Heat Transfer Measurements on Surfaces with Natural and Simulated Ice Accretion Roughness

by

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Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

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Abstract

An experimental setup was designed and built, and an experimental method was developed to measure and compare the convective heat transfer coefficient of natural and simulated ice accretion roughness. The natural ice accretion roughness were castings made from accretions at the NASA Lewis Icing Research Tunnel (IRT). One of these castings was modelled using a Spectral Estimation Technique (SET) to produce three roughness element patterns. Both the casting and the three roughness element patterns were inserted in a flat plate and tested in a “dry” wind tunnel. The experimental setup was capable of producing and measuring pressure gradients, of measuring boundary layer thicknesses, and of measuring temperature gradients over the spatial scale of the roughness elements size. Absolute convective heat transfer coefficients were calculated for the smooth flat plate and compared to theoretical results. Tests were done with the flat plate at a 0° angle of attack, where the boundary layer was found to be turbulent, and probably separated. A second series of tests were done with the flat plate at a 20° angle of attack, where the boundary layer was laminar. The heat transfer coefficients for the smooth plate at a 0° angle of attack did not match theoretical results. Results from this case are not conclusive but show that the average heat transfer enhancement of the casting was 1.8-3 times the enhancement of the element arrays. Results from the flat plate at a 20° angle of attack do match well with theory and show that the element arrays have average heat transfer enhancements ranging from 1.6 to 2.8. The heat transfer coefficient profiles are different for the three element arrays, indicating that the way the elements are laid out is important. The concentration of elements is important since the heat transfer enhancement is localized over the elements. The spacing between elements in both the flow and span direction is important since the wakes of heat transfer enhancements and the interaction between wakes and elements contribute to the average enhancement. This study shows that SET is a powerful roughness modelling technique. The experimental setup and technique described in this study is also a powerful way of comparing heat transfer coefficients for natural and simulated ice roughness.

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Chapter 1
Introduction

1.1 Motivation

Aviation under icing conditions has proven to be extremely hazardous causing several accidents. Several international agencies, including the Icing Technology Branch at the NASA Lewis Research Center, have been trying for several years to understand, predict and prevent aviation accidents related to icing conditions. The work of the Icing Technology Branch can be divided in four areas: wind tunnel icing testing at the Icing Research Tunnel (IRT), airplane icing testing, developing de-icers and anti-ice mechanisms, and developing a computer code called LEWICE.

The areas of wind tunnel testing, airplane testing, and code developing are related. Wind tunnel icing testing is controllable and thus more practical than airplane testing. However, wind tunnel test results have to be validated by airplane test results to ensure that the wind tunnel ice accretion process is a proper model of the natural process. Computer code simulations are much more economical than wind tunnel or airplane tests. However, simulation results have failed to match observed wind tunnel and airplane test results for ice accretions under glaze ice conditions [6]. This mismatch is due to an inappropriate heat transfer and boundary layer transition model in LEWICE. Because of the economical advantages of code predictions over wind tunnel or airplane tests, the micro-physics of the ice accretion process need to be better understood and a better heat transfer and boundary layer transition model for LEWICE needs to be developed.

1.2 Current and Proposed Ice Accretion Modeling

The ice accretion process occurs when an object flies through a cloud of super-cooled water droplets. Some important parameters to this process are the airspeed relative to the object, ambient temperature, mass of water per unit volume or Liquid Water Content (LWC), and the size of the water droplets or Mean Volume Diameter (MVD). As the
super-cooled water droplets impinge on the object’s surface, the ice accretion is determined primordially by a heat balance between convective heat transfer at the surface and the release of latent heat of fusion as the water droplets freeze [6]. The state of the boundary layer influences the heat transfer process since a turbulent boundary layer has a higher convective heat transfer than a laminar boundary layer. The initial ice roughness influences the state of the laminar boundary layer since the initial ice roughness can cause transition from a laminar to a turbulent boundary layer. Thus, the initial ice roughness is very important in the ice accretion process coupling the heat transfer process and the state of the boundary layer.

The effect of ice accretion roughness on heat transfer and boundary layer transition is modelled in LEWICE as shown schematically in Figure 1.1. Currently, the effect of the ice accretion roughness is modelled using the Equivalent Sand Grain Roughness (ESGR) model, as shown on the left side of Figure 1.1. The ESGR model characterizes the ice accretion roughness with a single parameter $k$. A Reynolds number based on $k$, $Re_k$, is used to determine boundary layer transition. Once transition occurs, turbulent heat transfer equations are used with $k$ as a parameter. When glaze ice shape predictions are done, $k$ is adjusted until the experimentally observed shape is obtained. The value of $k$ needed to produce the observed ice shape often bears little significance to the roughness scales observed. Thus, $k$ has little physical meaning, as could be expected since the complicated effect of the ice accretion roughness on the heat transfer and boundary layer transition can not be modelled with a single parameter.

A heat transfer modelling approach based on the micro-physics of the ice accretion process has been proposed [12], as shown schematically on the right of Figure 1.1. This heat transfer model incorporates extensive data gathered during icing experiments at the IRT. These experiments have provided high-magnification, close-up video images of the accretion process spanning from the first seconds of the accretion until the final ice shape is established approximately 10 minutes later [6]. Image processing techniques have been used to extract from these video images roughness characteristics corresponding to different cloud conditions. These roughness characteristics can be used to construct physical approximations to the early ice accretion roughness in order to do “dry” wind tunnel tests, concentrating on the effect of the roughness on the convective heat transfer at the surface.
In this manner, a heat transfer model based on the micro-physics of the ice accretion process can be developed, providing an alternative to the ESGR model.

![Diagram](image)

**Figure 1.1:** Schematic of current and proposed heat transfer model in LEWICE. Figure reproduced from Orr et al. [12]

### 1.3 Previous Heat Transfer and Boundary Layer Transition Studies

Heat transfer studies have been done by Henry et al. [7], and Masiulaniec et al. [5][10]. Boundary layer transition studies have been done by Bragg et al. [1][2][3]. An icing roughness characterization technique has been developed by Orr et al. [11][12]. These studies will be discussed in this section.

#### 1.3.1 Henry et al.’s Research

Henry et al. studied the variation in convective heat transfer coefficients on hemispherical roughness elements on a flat plate in a “dry” wind tunnel using Infra Red (IR) temperature measurement techniques. Figure 1.2 shows a schematic of Henry’s setup. Plastic hemispherical roughness elements, on the order of 2-6mm diameter, and element arrays were placed on a Plexiglas flat plate. The surface was uniformly heated with 3 IR heat lamps.
Temperature variations were measured using an IR camera. With these temperature measurements, Henry was able to calculate relative convective heat transfer coefficients. The IR temperature measuring technique is non-invasive and only limited by the spatial resolution of the IR camera.

Three series of tests were done with laminar and/or turbulent boundary layers. The effect of roughness element height for single elements, the effect of interaction between multiple roughness elements, and the effect of arrangement and packing density for multiple roughness elements were studied. The tests were done at Reynolds numbers ranging from 70,000 to 450,000.

Figure 1.3 shows a comparison of heat transfer enhancement profiles for arrangements of different packing densities in a turbulent boundary layer. The relative heat transfer coefficient (HTCp/HTCu) is defined as the coefficient of the perturbed area referenced by the coefficient at the unperturbed area, where the unperturbed area is upstream of the first roughness element, and perturbed refers to downstream of the first roughness element. The heat transfer coefficient enhancement in the dense roughness zone is observed to be between the minimum and the maximum values obtained for the 2mm spaced roughness elements region.

Henry observed significant enhancement in heat transfer on single roughness elements when the elements protruded into the boundary layer, or when the ratio of roughness height to boundary layer thickness (k/δ) was greater than 1. The highest heat transfer was observed on the upstream face of the elements. Heat transfer enhancement was greater for laminar boundary layers than turbulent boundary layers. For closely packed element regions, the heat transfer was observed to be uniform. For element separations greater than the element’s radius, the heat transfer on each element was observed to be similar to that observed for individual elements.

Some limitations of this study are that smooth flat plate heat transfer coefficients were not calculated and compared with theoretical results. Also, the boundary layer thickness was not measured, but calculated from theory. Measurement of the experimental boundary layer thickness could be critical because of the importance of the parameter k/δ.
Figure 1.2: Schematic of Henry’s Setup. Figure reproduced from Henry et al. [7]

Figure 1.3: Comparison between heat transfer coefficient enhancement with densely packed roughness elements and 2mm spaced roughness elements in a turbulent boundary layer. Figure reproduced from Henry et al. [7]

1.3.2 Masiulaniec et al.’s Research

Masiulaniec et al. studied the convective heat transfer coefficient of natural ice accretion aluminum castings on a flat plate in a “dry” wind tunnel. The castings were obtained from a series of ice accretions grown in the IRT on 0.46 x 0.46m (18”x18”) flat plates. These accretions corresponded to different cloud conditions, and were called: closely spaced rough glaze, loosely spaced rough glaze, closely spaced mildly rough glaze, smooth glaze, smooth rime, rime with small feathers, and rime with very large feathers [5][10]. The flat
plate castings were EDM cut into strips running along the flow direction. One of these strips was cut into pieces of size 1.3x 3.2x1.3cm (0.5”x1.25”x0.5”). These pieces were then mounted on a flat plate heat transfer model to do tests in a “dry” wind tunnel, as shown in Figure 1.4. The pieces were thermally insulated from each other and from the flat plate. The pieces were heated from the bottom by electric heaters. Temperature was measured by thermocouples. A detailed heat balance allowed for the calculation of the local Stanton number.

![Figure 1.4: Schematic of Masiulaniec’s heat transfer model installed in wind tunnel. Figure reproduced from Masiulaniec et al. [5][10].](image)

A series of tests was done with a smooth flat plate. Smooth flat plate Stanton numbers were calculated and compared to theoretical results obtaining good agreement [10]. Another series of tests was done with the eight roughness flat plate models, called plate #1 through plate #8. A set of tests studied the different plates at 5° angle of attack and different free stream velocities. Another set studied plate #1 at angles of attack ranging from 5° to 41°. The Reynolds number tested ranged from 45,000 to 1,500,000. Figure 1.5 shows a
plot of Stanton number versus Reynolds number for plate #5 at 5° angle of attack and various free stream velocities. The Stanton number is greater for the roughened plate than for a turbulent smooth flat plate.

Masiulaniec et al. observed that the Stanton number increases over the flat plate, first starting close to the laminar smooth solution and then transitioning to values higher than the turbulent smooth solution. As the roughness of the plate is increased, the transition point moves closer to the leading edge. Also, as the roughness of the plate is increased, the heat transfer increases until a certain level of roughness is reached. Beyond this point, the roughness does not have an effect on the heat transfer, and the heat transfer enhancement becomes a function only of the Reynolds number. The Stanton number changes significantly for different angles of attack, decreasing with increasing angle, showing the importance of the pressure gradient.

A limitation of this study is that it does not provide new information about the micro-physics of the ice accretion process.

**Figure 1.5:** Stanton number vs. Reynold’s number for natural ice roughness plate #5. Figure reproduced from Masiulaniec et al. [5]
1.3.3 Bragg et al.’s Research

Bragg et al. studied the effect of isolated and distributed hemispherical roughness elements on the state of the boundary layer. The roughness elements were placed on the leading edge of a NACA 0012 airfoil and “dry” wind tunnel tests were done. The airfoil was placed vertically on the test section and its angle of attack could be changed, as shown schematically in Figure 1.6. A hot wire probe on a traversing strut was used to measure the boundary layer thickness at various places on the airfoil. Isolated and distributed roughness elements, 0.35 and \(0.75\, \text{mm}\) in height and spaced 1.3 diameters, were placed at distances varying from 4 to \(24\, \text{mm}\) from the leading edge. These roughness element heights and spacing were based on measurements taken from close-up video images of an IRT experiment done by Shin [14].

Several tests were done in this study with both isolated and distributed roughness elements. These tests studied the effect of the roughness height, the effect of the roughness distance from the leading edge, and the effect of tunnel turbulence. These tests were done at Reynolds number ranging from 750,000 to 2,250,000.

Bragg et al. found that the roughness elements initiated a slow transition to a turbulent boundary layer. The transition was found to be a function of the pressure gradient on the airfoil and of \(k/\delta\). Bragg concluded that a fully developed turbulent boundary layer, and heat transfer coefficients corresponding to turbulent boundary layers, can not be assumed on the roughness.

![Figure 1.6: Schematic of Bragg’s Setup. Figure reproduced from Bragg et al. [2]](image-url)
1.3.4 Orr et al.’s Research

Orr et al. developed a Spectral Estimation Technique (SET) which describes images of early ice accretion roughness by a characteristic “bead” size and spacing. SET has been applied to the close-up video images presented by Hansman et al. [6]. SET has also been applied to digital images of the natural ice roughness castings taken by Masiulaniec et al. [12]. The parameters obtained by the latter SET analysis have been used to build a series of roughness element patterns by epoxy bead deposition using an automated syringe. These simulated roughness element patterns are suitable for “dry” wind tunnel heat transfer experiments. A detailed description of the SET algorithm, its validation, and the epoxy bead deposition technique can be found in Orr [11][12].

1.4 Objective

The objective of this experiment is to study the effect of both natural ice roughness and roughness simulated using SET on the convective heat transfer on a surface. Based on results drawn from the previous research discussed, the experimental setup and technique should study the heat transfer enhancement on roughness elements, the effect of the pressure gradient on the flow, and the effect of the parameter $k/\delta$.

The experimental approach was to conduct a flat plate study where natural and simulated roughness were inserted interchangeably. Absolute and relative convective heat transfer coefficients were calculated from the surface temperature, measured by both thermocouples and an IR technique similar to Henry’s [7].

The experimental setup and technique developed in this study will complete the proposed heat transfer model based on the micro-physics of the ice accretion process, providing an alternative for the current ESGR model in LEWICE.
Chapter 2
Theoretical Analysis

In this section, the calculation of the convective heat transfer coefficient of airflow over a flat plate is discussed. The calculation of this coefficient requires a heat balance for a heated flat plate with airflow. A heat balance calculation for a heated flat plate but without airflow is also presented. The calculation of the theoretical boundary layer thickness, and the coefficient of pressure is discussed.

2.1 Calculation of Convective Heat Transfer Coefficient

The calculation of two types of convective heat transfer coefficients, relative and absolute, is presented.

2.1.1 Calculation of Relative Convective Heat Transfer Coefficient

The convective heat transfer coefficient can be referenced to an appropriate value giving a relative coefficient. Henry developed a simple technique to calculate relative coefficients [7], as discussed in this section.

![Figure 2.1: Heat Balance on Roughness Element](image)
Consider a roughness element as shown in Figure 2.1. When steady state is reached, the incoming heat flux $Q_{rad,in}$ is balanced by the sum of the heat flux losses, which are the convective flux $Q_{conv}$, the conduction flux $Q_{cond}$, and the radiation flux $Q_{rad,out}$:

$$Q_{rad,in} = Q_{out} = Q_{conv} + Q_{cond} + Q_{rad,out} \quad (2.1)$$

If the roughness element and the flat plate are made of a non-conducting material, the conduction flux is negligible. If surface temperatures are kept relatively close to ambient temperatures, the radiation flux is also negligible. Under these assumptions, the heat balance is dominated by the incoming radiation flux and the convection flux loss, defined as:

$$Q_{conv} = h (T_{sur} - T) \quad (2.2)$$

where $h$ is the convective heat transfer coefficient, $T_{sur}$ is the surface temperature and $T_{inf}$ is the free stream temperature. If the incoming heat flux is uniform over the surface, the convection flux is also uniform. Calling the plate upstream of the roughness element the unperturbed area and the roughness element the perturbed area, the following relation holds:

$$h_p (T_{sur} - T_p) = h_u (T_{sur} - T_u) \quad (2.3)$$

where the subscript $u$ refers to unperturbed and $p$ to perturbed. The convective heat transfer coefficient can then be referenced to its value in the unperturbed area upstream of the roughness element in the following way:

$$\frac{h_p}{h_u} = \frac{T_u - T_m}{T_p - T_\infty} \quad (2.4)$$

### 2.1.2 Calculation of Absolute Convective Heat Transfer Coefficient

To calculate absolute convective heat transfer coefficients, all the terms in the heat balance equation (2.1), and repeated below, need to be known:

$$Q_{rad,in} = Q_{conv} + Q_{cond} + Q_{rad,out} \quad (2.5)$$

We define the convection flux as:

$$Q_{conv} = h (T_{sur} - T_{aw}) \quad (2.6)$$

where $T_{aw}$ is the adiabatic wall temperature, defined as:

$$T_{aw} = T_\infty + \sqrt{Pr} (T_{tot} - T_m) \quad (2.7)$$

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where $T_{tot}$ is the total or stagnation temperature, and $Pr$ is the Prandtl number. Given these definitions, the absolute convective heat transfer coefficient is calculated as:

$$h = \frac{Q_{rad,in} - Q_{rad,out} - Q_{cond}}{T_{sur} - T_{aw}}$$  \hspace{1cm} (2.8)

The heat fluxes in equation (2.8) are calculated in a simple fashion. The incoming radiation flux, produced by IR heaters, is defined as:

$$Q_{rad,in} = F\sigma T_{h}^{4} - T_{sur}^{4}$$  \hspace{1cm} (2.9)

where $F$ is the view factor, $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon_{h}$ is the emissivity of the heater, and $T_{h}$ is the temperature of the heater. The view factor gives, given the size and position of the heater relative to the surface, the fraction of the radiation leaving the heater that reaches the surface [8]. The conduction flux is defined as:

$$Q_{cond} = \frac{k}{t} (T_{surtop} - T_{surfbottom})$$  \hspace{1cm} (2.10)

where $k$ is the thermal conductivity of the flat plate, $t$ is the thickness of the flat plate, and the subscripts $\text{top}$ and $\text{bottom}$ refer to the top and bottom surfaces of the flat plate. The radiation flux is defined as:

$$Q_{rad,out} = \sigma \epsilon_{sur} (T_{surf}^{4} - T_{\infty}^{4})$$  \hspace{1cm} (2.11)

where $\epsilon_{sur}$ is the emissivity of the surface.

### 2.1.3 Theoretical Convective Heat Transfer Coefficients

Considering a semi-infinite flat plate, with arbitrary and specified surface temperature, embedded in a stream with uniform velocity, the theoretical convective heat transfer coefficient can be calculated [9]. Let the surface temperature at point $x$ be expressed as:

$$T_{x} = T_{\infty} + \sum_{n} B_{n} x^{n} + A$$  \hspace{1cm} (2.12)

where $B_{n}$ and $A$ are constants. Then, the heat flux at $x$ for a laminar boundary layer can be expressed as:

$$Q_{x} = 0.332 \frac{k}{x} (Pn \epsilon \frac{1}{3} \frac{1}{Re^{\frac{1}{3}}} \left( \sum_{n} nB_{n} \frac{4}{3} x^{n} \beta_{n} + A \right)$$  \hspace{1cm} (2.13)

where $\beta_{n}$ is the beta function, defined as:
\[ \beta_n = \frac{\Gamma\left(\frac{4}{3}n\right) \Gamma\left(\frac{2}{3}\right)}{\Gamma\left(\frac{4}{3}n + \frac{2}{3}\right)} \]  

(2.14)

where \( \Gamma \) is the gamma function. Values for the beta and gamma function are tabulated and can be found in the literature [9]. The heat flux for a turbulent boundary layer is defined similarly to (2.13) as:

\[ Q_x = 0.0287 Pr^{0.6} Re^{0.8} \sum_n nB_n \frac{10}{9} x^n \beta_n + A \]  

(2.15)

The convective heat transfer coefficient for laminar and turbulent boundary layers is then calculated using the above definitions:

\[ h = \frac{Q_x}{(T_x - T_w)} \]  

(2.17)

The solution for the convective heat transfer coefficient for a flat plate with variable surface temperature and variable \( U(x) \), corresponding to a flat plate at an angle of attack, was not found in the literature. White [15] mentions that no simple and accurate solutions to this problem are known to him.

### 2.2 Heat Balance without Airflow

Consider a heated flat plate but without airflow. When steady state is reached, the incoming heat flux is balanced by the sum of free convection flux \( Q_{\text{free conv}} \), conduction flux \( Q_{\text{cond}} \), and radiation flux \( Q_{\text{rad, out}} \):

\[ Q_{rad, x} = Q_{\text{free conv}} + Q_{\text{cond}} + Q_{\text{rad, out}} \]  

(2.18)

If the terms in the right hand side are known, the distribution of incoming radiation can be calculated. The conduction and radiation flux terms are given as in (2.10) and (2.11). The free convection flux is defined as,

\[ Q_{fc} = \overline{h} (T_{\text{sur}} - T_w) \]  

(2.19)

where \( \overline{h} \) is an average free convection heat transfer coefficient defined as:
\[
\tilde{h} = \frac{k}{L} \bar{Nu}_L
\]  
(2.20)

where \( k \) is the conductivity of air, \( \bar{Nu}_L \) is an average Nusselt number based on a characteristic length \( L \), where these are given by:

\[
L = \frac{A_s}{P}
\]  
(2.21)

\[
\bar{Nu}_L = \left\{ \begin{array}{ll}
0.54 \frac{Ra_L^4}{(10^4 < Ra_L < 10^7)} \\
0.15 \frac{Ra_L^{1/3}}{(10^7 < Ra_L < 10^{11})}
\end{array} \right.
\]  
(2.22)

\( A_s \) is the surface area of the object being considered, and \( P \) its perimeter. \( Ra_L \) is the Rayleigh number, defined as:

\[
Ra_L = \frac{g \beta (T_{\text{sur}} - T_{\infty}) L^3}{\nu \alpha}
\]  
(2.23)

where \( g \) is the gravitation constant, \( \nu \) is the kinematic viscosity, \( \alpha \) is the thermal diffusivity, and \( \beta \) is defined as \( 1/T_f \), where \( T_f \) is the film temperature, defined as:

\[
T_f = \frac{T_{\text{sur}} + T_{\infty}}{2}
\]  
(2.24)

Combining the above equations, an expression for the laminar free convection flux is obtained:

\[
Q_{fc} = \frac{0.54 k}{L^{0.25}} \left( \frac{g \beta}{\nu \alpha} \right)^{0.25} (T_{\text{sur}} - T_{\infty})^{1.25}
\]  
(2.25)

The free convection flux for the heated plate at an angle of attack was taken to be the turbulent free convection flux for a horizontal plate, with a correction made for the angle of attack [4].

### 2.3 Calculation of Boundary Layer Thickness

Consider a flat plate at an angle of attack, as shown in Figure 2.2. The boundary layer thickness can be found by considering the similarity solution obtained by Falkner and Skan to the boundary layer equations. These have been called the solutions to the Falkner-Skan wedge flows [15].

Falkner and Skan proposed a solution to the boundary layer equations of the form:
\[ \eta = C y x^a \]  

(2.26)

where \( C \) and \( a \) are arbitrary constants. This solution implies a velocity behavior of the form:

\[ U = K x^{(2a+1)} = K y^m \]  

(2.27)

The constant \( C \) is chosen so that the Blasius solution is obtained for the plate at a 0° angle of attack, giving:

\[ C^2 = \frac{K (m+1)}{2u} \]  

(2.28)

The similarity solution is then given by:

\[ \eta = \sqrt[m]{\frac{m+1}{2} \left( \frac{U}{V_x} \right)} \]  

(2.29)

The boundary layer equation becomes:

\[ f'' + f f' + \beta \left( 1 - f^2 \right) = 0 \]  

(2.30)

with boundary conditions:

\[ f(0) = f'(0) = 0 \]

\[ f'(\infty) = 1 \]  

(2.31)

\( \beta \) gives a measure of the pressure gradient on the flow. It is defined and is related to the angle of attack in the following way:

\[ \beta = \frac{2m}{m+1} = \frac{2 \theta}{\pi} \]  

(2.32)

A positive value of \( \beta \) implies a favorable pressure gradient on the flat plate, or positive angles of attack \( \theta \) as defined in Figure 2.2. Negative values of \( \beta \) imply an adverse pressure gradient, and \( \beta \) equal to 0 gives the solution obtained by Blasius for flow without a pressure gradient.

Figure 2.3 shows laminar boundary layer profiles for \( \theta = 27^\circ \) and several free stream velocities.
2.4 Calculation of Coefficient of Pressure

Considering the flat plate at an angle of attack shown in Figure 2.2, the coefficient of pressure is defined as:

\[ C_{p_x} = \frac{p_x - p_{\infty}}{\frac{1}{2} \rho U^2} \]  (2.33)

where \( p_x \) is the static pressure at a distance \( x \) from the leading edge of the plate, \( p_{\infty} \) and \( U \) are the free stream static pressure and velocity respectively.
Chapter 3
Design of Experiment

In this section, the design and construction of the natural ice roughness castings and the simulated roughness element patterns will be described. Then, the design and construction of the experimental setup where the roughness samples were incorporated will be described.

3.1 Design and Construction of Roughness Samples

The roughness samples used in this study were the natural ice roughness castings obtained by Masiulaniec et al., and their SET simulated roughness, provided by Orr.

3.1.1 Natural Roughness Castings

The aluminum castings obtained by Masiulaniec et al. were already suitable for a flat plate study in a “dry” wind tunnel. However, since conduction losses were minimized in this study, the aluminum castings were copied into plaster castings. The aluminum castings were used to make a rubber mold. The liquid plaster was poured into the mold and allowed to dry. Having being dried, the plaster castings were removed and mounted on a Plexiglas base for rigidity. Three casting plugs were made, corresponding to plates #4, #5 and #7 from Masiulaniec’s study. An image of a natural roughness casting piece from plate #5 is shown in Figure 3.1, where the scale shown is in mm.

The process of making a casting out of a casting introduces some error into the study. However, the degradation of the roughness surface was not noticeable. The surface degradation making the plaster castings out of the aluminum castings was probably less than the degradation suffered when making the aluminum castings out of the natural ice roughness.
3.1.2 Roughness Element Patterns

The roughness element patterns were produced employing SET on the natural ice roughness casting image shown in Figure 3.1. Using the parameters extracted from SET, the natural ice roughness was modelled by a pattern of roughness elements of 0.93\(mm\) diameter, spaced 1.79\(mm\) from each other. With these characteristics, three roughness element patterns were built: a rectangular pattern, a staggered rectangular pattern, and a pseudo-random pattern, as shown in Figure 3.2. The bead density for the pseudo-random pattern is equal to the rectangular pattern bead density. The staggered array has adjacent rows 180\(^{0}\) out of phase. The bead patterns are laid on Plexiglas plugs with a base of the same size as the plaster casting base, or 17\(mm\) x 28\(mm\). Thus, the castings and the bead patterns could be inserted in a flat plate interchangeably for “dry” wind tunnel testing.

![rectangular array](image)
![staggered rectangular array](image)
![pseudo-random array](image)

**Figure 3.2**: Roughness element patterns provided by Orr (17\(mm\) x 28\(mm\))
3.2 Design and Construction of Experimental Setup

The experiment was conducted in a low velocity wind tunnel at the Heat Transfer Branch at NASA Lewis Research Center. The same wind tunnel used by Masiulaniec et al. in their flat plate heat transfer studies was used. In this study, the flat plate was mounted to the test section in a similar way as the heat transfer model in their study, as shown again in Figure 3.3. Air drawn from the test cell passed through a 4.85:1 contraction before entering the 15.2cm wide by 68.6cm high (6” x 27”) test section. The maximum velocity attainable was approximately 46m/sec (103mph). Clear tunnel turbulence levels were less than 0.5%. Four thermocouples located around the perimeter of the inlet of the tunnel measured the flow stagnation temperature.

![Schematic of wind tunnel with heat transfer model installed.](image)

**Figure 3.3:** Schematic of Wind Tunnel. Figure reproduced from Masiulaniec et al. [5]

Figure 3.4 shows a schematic side view of the flat plate in the wind tunnel’s test section. The flat plate was 15.2cm wide, the width of the test section, 50.8cm long and 1.3cm thick (6”x20”x0.5”), and was made out of Plexiglas. The plate had a beveled leading edge, at an angle of 3⁰, and a 1.5mm nose diameter. The plate was held to the tunnel’s side walls by two Plexiglas disks, shown as dashed circles in Figure 3.4, and to the bottom wall by a
pair of legs. The flat plate could be rotated around the disks to different angles of attack. The plugs were located 25.4cm (10") downstream from the leading edge at two spanwise locations. The plate was instrumented with a row of 12 pressure taps along its centerline. A pitot-static tube was placed upstream of the flat plate to measure free stream total and dynamic pressures.

**Figure 3.4: Schematic Side View of Flat Plate in Test Section**

Figure 3.5 shows a schematic top view of the location of the plugs in the plate and a detail of their insertion in the plate. The plugs were placed at two spanwise locations, as shown in the top view in Figure 3.5. As mentioned before, the width of the plate is 15.2cm (6"). The plugs were spaced 5cm (2") from center to center, giving a 3.6cm (1.4") spacing from the tunnel walls, assumed to be enough to avoid side wall effects on the flow over the roughness. The front view at the bottom of Figure 3.5 shows the three types of plugs used and how they were inserted in the plate. The plate was 1.3cm (1/2") thick and the plugs were 1cm (3/8") thick. In addition to the casting and roughness element pattern plugs, plain plugs were used for smooth flat plate heat transfer studies. When mounted, the plain
plugs were flush with the surface. The roughness element pattern plugs were also flush with the surface, only exposing the roughness elements to the flow. The height of the casting exposed to the flow was varied using the push-pull arrangement shown. The middle screw pulled on the plug and the two side screws pushed. Three heights were tested, varying 0.4 mm from each other. The top surface of the flat plate and plugs were painted flat black to aid in the IR camera measurements.

Two different measurement setups were used in this study, a boundary layer measurement setup and a temperature measurement setup.

![Diagram](image)

**Figure 3.5:** Schematic top view of the location of the plugs in the flat plate and front view detail of the plug insertion into the flat plate

### 3.2.1 Boundary Layer Thickness Measurement Setup

A schematic of the boundary layer thickness measurement setup is shown in Figure 3.6. A hot wire probe was attached to a traverser, capable of reaching the flat plate’s boundary layer. The traverser motor was attached to an aluminum plate. The aluminum plate rested on the tunnel’s top wall and could be set at five different positions spaced 5 cm (2”) apart in the flow direction. In addition, the traverser motor could be set at two spanwise locations 5 cm (2”) apart on the aluminum plate, directly above the two roughness plug locations. Hot wire probe velocity samples could be taken at a total of 10 locations on the flat plate.
An aluminum airfoil shield attached to the aluminum plate covered the traverser. This shield was needed to prevent the traverser from vibrating.

![Figure 3.6: Schematic of Boundary Layer Measurement Setup](image)

3.2.2 Temperature Measurement Setup

A schematic of the temperature measurement setup is shown in Figure 3.7. The flat plate was heated by four Osram Sylvania's Sylvatherm IR ceramic heaters (model# 066647), held by two steel plates to the tunnel’s top wall. The angle of the heater plates relative to the flat plate could be adjusted. The heater plates had fins which deflected the flow from the heaters, in order to minimize convective cooling. The heaters measured 12.2cm x 12.2cm (4.8" x 4.8"), and were rated for 1000W and 225V. The voltage of each heater, a constant resistance device, was controlled by a variac, or basically a transformer connected in series with the heater. By controlling the voltage, the temperature of each heater could be adjusted separately with the variacs.
Temperature was measured in two ways, with thermocouples (TCs) and with an IR camera. Thermocouples, marked with an ‘x’ in Figure 3.7, were located on the heaters and on the flat plate. Each heater came instrumented with a thermocouple placed on the middle of its surface. Thermocouples were placed on both the top and bottom surfaces of the flat plate. The top surface thermocouples were placed on 6 positions along the flow direction, located 5.1, 12.7, 20.3, 30.5, 38.1, and 45.7 cm (2, 5, 8, 12, 15, and 18") from the leading edge. At these locations, two thermocouples were placed at two spanwise locations, spaced 5.1 cm (2") apart, as shown in a top view of the flat plate in Figure 3.8. There were a total of 12 thermocouples on the top surface. Four thermocouples were placed on the bottom surface, directly underneath the thermocouples closest to the plugs.
Top surface temperatures were also measured with an Inframetrics 600 IR camera. The camera had an accuracy of $1K$, could resolve noise equivalent temperature differences of $0.05K$, and operated at the wavelength range of $8-14\mu m$, suited for the temperature range of this experiment. The view area of the camera was approximately $12.7cm \times 10.2cm$ ($5" \times 4"$), as shown by the dashed rectangle in Figure 3.8. The IR camera was mounted by the side of the wind tunnel and looked into the flat plate through a reflector and through a CLEARTRAN™ ZNS zinc sulfide window, provided by CVD Inc. This window provided a physical closing to the tunnel allowing IR wavelengths to be transmitted. A typical transmission plot for this window is shown in Figure 3.9. At the wavelength range that the IR camera operated, the window had a transmission of about 70%. It should be noted that the use of this window and of the reflector changed the internal calibration of the camera, and a new calibration needed to be done. The zinc sulfide window rested on a frame attached to the tunnel’s top wall.

The IR camera setup is shown in Figure 3.10. The camera consisted of a scanner and a 3X telescope. A 24” lens was used to magnify the view area as much as possible. Images could be seen real time on a monitor. A control box allowed for different data processing features, like line temperature plots and area averages. Images were recorded on a VCR for later analysis.
Figure 3.9: Typical Transmission for Zinc Sulfide Window (provided by CVD Inc.)

Figure 3.10: IR Camera Setup
Chapter 4
Experimental Procedure

Three types of measurements were done: pressure gradient measurements, boundary layer thickness measurements, and temperature measurements. The experimental procedure to take these types of measurements will be described.

4.1 Pressure Gradient Measurements

Pressure gradient measurements were done at several angles of attack and flow velocities. The angles of attack were 0°, 5°, 10°, 20°, and 30°. The flow velocities were 11.6, 19.3, 27.0, 34.8, 38.7, and 42.5 m/s. These measurements were done with and without the heaters in place to study whether the blockage produced by the heaters had a noticeable effect on the flow along the flat plate.

4.2 Boundary Layer Thickness Measurements

Actual boundary layer measurements were limited. However, a series of tests were done where the hot wire output was observed in an oscilloscope. Oscilloscope observations were done with the hot wire probe at various locations on the flat plate and angles of attack ranging from 0° to 20°. Actual boundary layer thickness measurements were done at angles of attack of 5° and 20°, and flow velocities of 39, 43, and 45 m/s.

In order to make boundary layer thickness measurements and oscilloscope observations, the hot wire probe was calibrated in an air jet facility of known exit velocity. Anemometer settings, such as probe cold and operating resistance, were set. The traverser plate was placed at the location where measurements were desired. The traverser was brought as close to the flat plate as possible, without the hot wire probe touching the surface. The traverser motor was set not to traverse down beyond this position. The hot wire probe was brought up and protected. Air flow was turned on and the probe was traversed down at 0.1 mm intervals and measurements were taken.


4.3 Temperature Measurements

The procedure to take temperature measurements can be divided in two parts. First, the heaters were controlled trying to achieve uniform heating on the plate without airflow. Then, once relatively uniform heating on the plate was achieved, airflow was turned on, and the convective heat transfer studies were done.

The heater angles and temperatures were adjusted to obtain uniform heating on the plate without airflow. Once this condition was reached, the heater temperatures were recorded. Then the flow was turned on. Since the heaters were cooled by the airflow, the heater temperatures would be less than recorded for the same setting on the variac. The voltage on the heaters was increased until the same recorded temperatures were reached. It was assumed that the radiation distribution reaching the plate was approximately the same as for the no airflow case. This procedure was repeated with the flat plate at a 20° angle of attack. Because of the cooling constraint and the different angles of attack, three different heater temperature settings were used, as shown in Table 4.1 and 4.2.

<table>
<thead>
<tr>
<th>Table 4.1: Heater Temperatures [°F] (θ=0°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>low speeds (U=27, 35m/s)</td>
</tr>
<tr>
<td>high speeds (U=43, 46m/s)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.2: Heater Temperatures [°F] (θ=20°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>not used</td>
</tr>
</tbody>
</table>

4.3.1 IR Camera Calibration

The IR camera thermograms were calibrated to a known length scale and temperature. In the thermograms, the pressure taps located at x=9" and x=11" were seen as dark dots. Another mark located at x=7.5" could be seen in the thermograms. The images were
cropped from the mark at \( x=7.5" \) to the tap at \( x=11" \) along the flow direction, and from plug edge to edge in the span direction. The pixel index numbers along the flow and span direction in each image were scaled accordingly.

The thermograms were also calibrated to the thermocouple temperature. The intensity of the thermogram at the thermocouple locations was measured. These intensity readings were converted to radiation level units, using parameters given by the IR camera. This conversion was needed since the camera adjusted the intensity of the images given the temperature range displayed. The radiation level units were then plotted versus thermocouple temperature to produce a calibration curve, as shown in Figure 4.1. The scatter in the data might be due to the “salt and pepper” noise in the thermograms. Ideally, the calibration should be made on each day of testing, since day to day changes might change the camera calibration [13]. Differences in thermogram and thermocouple readings ranged up to 6.2K.

![Figure 4.1: Calibration Curve for IR Camera](image)
4.3.2 Test Matrix

The test matrix for the heat transfer studies is shown in Figure 4.2. Tests were done with the flat plate at two angles of attack, 0° and 20°. For the two different angles of attack, three types of tests were done. First, tests with a smooth flat plate were done, then tests with the bead patterns and casting plugs were done. The three bead patterns and three castings described before were tested. The castings were tested at three different heights at 0° angle of attack. No castings were tested at 20° angle of attack. At 0° angle of attack, the velocities tested were 27.0, 34.8, 42.5, and 46.4 m/s. At 20° angle of attack, tests were run at 38.7 and 46.4 m/s.

<table>
<thead>
<tr>
<th></th>
<th>smooth plate</th>
<th>bead patterns</th>
<th>castings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>#1</td>
<td>#2</td>
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<tr>
<td>Θ=0°</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Θ=20°</td>
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<td></td>
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</tr>
</tbody>
</table>

Figure 4.2: Test Matrix for Heat Transfer Studies

4.4 Problems and Sources of Experimental Error

Several problems came up during this experiment. As mentioned before, the process of making a plaster casting out of an aluminum casting might have produced degradation of the surface roughness. However, no noticeable degradation was observed. It can be assumed that the plaster casting tested is an exact reproduction of the aluminum casting, originally modelled using SET.

It should be noted that the SET modeling is not really suited for the natural ice roughness casting. SET was designed to model early ice roughness, within approximately 30
seconds of the accretion. The castings in Masiulaniec’s studies were taken of accretions of a couple of minutes. For more details about the SET modelling of the natural ice casting see Orr [12].

An error was made when the rectangular roughness element array, shown in Figure 3.2(a), was constructed. As mentioned before, the SET models of the casting were arrays of 0.93mm diameter beads, spaced 1.79mm from each other. The roughness spacing modelled by SET is the roughness spacing along the flow direction. The roughness spacing along the span direction was varied in the three arrays constructed. In the rectangular array, the spacing seen along the span direction is 1.79mm, which should have been the spacing along the flow direction.

The assumption that the incoming radiation distribution was equal for different tests if the heater temperatures were equal was a source of experimental error. Day to day changes in ambient temperature would have changed the flat plate surface temperatures at a given velocity, thus changing the incoming radiation distribution $Q_{rad,in}$. 
Chapter 5

Results and Discussion

The results will be presented in three sections: Coefficient of Pressure, Boundary Layer Thickness and Convective Heat Transfer Coefficients.

5.1 Coefficient of Pressure

The coefficient of pressure along the smooth flat plate was calculated for different angles of attack and different free stream velocities. Some of the results are shown in Figure 5.1. At \( \theta=0^\circ \), within 2” from the leading edge, \( Cp_x=-1 \), indicating a region of separation and recirculation. Downstream of \( x=2" \), the flow has constant velocity but has accelerated slightly from its free stream value. This acceleration could have been produced as the flow passed the separated bubble. As the angle of attack is increased, a stagnation region is noticeable at the leading edge of the flat plate. Also, the flow acceleration increases as the angle of attack increases. At \( \theta=20^\circ \), \( Cp_x \) is approximately 0 at \( x=10" \), or the location of the plugs, indicating that the flow has accelerated back to its free stream value.

The effect of the blockage produced by the heaters on the coefficient of pressure along the flat plate at \( 0^\circ \) angle of attack is shown in Figure 5.2. The flow accelerates up to \( x=5" \), then reaches a relatively uniform velocity from \( x=5" \) to 15”. A comparison between Figure 5.2 and the top plot in Figure 5.1 shows that the blockage produced by the heaters has accelerated the flow to approximately \( 2U_{inf} \).
**Figure 5.1:** Coefficient of pressure profiles for smooth flat plate at different angles of attack and free stream velocities
Figure 5.2: Coefficient of pressure profiles for smooth flat plate at 0° angle of attack with the heaters on place

5.2 Boundary Layer Thickness

Boundary layer thickness measurements were limited. However, oscilloscope readings were used to determine the state of the boundary layer at the roughness location for different angles of attack. At 0° angle of attack, the boundary layer at the roughness location was turbulent. Not until 20° angle of attack was the flow laminar at the roughness location. The turbulence observed with the oscilloscope could have been the effect of separation produced by a relatively blunt leading edge.

Actual boundary layer thickness measurements were taken at 0° and 20° angle of attack, as shown in Figure 5.3. These measurements are not conclusive since the hot wire probe could not be traversed to closer than approximately 0.6mm from the flat plate. However, the upper plot in Figure 5.3 shows backflow, characteristic of a separated boundary layer profile, at approximately \( h=1mm \). The bottom plot is more uniform, typical of a laminar boundary layer, but a boundary layer thickness can not be determined.
5.3 Convective Heat Transfer Coefficient

The first step in calculating convective heat transfer coefficients was to calculate the incoming radiation distribution $Q_{rad,in}$. A heat balance for the heated plate without airflow under steady state conditions allowed for the calculation of $Q_{rad,in}$ from the plate's surface temperatures. Figure 5.4 shows the plate's surface temperature, as measured by thermocouples, at different instances in time while steady state conditions were reached. From these steady state surface temperatures, the incoming radiation distributions were calculated as shown in Figure 5.5. Three distributions were used, two at 0° angle of attack runs, and one at 20° angle of attack runs, which correspond to the conditions described in Tables 4.1 and 4.2. Two distributions were needed at 0° angle of attack because at high speeds ($U=43, 46m/s$), the convective cooling did not allow the temperature of the heaters
to reach the temperatures for the low speeds \( (U=27, 35m/s) \) distribution. At 20° angle of attack, only two heaters were used to heat the flat plate. Therefore, the radiation distribution at 20° angle of attack was lower than those for 0° angle of attack. Also, the heated area was less. The distribution was only calculated up to \( x=15'' \).

**Figure 5.4:** Flat plate surface temperature at various instances of time while the plate was heated without airflow (\( \theta=0^\circ \); low speeds \( U=27, 35m/s \); TC data)

**Figure 5.5:** Incoming radiation distributions calculated from heat balance without airflow. Two distributions for \( \theta=0^\circ \): low speeds \( U=27, 35m/s \) and high speeds \( U=43, 46m/s \). One distribution for \( \theta=20^\circ \).
5.3.1 Smooth Flat Plate Convective Heat Transfer Coefficients

Convective heat transfer coefficients were calculated for the smooth flat plate at the two angles of attack and compared to theoretical results. A heat balance allowed for the calculation of heat transfer coefficients from the flat plate’s surface temperatures. Thermocouple data, and heat transfer coefficient profiles over the whole flat plate will be presented.

0° Angle of Attack

Figure 5.6 shows thermocouple temperature readings for the smooth flat plate at 0° angle of attack at various free stream velocities. The calculated heat transfer coefficients are shown in Figure 5.7. The smooth plate coefficients do not match well with theory. The coefficient values transition from values close to the turbulent solution, except at $U=27m/s$, to values higher than the turbulent solution. This transition occurs between $x=5''$ and $x=8''$, indicating that the cause could have been the flat plate leading edge. The leading edge, from $x=0''$ to $x=5''$, was beveled at a 3° angle relative to the rest of the plate. The change in surface slope at $x=5''$ could have been separating the flow.

The difference between experimental and theoretical heat transfer coefficient values increases as the free stream velocity increases, indicating flow acceleration. The $C_{p_x}$ plot in Figure 5.2 shows that the blockage produced by the heaters has accelerated the flow to approximately $2U_{inf}$. The experimental heat transfer coefficient profiles were compared to the theoretical solution corresponding to twice the free stream velocity measured. The experimental heat transfer coefficient profiles were greater than the theoretical solution for $2U_{inf}$, suggesting mixing in the flow not present in a turbulent boundary layer.

The incoming radiation distribution $Q_{rad,in}$, calculated from the heat balance without airflow, could have been different than the actual distribution heating the plate in these studies, causing differences between experimental and theoretical results.
Figure 5.6: Temperature distribution on smooth flat plate at 0° angle of attack and various free stream velocities (TC data)
Figure 5.7: Experimental and theoretical convective heat transfer coefficients for smooth flat plate at 0° angle of attack and several free stream velocities. (Calculated from TC data)
Figure 5.8: Experimental and theoretical convective heat transfer coefficients for smooth flat plate at 20° angle of attack and several free stream velocities. (Calculated from TC data)

20° Angle of Attack

The heat transfer coefficients for the smooth flat plate at 20° angle of attack are shown in Figure 5.8. Results are compared to the theoretical solutions for laminar and turbulent boundary layers. The theoretical solutions account for variable temperature on the flat plate, but not for variable velocity. The heat transfer coefficient solution for flow over a flat plate with both variable temperature and free stream velocity was not found in the literature.
The smooth plate coefficients for $20^\circ$ angle of attack match well with the laminar solution. The different profile might be due to the acceleration of the flow, not accounted for in the convective heat transfer coefficient solution. The $C_p$ plot at $20^\circ$ angle of attack in Figure 5.1 shows that the velocity of the flow is lower than $U_{inf}$ upstream of $x=10^\prime\prime$, and higher than $U_{inf}$ downstream. This acceleration explains coefficients lower than theoretical at $x=5^\prime\prime$, and higher coefficients at $x=12^\prime\prime$ and $15^\prime\prime$. Higher coefficients at $x=2^\prime\prime$ might be due to a region of recirculation upstream of the stagnation point.

5.3.2 Effect of Roughness on the Convective Heat Transfer Coefficient

The discussion of the effect of roughness on the convective heat transfer coefficient will be divided in two parts. The first part presents the results from the studies done with the flat plate at $0^\circ$ angle of attack, where the boundary layer was turbulent, and probably separated. The second part presents the results from the studies done with the flat plate at $20^\circ$ angle of attack, where the boundary layer was laminar. In each part, two kinds of results will be presented. First, thermocouple data will be presented. The thermocouple data allowed to calculate heat transfer coefficient profiles over the whole flat plate. These results were compared to the results from the smooth flat plate studies and to theoretical calculations for smooth flat plates with turbulent and laminar boundary layers. Second, thermogram data will be presented. The thermogram data allowed to calculate detailed heat transfer coefficient profiles from $x=7.5^\prime\prime$ to $x=11^\prime\prime$. Both absolute and relative heat transfer coefficients were calculated from the thermogram data. Although three castings were tested, results for casting #5 will only be presented.

$0^\circ$ Angle of Attack

Thermocouple Data

Some of the convective heat transfer coefficient profiles for the plate with roughness element arrays and castings are shown in Figures 5.9, 5.10, and 5.11. These profiles are compared to the smooth flat plate results and the turbulent and laminar theoretical solutions. The profiles with and without the roughness should match upstream of the plugs ($x=10^\prime\prime$), where the flow is yet unperturbed. The profiles show good agreement upstream of $x=10^\prime\prime$. At $x=12^\prime\prime$, the coefficient profiles for the plate with the roughness have a higher value than...
the profile for the smooth plate, suggesting an enhancement produced by the roughness. Downstream of $x=15''$, the perturbed heat transfer coefficient values fall back to values close to the smooth results.

The heat transfer coefficient profiles for the plate with casting #5, height 3, shown in Figure 5.11, seem to be shifted up compared to the smooth flat plate results. This shift could have been due to day to day changes in ambient temperature.

It should be noted that to calculate smooth plate heat transfer coefficients, the readings from the two rows of thermocouples were averaged. To calculate heat transfer coefficients for the plate with the roughness samples, temperatures read by the row of thermocouples corresponding to the given roughness sample, were used. Thus, the heat transfer coefficient profiles for the plate with the roughness are more sensitive to temperature non-uniformities on the flat plate.
Figure 5.9: Convective heat transfer coefficient profiles for smooth plate and pseudo-random array (psu); (θ=0°; calculated from TC data)
Figure 5.10: Convective heat transfer coefficient profiles for smooth plate and staggered rectangular array (off); ($\theta=0^\circ$; calculated from TC data)
Figure 5.11: Convective heat transfer coefficient profiles for smooth plate and casting #5, height 3 (cas3); (θ=0°; calculated from TC data)
Thermogram Data

A typical thermogram for the 0° angle of attack studies is shown in Figure 5.12. Darker regions indicate cooler temperatures and higher convective heat transfer. The opposite is true for lighter regions. Note that the casting has cooler regions than the roughness element pattern, indicating higher convective heat transfer. Some problems encountered when analyzing the thermograms can be seen in Figure 5.12. Note that there is a bright spot at the right of the Figure. This bright spot is the result of light reflection, probably from the zinc sulfide window, and should not be considered as an area of high temperature. Also note a relatively bright region upstream of the roughness element pattern. Again, this is not a region of hotter temperature but the effect of the RTV used to cover the gap between the plug and the flat plate. The RTV had a different emissivity than Plexiglas, even after being painted flat black.

![Figure 5.12: Typical thermogram of heated staggered rectangular array and casting (θ=0°; U=46m/s)](image)

Figures 5.13 through 5.16 show detailed thermogram convective heat transfer coefficient profiles for all three arrays and for casting #5, height 3, all at $U=35m/s$. In all figures, the top plot shows a strip of the thermogram capturing the roughness element plug. The second is a plot of the temperature in the strip, averaged in the spanwise direction. The
average temperature of the roughness strip, or the perturbed area, is compared to the average temperature of the unperturbed area, calculated from a strip of smooth flat plate (not shown). The two strips were taken from the same thermogram, thus avoiding the mismatch problem seen in the thermocouple data. Only slight mismatches seen due to temperature non-uniformities along the span direction are seen in the thermogram data. Temperature non-uniformities can be seen in Figure 5.12. The ‘*’s in the second plot correspond to thermocouple data. The third is a plot of the convective heat transfer coefficient for the perturbed and unperturbed areas, calculated from the temperatures in the second plot. The fourth is a plot of the ratio of perturbed over unperturbed heat transfer coefficients. Note that if heat transfer enhancements are measured from the fourth plot, using as a baseline the value of $h_p/h_u$ upstream of the roughness and not the value of 1, the mismatch problem is eliminated.

From the roughness element arrays heat transfer coefficient profiles, no enhancement can be noticed. However, by looking at the ratio of perturbed and unperturbed coefficients, a slight enhancement can be seen for the pseudo-random and staggered rectangular arrays, while no noticeable enhancement is seen for the rectangular array. A noticeable enhancement can be seen for casting #5, at all three heights.

Figure 5.17 shows a summary of enhancement ratios for the pseudo-random and staggered rectangular arrays and all three heights of casting #5, at all velocities tested. The values plotted were obtained by averaging the enhancement profiles along the flow direction. The element arrays had slight enhancements of approximately 1.1, while casting #5 had enhancements ranging from 2 to 3.3.

Some expected results are not seen in Figure 5.17. First, the average enhancement for the casting should increase as the height of the casting is increased. Although the enhancement for height 3 is greater than the enhancement for height 1, except at $U=47 m/s$, the enhancement for height 2 does not follow the expected trend, except at $U=43 m/s$. Another expected result not observed was an enhancement increase as the flow velocity was increased. The enhancement insensitivity to $k$ points to a very thick boundary layer. The insensitivity to $U$ points to mixing in the flow.
Figure 5.13: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; ‘x’ shows TC location; ‘*’ corresponds to TC data (pseudo-random array; θ=0°, U=35m/s)
Figure 5.14: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; ‘x’ shows TC location; ‘*’ corresponds to TC data (staggered rectangular array; $\theta=0^\circ$, $U=35m/s$)
Figure 5.15: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; 'x' shows TC location; '*' corresponds to TC data (rectangular array; $\theta=0^\circ$; $U=35m/s$)
Figure 5.16: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; ‘x’ shows TC location; ‘*’ corresponds to TC data (casting #5, height 3; θ=0°; U=35m/s)
Figure 5.17: Average convective heat transfer coefficient enhancement for casting #5 (three heights), staggered rectangular array (off), and pseudo-random array (psu)

20° Angle of Attack
Thermocouple Data

Convective heat transfer coefficient profiles for the plate with all the roughness element arrays tested are shown in Figures 5.18, 5.19, and 5.20. These profiles are compared to the smooth plate results and the turbulent and laminar solutions. Upstream of the roughness, excellent agreement is observed between the profiles for the plate with roughness and the smooth plate. The convective coefficient transitions in all cases from its laminar boundary layer value to its turbulent boundary layer value, indicating that the roughness is tripping the boundary layer. The staggered rectangular and the rectangular arrays make the boundary layer reach turbulence between $x=10''$ and $x=12''$, while the pseudo-random array makes the boundary layer reach turbulence between $x=12''$ and $x=15''$. 
Figure 5.18: Convective heat transfer coefficient profiles for smooth plate and staggered rectangular array (off); ($\theta$=20°, calculated from TC data)
Figure 5.19: Convective heat transfer coefficient profiles for smooth plate and rectangular array (rec); (θ=20°; calculated from TC data)
Figure 5.20: Convective heat transfer coefficient profiles for smooth plate and pseudo-random array (psu); ($\theta=20^\circ$, calculated from TC data)
Thermogram Data

A typical thermogram for 20° angle of attack studies is shown in Figure 5.21. Darker regions indicate cooler temperatures and higher convective heat transfer. The opposite is true for lighter regions. In Figure 5.21, temperature gradients are more noticeable than in Figure 5.12, as expected from Henry's results which show higher convective heat transfer enhancement for laminar boundary layers. Also note in Figure 5.21 wakes of cooler regions downstream of the plugs, a result also observed by Henry. A bright spot can be seen at the center left of Figure 5.21. Note that the gaps between the plugs and the flat plate show as dark regions which should not be considered as regions of enhanced cooling produced by the roughness elements.

![Figure 5.21](image)

**Figure 5.21:** Typical thermogram of heated rectangular and staggered rectangular arrays (θ=20°; U=46m/s)

Figures 5.22 through 5.27 show detailed thermogram convective heat transfer coefficient profiles for the three roughness element arrays at the two free-stream velocities tested. In all cases considerable enhancement is observed, ranging in average values from 1.6 to 2.8.

The enhancement profile for the staggered rectangular array shows a considerable enhancement on the first row of elements, followed by a drop and subsequent slight rise in
enhancement, as shown in Figures 5.22 and 5.23. The enhancement profile for the rectangular array does not show the considerable enhancement observed in the first row of the staggered rectangular array. (Note that the first peak in Figures 5.24 and 5.25 is due to the gap between plug and plate). The enhancement profile rises more sharply than for the staggered rectangular array. The enhancement profile for the pseudo-random array shows three peaks which seem to correspond to the locations where there are higher concentrations of roughness elements. The rise in the enhancement profiles observed could be due to the interaction of the enhancement over single elements and wakes of upstream elements. Thus more enhancement is observed where roughness elements concentration is greater.

Figure 5.28 shows a summary of average enhancement ratios for the three roughness element arrays at the two velocities tested. The rectangular and staggered rectangular arrays show more enhancement than the pseudo-random array, probably due to the more efficient packing of elements. All three arrays show an increase of enhancement as the velocity is increased, as expected since $k/\delta$ is increasing.
Figure 5.22: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; 'x' shows TC location; '*' corresponds to TC data (staggered rectangular array; $\theta=20^\circ$, $U=35m/s$)
Figure 5.23: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; 'x' shows TC location; '*' corresponds to TC data (staggered rectangular array; $\theta=20^\circ$, $U=46\,m/s$)
**Figure 5.24:** (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; ‘x’ shows TC location; ‘**’ corresponds to TC data (rectangular array; θ=20°, U=35 m/s)
Figure 5.25: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; ‘x’ shows TC location; ‘*’ corresponds to TC data (rectangular array; θ=20°; U=46 m/s)
Figure 5.26: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; ‘x’ shows TC location; ‘*’ corresponds to TC data (pseudo-random array; θ=20°; U=35m/s)
Figure 5.27: (a) Thermogram image, (b) average surface temperatures for perturbed and unperturbed areas, (c) heat transfer coefficient profiles for perturbed and unperturbed areas, and (d) enhancement profile; ‘x’ shows TC location; ‘*’ corresponds to TC data (pseudo-random array; $\theta=20^\circ$; $U=46m/s$)
Figure 5.28: Average convective heat transfer enhancement for rectangular array (rec), staggered rectangular array (off), and pseudo-random array (psu); $\theta=20^\circ$

Comparison between $0^\circ$ and $20^\circ$ Angle of Attack Results

Although not tested under laminar boundary layer conditions, casting #5 is expected to produce a greater heat transfer enhancement than the roughness element arrays. Under turbulent boundary layer conditions, the staggered rectangular and the pseudo-random arrays were more effective producing heat transfer enhancement. Under laminar boundary layer conditions, the rectangular and staggered rectangular arrays were more effective. Since results under laminar boundary conditions were in agreement with results from theory or observed by other researchers, a comparison of different arrays in terms of enhancement should be done under these conditions.

Comparison to Henry’s Results

Heat transfer enhancement profiles under laminar boundary layer conditions were compared to the results obtained by Henry [7]. Localized heat transfer enhancement on the roughness elements when the spacing between elements is greater than the element’s
radius was observed as in Henry’s experiment and shown in Figure 1.3. A uniform enhancement profile was observed when the spacing was less than the element’s radius.
Chapter 6
Conclusions

The objective of this study can be divided in two parts. First, it was desired to design, build, and develop an experimental setup and technique that would be part of our proposed approach to better model the heat transfer of the ice accretion process. This setup needed to study and compare the heat transfer characteristics of simulated and natural ice roughness. The setup also needed to produce and measure pressure gradients and measure boundary layer thicknesses. The temperature measurement technique needed to give high spatial resolution to study the heat transfer characteristics over the length scale of the ice roughness. The second part of the objective of this study was to validate SET as a roughness modelling technique in terms of the impact of the simulated roughness on the heat transfer process.

6.1 Improvements to Experimental Setup and Technique

The experimental setup designed and built in this study is appropriate to the proposed approach to better model the ice accretion process. However, several improvements should be made.

First, improvements should be done to the flow quality. The flat plate’s leading edge should be fixed so that it does not induce separation. The effect of the blockage of the heaters should be minimized. The gaps between plugs and flat plate should be covered properly so that the flow is not altered, but also to avoid false IR camera readings. The flow quality can be checked from analysis of $C_{p_x}$ plots, boundary layer measurements or by comparing smooth plate heat transfer coefficients to theoretical results.

Secondly, some improvements should be made to the experimental procedure. The boundary layer thickness measuring technique should be improved until thicknesses can be calculated at various locations on the flat plate, and with the flat plate at different angles of attack. Improvements should also be done to the IR temperature measuring technique. Light reflections should be eliminated and surface emissivities kept uniform. The camera
should be carefully calibrated during testing and later corroborated during the data analysis stage. The flat plate should be uniformly heated to simplify data reduction.

Once these improvements have been made, a more comprehensive test matrix could be studied. A variety of both simulated and natural ice accretion roughness could be studied. The angle of attack of the flat plate could be set to different values in order to simulate the pressure gradients of flow over an airfoil. The effect of Reynolds number and of $k/\delta$ could be studied by testing over more free stream velocities. And both laminar and turbulent boundary layers could be studied.

### 6.2 Validation of SET Roughness Modelling

This study shows some observations which can help improve SET as a roughness modeling technique.

The heat transfer enhancement of the SET modelled roughness was lower than the enhancement of the casting. Since the enhancement was observed to be localized on the roughness elements, low enhancement points to low concentration of roughness elements, which could be due to the fact that SET was not suited for the natural roughness casting. The roughness element arrays could have produced higher heat transfer enhancement if the two major bead/spacing combinations observed in the SET analysis were used, as suggested by Orr [12].

The wakes of heat transfer enhancement produced by single roughness elements contribute to the average enhancement of the roughness element array. The interaction between wakes and roughness elements is also important. Thus, the roughness spacing in the flow and in the span direction are important. SET should be modified to model an image with both flow and spanwise spacings.

The enhancement profile for the casting was uniform along the flow direction, as were the profiles for the rectangular and staggered rectangular arrays. The enhancement profile for the pseudo-random array had peaks where the concentration of elements was greater. Although a pseudo-random arrangement of beads more closely resembles the roughness arrangement of natural ice, in terms of heat transfer enhancement this pseudo-random arrangement is not necessary.
A second iteration of this study, with the improvements to the experimental setup and technique, and with the improvements to the SET roughness models, would take us closer to a better heat transfer modeling of the ice accretion process.
References


