Impact of ice roughness morphology on convective heat transfer

Investigation of convective heat transfer enhancement for ice roughness morphologies using Direct Numerical Simulation

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In Short

- Investigation of ice roughness morphologies effects on convective heat transfer based on topology parameters and statistics.
- Direct Numerical Simulations of experimental and synthetic ice roughness morphologies performed with a high-order finite-difference solver implementing the Immersed Boundary Method technique.
- Improved unsterstanding of turbulent convection on ice-roughened walls and development of low-order models for RANS-based ice accretion solvers.

Motivation & Context: Aircraft icing occurs when flying through a cloud of supercooled droplets. Airworthiness standards require demonstrating the safety of operations in icing conditions. In this scenario, numerical codes for ice accretion prediction represent a valuable tool for early design, optimization and certification stages. A critical issue for such codes is represented by the modelling of heat exchange during ice accretion. The energy balance is heavily affected by the previous assessment of key variables such as the convective heat transfer coefficient h_{tc} extracted from a flow field solution, whose estimation is fundamental to achieve an accurate prediction of the ice growth. However, the complex ice topology, generally referred to as ice roughness, makes this task particularly challenging. In fluid dynamics, the understanding of rough surfaces effects on wall bounded turbulence is of practical importance in the prediction of a wide range of engineering fields other than aircraft icing. It is known that roughness highly impacts near-wall turbulence, modifying momentum properties and disrupting the viscous sublayer [1]. The specific case of ice roughness is characterized by a wide range of scales with strong dependence on operating conditions, and by a time evolution of the shape and its properties. Among others, McClain et al. [2] worked extensively on the characterization of rough geometries from experimental ice scans. The modelling of roughness effects in ice accretion codes tends to simplify specific shape features or statistics, reducing the problem to equivalent sand grain roughness and heat transfer coefficient correlations, generally related to icing-relevant parameters. The dependence on the specific numerical code is mostly dictated by the way are developed to improving the ice shape prediction to match experimental results, oftentimes discarding several variables that could also affect the ice accretion. This results in a limited characterization of the surface roughness evolution in time and space typical of in-flight icing morphologies, which leads to poor predictions of convective heat transfer variation during ice growth. In order to improve the current understanding on convective heat transfer enhancement on rough surfaces, the present research project aims at performing high-fidelity CFD simulations of turbulent flows over ice roughness morphologies, specifically targeting such mechanism.

Impact & Objectives The outcomes of this research are expected to significantly advance our understanding of icing phenomena and contribute to the improvement of predictive models in aerospace engineering applications. With the increasing computational resources at hand, exploring new methods relying on Direct Numerical Simulations (DNS) could provide a new perspective towards the usage of these numerical tools alternative to experiments. The analysis attempts to provide and test novel strategies targeting ice roughness effects; to reproduce heat transfer on ice-roughened surfaces with a numerical approach, improving the actual knowledge on enhancement mechanisms; finally, to improve models used in RANS simulations, which may be of practical and immediate use for current ice accretion solvers. In such a way, the present project is devoted to the investigation of numerical codes as means to deepen our understanding on the effect of ice roughness in the heat transfer physics towards the usage of ice accretion numerical codes as reliable certification tools.

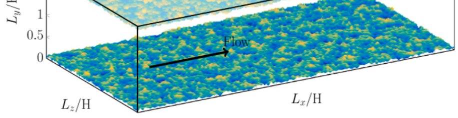

Figure 1: *Sketch of the computational domain incorporating rough wall, taken from [3].*

Numerical methodology: Direct Numerical Simulation (DNS) will be performed on realistic ice scans directly extracted from experiments, and on synthetic patches obtained through varying statistical properties of the scans. A periodic turbulent channel flow configuration featuring ice-roughened walls will be exploited to study the effect of different early-stage ice morphologies on convective heat transfer. This canonical configuration is an assessed methodology for the study of rough wall-bounded flows [3]. The open-source high-order finite-difference solver Incompact3d [4] will be used to solve the incompressible Navier-Stokes equations with passive scalar transport for the thermal part. Fractional time stepping is used for time advancement, solving a Poisson equation to enforce the incompressible condition. The Poisson equation is fully solved in spectral space via the use of relevant 3D Fast Fourier transforms (FFTs), allowing the use of any kind of boundary conditions for the velocity field. The code implements the Immersed Boundary Method to account for the complex solid boundary, based on a direct forcing term in the Navier-Stokes equations to ensure a no-slip boundary condition at the wall.

Preliminary work: The preliminary work for the project focused mainly on the geometry processing of ice roughness. The analysis is based on the experimental ice shapes scans obtained at the TU Braunschweig Icing Wind Tunnel within the ICE-GENESIS project [5]. This database consists of several .stl geometries representing different icing conditions. For the present problem, low accretion times ice shapes are considered, excluding complex geometry features and very high-roughness normally found in the forms of horns or feathers in glaze ice conditions. A transitory, initial phase of ice accretion is targeted, being phisically more relevant for the study of convective heat transfer enhancement. The Self-Organizing-Maps algorithm proposed by McClain et al. [2] has been implemented in Matlab© to efficiently unwrap the available geometries, and extract roughness patches representing the accreted ice on a flat wall. Different roughness zone are distinguished based on the typical ice morphology properties, as the mean roughness distribution obtained from the SOM algorithm (see Fig. 2). With proper surface processing strategies, we are currently able to generate several homogeneous patches for each case with specific properties. Periodicity required by the flow configuration is retrieved through a mirroring procedure. The solver Incompact3d has been compiled on HLRN Lise login nodes and tested by simulating a smooth periodic channel at $Re_\tau = 180$ including the passive scalar, exhibiting good parallelization performances up to very large meshes.

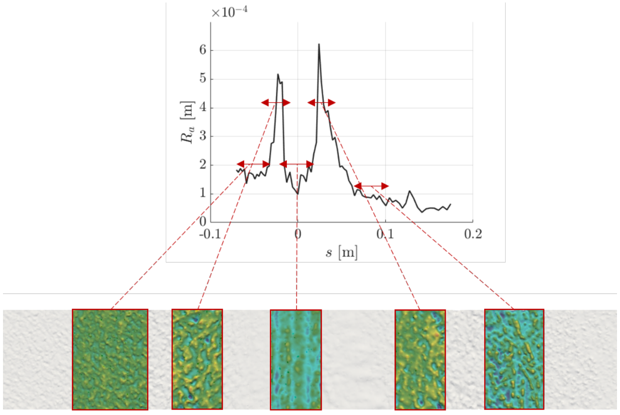

Figure 2: *Distinction of roughness zones on an exemplary unwrapped ice geometry.*

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https://traces-project.eu/
https://www.tu-braunschweig.de/ism/forschung-und-arbeitsgruppen/mehrphasenstroemungen-und-vereisung

More Information

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Project Partners

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DFG Subject Area

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