuss effects of drag coefficient models on particle trajectory and collection efficiencies. Three models, which are Ganser, Haider & Levenspiel and Hölzer & Sommerfeld, are used in this comparison study. These models are applicable to non-spherical particles and corresponding formulations are given in chapter 2. Diameter and aspect ratio have been varied to deal with particles having different shapes. By varying these two parameters, it is possible to reach different values of sphericity, crosswise sphericity, equivalent diameter, Stokes number and Reynolds number. Thus, aim of this study is to define each model range of validity.

3.2 Analyses Parameters

Input parameters, which are used in these comparisons, are shown in Table 3.1. Diameter and aspect ratio are arranged to obtain increasing equivalent diameter and Reynolds number from case #1 to case #6. Six different analyses conditions are examined in this study. NACA 0012 wing section, having 1 m chord, is used in this comparison case. Flow field parameters are calculated with 2D potential flow solver. Corresponding parameters are evaluated for the analyses cases with 60 m/s free stream velocity, 0.6969 kg/m^3 air density, 54 019.9 Pa static air pressure, 270 K air temperature and $1.645 \times 10^{-5} \text{ Pa s}$ air viscosity. Sphericity in addition to the equivalent diameter, Reynolds number and Stokes number are given in Table 3.2.

Table3.1: Analyses conditions with different diameter and aspect ratio values.

Case	Crystal Diameter (μm)	Aspect Ratio
1	50	0.05
2	50	0.3
3	50	2.0
4	180	0.05
5	180	0.3
6	180	2.0

Table3.2: Flow field and particle parameters for corresponding analyses conditions.

Case	Equivalent diameter d_p , (μm)	ϕ	$\phi_{\perp}$	Reynolds number	Stokes number
1	21.09	0.27	0.14	53.60	0.09
2	38.31	0.76	0.44	97.39	0.30
3	72.11	0.93	0.79	183.30	1.05
4	75.91	0.27	0.14	192.59	1.17
5	137.94	0.76	0.44	350.62	3.86
6	259.60	0.93	0.79	659.89	13.66

Being the ratio of inertial resistance to viscous resistance, Reynolds number is an important parameter for determining particle behavior in the fluid flow. However, Stokes number is introduced here as an additional parameter. It is used in order to define correctly the effect of flow on particle trajectory and can be calculated with the following relation:

$$St = \frac{\rho_p d_p^2 V_{\infty}}{18\mu_a c} \quad (3.1)$$

Stokes number is a dimensionless parameter corresponding to the behavior of particles suspended in a fluid flow and is defined as the ratio of the characteristic time of a particle to a characteristic time of the flow. Particles with low Stokes number follow fluid streamlines whereas for large Stokes number, the particle inertia dominates so that the particle will continue along its initial trajectory. If the Stokes number is small, that is much less than 1, it means that the particle motion is tightly coupled with the fluid motion. On the other hand, if the Stokes number is large, the particles are not influenced by the fluid.

Three different sphericity and crosswise sphericity values are used in this study. Drag model prediction variations are drawn for each one with respect to Reynolds number and shown in Figure 3.1. As it is indicated in these comparison figures, the agreement between Ganser and Hölzer & Sommerfeld fits are better especially at low sphericity and crosswise sphericity values. It can be noted that the rate of change in drag values are higher at low Reynolds number and all models' behaviors are similar. Moreover, curves start to deviate from each other with increasing Reynolds number and their rate of change decreases.

Collection efficiency curves are compared for the three drag coefficient models at each analysis and are depicted in Figures 3.2 and 3.3. As it is shown in these figures, since crosswise sphericity is not considered in Haider & Levenspiel drag coefficient model, the results which belong to this model differ more than the other models. Moreover, when Reynolds number and Stokes number decrease, results start to deviate from each other. In other words, for the analyses #4-6, which have higher diameter, results are nearly coincident. This is not due to the equivalence of drag coefficient models' predictions but due to the decreasing effect of drag force on trajectories. However, except case #1, which has less sphericity and crosswise sphericity, the differences between the curves are negligible. The importance of the sphericity increases especially when it is much less than 1. Moreover, when it is greater than 0.5 collection efficiency curves could not be distinguished.

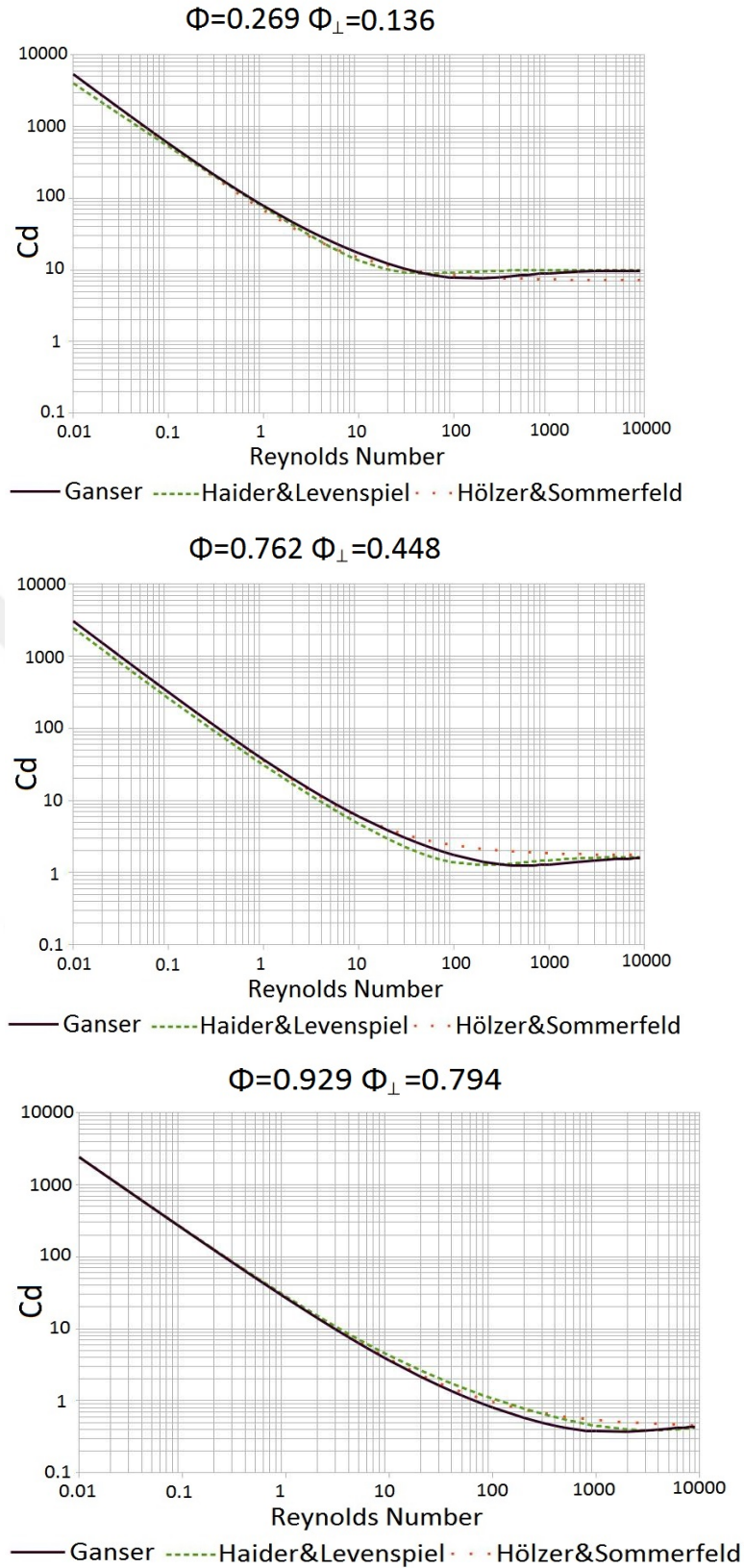
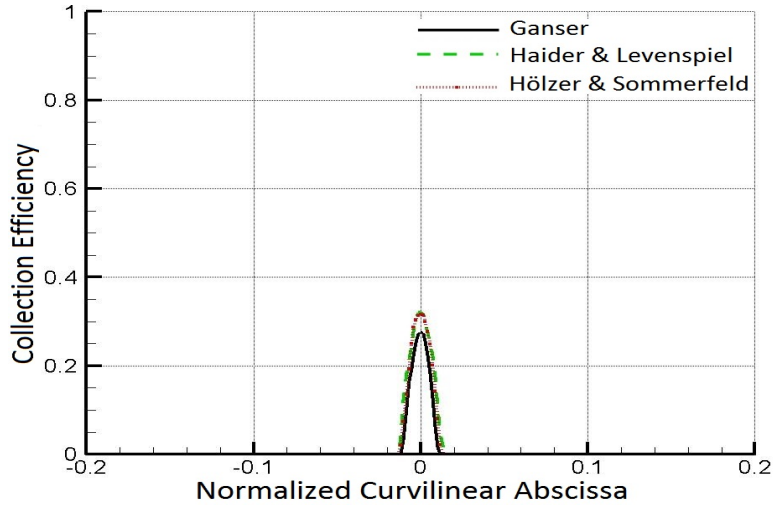


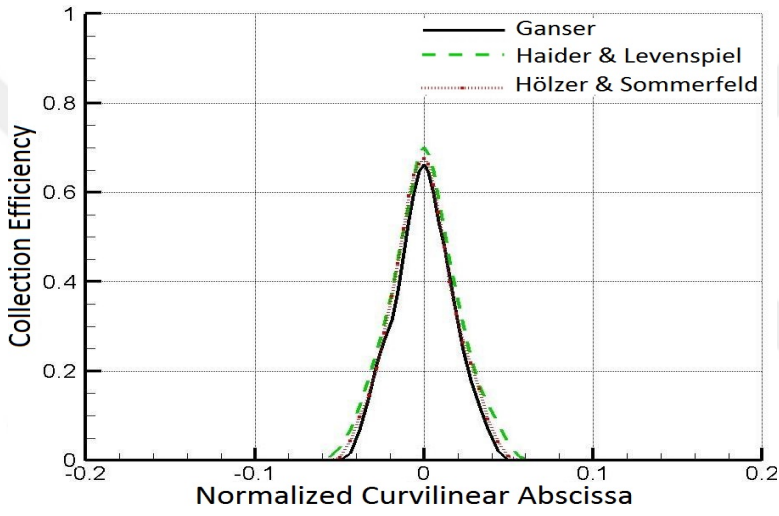
Figure 3.1: Drag model prediction variations with respect to Reynolds number at three different ϕ and $\phi_{\perp}$ values.

It should be noted that as particle diameter and aspect ratio increase, the impingement zone on the airfoil becomes wider. The peak value of the collection efficiency is greater when the particle is bigger. However, for case #1, which corresponds to the smallest particle, maximum value of the collection efficiency is around 0.5. Thus, larger particles follow ballistic trajectories due to their higher inertia resulting in higher collection efficiencies and wider impingement zones. On the other hand, smaller particles follow curved trajectories due the effect of drag force and gravity.

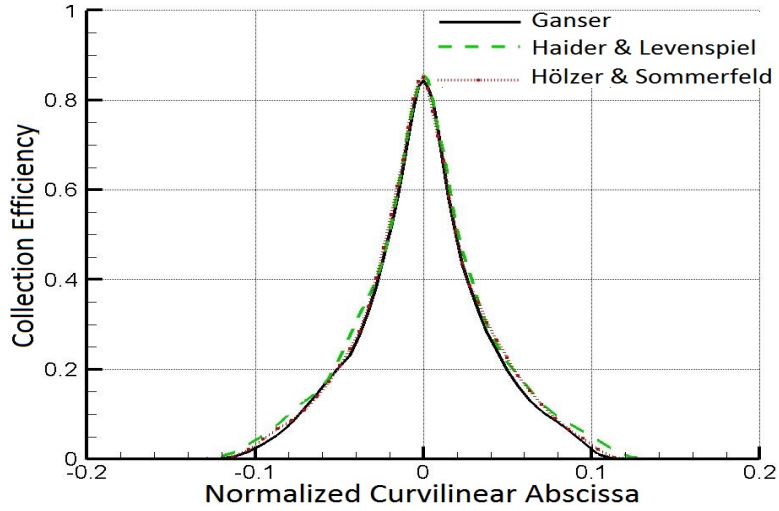
It can be observed from these comparisons that the influence of the model is very low for particles with a moderate aspect ratio. Moreover, for highly non-spherical particles, sensitivity of the collection efficiencies to the models increases. It is not shown in the comparisons but particles having much higher aspect ratio produce similar results to the ones which have much less aspect ratio. Since in both conditions, sphericity is much less than 1. Finally, when the collection efficiencies at the leading edge which correspond to peak values at 0° angle of attack are compared, Haider & Levenspiel model predictions are the highest and the Ganser model predictions are the lowest.



(a) Case #1, $d_p = 21.09 \mu\text{m}$, $\phi = 0.27$, $\phi_{\perp} = 0.14$, $Re = 53.60$ and $St = 0.09$

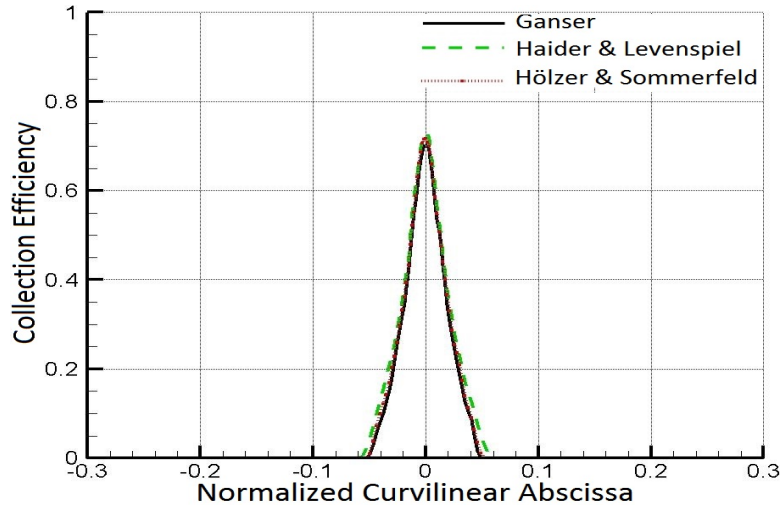


(b) Case #2, $d_p = 38.31 \mu\text{m}$, $\phi = 0.76$, $\phi_{\perp} = 0.44$, $Re = 97.39$ and $St = 0.30$

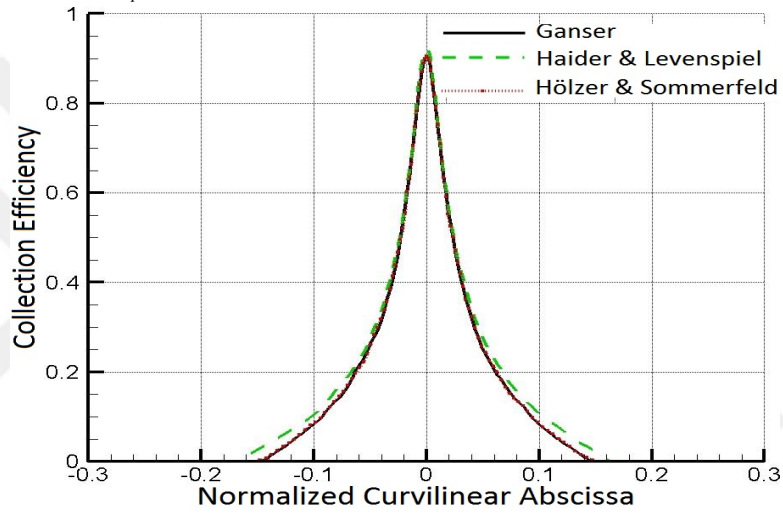


(c) Case #3, $d_p = 72.11 \mu\text{m}$, $\phi = 0.93$, $\phi_{\perp} = 0.79$, $Re = 183.30$ and $St = 1.05$

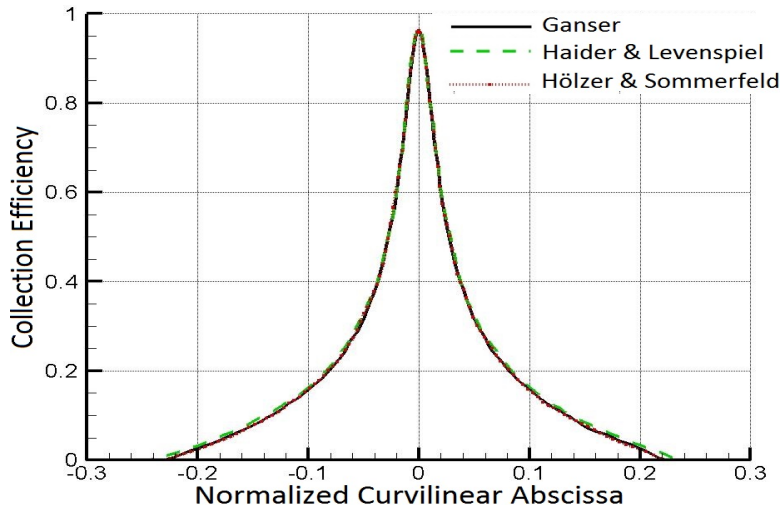
Figure 3.2: Collection efficiency comparisons for cases #1 to #3 at which crystal diameters are $50 \mu\text{m}$.



(a) Case #4, $d_p = 75.91 \mu\text{m}$, $\phi = 0.27$, $\phi_{\perp} = 0.14$, $Re = 192.59$ and $St = 1.17$



(b) Case #5, ($d_p = 137.94 \mu\text{m}$, $\phi = 0.76$, $\phi_{\perp} = 0.44$, $Re = 350.62$ and $St = 3.86$).

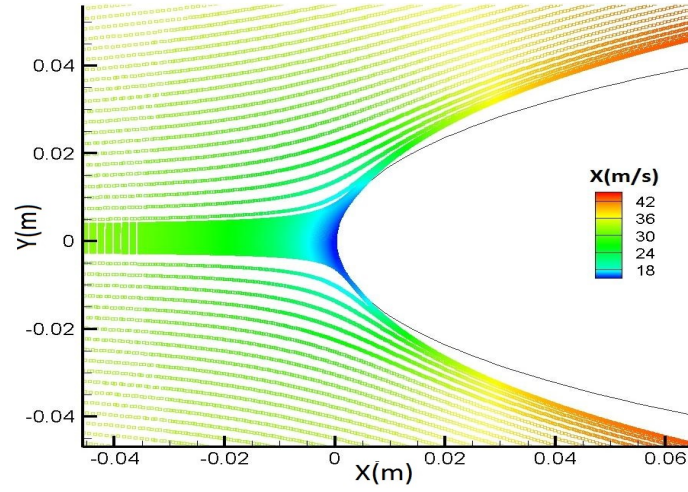


(c) Case #6, $d_p = 259.60 \mu\text{m}$, $\phi = 0.93$, $\phi_{\perp} = 0.79$, $Re = 659.89$ and $St = 13.66$

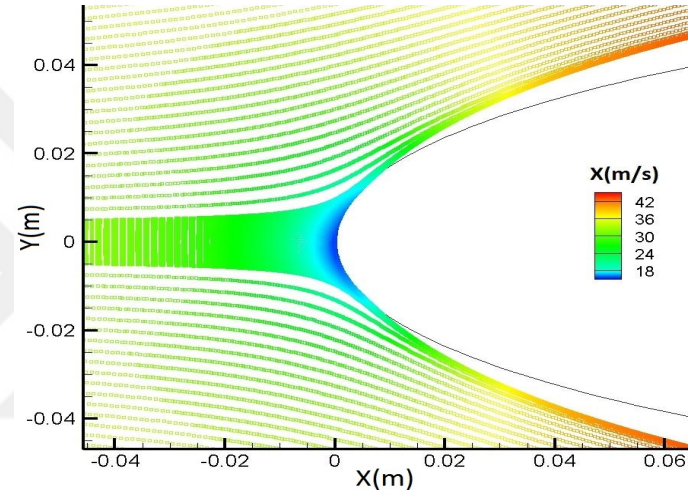
Figure 3.3: Collection efficiency comparisons for cases #4 to #6 at which crystal diameters are $180 \mu\text{m}$.

Particle velocity is compared for case #1 and case #6 in addition to the collection efficiency curves. The comparisons are shown in Figures 3.4 and 3.5. Particles are colored with horizontal component of the velocity. Since the trajectory computations are performed with Lagrangian method, step size of the particle is decreased only when it is closer to the airfoil to reduce the computational cost. As it is shown in these figures, even at case #1, the velocity component variations are not high. On the other hand, at case #6 these differences are much lower. Moreover, at both conditions, velocity components which are calculated using Haider & Levenspiel model are slightly higher than others as expected from the behavior of the collection efficiency curves. Particle impinging velocities are low for other two model predictions which also results in smaller collection efficiencies and narrower impingement zones. Moreover, in these comparison cases, LWC and IWC are assumed as 7 g/m^3 and duration is 10 minutes which are required for ice shape prediction calculations.

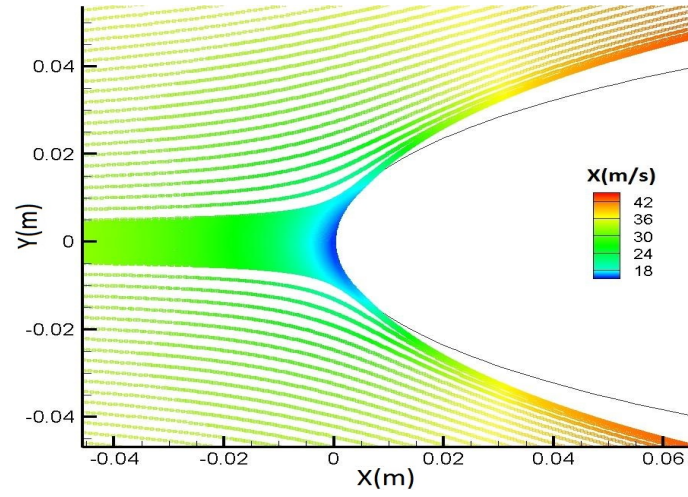
As it is shown in Figure 3.6 differences in collection efficiency curves of case #1 lead to different ice shapes. However, even in case #1, these differences are not so much. In this analysis diameter, sphericity and crosswise sphericity are too low and some deviations in ice shape predictions are expected. On the other hand, since collection efficiency curves are nearly coincident in the other analyses conditions, the differences between ice shapes can be ignored. Ice shape comparisons of case #6 are depicted in below part of the Figure 3.6 as an example. Since it takes crosswise sphericity into consideration and its ice shape predictions are generally in between the other two models, Hölzer & Sommerfeld drag model is used in this thesis study and corresponding calibrations are performed while comparing with experimental results.



(a) Ganser drag model.

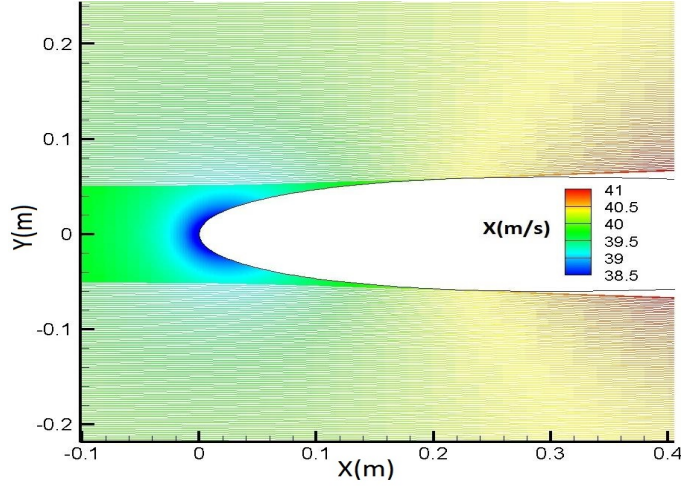


(b) Haider & Levenspiel drag model.

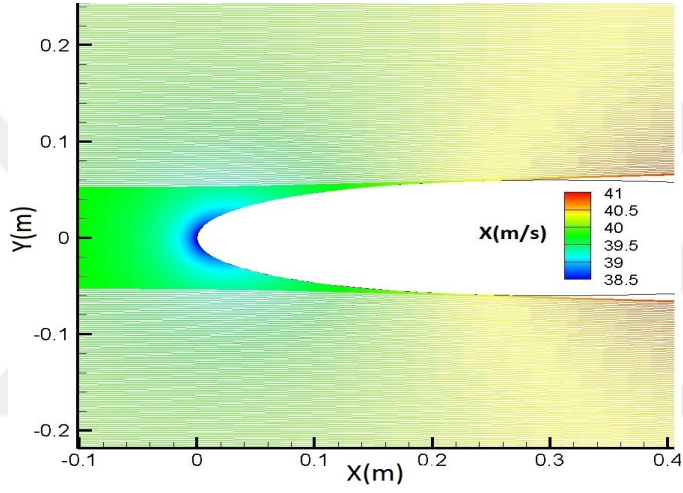


(c) Hölzer & Sommerfeld drag model.

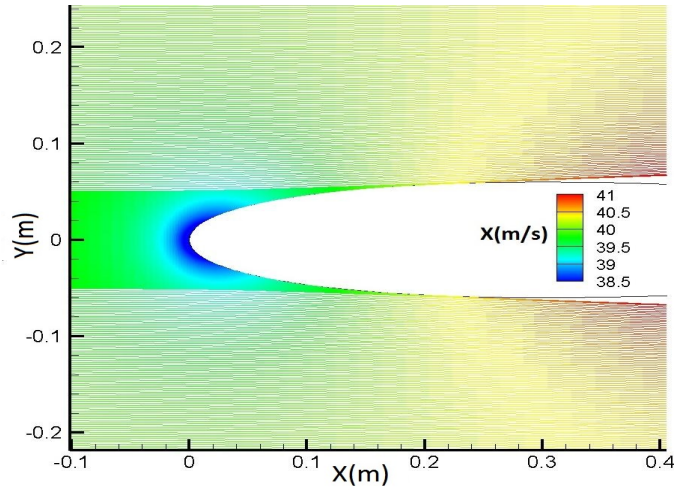
Figure 3.4: Case #1, X velocity contours comparisons with different drag models. ($d_p = 21.09 \mu\text{m}$, $\phi = 0.27$, $\phi_\perp = 0.14$, $Re = 53.60$ and $St = 0.09$)



(a) X velocity contours comparison with Ganser drag model.

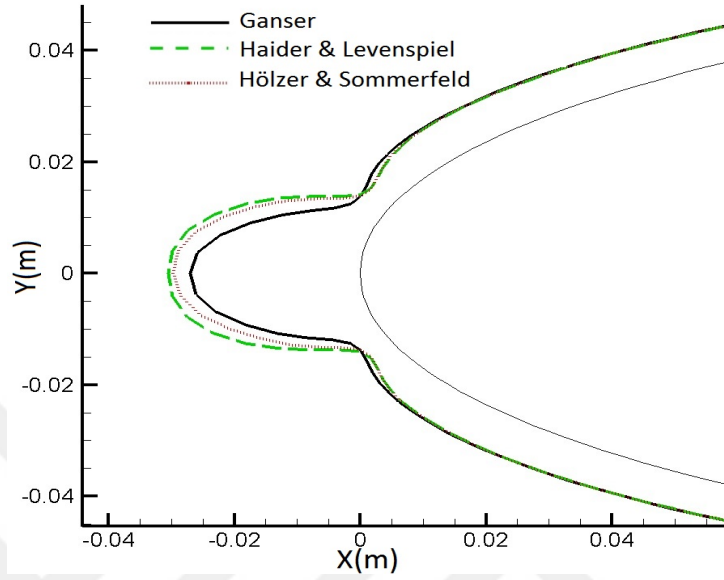


(b) X velocity contours comparison with Haider & Levenspiel drag model.

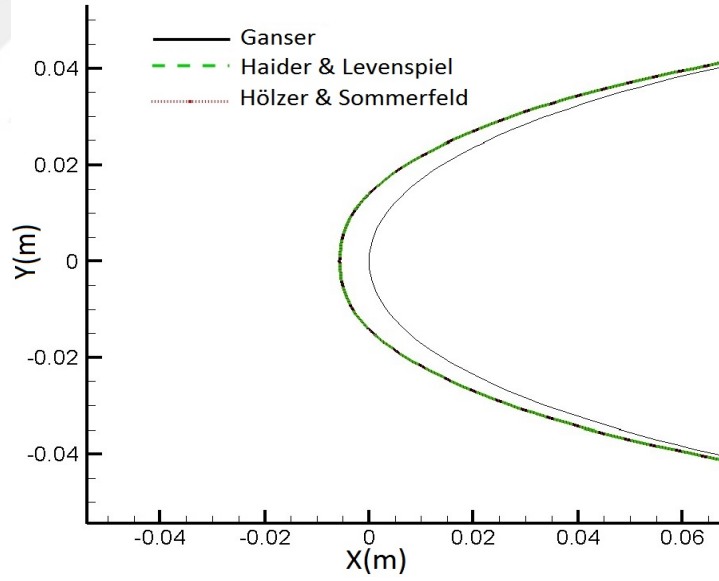


(c) X velocity contours comparison with Hölzer & Sommerfeld drag model.

Figure 3.5: Case #6, X velocity contours comparisons with different drag models.
($d_p = 259.60 \mu\text{m}$, $\phi = 0.93$, $\phi_{\perp} = 0.79$, $Re = 659.89$ and $St = 13.66$)



(a) Case #1, $d_p = 21.09 \mu\text{m}$, $\phi = 0.27$, $\phi_{\perp} = 0.14$, $Re = 53.60$ and $St = 0.09$



(b) Case #6, $d_p = 259.60 \mu\text{m}$, $\phi = 0.93$, $\phi_{\perp} = 0.79$, $Re = 659.89$ and $St = 13.66$

Figure 3.6: Ice shape comparisons obtained by using different drag models.



CHAPTER 4

STUDY ON HEAT EXCHANGE AND PHASE CHANGE MODELS

Computations for validation of the heat transfer and phase change models are detailed in this chapter first. Then evaluations on effects of these models on particle trajectory and accreted ice shapes are given.

4.1 Validation of the Models

Implemented heat transfer and phase change model is validated by using Hauk's experiments which were performed within the scope of HAIC project [32]. As explained in his study that individual ice particles are suspended by using an acoustic levitator and are placed in a chest freezer. Melting process of the particles are initiated with warmer air stream. Corresponding ambient and flow parameters are controlled. The melting process of the ice crystals is recorded till to the time when they become pure droplets with a high speed camera. The melting time of particles and their diameters are measured. Corresponding total melting time and final droplet diameter after melting process are compared with the computational results.

ONERA models are used in this study which are discussed in chapter 2. Test matrix, which is given in the study of Hauk *et al*, is given in Table 4.1. It includes ambient and flow parameters which affects total melting time. These parameters are varied in this study to evaluate the accuracy of the numerical model. Moreover, both spherical and irregular particles are used in experiments to examine effect of particle shape as well. More detailed information regarding this experiment can be found in [32].

Table4.1: Melting model test matrix [32].

Case #	Flow Velocity (m/s)	RH (%)	Particle Shape	Flow Temp. (°C)	Initial Temp. (°C)	Ambient Pressure (Bar)
1-4	1	4	spherical	20	-17	0.949
5-19	1	4	irregular	20	-17	0.955
20-25	1.25	4	spherical	20	-18	0.972
26-31	1.25	4	irregular	20	-18	0.952
32-36	0.75	62	spherical	15	-17	0.951
37-53	0.75	62	irregular	15	-17	0.952
54-57	1	73	spherical	20	-18	0.949
58-79	1	73	irregular	20	-18	0.954

Gas is modeled as mixture of air and water vapor in this study. Corresponding gases and ice physical properties are given in Table 4.2.

Table4.2: Analyses conditions with different diameter and aspect ratio values.

Air specific Heat Capacity (J/(kg K))	Water Vapor Specific Heat Capacity (J/(kg K))	Ice Specific Heat Capacity (J/(kg K))	Water Specific Heat Capacity (J/(kg K))
1006	2021	2108	4220

In addition to the relations given in chapter 2 following expressions are required for computations.

$$\mu_a = \mu_0 \left(\frac{T}{T_0} \right)^{1.5} \frac{T_0 + 110.4}{T + 110.4} \quad (4.1)$$

where $\mu_0 = 1.7111 \times 10^{-5}$ Pa s and $T_0 = 273.15$ K. As it is depicted in Figure 4.1 that the experimental melting time for irregular shaped particles are smaller than the calculated melting time due to their higher surface area. However, general consistency of the numerical predictions are good. The flow relative humidity has an important effect on mass exchange during phase change and on melting duration. Thus, corresponding melting time decreases with increasing relative humidity as it is shown in the same figure.

Final liquid droplet diameters are compared in addition to the melting time comparisons in Figure 4.2. As in the melting time comparisons, numerically calculated final

liquid droplet diameters also seem consistent. Maximum difference between the experimental and calculated droplet diameter is around 4%. The success of the models seems similar for both spherical and irregular shapes when final droplet diameters are considered.

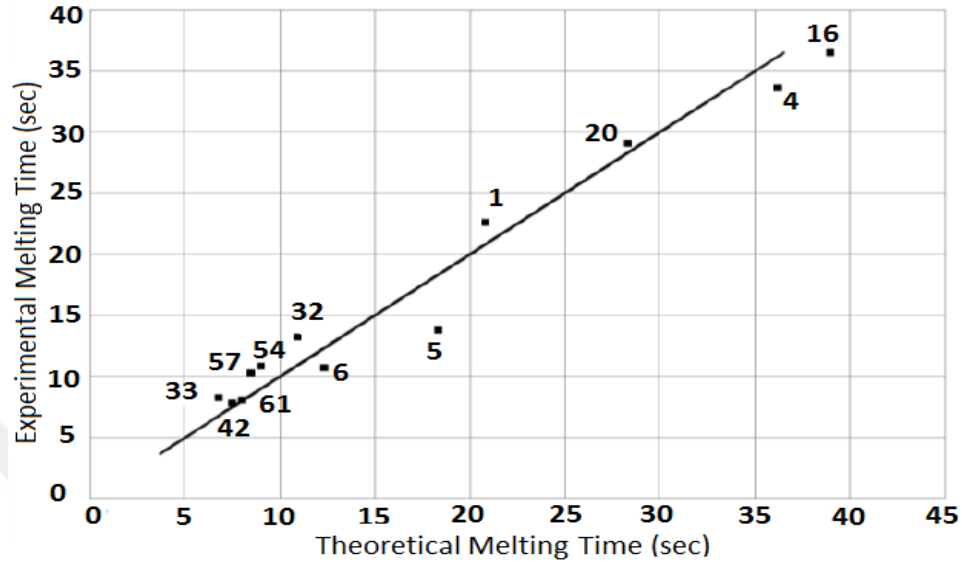


Figure 4.1: Experimental and calculated melting time comparisons for the particles having different properties as given in Table 4.1.

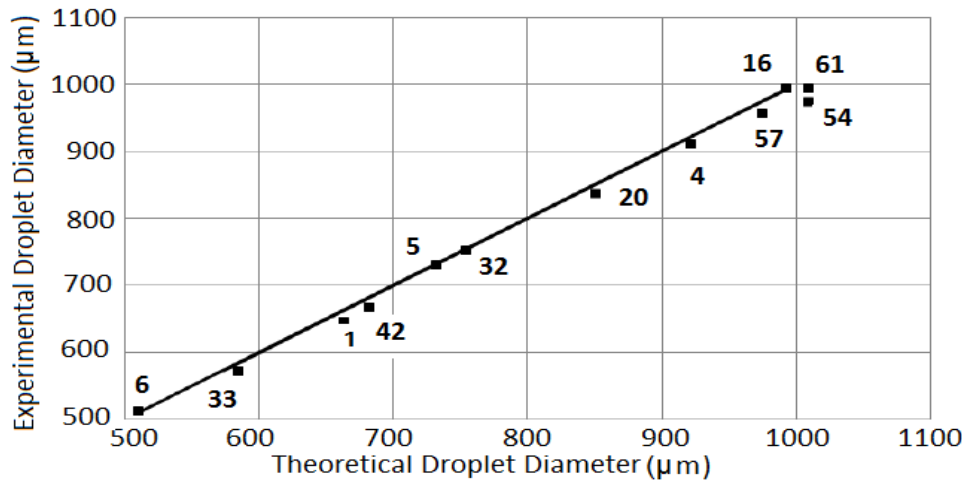


Figure 4.2: Experimental and calculated droplet diameter comparisons for the particles having different properties as given in Table 4.1.

Thus, as given in previous figures except for a small number of analyses conditions, the agreement between the experimental and computational results is good. The

mean relative error between the experimental and numerical melting time prediction is around 10% when ONERA models are used.

4.2 Effect of Heat Exchange Model on Accreted Ice Shape

Effects of heat transfer and phase change models on the trajectory of the particle and accreted ice shapes are discussed in this part. For this purpose, ice accretion test case which is used in Chapter 3 is detailed by taking particles temperature variation into considerations as well. In this test case, both droplets and ice crystals are injected in the air flow. The presence of droplets allows creation of liquid film which is the necessary condition for ice crystals to stick to the wall. NACA 0012 airfoil having 1 m chord is used in this comparison test case and the flow angle of attack is 0° . Flow parameters are evaluated at 60 m/s free stream velocity, 0.6969 kg/m^3 air density, 54 019.9 Pa static air pressure, -3.15°C air temperature and $1.645 \times 10^{-5} \text{ Pa s}$ air viscosity. Corresponding ice accretion parameters are given in Table 4.3.

Table4.3: Flow field parameters to be used in ice accretion analyses.

Flow Velocity (m/s)	ϕ	$\phi_\perp$	Flow Temp. ($^\circ\text{C}$)	Initial Temp. ($^\circ\text{C}$)	LWC (g/m^3)	IWC (g/m^3)	Humidity (%)
60	0.269	0.136	20	-17	7	7	4

It is assumed that ice crystals enter warmer airfield from 1 m ahead of the wing section. The initial temperature of the ice crystals is -17°C and due to the heat transfer between ice crystals and surrounding their temperature increases up to 0°C as shown in Figure 4.3. These warmer airflow conditions may occur around heated surfaces or within the aircraft engine.

In addition to the heat exchange with surrounding, masses of ice particles may vary as well. In this test case, mass of the ice crystal reduces up to $48 \mu\text{m}$ before impact due to the sublimation as depicted in Figure 4.4. Since the duration before impingement is short, the particle temperature could not reach to melting temperature. Thus, reduction in diameter and particle mass is very low. Moreover, due to the great uncertainty on the value of the initial sphericity in real flow, a parametric study was

performed within HAIC project to check if sphericity could have a strong influence on this model predictions. As expected, due to the high crystal inertia, sphericity effect on the particle trajectory appears to be very weak for these running conditions.

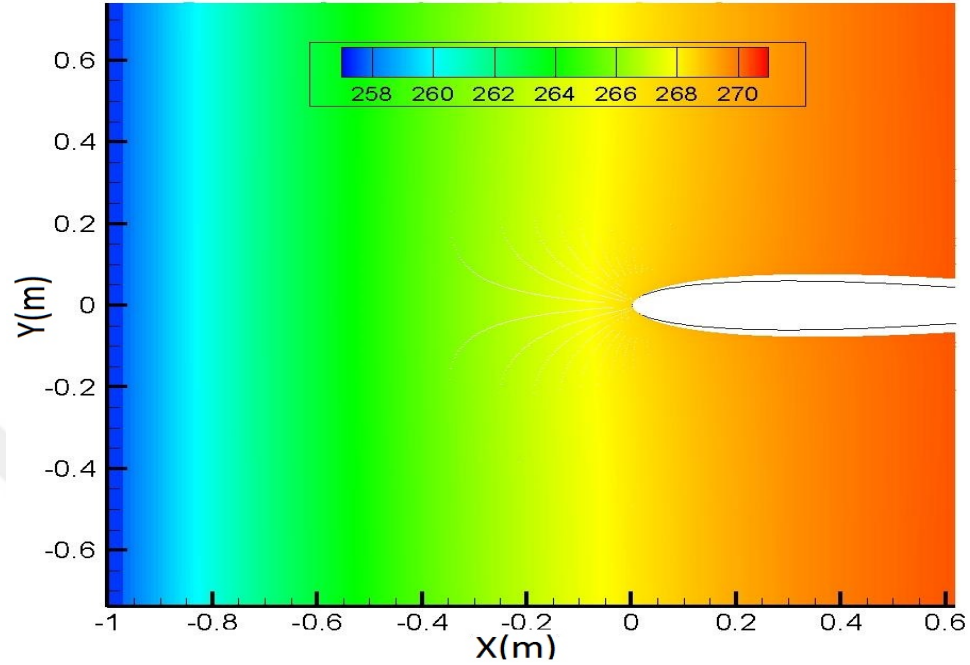


Figure 4.3: Ice crystal temperature variation when heat exchange model is enabled (K). Flow temperature is 293.15 K and crystal initial temperature is 256.15 K.

Since these heat transfer and mass transfer phenomena change the impact temperature and mass of the ice crystals, mass and energy balance relations are modified. Effect of enabling these models can be seen on accreted ice shape in Figure 4.5. Due to the increasing particle temperature, accreted ice thickness reduces to 2.5 mm on the leading edge of the airfoil in this test case. Change in the accreted ice shape may be more noticeable depending on the air flow conditions and initial temperature of the ice crystals.

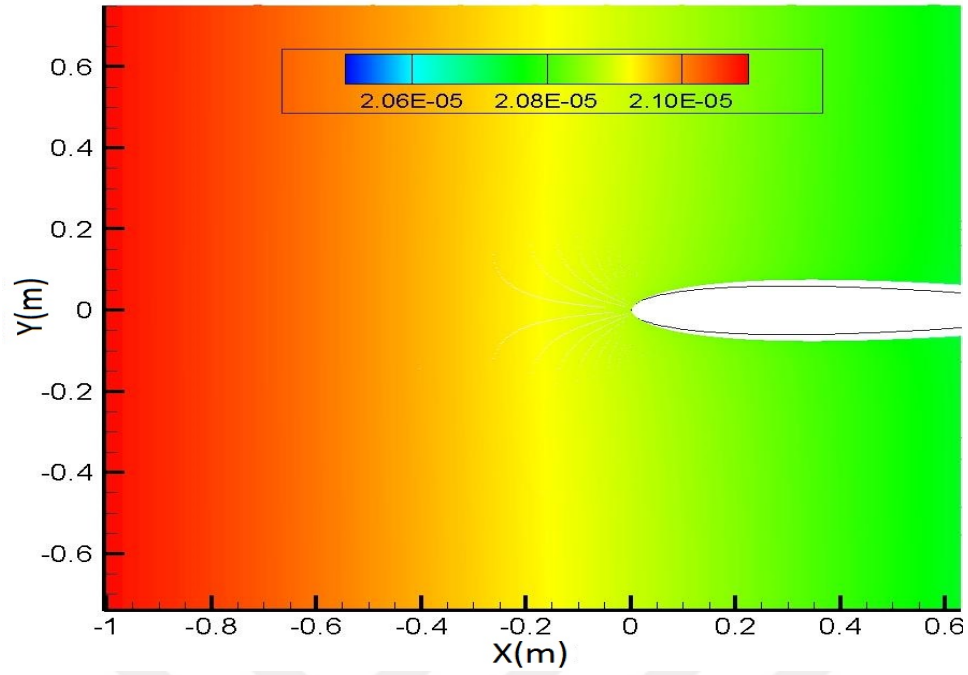


Figure 4.4: Ice crystal diameter variation due to melting when heat exchange model is enabled (μm).

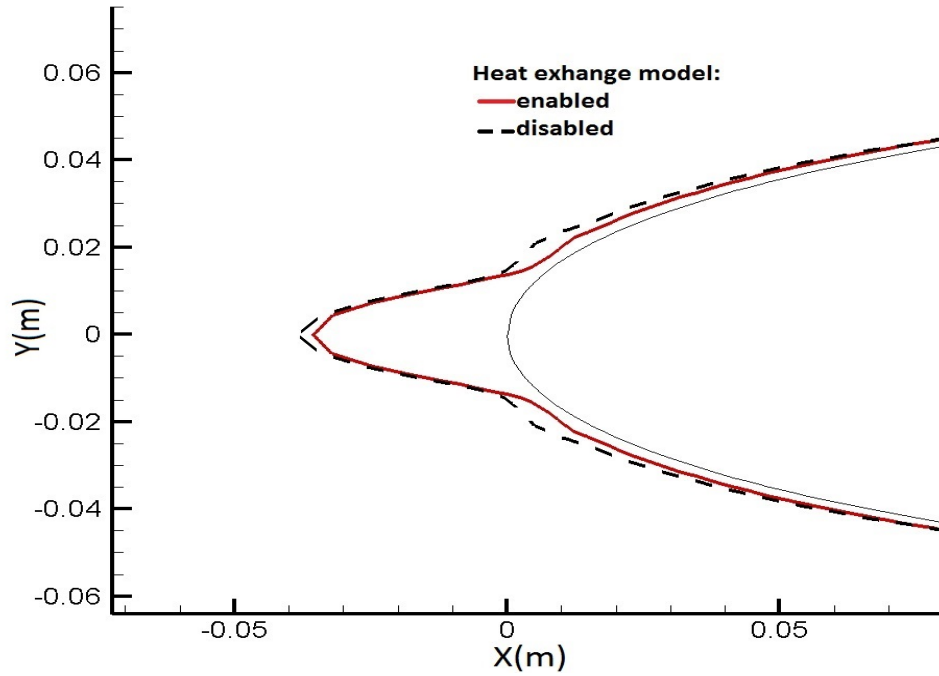


Figure 4.5: Influence of the heat transfer and phase change models on accreted ice shape with the flow and icing parameters given in Table 4.3.

CHAPTER 5

STUDY ON IMPACT MODEL AND SECONDARY PARTICLE BEHAVIOR

Parametric study for evaluation of the implemented impact model is discussed first in this chapter. Then calibration of the adjustable parameter for stick probability is performed by using NASA-NRC experiments which is given in the study of Currie *et al* [25].

5.1 Evaluation of the Implemented Impact Model

As it is discussed in the impact modeling part in chapter 2, some of the ice crystals may not adhere to the wall upon impact. These particles may bounce and continue to their way as secondary particles which may hit to the wall at another location and may contribute to ice accretion at that location. Thus, trajectory calculations of secondary particles are crucial for prediction of ice accretion.

Effect of drag coefficient models on secondary particle trajectories will be examined as well at this section. For this purpose, case #1 and case #6 are selected. As it is given in Table 5.1, case 1 particles have the smallest diameter and aspect ratio within the selected cases. On the other hand, case 6 particles have the highest diameter and aspect ratio within the selected cases.

Bouncing particles and rake position behind the airfoil are shown in Figure 5.1. All particles are assumed to bounce upon impact around the NACA 0012 leading edge. Fragmentation option is closed for this analysis. Moreover, passing particle Y co-

ordinates and X velocity component computations are performed at this shown rake position. Thus, computed particle velocities are belong to this rake position which is 1 m behind from the trailing edge.

Table5.1: Flow field and particle parameters revisited for case#1 and case#6.

Case	Equivalent diameter $d_p, (\mu\text{m})$	ϕ	$\phi_{\perp}$	Reynolds number	Stokes number
1	21.09	0.269	0.136	53.60	0.09009
6	259.60	0.929	0.794	659.89	13.65648

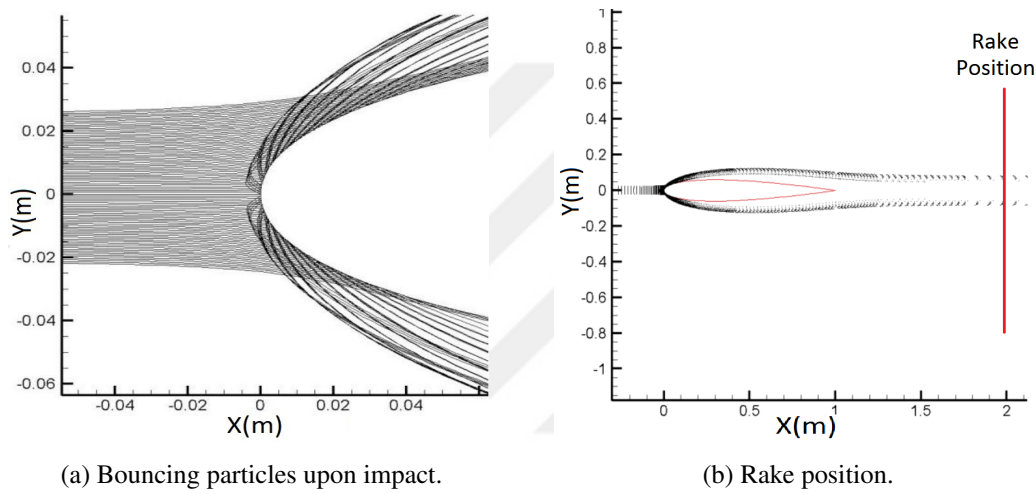


Figure 5.1: Secondary particle behavior upon impact and at rake position for case #1.

X velocity component and Y positions at which particles pass through at rake are depicted in Figure 5.2 and in Figure 5.3 for case #1 and case #6. It was discussed in the previous sections that collection efficiency curves deviate from each other when sphericity differs from 1 especially for particles having smaller diameters. However, when secondary particle behaviors at rakes are examined, all trajectories nearly coincide.

Usage of different drag coefficient models does not cause much difference in Y position of the particle, just a few cm variations are seen in Y positions for these cases. Moreover, it should be noted that these differences are more for the particles having bigger diameters. In spite of this bigger difference, Y position of the particles can be

accepted as coincident also. Since, the particles having bigger diameters spreads in a larger area, these variations in Y position corresponds to a smaller error in terms of percentage. Thus, with increasing particle diameter, the importance of the drag force on the trajectory calculations decreases and difference in effects of drag coefficient models' predictions become unimportant.

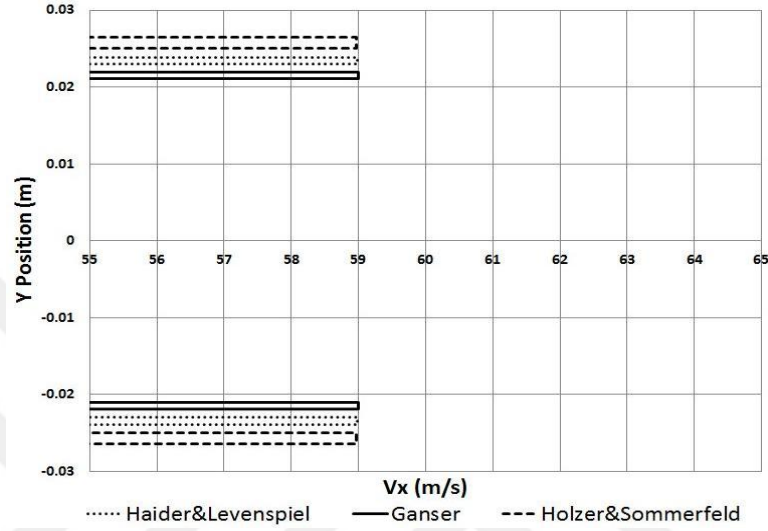


Figure 5.2: X Velocity Components vs Y Position Comparison for case #1. ($d_p = 21.09 \mu\text{m}$, $\phi = 0.27$, $\phi_{\perp} = 0.14$, $Re = 53.60$ and $St = 0.09$)

5.2 Calibration of the Adjustable Parameter

As discussed in chapter 2, the impact model is based on deposition probability of the upcoming ice crystals. An adjustable parameter, K_l , is used in this model and further calibrated in this study with the experimental data given in the study of Currie *et al* [25]. Case #543 and case #553 are simulated for this purpose and partial validation. One of the objectives is to use the measured ice growth rate at the leading edge in order to calibrate the value of dimensionless parameter, K_l , which is used for mixed phase icing conditions and which governs the sticking rate. Case #543 and case #553 [25] operating conditions are summarized in Table 5.2. Test section has 220.90 mm chord and more detailed information related to this experiment are given in chapter 6.

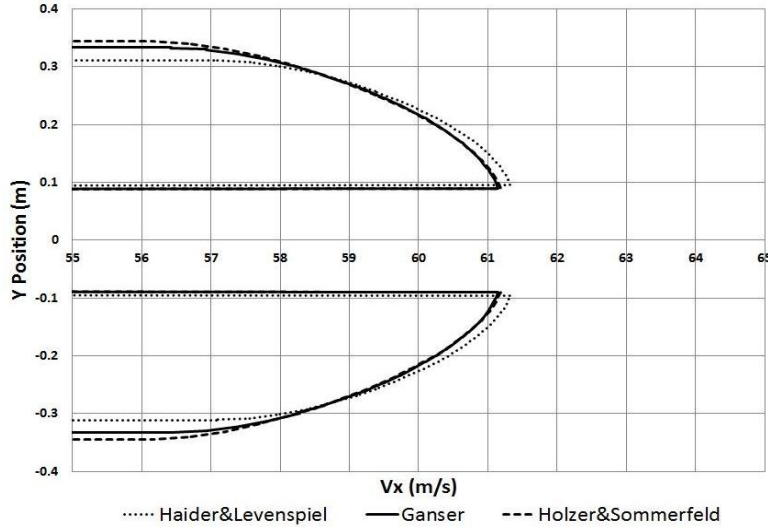


Figure 5.3: X Velocity Components vs Y Position Comparison for case #6. ($d_p = 259.60 \mu\text{m}$, $\phi = 0.93$, $\phi_{\perp} = 0.79$, $Re = 659.89$ and $St = 13.66$)

Table 5.2: Analyses conditions from NASA-NRC experiment [25].

Case	Mach Number	Total Temp. (°C)	Total Press. (kPa)	IWC (g/m ³)	LWC (g/m ³)	Relative Humid. (%)	Crystal MVD (μm)	Droplet MVD (μm)
543	0.25	13	44.8	7	2.9	8	70	40
553	0.25	6	44.8	7	2.9	30	70	40

Figures 5.4 and 5.5 show the ice shapes obtained after 180 second of accretion for five different values of the model parameter K_l . In the study of Trontin *et al* [68], two different functions which are related to sticking ratios of solid and liquid parts in mixed phase conditions are introduced. Dimensionless parameters which are K_c and K_l are determined by calibration. K_c is used when partially melted ice crystals are used. However, in these cases ice crystals are pure solid and both water droplets and ice crystals are thrown towards to the test section separately. The larger K_l , the larger is the deposition rate and the larger is the ice thickness. Moreover, erosive effects as defined in chapter 2 are accounted for in this calibration study.

According to the corresponding experimental ice growth rates at the leading edge, total length after 180 seconds is 14.16 mm for case #543 and 14.35 mm for case #553. The choice $K_l = 2.25$ leads to a quite good agreement between numerical and experimental results.

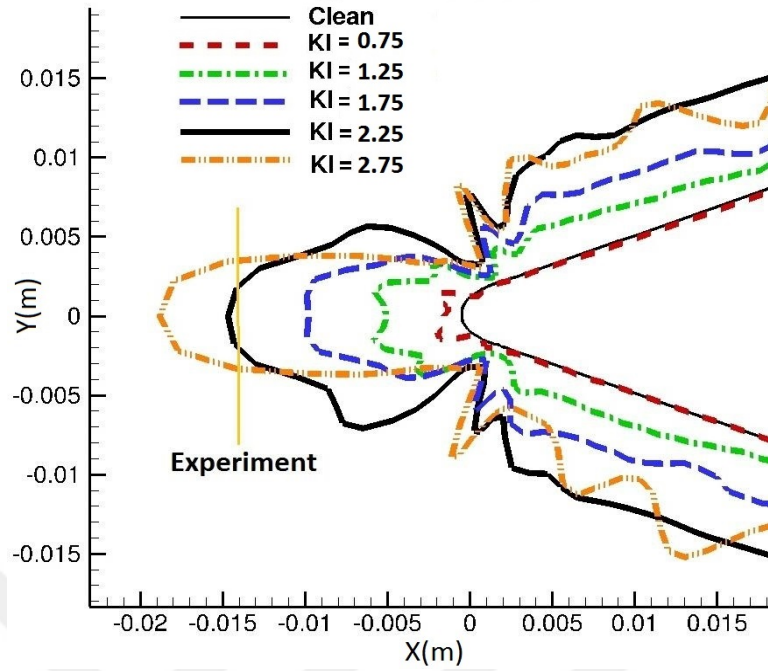


Figure 5.4: Influence of K_I on ice shape for case #543. The yellow line shows the leading edge ice thickness experimental result after 180 seconds.

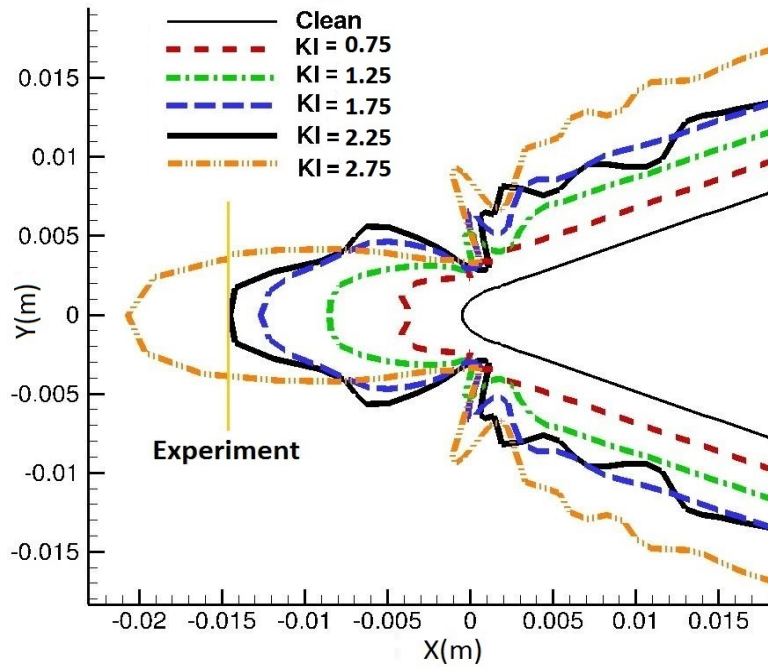


Figure 5.5: Influence of K_I on ice shapes for case #553. The yellow line shows the leading edge ice thickness experimental result after 180 seconds.



CHAPTER 6

STUDY ON ACCRETION MODEL

Validation studies of the accretion and erosion models are carried out in this part of the thesis. COX [11] and NASA-NRC [25] experiments have been used for this purpose.

6.1 Comparison by Using COX Icing Wind Tunnel Experimental Results

Al-Khalil *et al* [11] performed mixed phase ice accretion experiments by using NACA 0012 airfoil having 0.91 m chord length. The test section in the icing wind tunnel has a height of 1.83 m and a width of 2.74 m. The aim of this comparison is to validate mixed phase ice accretion models and the erosion model implemented in the current computational tool. For validation purposes, two rime ice and two glaze ice test cases are selected. Flow and icing parameters of the selected test cases are given in Table 6.1. The airfoil is placed in the middle of test section and mounted horizontally. Thus, the angle of attack is 0° .

Table6.1: Analyses conditions from COX experiments [11].

Case	Airspeed (m/s)	Total Temp. (°C)	Total Press. (kPa)	IWC (g/m ³)	LWC (g/m ³)	Crystal MVD (μm)	Droplet MVD (μm)
9	53.60	-5.55	100	-	0.7	-	20
10	53.60	-5.55	100	0.7	0.7	200	20
19	53.60	-11.10	100	0.7	0.3	150	20
20	53.60	-11.10	100	0.3	0.7	150	20

A monodisperse distribution of the injected ice particles and water droplets is assumed. The MVD for ice crystals is $150\mu\text{m}$ for cases 19 and 20 (snow gun) and around $200\mu\text{m}$ for case 10 (ice shaver). For the water droplets, the *MVD* is $20\mu\text{m}$. For all computations, the heat exchange between the particles and the surrounding air is neglected. Thus, mass loss of particles due to evaporation and sublimation is neglected. Total experiment duration is 600 seconds at all analyses. Collection efficiencies of cases 9 and 10 are depicted in Figure 6.1 and corresponding ice shape comparisons with experimental shapes are shown in Figure 6.2. These two cases correspond to glaze ice conditions due to high temperature, which is also made evident by the ice shapes depicted in Figure 6.2. On the other hand, cases 19 and 20 correspond to rime ice conditions due to low temperatures, which is evidenced by the ice shapes in Figure 6.4.

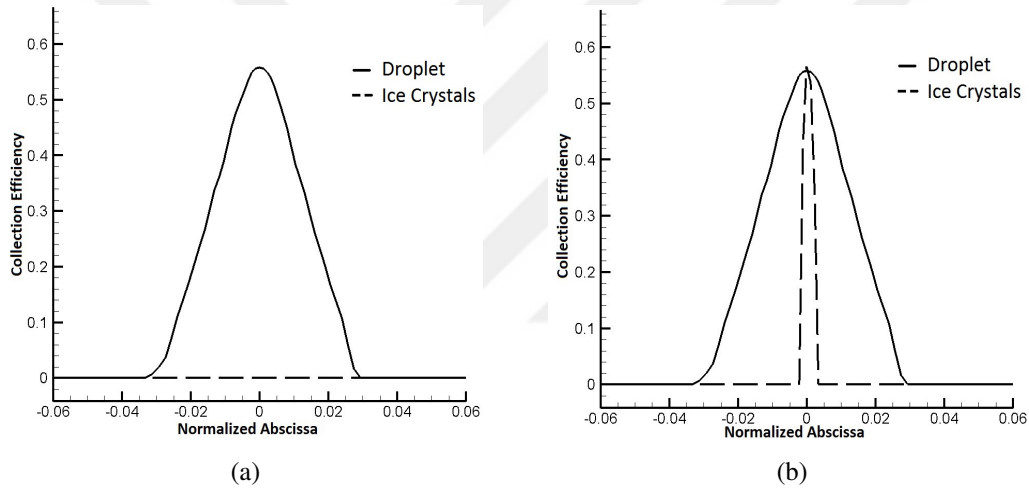


Figure 6.1: Collection efficiency of liquid and solid cloud particles for (a) Case #9 pure droplet case (b) Case #10 mixed phase case.

When collection efficiencies of liquid and solid cloud particles are compared, quite different curves are obtained, mainly due to the bouncing solid particles. Moreover, erosion effects are obviously more significant in mixed glaze ice conditions than in rime ice conditions. In case #9 only droplet particles are used. Formation of horns indicates glaze ice accretion where excess water moves to neighboring cells as run back water. However, in case #10 in which ice crystals are added, the accreted ice is decreased surprisingly. A slight decrease in accreted ice around the leading edge can be seen in the comparisons. Erosion might be the main reason for this reduction.

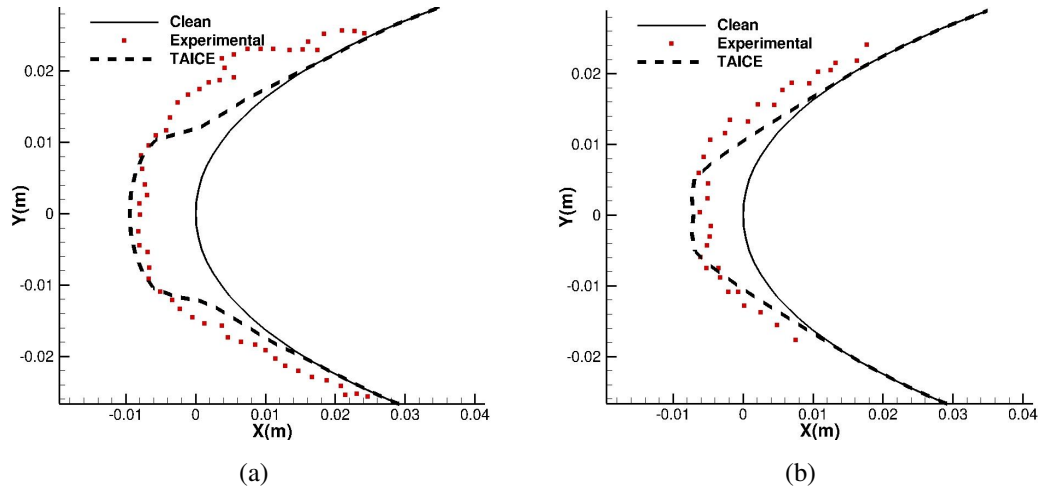


Figure 6.2: Glaze ice shape comparisons for (a) Case #9 pure droplet case, $LWC = 0.7$, $IWC = -$ (b) Case #10 mixed phase case, $LWC = 0.7$, $IWC = 0.7$.

In Figures 6.3 and 6.4, it is clearly seen that ice accretion occurs only due to supercooled water droplets present in the cloud because the collection efficiency of the ice crystals is zero. Since liquid water does not accumulate above the ice layer, solid cloud particles do not stick to the surface and hence do not contribute to ice accretion. The only noticeable effect of the ice particles is the erosion of the accreted ice near the impingement limits.

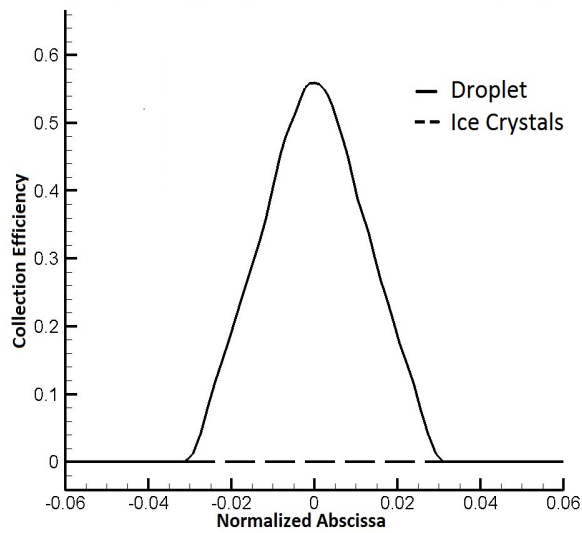


Figure 6.3: Collection efficiency of liquid and solid cloud particles for Case #19 and Case #20.

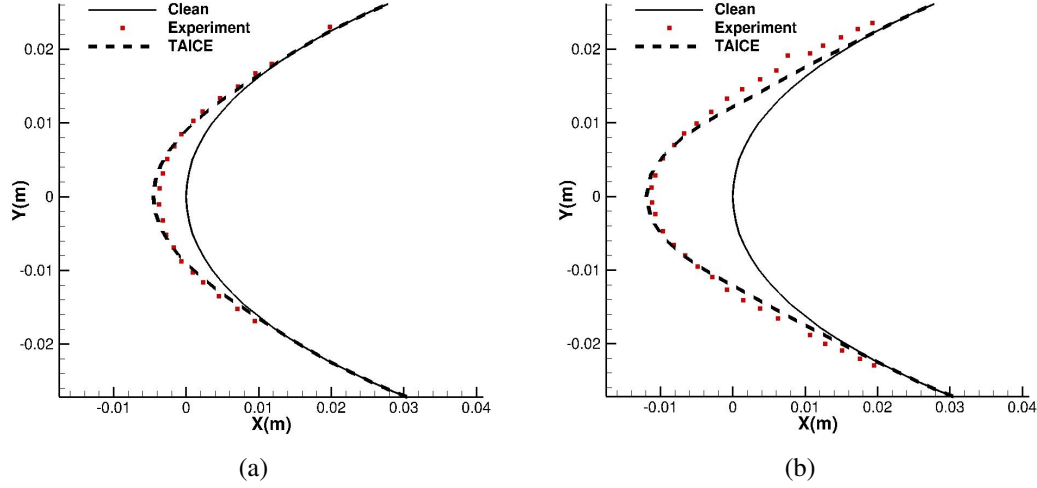


Figure 6.4: Rime ice shape comparisons for (a) Case #19, $LWC = 0.3$, $IWC = 0.7$ (b) Case #20, $LWC = 0.7$, $IWC = 0.3$.

6.2 Comparison by Using NASA-NRC Icing Wind Tunnel Experimental Results

These experiments were performed in the NRC icing wind tunnel. As in the Cox experiments, both ice crystals and water droplet particles are used to generate mixed phase icing conditions. The particles are launched towards a wedge section from a 1.27 m distance. Aim of including such an experimental case is to assess icing in warmer conditions. In presented both running conditions, air temperature is greater than 0°C as given in Table 6.2. Three of the icing conditions are selected for analyses. Since exact ice shapes are not given in the reference study, only leading edge ice thicknesses are compared below[25]. Moreover, shedding is not modeled in the analyses. Thus selected icing conditions are given in Table 6.2.

Table6.2: Analyses conditions from NASA-NRC experiment revisited [25]

Case	Mach Number	Total Temp. ($^{\circ}\text{C}$)	Total Press. (kPa)	IWC (g/m^3)	LWC (g/m^3)	AOA ($^{\circ}$)	Crystal MMD (μm)	Droplet MVD (μm)
543	0.25	13.0	44.8	7.0	2.9	0	70	40
553	0.25	6.0	44.8	7.0	2.9	0	70	40
522	0.25	20.0	44.8	17.0	1.1	-6	70	40

In all cases the duration of the accretion is three minutes. Calculated leading edge ice thicknesses are consistent with the experimental results as depicted in Figure 6.5 when erosion model is activated. Moreover, in order to increase the accuracy of the prediction, since air temperature is greater than 0 °C heat and mass transfer along the trajectory for ice crystals is taken into account. Thus, when particles reach the test section, their temperature increases to -8 °C while at the launch plane (1.27 m upstream of the test section) the crystal temperature is -15 °C as given in chapter 4. Moreover, leading edge ice growth ratios are compared as well in Figure 6.6. As it is shown in this figure, experimental and numerical results are consistent in both analyses .

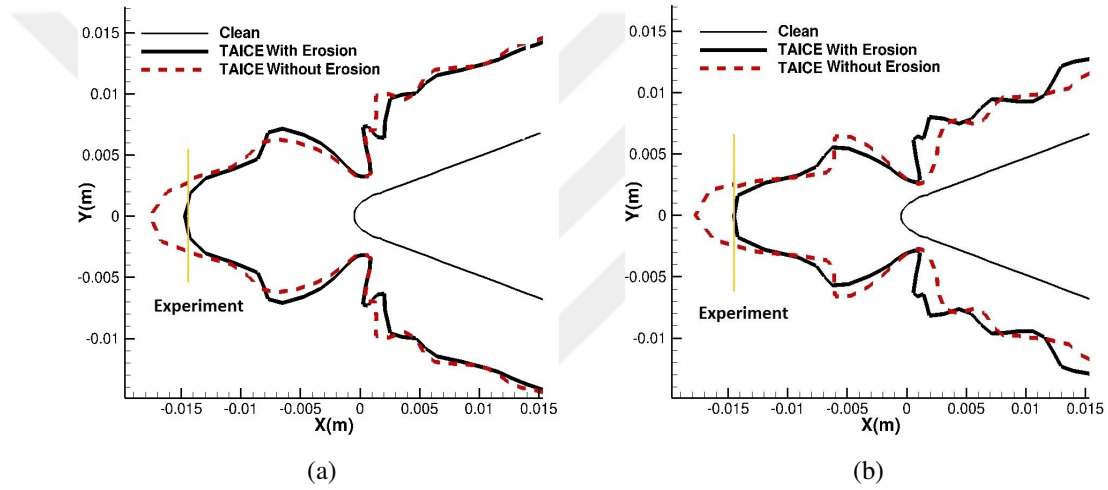


Figure 6.5: Ice shape comparisons. The yellow line shows the leading edge ice thickness experimental result after 180 seconds. (a) Case #543 $T_{Tot} = 13.0$ °C (b) Case #553 $T_{Tot} = 6.0$ °C.

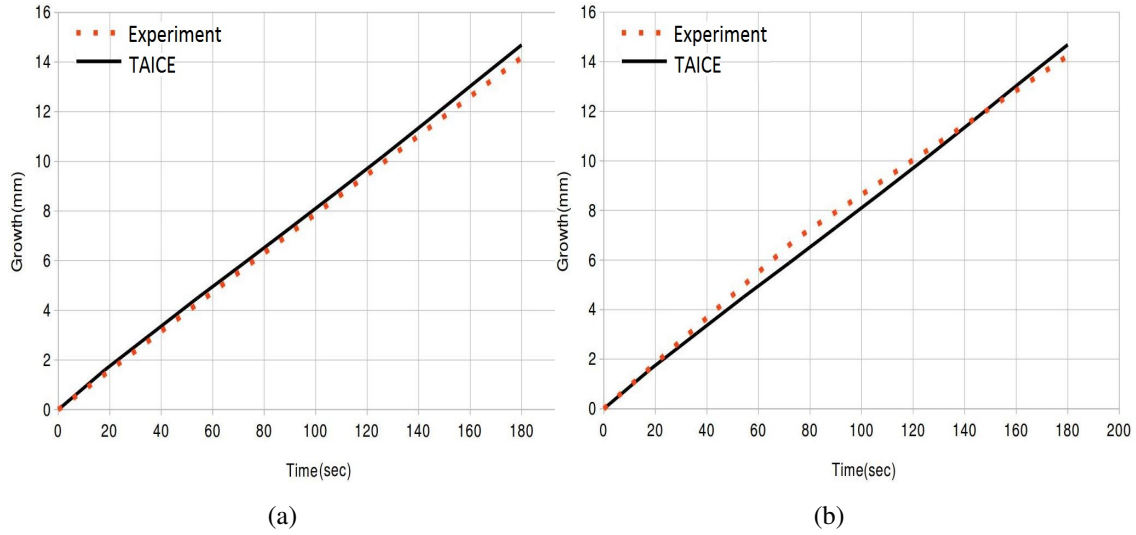


Figure 6.6: Leading edge ice growth rate comparison (a) Case #543, $T_{Tot} = 13.0$ °C (b) Case #553, $T_{Tot} = 6.0$ °C.

Moreover, in Figure 6.7 effect of crystal melting after impact is depicted for case #543 and #553. For both conditions, by allowing melting of ice crystals after impact depending on the energy level within the control volume, the accuracy of the prediction is increased.

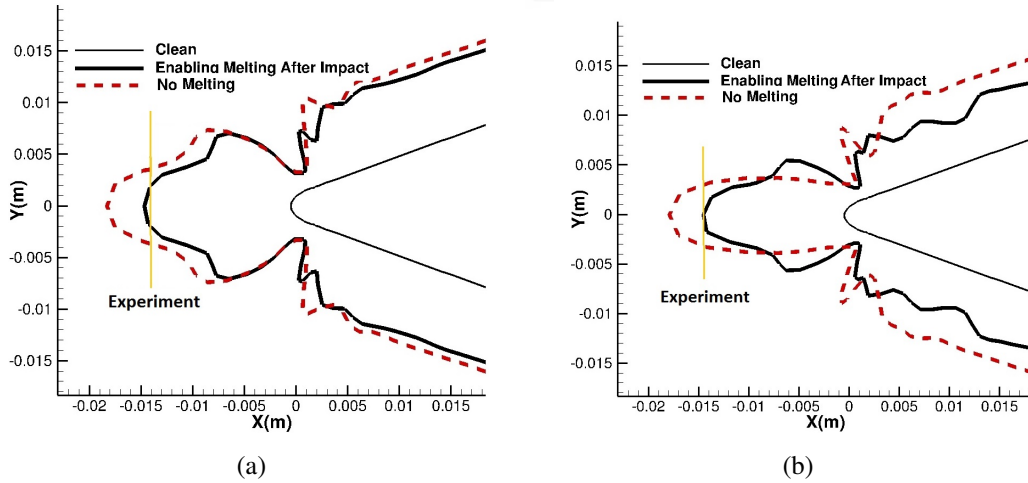


Figure 6.7: Melting model effect after impact. The yellow line shows the leading edge ice thickness experimental result after 180 seconds (a) Case #543 $T_{Tot} = 13.0$ °C (b) Case #553 $T_{Tot} = 6.0$ °C.

Ice shape comparisons are depicted for case #522 in Figure 6.8. According to the Currie *et al*[25], thickness of the accreted ice after 60 seconds is in between 12 mm

and 26 mm. Since these values are quite different, this experimental result has not been used for calibration. However, as it is shown in Figure 6.8, computational result is in between the given range limits.

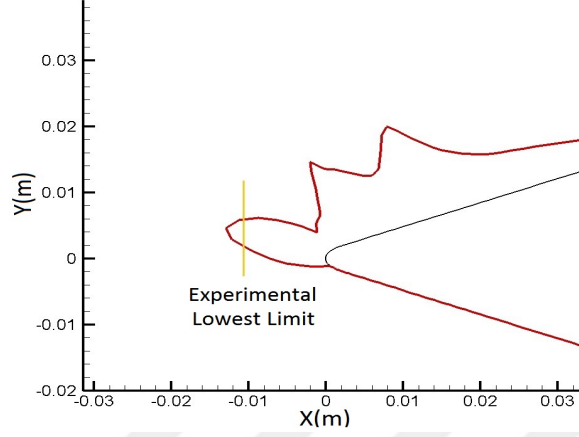


Figure 6.8: Ice shape comparison for Case #522 after 60 s of accretion. $T_{Tot}=20.0$ °C. $LWC = 1.1 \text{ g/m}^3$, $IWC = 17.0 \text{ g/m}^3$. The yellow line shows the minimum leading edge ice thickness experimental limit.

6.3 Comparison by Using NRC Icing Wind Tunnel Experimental Results

Another experimental result is provided by Lozowski *et al* [40]. Icing conditions are given in Table 6.3. According to their study, crystals and droplets MVD are not clear and only ranges have been specified for both values. Corresponding maximum and minimum ice shapes have been computed by using the limit values within the specified range. Although the validity of the roughness model is questionable for such small diameter circle, as it is shown in 6.9, the model predictions and the experimental data can be considered as good. Condition 1 refers to ice crystal $MVD = 1000 \mu\text{m}$, droplet $MVD = 60 \mu\text{m}$ and condition 2 refers to ice crystal $MVD = 100 \mu\text{m}$, droplet $MVD = 80 \mu\text{m}$ in this figure.

Table6.3: Analyses conditions from NRC experiment [40].

Case	Mach Number	Static Temp. (°C)	IWC (g/m ³)	LWC (g/m ³)	Crystal MMD (μm)	Droplet MMD (μm)	Duration (s)
47CM	0.38	-22	1.0	0.4	100-1000	60-80	300

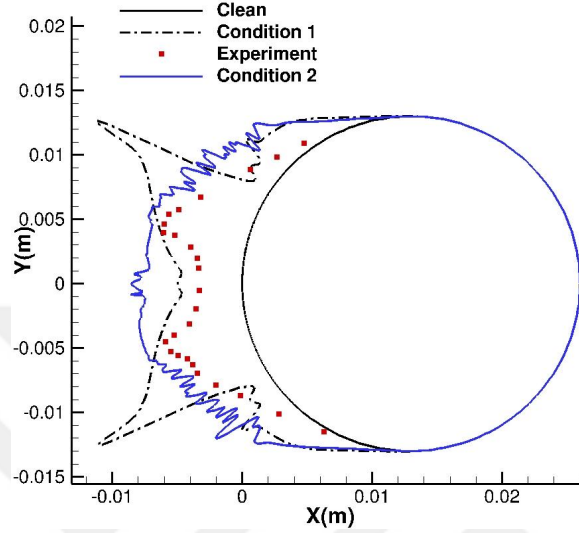


Figure 6.9: Ice shape comparison for case #47CM after 300 s of accretion. Condition 1 refers to ice crystal $MVD = 1000 \mu\text{m}$, droplet $MVD = 60 \mu\text{m}$ and condition 2 refers to ice crystal $MVD = 100 \mu\text{m}$, droplet $MVD = 80 \mu\text{m}$.

6.4 Assessment of Parameters Affecting Ice Shapes

This section gives information about the analyses parameters which affect the accreted ice shapes. Analyses are performed by varying each parameter and results are compared with glaze icing experimental case # 10 as given in Table 6.1 [11].

6.4.1 Number of Time Steps

It is known that accreted ice on body has influence on the flowfield. Single step analyses mostly lead to wrong ice shapes due to this reason. Moreover, too much increase in the number of time steps is also not preferred due to possible numerical errors such as round off. Thus, multi-step analyses should be performed in order to increase the accuracy of the predictions. Determining the number of time steps for each ice ac-

cretion analysis requires a preliminary work as stated in the LEWICE manual[6]. A relation similar to the recommended one in LEWICE manual is used in this study. It should be noted that in order to use this relation, IWC is also included in addition to the LWC. However, this relation is applicable only to glaze ice conditions. Since in rime ice conditions, effect of ice crystals on accreted ice shapes can be negligible in most cases, including IWC in this relation may lead to wrong time step numbers.

$$TimeSteps = \frac{(LWC + IWC)(V)(Time)}{(chord)(\rho)(0.01)} \quad (6.1)$$

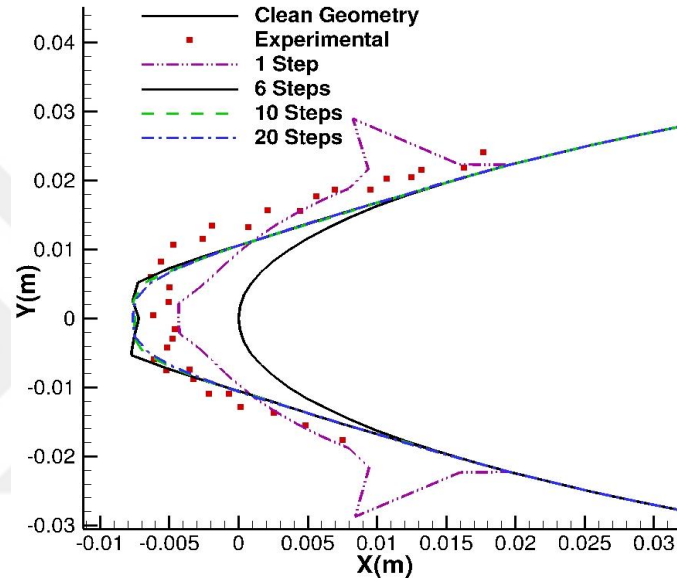


Figure 6.10: Ice shape comparisons for varying time step numbers from 1 to 20.

Analyses are performed for 1, 6, 10 and 20 multi-steps and corresponding comparisons are depicted in Figure 6.10. Required number of time steps is 6 according to equation 6.1 when nearest integer number is chosen. As expected, further increase in time step number does not increase the accuracy of the predictions. Moreover, since number of steps is directly related with the analyses duration, it causes further increase in the cost of the analyses. On the other hand, lower step analyses are also eliminated due to low accuracy.

6.4.2 Number of Panels

Number of panels and boundary layer grids have direct influence on accreted ice on the surface. One reason is that they affect flowfield variables and heat transfer coefficients. Another reason is that the ice thicknesses are calculated for these points. A comparison is shown in Figure 6.11 for three different panel numbers and corresponding computational times are given in Table 6.4.

Table 6.4: Number of panels and boundary layer grids

Case	Number of Panels	Number of Boundary Layer Grids	Computational Time (s)
Coarse	101	401	180
Medium	401	801	425
Fine	701	1401	1050

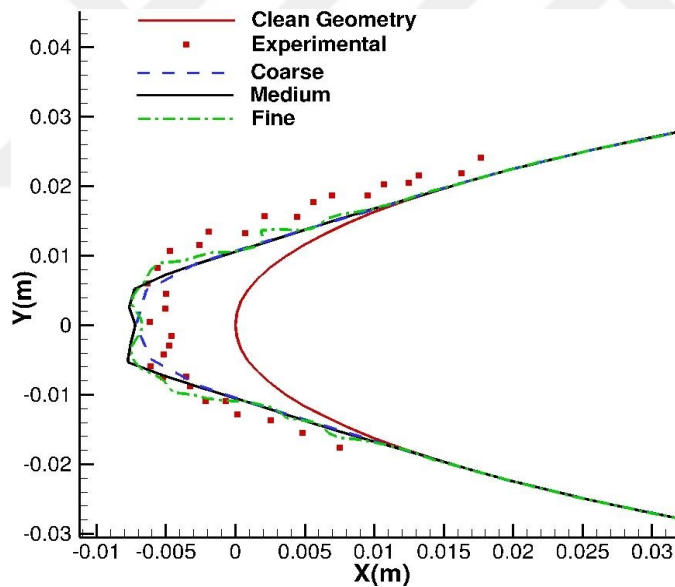


Figure 6.11: Ice shape comparisons for varying panel number.

As it is depicted in Figure 6.11, varying number of panels changes the accreted ice shape on the surface. The accuracy of the coarsest one is good but capturing complicated ice shapes will be difficult due to less number of panels. Predictions of the finest one is also acceptable but it increases the computational time as shown in Table 6.4. Thus, the medium one is chosen as the optimum number of panels.

6.4.3 Aerodynamic Performance Evaluation of the Iced Wing Section

It is stated in chapter 1 that ice accretion on aircraft components may result in degradation of aerodynamic performance, alteration of stability and control characteristics often in an unpredictable manner, severe reduction in engine performance, false flight data readings and increase in weight. Affect of ice crystal accretion on external components of the aircraft is similar to the ice accretion due to droplets. In this part, aerodynamic performance evaluation study is performed for the wing section after ice accretion. Case #10 in Cox experimental tests is used for this purpose [11]. Icing conditions and flow field parameters are given in Table 6.5.

Table6.5: Analyses conditions from COX experiments revisited [11].

Case	Airspeed (m/s)	Total Temp. (°C)	Total Press. (kPa)	IWC (g/m ³)	LWC (g/m ³)	Crystal MVD (μm)	Droplet MVD (μm)
10	53.60	-5.55	100	0.7	0.7	200	20

Navier - Stokes analyses were performed for prediction of aerodynamic performance of the wing section. Grid on NACA 0012 after ice accretion is shown in Figure 6.12. Additional information related to the CFD analyses are given in Table 6.6. K- ω turbulence model with shear stress correction is used in the analyses. Surface roughness can be predicted with the following relation, which is discussed in detail in chapter 2. However, since the variation of the surface roughness height is low in this case, mean value is calculated and applied in the analyses.

$$k_s = \left(\frac{4\sigma_w \mu_w}{\rho_w} F \tau \right)^{1/3} \quad (6.2)$$

where σ_w is surface tension. Fraction of the body surface that is wetted by water droplets is denoted by F , while τ denotes surface shear stress.

Table6.6: Navier - Stokes analyses parameters for aerodynamic performance evaluation.

Turbulence Model	Grid Size	Reynolds Number	y+	AOA Range (°)	Mean Surface Roughness Height (mm)
K- ω SST	45,000	2.3 x 10 ⁶	< 1	0 - 16	0.5

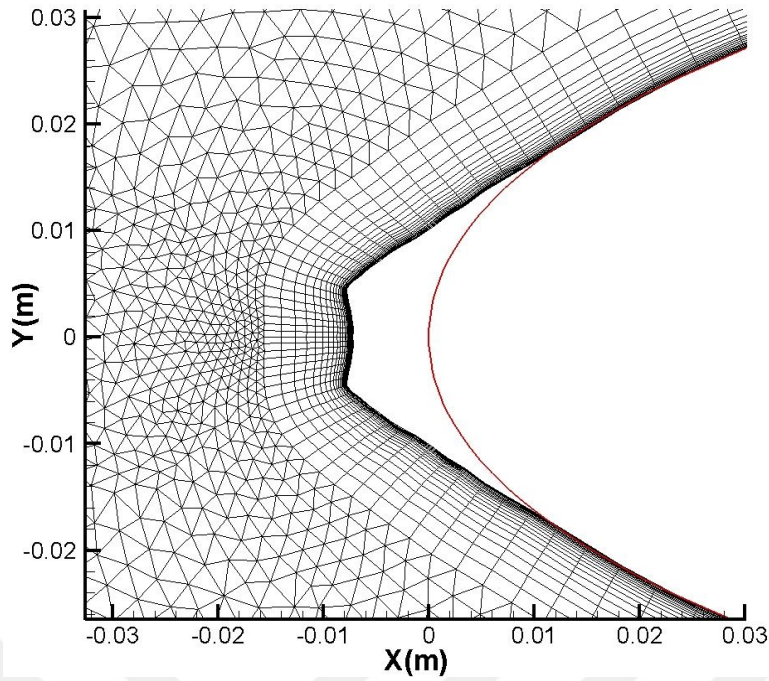


Figure 6.12: Grid on NACA 0012, which is prepared for Navier-Stokes analyses.

Pressure contours and velocity vectors are depicted in Figure 6.13. As it is shown in this figure, ice accretion on airfoil causes early stall as stated before. Flow direction is reversed within the boundary layer at the upper part of the airfoil.

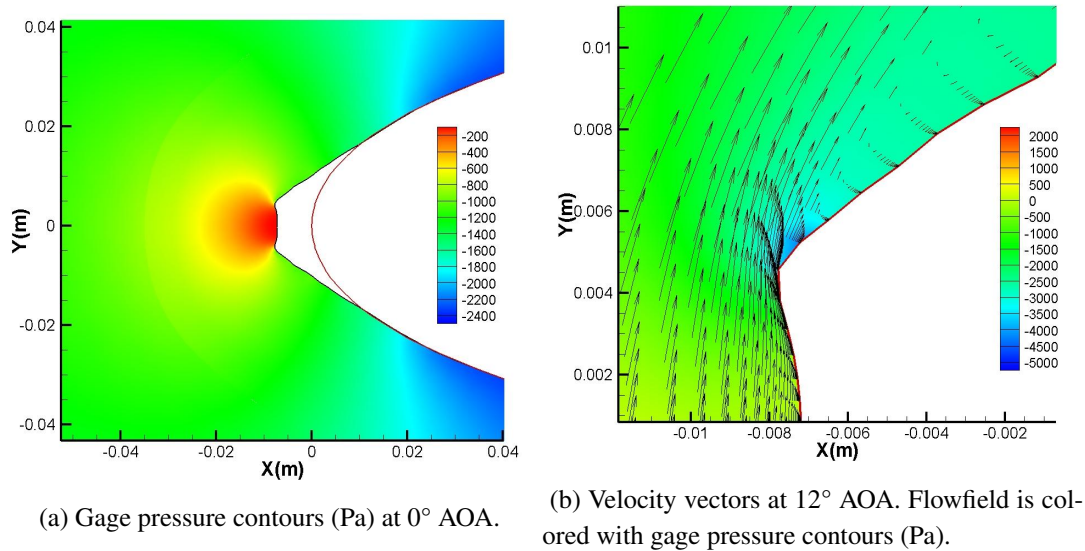
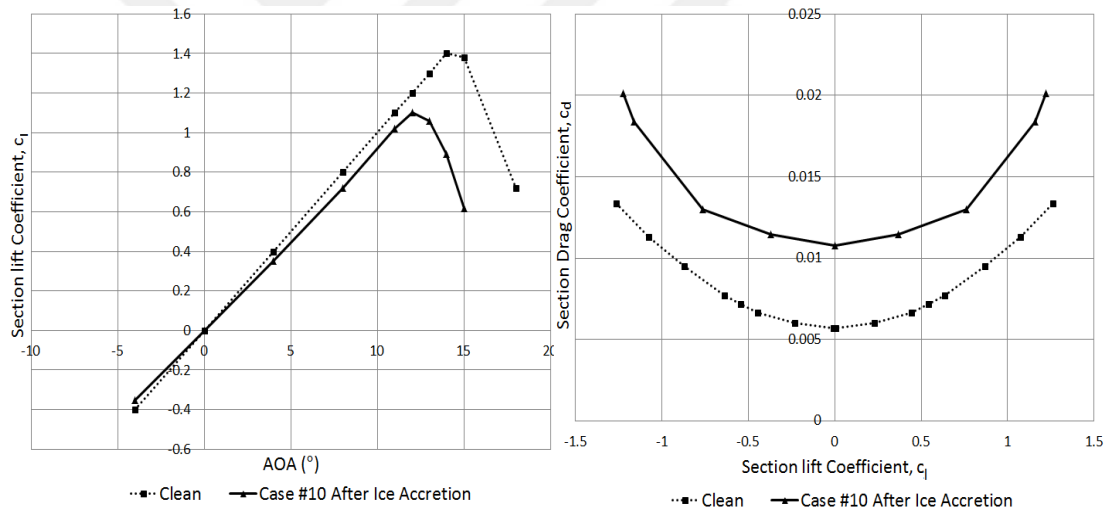


Figure 6.13: Pressure contours and velocity vectors of the iced airfoil case.

Case #10 is analyzed after ice accretion and shown in Figure 6.14. Clean NACA 0012 is analyzed as well for comparison. Sectional lift coefficient, c_l , vs. AOA and c_l vs. sectional drag coefficient, c_d , comparisons are depicted in Figure 6.14. As it is shown in these figures, lift curve slope, $c_{l,max}$ and stall angle decrease after ice accretion. Moreover, nearly 0.005 increase, which corresponds to the $c_{d,0}$ value, in c_d is obtained at each c_l value. As it is stated before, increase in drag coefficient is mainly due to the increase in surface roughness height. Laminar flow to turbulent flow transition is caused primarily by the surface roughness. Moreover, once turbulent, further increase in surface roughness enhances the skin friction coefficient and increases the effective surface area. The transition location moves upstream very rapidly as AOA increases. It causes an early transition to turbulent boundary layer. Since the analyzed iced airfoil does not have horns or sharp edges, pressure drag contribution in total drag is limited for this condition [54, 7].



(a) c_l vs. AOA comparison of the wing section after and before ice accretion. (b) c_l vs. c_d comparison of the wing section after and before ice accretion.

Figure 6.14: Aerodynamic performance comparison after and before ice accretion.



CHAPTER 7

INDUSTRIAL APPLICATIONS AND BEST NUMERICAL PRACTICES

Industrial applications and corresponding numerical best practices are given for ice crystal accretion in this chapter. In the first part of the chapter, test cases results dedicated to probe environment are presented. Then second part is devoted to ice crystals icing in engine environment.

7.1 Ice Accretion on Representative Probe Environment

Aim of these analyses is to show capability of solving mixed phase icing condition on probe geometry. Axisymmetric assumption has been used in this test case. As discussed in the previous chapters Hess-Smith Panel Method has been enabled for flow field computations. Thus, the geometry has been divided just into some panels for the computations. Corresponding axisymmetric geometry with the panel end points is depicted in Figure 7.1.



Figure 7.1: Simplified axisymmetric probe geometry used in computations.

In order to evaluate all implemented models to TAICE, some run conditions have been determined to obtain sample ice shapes. Run conditions have been selected similar to

the used ones in COX [11] experiments. Corresponding analyses conditions are given in Table 7.1. In addition to the parameters given in the table, it should be noted that surrounding temperature is 30°C , angle of attack is 0° and duration for analyses is 300 seconds.

Table7.1: Analyses conditions for probe case

Case	Airspeed (m/s)	Crystal Temp. (°C)	Static Press. (kPa)	IWC (g/m³)	LWC (g/m³)	Crystal MVD (μm)	Droplet MVD (μm)
1	75	-9.3	95.8	0.3	0.7	100	50
2	75	-9.3	95.8	0.7	0.3	100	50
3	75	-29.9	95.8	0.3	0.7	100	50
4	75	-29.9	95.8	0.7	0.3	100	50
5	75	-9.3	95.8	-	0.7	100	50
6	75	-29.9	95.8	-	0.7	100	50

Full mixed phase icing analyses have been performed with the given data by using TAICE. In order to obtain sample ice shapes, in addition to the ice crystals water, droplets are also included in the analyses. Since during the flight warmer flow conditions may occur around the heated surfaces, surrounding temperature may not be equal to ambient temperature. Thus, in these analyses, surrounding temperature has been fixed to 30°C and heat transfer between the particle and the surrounding is enabled.

Ice crystals trajectories colored with particles velocities and particles temperature are shown in Figures 7.2 and 7.3. Since the temperature of the ice crystal affects the impingement ratio of the particles and amount of accreted ice on the surface, heat transfer and phase change models are activated during the trajectory. It is noted that starting from 243.25 K, particle temperature increases up to 262 K before entering the probe within last 50 cm of its trajectory. Then, run conditions have been analyzed with TAICE and corresponding ice shapes are shown in Figure 7.4. Run parameters have been arranged to obtain both rime and glaze icing conditions. Moreover, in order to clearly evaluate and isolate the effects of the ice crystals same analyses have been performed only with water droplets.

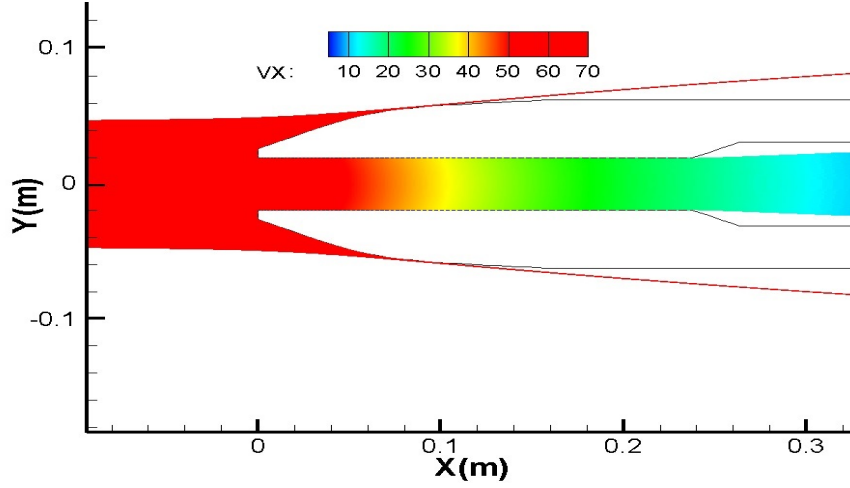


Figure 7.2: Axial velocity contour in crystal trajectories (m/s) case #6 $V_\infty = 75.0$ m/s.

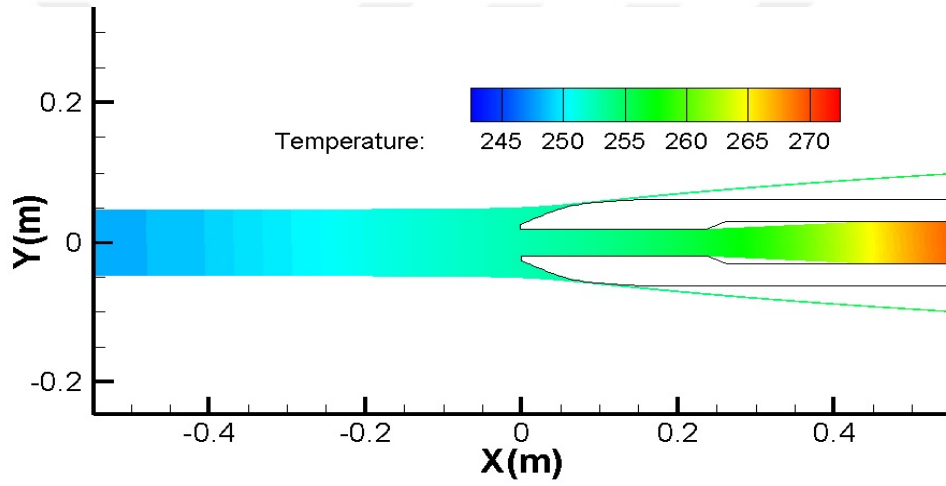
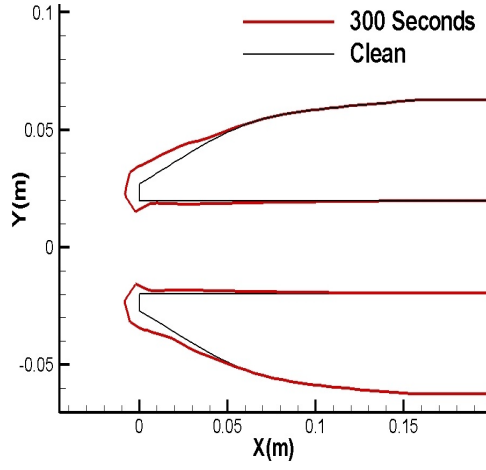
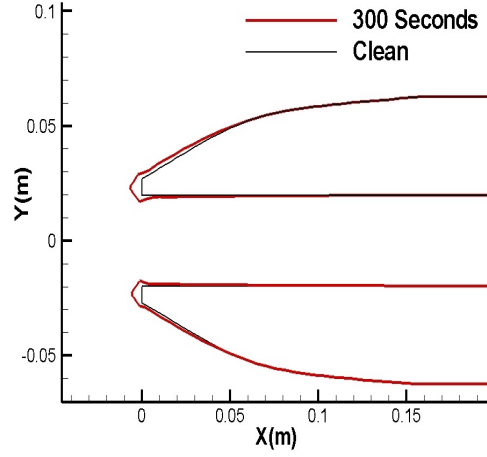


Figure 7.3: Temperature contours in crystal trajectories (K) case #6 $T_{Tot} = 303.15$ K.

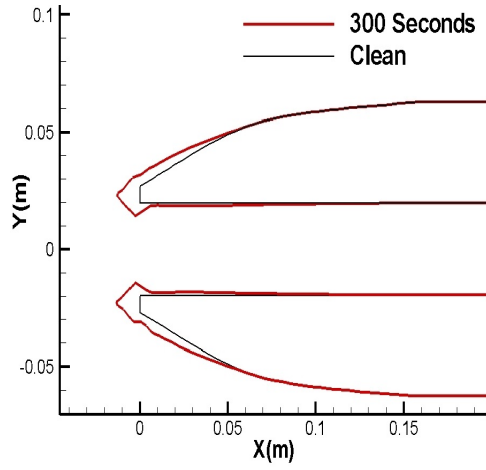
As it is shown in Figure 7.4, ice has been accreted where the crystal particles bounce off the surface. The effect of erosion has been noted in the analyses which have greater IWC. Due to a series of factors such as high fragmentation and bouncing of the ice particles that strikes on the probe, and mostly the cold wall of the surface of the probe, less sticking and hence less amount of ice accretion is seen. Glaze ice is observed only at a few panels due to the short accretion time even at -9.3°C . The number of corresponding panels would be higher, if the accretion time is further increased. Since the number of panels at which which glaze ice occurs is less, the effect of ice crystals is low on the accreted ice shape. Thus, accreted ice on the surface is directly proportional to the liquid water content of the flow.



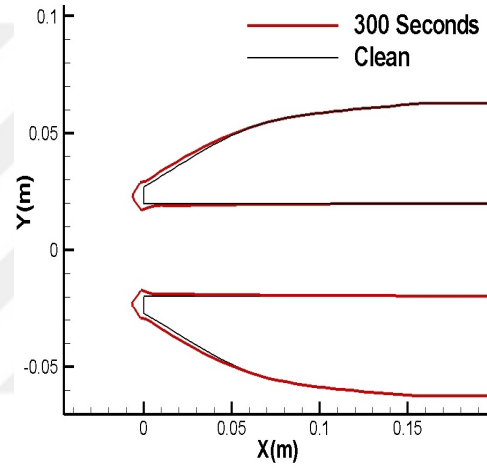
(a) Case #1, $T_{crystal} = -9.3^{\circ}\text{C}$, $IWC = 0.3 \text{ g/m}^3$, $LWC = 0.7 \text{ g/m}^3$



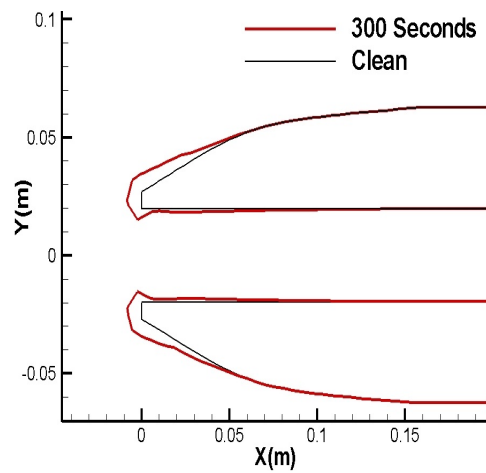
(b) Case #2, $T_{crystal} = -9.3^{\circ}\text{C}$, $IWC = 0.7 \text{ g/m}^3$, $LWC = 0.3 \text{ g/m}^3$



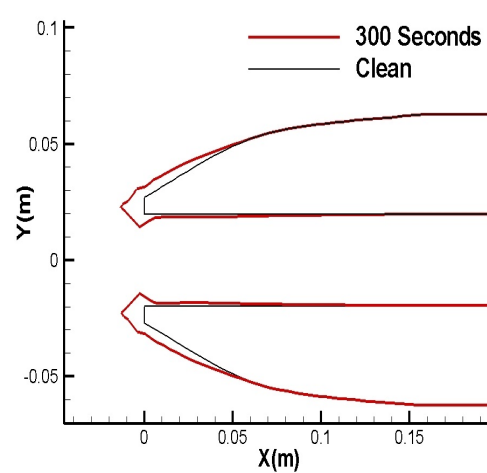
(c) Case #3, $T_{crystal} = -29.9^{\circ}\text{C}$, $IWC = 0.3 \text{ g/m}^3$, $LWC = 0.7 \text{ g/m}^3$



(d) Case #4, $T_{crystal} = -29.9^{\circ}\text{C}$, $IWC = 0.7 \text{ g/m}^3$, $LWC = 0.3 \text{ g/m}^3$



(e) Case #5, $T_{crystal} = -9.3^{\circ}\text{C}$, $LWC = 0.7 \text{ g/m}^3$



(f) Case #6, $T_{crystal} = -29.9^{\circ}\text{C}$, $LWC = 0.7 \text{ g/m}^3$

Figure 7.4: Ice shapes for probe cases .

7.2 Ice Accretion on Representative Engine Inlet

Objectives of analyses are to show capability of solving mixed phase ice accretion problem on engine inlet and to assess particles trajectories results. Engine inlet geometry is shown in Figure 7.5. Analyzed run conditions are given in complementary part which is adopted just for showing capability.

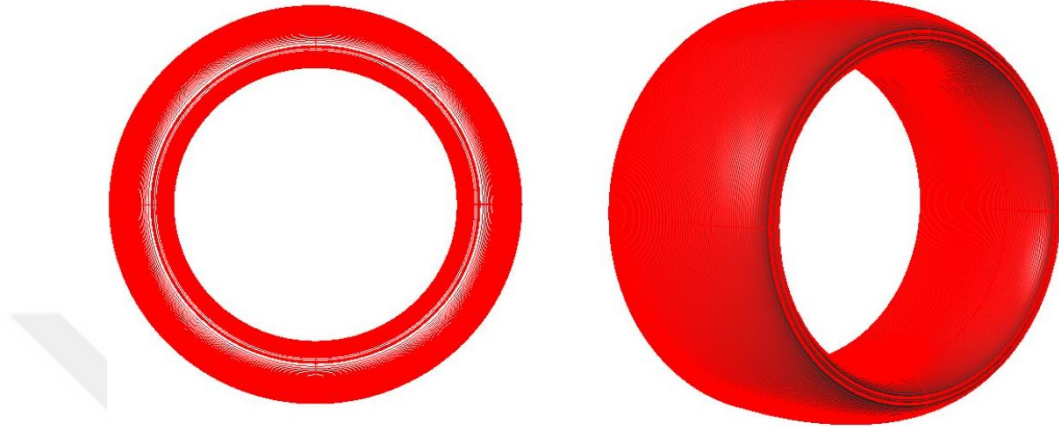
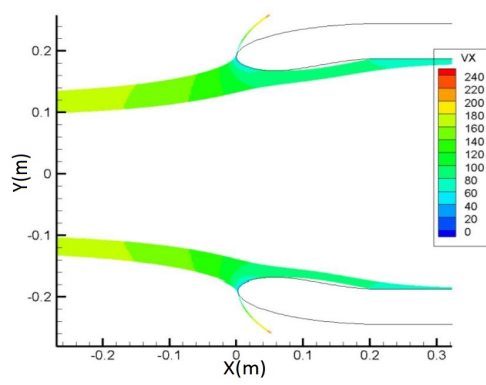


Figure 7.5: Axisymmetric engine inlet geometry used in the computations [59].

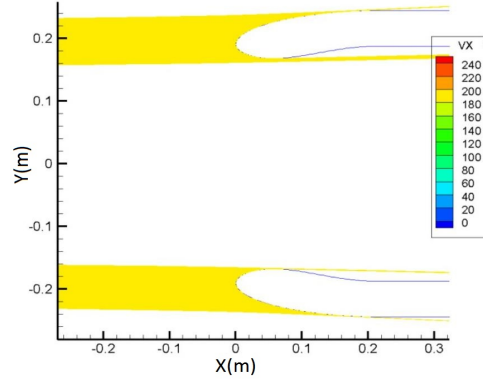
Following test points, given in Table 7.2, have been analyzed in this part. As in the probe test case angle of attack is 0° . MVD, flight speed and sphericity have been varied to evaluate their respective effect on trajectories. In Figure 7.6, trajectories are compared for different MVD and flight velocities. As expected, with increasing MVD, the effect of flow field on trajectories of ice crystals decreases. When MVD equal to $1000\mu\text{m}$ trajectories become exact linear. Moreover, it is known that increasing flight speed increases the kinetic energy of the impacting particles. When the airspeed is high ice crystals do not have enough time to deviate from the obstacle, thus more particles impact on the engine inlet.

Table 7.2: Analyses conditions for trajectory comparison in engine inlet geometry.

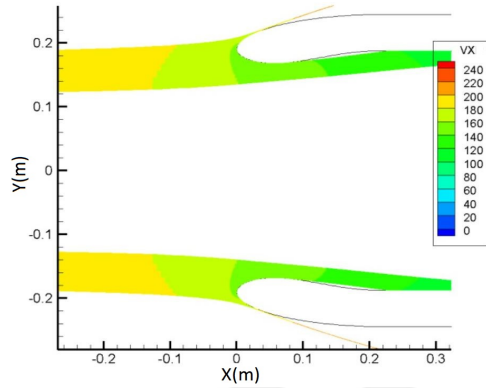
Case	Airspeed (m/s)	$\dot{m}$ (kg/s)	Static Press. (kPa)	Sphericity	Crystal MVD (μm)	Crystal Temp. ($^\circ\text{C}$)
1	200	10.42	95.84	1.0	20	-29.9
2	200	10.42	95.84	1.0	1000	-29.9
3	200	10.42	95.84	1.0	100	-29.9
4	75	10.42	95.84	1.0	100	-29.9
5	200	10.42	95.84	0.2	100	-29.9



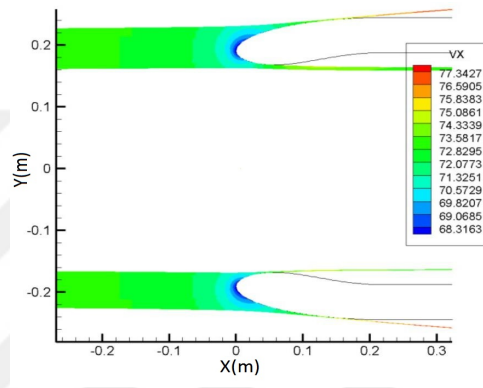
(a) Case #1, $V_{\infty} = 200$ m/s, $MVD = 20$ μ m



(b) Case #2, $V_{\infty} = 200$ m/s, $MVD = 1000$ μ m

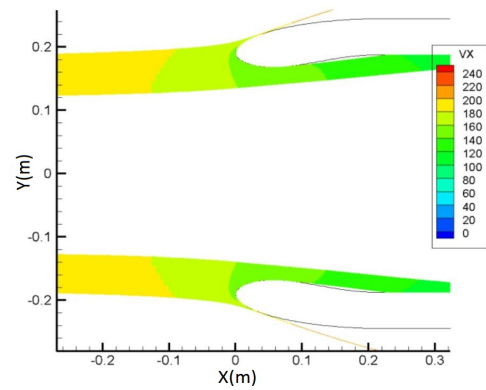


(c) Case #3, $V_{\infty} = 200$ m/s, $MVD = 100$ μ m

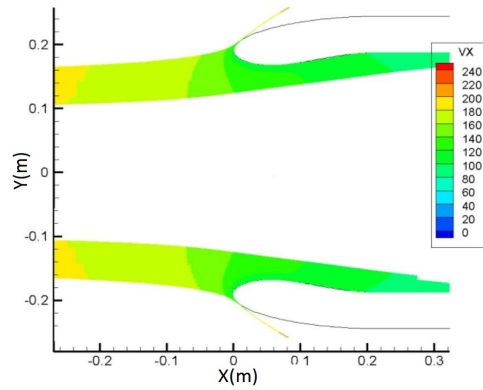


(d) Case #4, $V_{\infty} = 75$ m/s, $MVD = 100$ μ m

Figure 7.6: Ice crystals trajectory comparison with varying flight speed and crystal MVD. Trajectories colored with axial velocity component (m/s).



(a) Case #3, $\phi = 1.0$



(b) Case #5, $\phi = 0.2$

Figure 7.7: Ice crystals trajectory comparison with varying crystal sphericity. Trajectories colored with axial velocity component (m/s).

Two different sphericity values (1 and 0.2) are used for trajectory comparison in Figure 7.7 and trajectories are colored with axial velocity. Hölzer & Sommerfeld drag force coefficient model is used in this comparison study and it is seen that decreasing sphericity caused ice crystal particles deviate from the obstacle. Moreover, velocities of the particles decrease due to the increase in the calculated drag coefficient.

7.3 Complementary Calculations for Engine Inlet Case

Parameters which are given in Table 7.3 have been determined similar to the used ones in COX [11] experiments. Moreover, droplet diameters are 20 μm in all cases. Two different temperatures have been selected to constitute rime and glaze icing conditions. LWC and IWC values are varied within the same range as in the previous analyses where the erosion model is calibrated. Furthermore, mass flow rates have been varied additionally which gives also a chance to evaluate implemented engine inlet model of TAICE.

Table 7.3: Analyses conditions for engine inlet geometry.

Case	IWC (g/m^3)	LWC (g/m^3)	$\dot{m}$ (kg/s)	Static Press. (kPa)	Crystal MVD (μm)	Crystal Temp. ($^{\circ}\text{C}$)	Duration (s)
1	0.3	0.7	7.80	95.84	100	-9.3	1800,3600
2	0.7	0.3	7.80	95.84	100	-9.3	1800,3600
3	0.3	0.7	10.42	95.84	100	-9.3	1800,3600
4	0.7	0.3	10.42	95.84	100	-9.3	1800,3600
5	0.3	0.7	7.80	95.84	100	-29.9	1800,3600
6	0.7	0.3	7.80	95.84	100	-29.9	1800,3600
7	0.3	0.7	10.42	95.84	100	-29.9	1800,3600
8	0.7	0.3	10.42	95.84	100	-29.9	1800,3600
9	-	0.7	7.80	95.84	-	-9.3	1800,3600
10	-	0.7	10.42	95.84	-	-9.3	1800,3600
11	-	0.7	7.80	95.84	-	-29.9	1800,3600
12	-	0.7	10.42	95.84	-	-29.9	1800,3600

In Figure 7.8, ice crystals trajectories are depicted for case #1 icing conditions. It should be noted that during the trajectory of the ice crystals, heat transfer is ignored. Moreover, fragmentation model is activated and some of the ice crystals bounce off the wall when they hit to the surface.

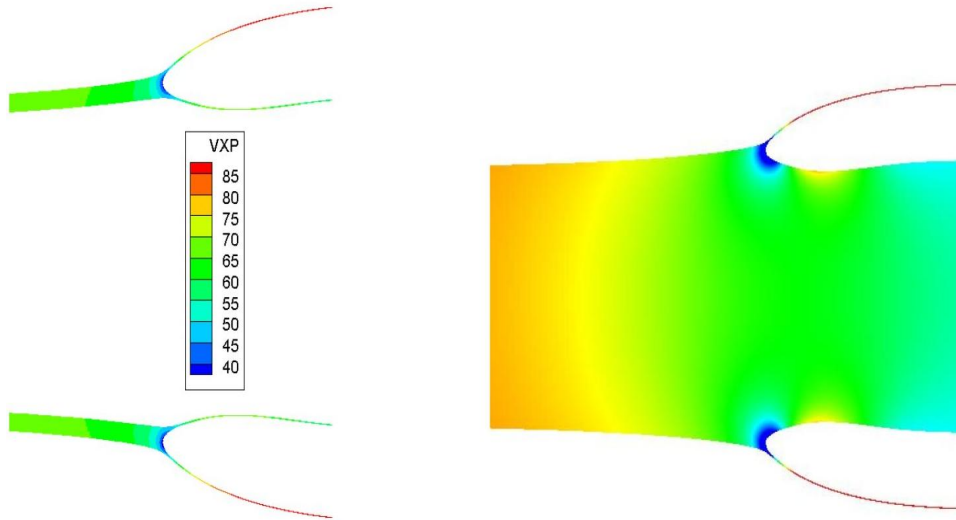


Figure 7.8: Axial velocity contours in ice crystal trajectories case #1 (m/s).

In Figure 7.9, all accreted ice shapes are shown together. Since the flow is symmetric, accreted ice shapes are also symmetric and due to the low LWC and IWC values, accretion rate is too low and analyses time has been increased up to 3600 seconds in order to make ice shapes visible and to obtain glaze ice at some panels..

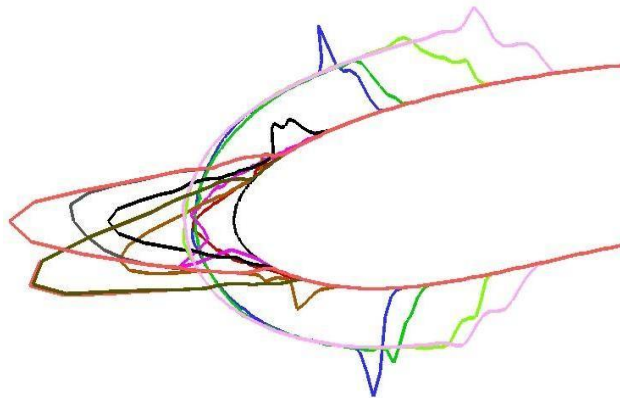
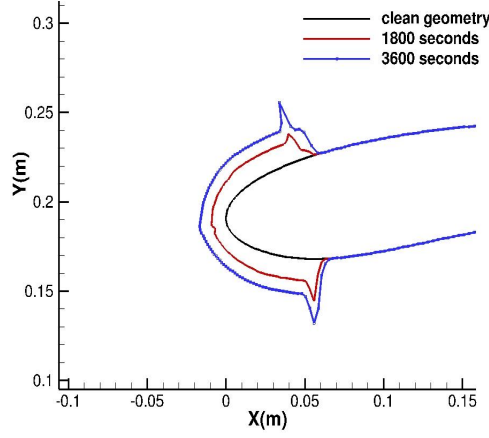


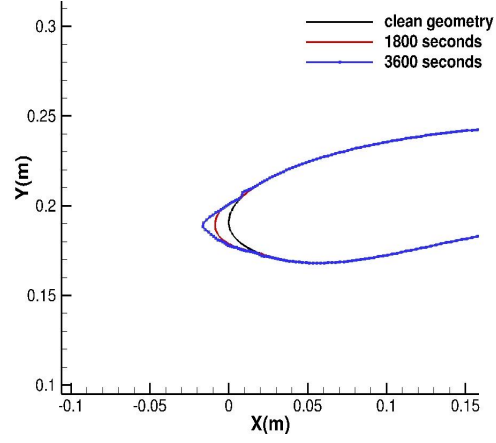
Figure 7.9: All of the ice shapes computed on axisymmetric engine inlet.

Run conditions have been analyzed with TAICE and corresponding ice shapes are shown in Figure 7.10 and in Figure 7.11. Run parameters have been arranged to obtain both rime and glaze icing conditions. Glaze ice is observed at all panels at -9.3 °C after 1800 seconds. Thus, high erosion effect is seen. Ice crystals cause to reduce the accreted ice on the surface. Moreover, at all run conditions when the ice shapes of 1800 seconds and 3600 seconds are compared it is observed that ice accretion rate decreases. Erosion and accreted ice affect on the flow field are the main reasons for this reduction. At -29.9 °C rime ice occurs at most of the panels. Thus, effect of ice crystals is negligible compared to the glaze ice cases.

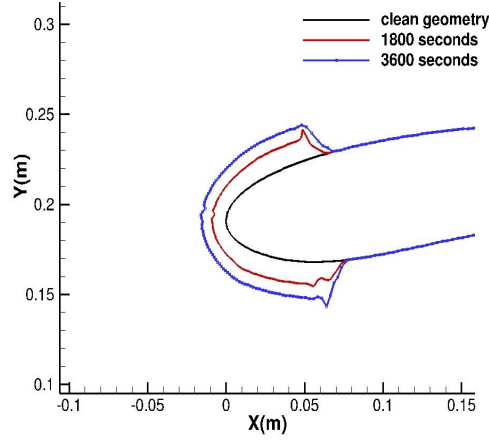




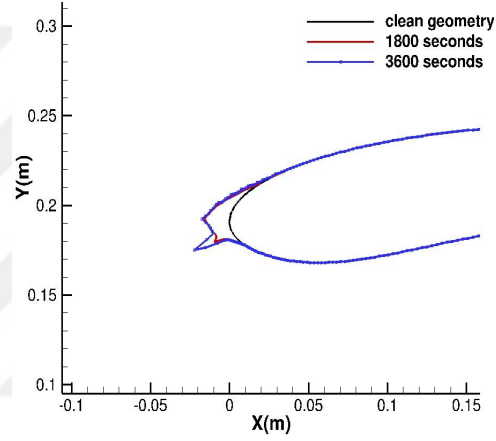
(a) Case #1, $T_{crystal} = -9.3\text{ }^{\circ}\text{C}$, $\dot{m} = 7.80\text{ kg/s}$, $IWC = 0.3\text{ g/m}^3$, $LWC = 0.7\text{ g/m}^3$



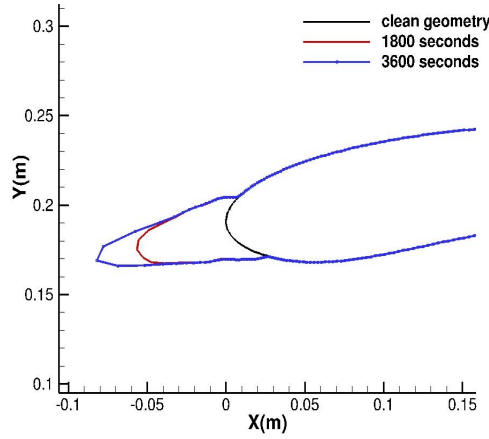
(b) Case #2, $T_{crystal} = -9.3\text{ }^{\circ}\text{C}$, $\dot{m} = 7.80\text{ kg/s}$, $IWC = 0.7\text{ g/m}^3$, $LWC = 0.3\text{ g/m}^3$



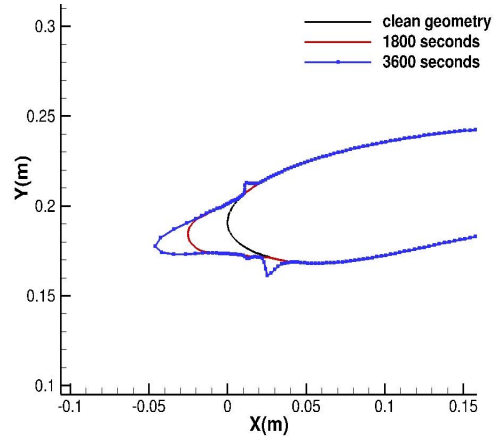
(c) Case #3, $T_{crystal} = -9.3\text{ }^{\circ}\text{C}$, $\dot{m} = 10.42\text{ kg/s}$, $IWC = 0.3\text{ g/m}^3$, $LWC = 0.7\text{ g/m}^3$



(d) Case #4, $T_{crystal} = -9.3\text{ }^{\circ}\text{C}$, $\dot{m} = 10.42\text{ kg/s}$, $IWC = 0.7\text{ g/m}^3$, $LWC = 0.3\text{ g/m}^3$

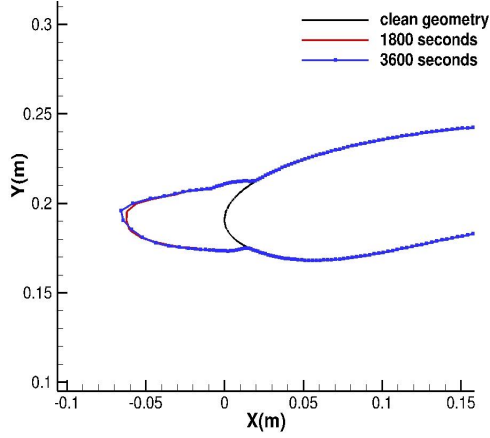


(e) Case #5, $T_{crystal} = -29.9\text{ }^{\circ}\text{C}$, $\dot{m} = 7.80\text{ kg/s}$, $IWC = 0.3\text{ g/m}^3$, $LWC = 0.7\text{ g/m}^3$

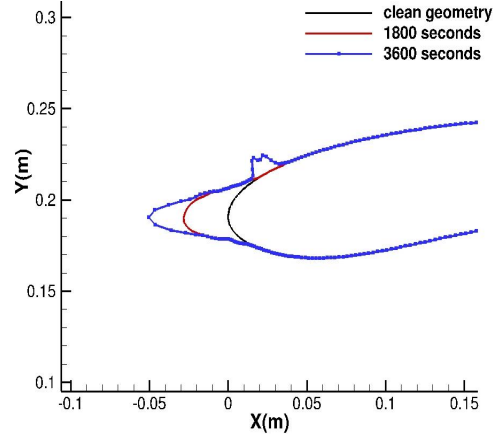


(f) Case #6, $T_{crystal} = -29.9\text{ }^{\circ}\text{C}$, $\dot{m} = 7.80\text{ kg/s}$, $IWC = 0.7\text{ g/m}^3$, $LWC = 0.3\text{ g/m}^3$

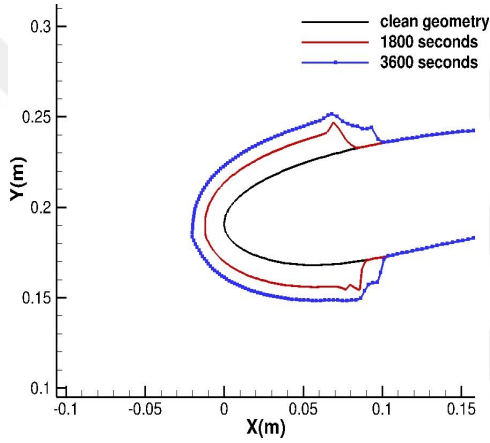
Figure 7.10: Ice shapes for engine inlet cases #1 to #6.



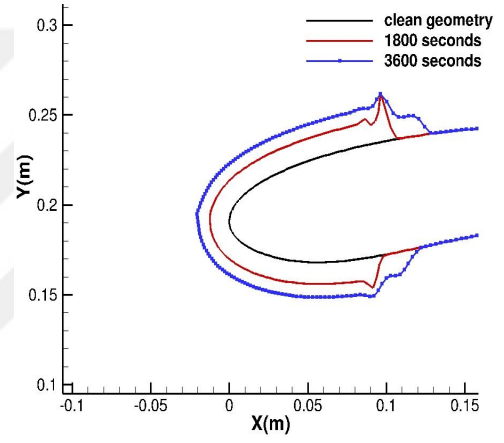
(a) Case #7, $T_{crystal} = -29.9\text{ }^{\circ}\text{C}$, $\dot{m} = 10.42\text{ kg/s}$, $IWC = 0.3\text{ g/m}^3$, $LWC = 0.7\text{ g/m}^3$



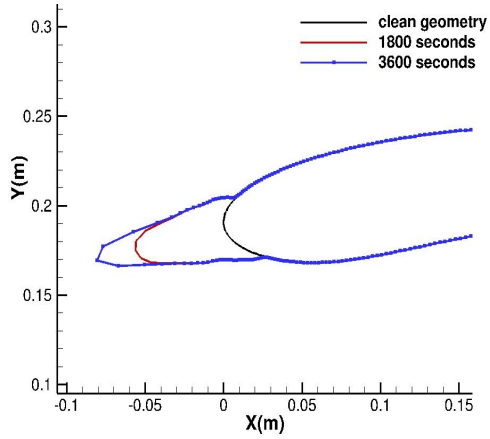
(b) Case #8, $T_{crystal} = -29.9\text{ }^{\circ}\text{C}$, $\dot{m} = 10.42\text{ kg/s}$, $IWC = 0.7\text{ g/m}^3$, $LWC = 0.3\text{ g/m}^3$



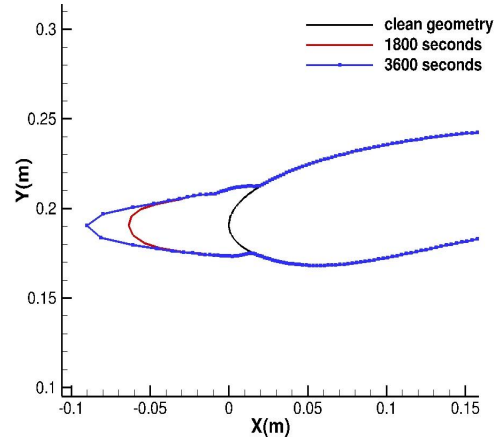
(c) Case #9, $T_{crystal} = -9.3\text{ }^{\circ}\text{C}$, $\dot{m} = 7.80\text{ kg/s}$, $IWC = -, LWC = 0.7\text{ g/m}^3$



(d) Case #10, $T_{crystal} = -9.3\text{ }^{\circ}\text{C}$, $\dot{m} = 10.42\text{ kg/s}$, $IWC = -, LWC = 0.7\text{ g/m}^3$



(e) Case #11, $T_{crystal} = -29.9\text{ }^{\circ}\text{C}$, $\dot{m} = 7.80\text{ kg/s}$, $IWC = -, LWC = 0.7\text{ g/m}^3$



(f) Case #12, $T_{crystal} = -29.9\text{ }^{\circ}\text{C}$, $\dot{m} = 10.42\text{ kg/s}$, $IWC = -, LWC = 0.7\text{ g/m}^3$

Figure 7.11: Ice shapes for engine inlet cases #7 to #12.



CHAPTER 8

MIXED PHASE ICE ACCRETION PREDICTION WITH TAICE3D

Mixed phase ice accretion prediction capability of the 3D version of TAICE is presented in this chapter. First, computational approach while performing numerical analyses is detailed. Then, in-flight ice formation results on finite wings are given. COX and TUBS experimental results are used for ice shape comparisons on wing sections in order to validate the tool. Thus, the present study is an effort to extend the previous work on two-dimensional analysis to three dimensions and to predict ice shapes with the new tool.

8.1 Computational Approach

Computational analysis begins with the calculation of the flow field variables as in the 2-D version. 3-D panel method is used to calculate the velocity distribution around the given geometry. Liquid and solid cloud particles are released at the same time at a sufficiently far upstream location and the Lagrangian method is used to compute the trajectories. Since trajectory calculations constitute nearly 99% of the whole computational time, this part is parallelized by using MPI. The given geometry is divided into spanwise panels and trajectories of the cloud particles which are released for each spanwise panel are computed with different threads [57]. Four spanwise panels are used in this comparison study. For the thermodynamic relations, two dimensional Integral Boundary Layer relations are utilized. Then, collection efficiencies are computed at each chordwise panel upon calculating impact locations of the particles.

Finally, ice accretion predictions are performed by using the modified version of the Extended Messinger Model and ice shapes are obtained.

The developed tool allows performing multi-layer analyses and in order to increase the accuracy, total exposure time is divided into segments. Since accreted ice affects the flow field variables, whole analysis is repeated for each time segment in the multi-layer mode. To show the trajectories COX-10 experimental case is analyzed [11]. Constant chord is assumed along the wing having 2.74 m span, which is the wind tunnel test section width as indicated in the study of Al-Khalil *et al* [11]. Parameters are given in Table 8.1 for this run condition.

Table8.1: Analyses conditions from COX experiments revisited [11].

Case	Airspeed (m/s)	Total Temp. (°C)	Total Press. (kPa)	IWC (g/m ³)	LWC (g/m ³)	Crystal MVD (μm)	Droplet MVD (μm)
10	53.60	-5.55	100	0.7	0.7	200	20

Droplet and ice crystal particle trajectories are calculated for case #10 and shown in Figure 8.1. Moreover, a closer view is also included for both type of particles as indicated in Figure 8.2.

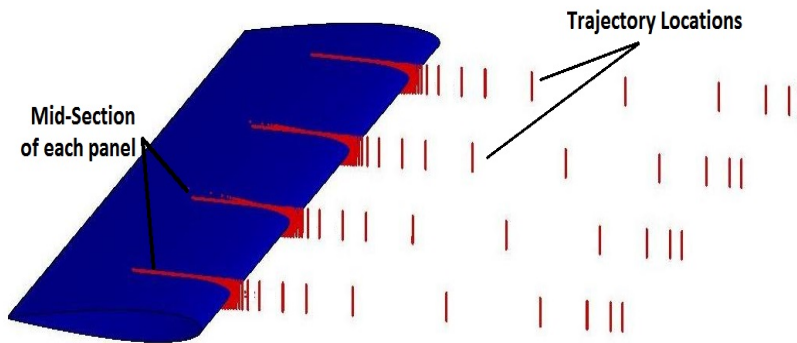


Figure 8.1: Crystal trajectories at $V_{\infty} = 53.60$ m/s, $T_{tot} = -5.55$ °C, $MVD = 200$ μm.

In this sample case, the total wing span is divided into 4 segments and particle trajectories are calculated in the middle of each section. Since the twist angle of the wing is zero and has constant chord, each segment of the wing sees the same angle of attack in this validation case. Then, accreted ice shapes of each segment are connected with the neighboring ones to obtain the 3-D ice shape.

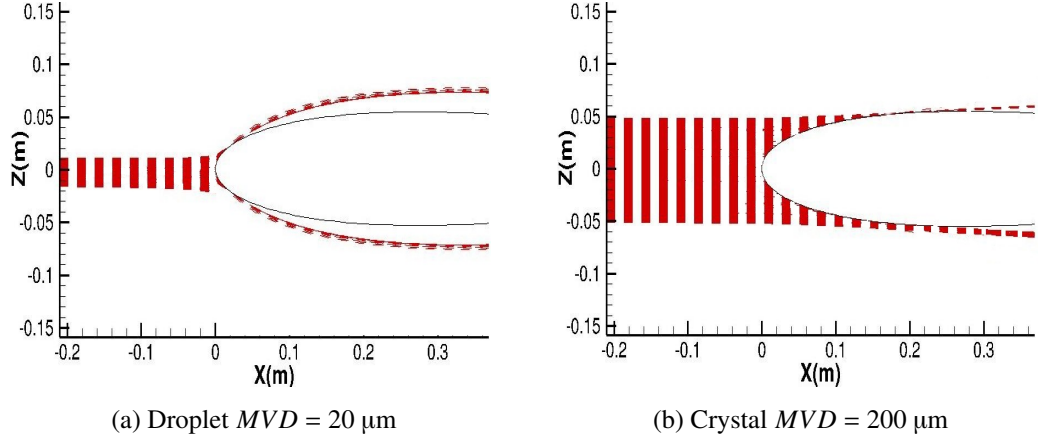


Figure 8.2: Particle trajectories closer view at $V_{\infty} = 53.60 \text{ m/s}$, $T_{tot} = -5.55 \text{ }^{\circ}\text{C}$. (a) Droplets (b) Crystals

Since crystals have greater MVD, their impingement zone is wider on the wing. Thus, the difference between upper and lower release point Z coordinates are higher and step size of the crystals is increased in order to reduce computational time. Moreover, as it is depicted in the closer view in Figure 8.2, droplets deviate more than crystals when they come closer to the wing due to their smaller size.

Collection efficiency distributions are shown in Figure 8.3 for both type of particles. As discussed before, ice crystals impact at a wider zone and the highest value of the collection efficiency is higher when compared with water droplets.

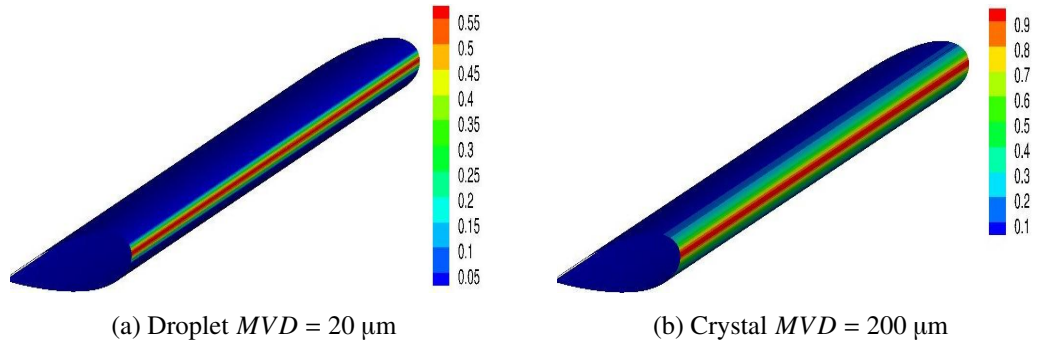


Figure 8.3: Collection efficiency comparison of particles at $V_{\infty} = 53.60 \text{ m/s}$, $T_{tot} = -5.55 \text{ }^{\circ}\text{C}$. (a) Droplets (b) Crystals

8.2 Ice Shape Comparisons

8.2.1 Comparisons by Using COX Experimental Data

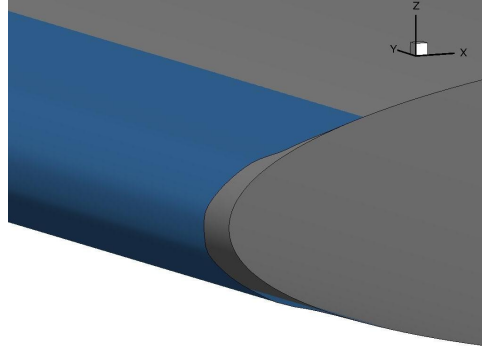
Al-Khalil *et al* [11] performed mixed phase ice accretion experiments by using NACA 0012 airfoil having 0.9144 m chord length. The test section in the icing wind tunnel has a height of 1.83 m and a width of 2.74 m. Ice accretion prediction runs are performed in 6 time steps which are calculated as the optimum time step number as discussed in the previous section. Medium dense panels are preferred in 3-D computations after compromising accuracy and required computational time. Span is divided into 4 segments and 301 panel points are used at each segment. For validation purposes, 2 rime ice and 2 glaze ice test cases are selected. Corresponding icing and flow parameters are introduced in Table 8.2.

Table8.2: Analyses conditions from COX experiments [11].

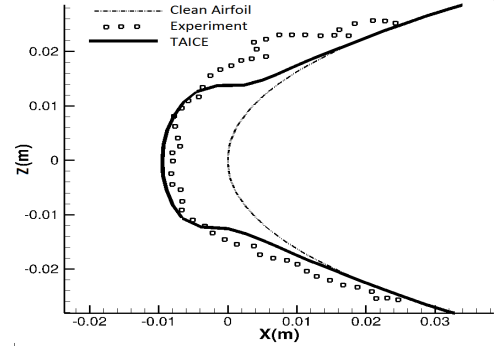
Case	Airspeed (m/s)	Total Temp. (°C)	Total Press. (kPa)	IWC (g/m ³)	LWC (g/m ³)	Crystal MVD (μm)	Droplet MVD (μm)
9	53.60	-5.55	100	-	0.7	-	20
10	53.60	-5.55	100	0.7	0.7	200	20
19	53.60	-11.10	100	0.7	0.3	150	20
20	53.60	-11.10	100	0.3	0.7	150	20

Computational and experimental ice shape comparison is given in Figure 8.4 for case #9 which is a pure droplet case. The computational result is consistent for this pure droplet case when compared with the experimental one.

Case #10 corresponds to another glaze ice condition. In this case, in addition to the droplets ice crystals having IWC equal to 0.7 g/m³ are included in the computations. Figure 8.5 indicates that including ice crystals in the analyses does not cause an increase in the accreted ice on the surface due to erosion.

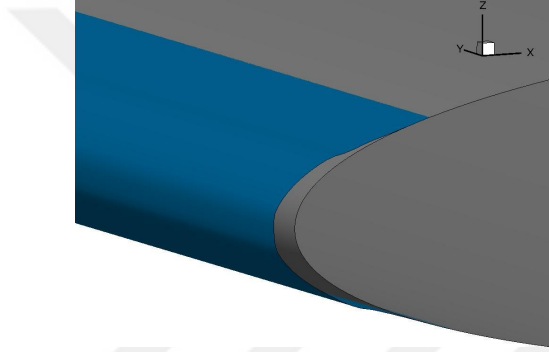


(a) Far view of the accreted ice.

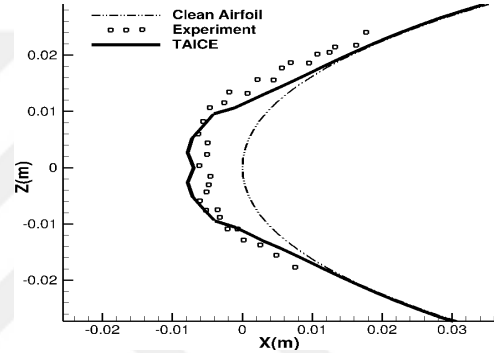


(b) Near view of the accreted ice and comparison with experimental data.

Figure 8.4: Accreted ice shape comparison for case #9, $T_{tot} = -5.55$ °C, $LWC = 0.7$ g/m³. Black line shows accreted ice after 600 s.



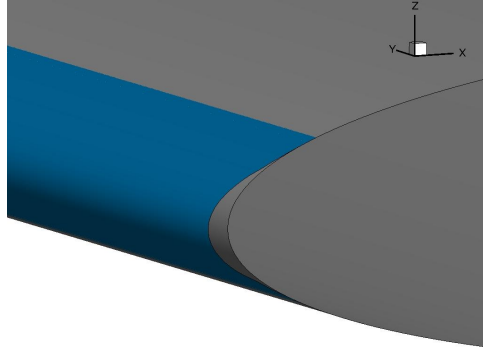
(a) Far view of the accreted ice.



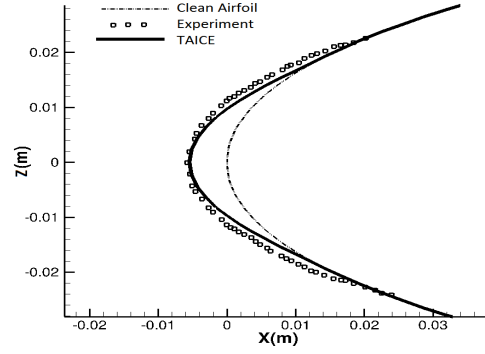
(b) Near view of the accreted ice and comparison with experimental data.

Figure 8.5: Accreted ice shape comparison for case #10, $T_{tot} = -5.55$ °C, $LWC = 0.7$ g/m³, $IWC = 0.7$ g/m³. Black line shows accreted ice after 600 s.

Case #19 and Case #20 correspond to rime ice conditions due to lower temperature. Ice crystals do not stick to surface in these cases and their contribution to ice shapes is only due to erosion. Corresponding ice shapes are shown in Figures 8.6 and 8.7 respectively.

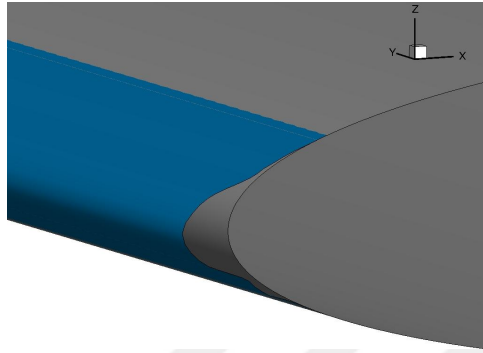


(a) Far view of the accreted ice.

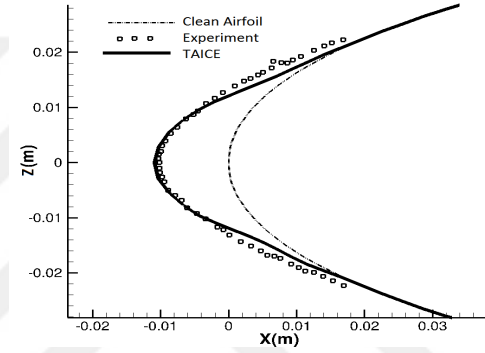


(b) Near view of the accreted ice and comparison with experimental data.

Figure 8.6: Accreted ice shape comparison for case #19, $T_{tot} = -5.55$ °C, $LWC = 0.3$ g/m³, $IWC = 0.7$ g/m³. Black line shows accreted ice after 600 s.



(a) Far view of the accreted ice.



(b) Near view of the accreted ice and comparison with experimental data.

Figure 8.7: Accreted ice shape comparison for case #20, $T_{tot} = -11.10$ °C, $LWC = 0.7$ g/m³, $IWC = 0.3$ g/m³. Black line shows accreted ice after 600 s.

8.2.2 Comparisons by Using TUBS Experimental Data

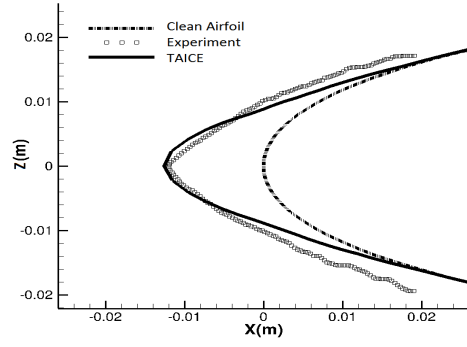
Icing experiments have been performed in the TUBS icing wind tunnel facility. NACA 0012 airfoil having 0.5 m chord has been used in these tests. Selected icing conditions for the validation analyses are given in Table 8.3. Tests have been performed at three different temperatures and at each temperature LWC and IWC values are varied. Droplet clouds are generated by a spray bar within 1.3 to 5 g/m³. On the other hand, ice crystals have a wider range and IWC of the injected crystals have been increased up to 13.6 g/m³. The accretion time is 2 minutes for all runs and the flow angle of attack is 0°. Further details about the experiment facility and tests can be found in the study of Baumert *et al* [14, 15, 13].

Accreted ice shapes on the NACA 0012 airfoil are depicted in Figures 8.8 - 8.10. In these figures, TAICE results are compared with the experimental data. Dotted lines refer to the experimental results and black lines correspond to the TAICE results. Differing from the COX experiments, IWC and LWC reach higher values here. Thus, erosion and impingement models require further calibration.

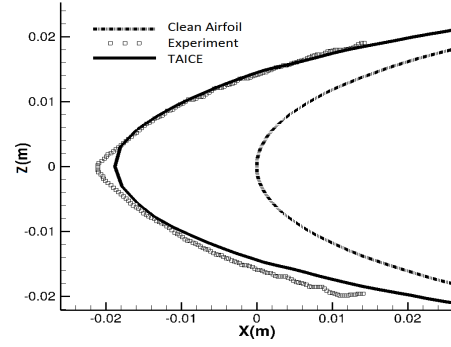
Table8.3: Analyses conditions from TUBS experiments.

Case	Airspeed (m/s)	Static Temp. (°C)	Static Press. (Pa)	IWC (g/m³)	LWC (g/m³)	Crystal MVD (μm)	Droplet MVD (μm)
1	40	0	101325	10.6	1.45	130	80
3	40	0	101325	8.7	3.4	130	80
5	40	0	101325	3.8	3.4	130	80
8	40	-5	101325	10.6	1.45	130	80
10	40	-5	101325	8.7	3.4	130	80
12	40	-5	101325	3.8	3.4	130	80
15	40	-15	101325	10.6	1.45	130	80
16	40	-15	101325	8.7	3.4	130	80

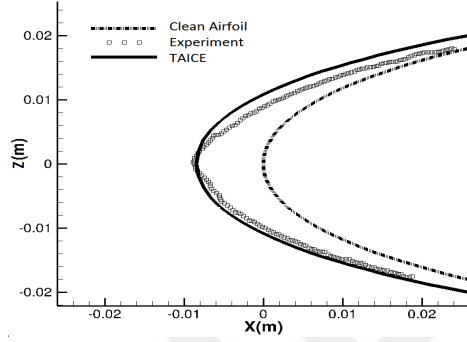
Following figures indicate that increasing the droplet ratio first causes more ice crystals to stick to the surface. However, further increase in the droplet ratio does not cause additional increase in the thickness of the accreted ice. On the contrary, reduction in the accumulated ice has been noted due to the erosion effect in these experimental tests. Analysis results seem consistent with the experimental data for all compared conditions. However, a few points should be emphasized here. First of all, accreted ice in the experiments have triangular shapes and sharp edges. On the other hand, ice shapes obtained with TAICE are more smooth. Moreover, at -15 °C TAICE overestimates the ice shapes, which indicates that the erosion effect is more than predicted at this temperature.



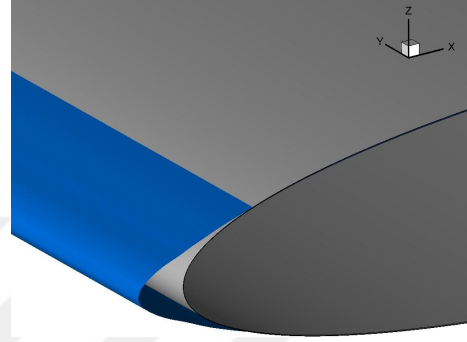
(a) Case#1, $\eta_d = 12.0\%$



(b) Case#3, $\eta_d = 28.6\%$

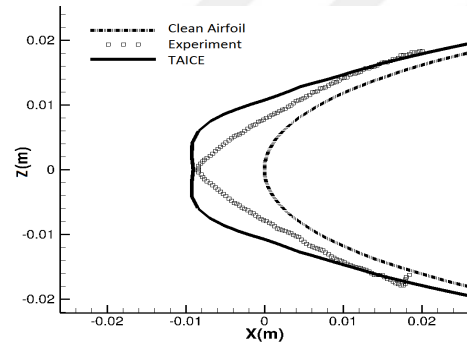


(c) Case#5, $\eta_d = 47.2\%$

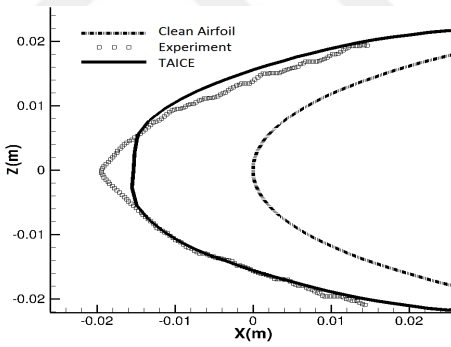


(d) Far view of the Case#1 accreted ice shape.

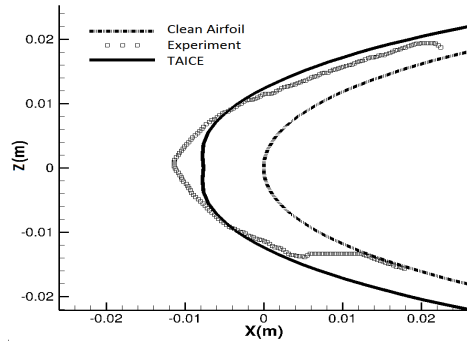
Figure 8.8: Accreted ice shape comparison at $T_s = 0\text{ }^\circ\text{C}$ after 120 s.



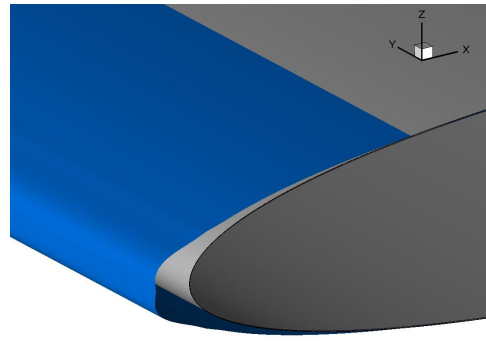
(a) Case#8, $\eta_d = 12.0\%$



(b) Case#10, $\eta_d = 28.6\%$

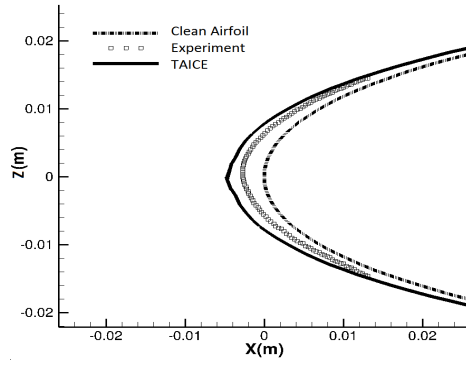


(c) Case#12, $\eta_d = 47.2\%$

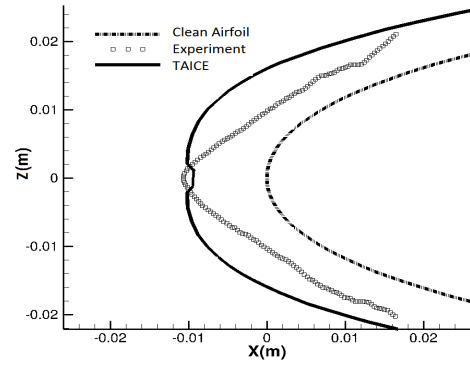


(d) Far view of the Case#8 accreted ice shape.

Figure 8.9: Accreted ice shape comparison at $T_s = -5\text{ }^\circ\text{C}$ after 120 s.



(a) Case#15, $\eta_d = 12.0\%$



(b) Case#16, $\eta_d = 28.6\%$

Figure 8.10: Accreted ice shape comparison at $T_s = -15\text{ }^{\circ}\text{C}$ after 120 s.



CHAPTER 9

CONCLUSION

Ice crystal accretion has been noted as the cause of a number of in-flight events and has therefore attracted the attention of the global aircraft icing community. To increase the understanding the mechanisms of ice crystal accretion and to optimize aircraft safety in glaciated icing conditions, several projects and working groups focus on ice crystal icing research. For the same purpose this thesis aims developing a computational tool for ice accretion prediction with mixed phase cloud particles. A mathematical model which was initially developed by Myers [47] has been further extended in this thesis by including solid ice particles in the computations. In Myers approach, temperature variations along both ice and water layers are modeled. With a fixed and known temperature at the substrate, initially rime ice grows until the surface temperature of the ice layer reaches the freezing temperature. At this time, substrate becomes totally insulated and this yields both ice and water accretion on the surface. In addition to separately modeled ice and water layers, another advantage of using this approach is that it provides exact formula for the ice thickness in which glaze ice is first observed. However, up to now this model has not been extended further for mixed cloud icing conditions. This is a motivating factor for this thesis to focus on this problem. Moreover, the mentioned extension of this model is not sufficient for accurate prediction alone. To improve accuracy, particle trajectory and impingement calculations in TAICE have been modified as well. Initially, TAICE, which is an in-house developed ice accretion prediction tool, was applicable to icing conditions including only water droplets. Heat transfer, phase change, drag force coefficient, impingement and erosion models have been implemented in order to utilize this tool for mixed phase icing conditions.

Three different drag coefficient models have been implemented to TAICE and comparison study has been performed to define each model applicable ranges. According to the performed analyses all models produce similar results as expected when sphericity and crosswise sphericity values are around one which means the particle is nearly spherical. However, when they differ from one and when the particle diameter gets smaller, ice shape predictions start to deviate from each other. As it is discussed in drag models predictions comparison chapter, since it takes crosswise sphericity into consideration and its ice shape predictions are generally in between the other two models, Hölzer&Sommerfeld drag model has been used in this thesis study and corresponding calibrations have been performed in erosion parameters while comparing with experimental results. Furthermore, ice crystals may pose a threat especially when they encounter warmer flow conditions and such conditions generally occur around the heated surfaces like pitot probes. Since ice crystal temperature is below freezing point, they may change phase before impinging on the surface, which increases their sticking probability. Thus, the heat transfer and phase change models which are modified to be applicable for non-spherical particles have been used in this study. Corresponding analyses have been performed for validation of the model and compared with the experimental results given in the study of Hauk *et al*[32].

Being a solid substance ice crystals necessitates a different approach while performing impingement computations. They may just bounce off from the wall or they may stick to the wall depending on the accreted water film thickness on the substrate or particle surface. In addition, particles may split into smaller fragments upon contact to the surface and some of the fragments may adhere to the wall and others may be re-emitted into the flow. One more issue for sticking part of the ice crystals is to calculate the ratio of these solid particles which may melt after impact. Three different scenarios are introduced in this study for better prediction of the melting ratio. For ice crystals there is a possibility of them being non-spherical and this makes ice crystals different from water droplets. Drag force coefficient and heat transfer models which are applicable to non-spherical particles have been implemented to TAICE for this purpose.

Another important phenomena which should be taken into consideration is erosion. In mixed phase icing experiments it is observed that upcoming ice crystals lead to

decrease in the total amount of accreted ice on the surface. Thus, an erosion model has been implemented as well to take into account this effect. Calibrated erosion and impingement models are used in the analyses with three different sets of experimental data and good improvements on ice shapes have been noted for both cases. However, number of validation cases used is not enough to reach a final decision on the validity of the developed computational tool. Generally, rime ice predictions seem to agree better with experiment compared to the glaze ice predictions. The accuracy of the numerical results decreases when the influence of ice crystals on accreted ice shape increases. Moreover, an additional chapter has been added in order to test the prepared tool with real industrial test cases. Thanks to the implemented models, calculations on a probe industrial test case and on an engine inlet test case have been performed easily.

The presented work in this thesis have contributed to the better understanding of the processes relevant for mixed phase icing. Further research still needs to be done to cope with this form of icing and to reach better predictions. Future work should be conducted on further validations of the tool by using new data and models developed using mixed phase icing experiments. Moreover, issues related to film dynamics and runback water mechanism should be focused on more to model the water film behavior better. Last but not least ice particle impact onto a thin water film should be further investigated which is directly related with the accuracy of the predictions.



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