Computational and experimental modeling of icing processes by means of PNRPU high-performance computational complex

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Abstract. The article deals with the calculation and experimental modeling of icing processes by means of the high-performance computing complex (HPC) at PNRPU. The results of a computational experiment on estimating the parameters of gas-dynamic flow in the model small-sized climatic wind tunnel (ESCWT) allowed specifying requirements for the experimental setup components. We presented design scheme and the main elements of the model ESCWT. We selected architectural, hardware and software solutions for connecting the model ESCWT and the HPC at PNRPU. We obtained first results of physical experiments confirming the working capacity of the created in PNRPU model small-sized climatic wind tunnel.

1. Relevance of the problem
The current fundamental scientific problem of ice accretion on the aircraft elements in flight conditions is one of the most important factors of natural impact significantly influencing flight safety [1]. The ice build-ups formed on the surface of the aircraft wings lead to a significant reduction in the aerodynamic characteristics and controllability of the aircraft. Ice formed at the input sections of aircraft engines can fall and get into the engine, which, in turn, can lead to aserious damage of the compressor elements and, in the end, cause it to stop. Accident statistics, according to Army AircraftIcing (2002), shows that in the period from 1985 to 1999, there were 255 cases of aircraft icing, of which 12% - with victims, with losses amounting to $ 28 million. According to the Aircraft Owners and Pilot Association (2007) - 202 cases of aircraft icing from 1998 to 2007, of which 21% - with victims. The urgency of the problem is not decreasing at the present time. A recent example is the crash of the AN-148 aircraft due to iceaccretion on February 11, 2018. Particular attention should be given to these issues in connection with thecreation of a new family of aircraft engines PD-14.

Regarding the current state of research into iceaccretionby the world scientific organizations [2-8], it is possible to single out two most developed foreign competence centers of modeling icing processes and protection from aircraft icing: the North American group of organizations and the European group.
The main scientific centers of the North American group are NASA Glenn Research Center (USA) and NRC (Canada). These organizations have a good experimental base - wind tunnels which can simulate icing and a single ice accretion prediction code LEWICE.

The main scientific centers of the European group are ONERA, CIRA and Cranfield University. They also have a large number of different experimental installations; however, they all have their own calculation codes for ice accretion modeling.

At present, there are a number of wind tunnels in the Russian Federation: ADT T-101 (30 MW), ADT T-102 (500 kW), ADT T-103 (4400 kW), ADT T-104 (28.4 MW), ADT T-105 (450 kW), ADT T-106 (32 MW), ADT T-128 (100 MW), ADT T-1-2 (1000 kW), and ADT T-5 (315 kW) located in FSUE TsAGI, Zhukovsky, and T-324 (0.5 MW), T-313, T-325, T-326, T-327, T-333, IT-302, AT-303 at Kawasaki ITAM, Novosibirsk, etc. They are able to reproduce almost the entire list of flight conditions (regulated by the existing domestic standards) and are used to certify aviation equipment. Some of them have been refined for aerodynamic testing in icing conditions.

Tests on these large-sized wind tunnels cause an extremely high level of energy consumption during operation. As a result, this leads to a high cost of testing related, among other things, to the need to use drives and large-capacity refrigerators, large areas of production facilities, and a sufficient number of highly qualified maintenance personnel.

Modern methods of designing and creating anti-icing systems include both the stage of mathematical modeling of ice accretion and the operation of protection systems for selecting the most optimal scheme, and the stage of testing the system in icing conditions (natural or artificial) to determine the actual efficiency. At the same time, the existing methods (including foreign ones) of mathematical modeling of physical processes occurring during ice accretion and operation of de-icing systems necessitate a large amount of experimental work, as well as the development of techniques for modeling icing processes.

2. Investigation of ice accretion

To investigate icing processes on the elements of aircraft structures, the authors plan to conduct computational experiments on the high-performance computing complex (HPC) of PNRPU, physical modeling of ice accretion in a small-sized climatic wind tunnel (ESCWT), verification of numerical models and further scaling of parameters for real-size structures.

The article deals with the problem of creating the ESCWT. Below are the main stages of its development:

1. Gas-dynamic design of the tract, taking into account the compressor modeling;
2. Integration of measurement and registration systems using Particle Image Velocimetry [9] and Particle Dynamics Analysis systems, a modular National Instruments platform, a complex of sensors, and a video surveillance system [10, 11];
3. Search for architectural, hardware and software solutions for connecting the ESCWT and HPC;
4. Development of the automatic microcontroller complex;
5. Calculation of gas dynamics and design parameters of individual ESCWT systems (vacuuming, injectors, air cooling, a drop catcher, etc.);
6. Constructive optimization of individual elements and the system as a whole (reducing aerodynamic resistance and achieving laminar flow) [12, 13].

3. Model ESCWT sketch development

Due to the complexity and interdisciplinarity of each stage, it was decided to create a simpler model for the ESCWT in PNRPU, but with the consistency of all ESCWT systems development.

At the initial stage, a preliminary design sketch of the model ESCWT was worked out (Figure 1), which includes the following elements:

1. Freezer – to completely place the wind tunnel in its internal volume, with the ability to adjust the required temperature;
2. Supercharger with a rectifying element [14] – to supply a uniform flow of air to the working area entrance;
3. Steam humidifier – to create a specified humidity in the working area of the wind tunnel;
4. IP camera with infrared illumination – to track the ice accretion of the experimental model in real time in the absence of light;
5. Weather station with remote wireless sensors – to measure temperature, speed and humidity in the freezer, and to read static gas dynamic characteristics in real time;
6. Aerodynamic circular section of an optically transparent material – a working part of the wind tunnel, in which the experimental model is directly placed;
7. The manual control system of the fan speed and the heater temperature – to allow for smooth adjustment of the required parameters;
8. Temperature, humidity and pressure sensors – to measure gas-dynamic parameters in the working area of the wind tunnel;
9. The automatic control system, which is a microcontroller unit based on the Arduino system for real-time control of the freezer and steam humidifier activation/deactivation, using sensor data and data from pre-prepared control programs.

![Design scheme of the model ESCWT](image)

**Figure 1.** Design scheme of the model ESCWT.

4. **Conducting numerical calculations of gas-dynamic processes in the model ESCWT**

Based on the developed model ESCWT design scheme, the overall dimensions of the supercharger and the working part, and also the distance to the freezer walls were preselected. Numerical calculations of gas-dynamic processes were carried out to evaluate the nature of the flow in the freezer and the working part of the model ESCWT, as well as to select the necessary components of the experimental setup with specific gas-dynamic parameters and overall dimensions [15].

The following physical statement was adopted:
1. Gas-dynamic processes are considered in a stationary formulation;
2. Non-reacting perfect gas flow is considered;
3. Gas-dynamic flow is viscous and single-phase;
4. Gravity is not taken into account;
5. The flow in the working area, in the supercharger and in the internal cooled volume of the freezer is investigated simultaneously;
6. The walls of the working part are impermeable, adiabatic and non-rough (it is assumed that all the rough elements are inside the viscous layer), with adherence of particles;
7. To set the input / output boundary conditions, a gap in the zone after the supercharger is accepted.

The following solid-state 3D model of the model ESCWT is constructed (Figure 2).
In accordance with the accepted physical formulation, a mathematical model is developed, which is based on the conservation laws of mass, momentum, and energy, and is closed by the equations of the ideal compressible gas state and turbulence, as well as by the initial and boundary conditions [16]. It is required to solve a system of four independent equations—the system of Navier-Stokes equations (1-4):

- law of mass conservation

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0
\]  

(1)

- law of momentum conservation

\[
\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot (\rho \mathbf{V} \otimes \mathbf{V}) = -\nabla P + \nabla \left( (\mu + \mu_t) \nabla \mathbf{V} + (\nabla \mathbf{V})^T \right)
\]  

(2)

- law of energy conservation

\[
\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho H \mathbf{V}) = \frac{\partial P}{\partial t} + \nabla \left( \frac{\lambda}{c_p} + \frac{\mu_t}{\Pr_t} \nabla H \right)
\]  

(3)

- equation of state

\[
P = \rho RT
\]  

(4)

where \( t \) is time, \( \rho \) – density, \( \mathbf{V} \) – velocity, \( P \) – pressure, \( \mu \) – dynamic viscosity, \( \mu_t \) – turbulent dynamic viscosity, \( H \) – enthalpy, \( c_p \) – heat capacity, \( \lambda \) – coefficient of thermal conductivity, \( \Pr_t \) – turbulent Prandtl number, and \( R \) – universal gas constant.

The mathematical model is closed by the following initial and boundary conditions:

\[
P_{\text{total}}\bigg|_{\text{input}} = 101325 \text{ Pa}
\]

\[
T_{\text{total}}\bigg|_{\text{input}} = 253,15 \text{ K}
\]

\[
G_{\text{output}} = -0.64 \text{ kg/s}^2
\]

The mass flow corresponds to the maximum assumed supercharger power to achieve the flow velocity in the working area of 18 m/s.

To solve the original system of partial differential equations, the solid-state 3D model of the model ESCWCT was divided into cells. The mesh model was built using ANSYS Mesher. The number of finite elements was 2.76 million. The mesh model mainly consists of hexagonal elements. The maximum element size is 10 mm.
As the hardware for the computational experiments, the resources of the HPC at PNRPU (peak performance 24 TFlops) were used. The main technical characteristics of the PNRPU HPC [17]:
- 95 computational nodes;
- 128 four-core processors Barcelona-3 (total 512 cores);
- 62 eight-core processors Intel Xeon E5-2680 (total 480 cores);
- Peak performance: 24,096 TFlops;
- Performance in the Linpack test package: 78%;
- The information storage system volume: 27 TB;
- The RAM volume is 5888 GB (32 GB / node with Barcelona-3 processors, and 128 GB / node with Intel Xeon E5-2680);
- 12 computing modules GPU NVIDIA Tesla M2090 (512 cores, 6 GB).

As a result of gas-dynamic calculations, fields of velocities, static and total pressures, temperatures and other gas-dynamic parameters were obtained. Below are the fields of the flow lines (Figure 3), of the excess pressure (Figure 4), and of the total temperature (Figure 5).

The obtained distribution fields of the total pressures and temperatures are uniform. The numerical values correspond to the given values at the boundaries.

Based on the results of the gas-dynamic calculations, ANSYS revealed the possible overall dimensions of the supercharger and the working zone of the model ESCWT. High homogeneity of the gas-dynamic flow in the working zone was obtained. Gas-dynamic parameters were found to ensure a uniform flow at the supercharger inlet.

The numerical calculations made it possible to form detailed technical requirements for the necessary model ESCWT components.

5. Search for architectural, hardware and software solutions for connecting the model ESCWT and HPC at PNRPU
To connect the model ESCWT and PNRPU HPC with fiber-optic communication channels, a detailed hardware scheme was developed (Figure 6) [18, 19].

There is an optical fiber connecting the rooms with the model ESCWT and HPC. A scheme is proposed to connect the PNRPU HPC at 10 and 1 Gb/s, data storage systems (10 Gb/s) with the National Instrument system for measuring and recording fast processes and PCs with the installed software necessary for the model ESCWT operation [20], i.e., unification of computing and experimental devices in a single scientific and educational network is realized. To work remotely on the HPC nodes and to process the data received from the model ESCWT, the option of including the
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nettops in the network was developed. The scheme of the Public Internet access through VLAN was offered.

![Figure 6. Hardware optical scheme for connecting the model ESCWT and PNRPU HPC.](image)

At the same time, integration of this complex with the regional scientific and educational cyberinfrastructure of the GIGAURAL network with the possibility of access to the URAN supercomputer at the Krasovskii IMM, UB RAS, in Ekaterinburg at a speed of not less than 10 Gb/s was proposed [21].

6. Conducting physical experiments on the model ESCWT

Based on the results of gas-dynamic calculations, the model ESCWT was created at PNRPU. The experimental model of the wing profile NACA 0012 and the experimental model stand were manufactured and assembled. The microcontroller unit was assembled, and the system for maintaining the necessary gas-dynamic parameters in the working zone of the model ESCWT was implemented. The general view of the model ESCWT is shown in Figure 7.

A series of the first physical experiments was performed on the model ESCWT. Figure 8 shows the graph of the change in the static temperature in the working zone of the wind tunnel and in humidity with time for one of the starts of the model ESCWT. The sharp jump in humidity in Figure 8 is due to the steam supply to the ESCWT working area.

Figure 9 shows ice accretion on the NACA 0012 wing profile at 253.15K and 70% humidity.

The first data of physical experiments on the model ESCWT have been obtained, and operability of the experimental setup has been proved.

7. Conclusions

1. The results of a computational experiment on estimating the gas-dynamic flow parameters in the model ESCWT were obtained, which allowed forming detailed technical requirements for the necessary components of the experimental setup;
2. Based on the data of computational experiments, a model ESCWT was created at PNRPU;
3. The microcontroller block of the measuring and recording system was developed and adapted to the experimental installation;
4. Optical scheme for the interaction of the model ESCWT and HPC at PNRPU with the possibility of connecting to the regional scientific and educational cyberinfrastructure of the GIGAURAL network at a speed of 10 Gb/s was developed;

5. The first physical experiments on ice accretion modeling were carried out, the real-time experimental data were obtained, and the performance of the model ESCWT was confirmed;

6. It is possible to use the developed architectural, hardware, software solutions for connecting ESCWT and HPC at PNRPU, as well as for numerical simulation methods of gas-dynamic processes in the ESCWT.

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