Transient Temperature Measurements During In-Flight and Wind Tunnel Investigations of Icing Phenomena

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ABSTRACT

The paper deals with a problem of transient temperature measurements performed on the airfoil exposed to icing conditions. Two types of investigations are discussed: in-flight tests and laboratory icing experiments in a wind tunnel. In the first case measurements were performed during test flights of the Polish TS-11 „Iskra" jet plane. A specially designed on board temperature measurement system was utilised to record the temperature changes in five selected points at the wing. Experiments of the second kind were performed on the NACA0012 model airfoil in a small scale icing research tunnel. In this case a multichannel temperature measurement laboratory system was applied. The experiments were focused on the icing phenomena investigations. The obtained results were analysed in view of the supercooled fuel effect on the heat transfer and on temperature distribution.

1.0 INTRODUCTION

The aircraft icing phenomena still attain great attention [1], [2]. It is mostly because the aircraft icing may pose a severe hazard to life and because the removal and prevention of ice formation on aircraft components is vital to aircraft performance and operation. The intense ice accretion may lead to deterioration in aerodynamic characteristics of the aircraft, increase of its mass and shifting of the mass centre, variation in engine thrust or wrong indications of the onboard control instruments. A special attention to icing problems should be paid in view of military aircraft operation. This concerns both manned and unmanned planes whose readiness to operate in different weather conditions is crucial.

For the above mentioned reasons, broad studies of the icing phenomena are conducted all over the world. Computer codes for simulation of icing are worked out and experimental researches, both in-flight and wind tunnel, are carried out. Because of a variety of combinations of physical parameters influencing the icing process there is still a need for more experimental data. One of the key investigated parameters is the temperature and one of the most reliable sources of the experimental data is temperature measurement performed during real flight. However, there are certain limitations of the range of flight tests. The reasons are flight safety restrictions, random character of weather conditions, cost limitations etc. So, whenever is possible, flight test results should be verified and complemented. The very effective way of experimental verification is icing research tunnel (IRT) investigation.

In the present paper we discuss results of a complementary, in-flight and IRT, investigation of the airfoil filled with the fluid (fuel or the fluid modelling supercooled fuel). Experiments of the first kind were performed during test flights of Polish TS-11 „Iskra" jet plane (see Fig. 1). The temperature changes of the airfoil surface were investigated in all kinds of atmospheric conditions in March [6]. Special attention was

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paid to icing conditions encountered by the aircraft while passing the clouds. Experiments of the second kind were performed on the NACA0012 model airfoil in a small scale icing research tunnel (see Fig. 2; [5]). The IRT is a property of the Institute of Aviation Technology of the Military University of Technology in Warsaw put in service in 2002. The details concerning the methodology of measurements and the obtained results are provided below.

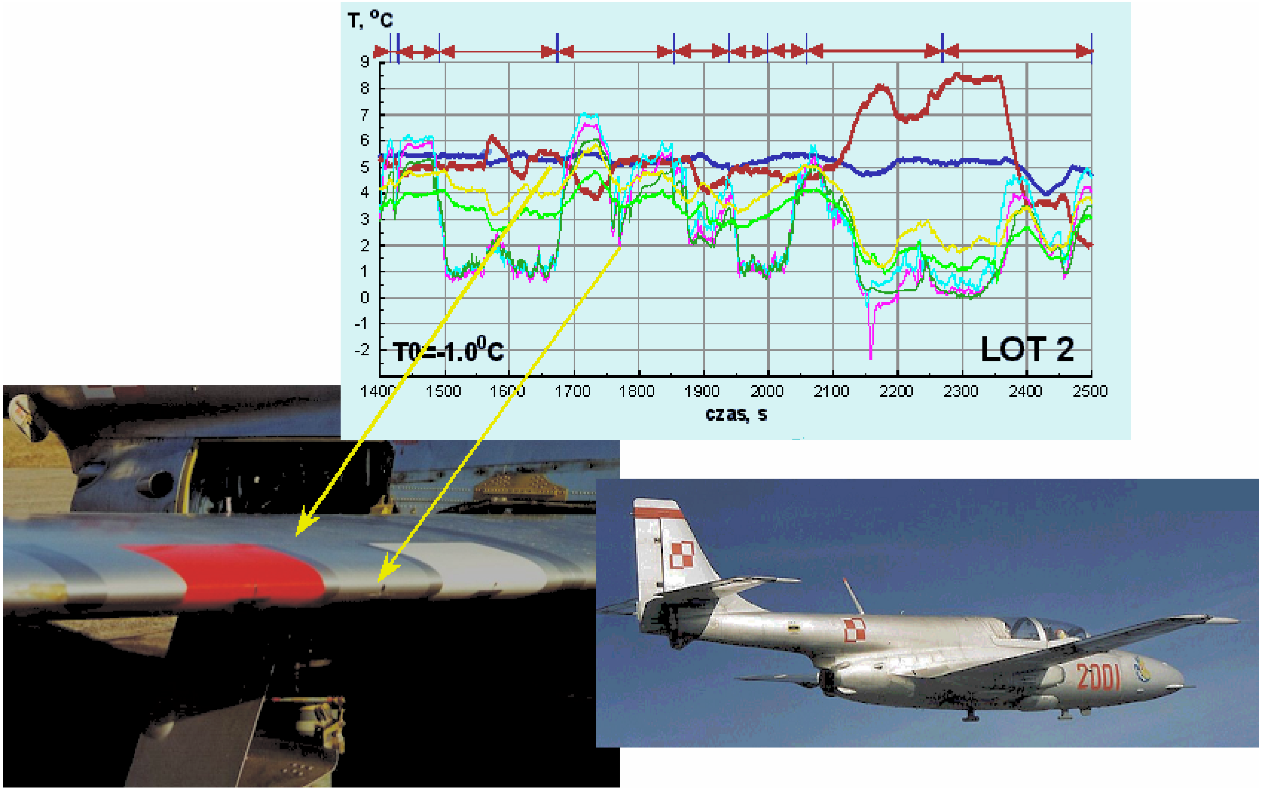
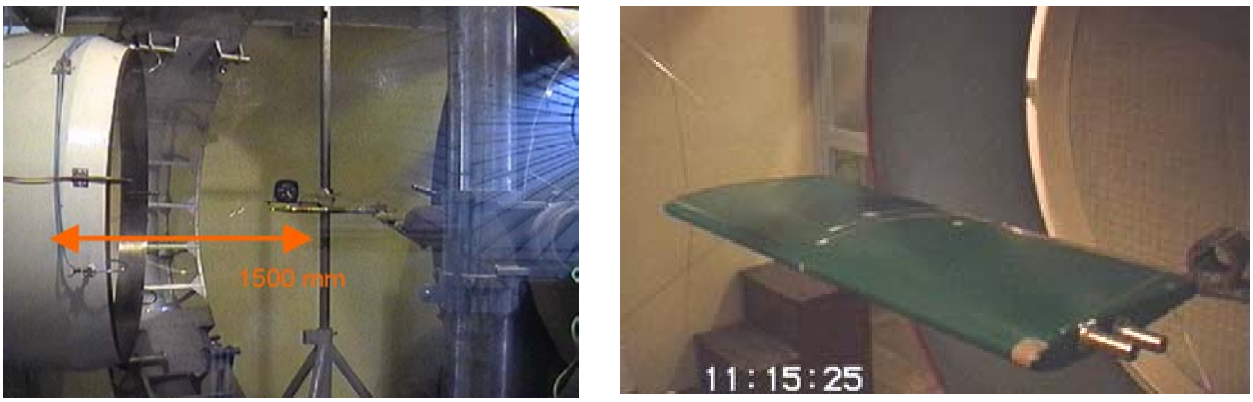


Figure 1: Test flights: three coloured section of the wing prepared for temperature sensors installation (on the left), the TS-11 Iskra jet (on the right) and a diagram of results with indicated thermocouples location (upper part).



a **b**

Figure 2: Icing research tunnel investigations: a – the IRT test chamber; b – the NACA 0012 airfoil model prepared for investigations (white spots close to the central line are thermocouples endings; on the right side there are visible pipe connectors for the supercooled fluid supply).

2.0 ARRANGEMENT OF EXPERIMENTS

2.1 In Flight Testing Apparatus

Because of specific measurement conditions, while planning experiments the attention was focused on durability and reliability of the onboard measuring system. It was also important to design the apparatus compatible with the aircraft onboard devices and the power supply. It should be underlined that the regular TS-11 Iskra aircraft was not designed for carrying any research instruments. Regarding limited choice of commercially available apparatus it could have affect the precision of temperature signals recording. Balancing the needs, a thermocouple (TC) multichannel temperature measurement system was assembled (see Fig. 3). The system consisted of:

- temperature sensors – 0.5 mm in diameter type K sheathed thermocouples (TCs). Small dimensions ensured minimum distortion of both temperature and the airflow fields. In order to ensure a short response time the exposed “hot” junctions were utilised.
- transducers – Czaki TCD-3000 thermoelectric signal amplifiers with automatic correction of the cold junction temperature. Transducers adjusted the level of TC’s signals to a certain voltage input range of data recorder.
- RC-1 16 channel digital data recorder. Basic parameters of this instrument were as follows: voltage input range from 0 to 5 V, maximum sampling rates 10 S/s^{-1} (10 Hz equivalent frequency), resolution 12 bits, maximum recording time 2 h, input resistance 470 kΩ.

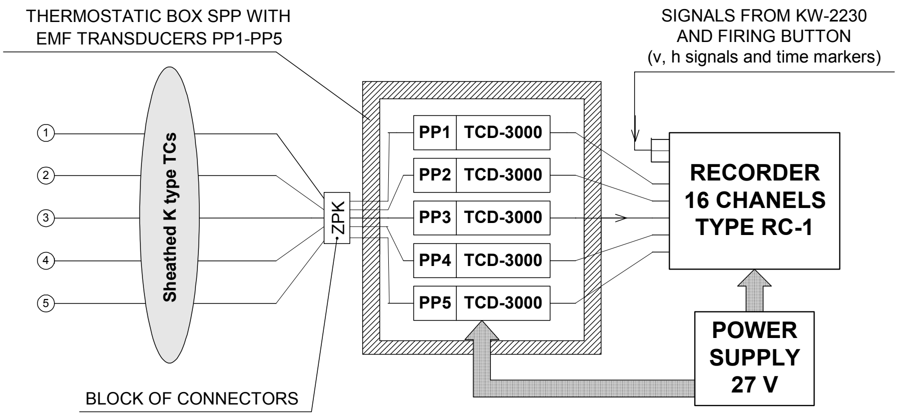


Figure 3: A scheme of the onboard system for the temperature, speed and altitude signals recording.

The thermocouple wires were fastened along the plane with an adhesive tape usually utilised in flight tests. The endings of TCs were glued to the plane surface at the measuring spots with a highly thermally conductive epoxy Omegabond-200. The thermal conductivity of the epoxy after curing is about 1.4 $W{\cdot}m^{-1}{\cdot}K^{-1}$. The strength of bonding was sufficient to endure aerodynamic tearing forces that occur in flight. Location of the temperature sensors on the plane is shown in Figure 4.

Prior to installation the whole system was calibrated and tested. During the calibration all system’s components were placed into a specially designed isothermal low temperature chamber in order to examine the apparatus in conditions close to those typical for real flights. The calibration data from within –30 ^oC to 20 ^oC were fitted with a line and linear thermal characteristics were utilised in further calculations. The accuracy of the temperature measurements was estimated to be better than 0.5 ^oC while the characteristic time of the every TC channel response not greater than 1 s [7].

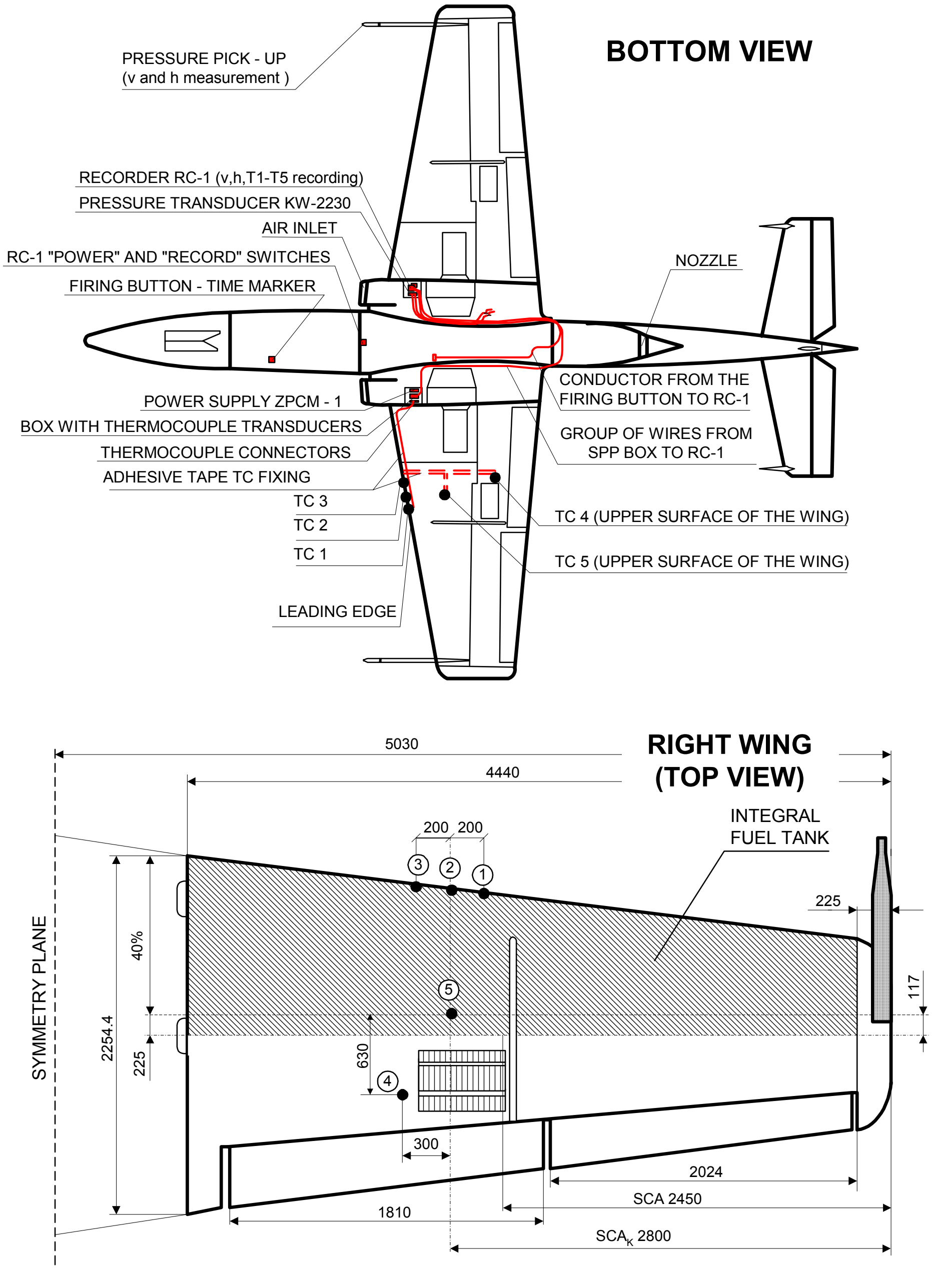


Figure 4: Onboard location of the experimental apparatus and indication of temperature sensors positioning.

2.2 Icing Research Wind Tunnel Apparatus

The laboratory tests were performed using a subsonic icing research wind tunnel (IRT). The tunnel has a testing chamber of a circular cross section of a 1.3 m diameter (Fig. 2.a). The maximum air speed depends on the actual inner air temperature but it could be roughly estimated to about 40 m/s. The IRT cooling installation enables inner air temperature to achieve the minimum about $-10\,^{o}$C in the circumstances of maximum air flow under ambient air temperature around 25 ^{o}C. Water aerosol is supplied by three atomisers to simulate liquid atmospheric water. The water droplet diameter varies from about 1 μm to about 5 μm. The liquid water content can be estimated from the aerosol stream dimension, water discharge and the doze duration.

The temperature of the investigated object was measured using thermocouples. Double teflon tubing K type thermocouples of wire diameter about 0.06 mm were applied. Thermocouples were manufactured by spark welding uncovered 1.5 mm wire ends. 1.5 m long thermocouples were connected to about 5 m long extension wires which transferred signals outside the low temperature test chamber. The connections were placed into a protecting box. In some cases the temperature measurements were also been controlled using an infrared camera.

The transient temperature signals were recorded using two types of data acquisition boards. The first one was NI 4350 USB Temperature and Voltage Meter system applied together with 14 miniconnectors rack-mount adapter TC-2190. With this module the temperature signals from all channels were scanned at least every 2 s. Regarding the investigated phenomena the system enables quasi-dynamic measurements. Dynamic studies were made using the second one - the NI SCXI temperature measurement system (1000 chassis, 1125 input module, 1328 terminal block) in 8 channels configuration based on a NI PCI-6036 16-bit data acquisition card. In these cases readings from all scanned channels were made at every 1 ms. Both systems were equipped with a cold junction sensor and compensation module. The accuracy of the temperature measurement after systems calibration is better than 0.2 ^{o}C for the investigations discussed here.

The investigated object was a model airfoil NACA 0012 500 mm wide of 230 mm chord and of 30 mm maximum height. One of the side surfaces of the airfoil had inlets allowing filling the inner space with liquid substituting the fuel (comp. Fig. 2.b). Ten thermocouples were provided for the airfoil (Fig. 5). In order to prevent the airflow disturbance narrow wedge cuttings from 0 to 0.5 mm deep were made on the surface of the investigated object to place the thermocouple junctions in. The junctions remained in contact with the investigated object surface while the cut-outs were filled with a thermally conductive resin (Omegabond-200). All experiments were recorded using a digital video camera.

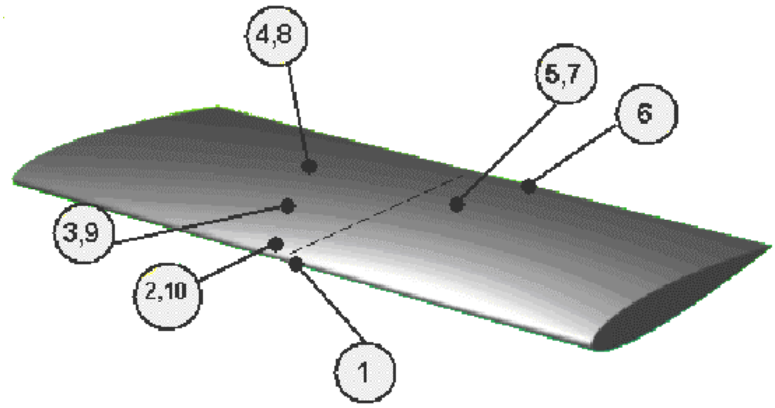


Figure 5: Indication of the temperature measurement sensors positioning on the NACA 0012 model airfoil (the doubled numbers indicate two sensors – the first located on the upper surface and the second placed just opposite at the bottom).

3.0 RESULTS OF EXPERIMENTS

3.1 In Flight Transient Temperature Recordings

The data discussed here was collected on four test flights performed on 16th, 17th and 20th (2 flights) of March 2000. During every test flight the second pilot of a two seats training jet aircraft TS-11 „Iskra" was operating the research apparatus and making the notes for a further reporting. During flights effects of the ambient temperature and the temperature changes with the altitude, weather and flight conditions including sun exposure, rain and snow fall, supercooled moist air in clouds, etc. on the airfoil surface temperature and temperature distribution were investigated. The recorded signals were: the aircraft velocity *v*, altitude *h*, temperatures $t_1 \div t_5$ from five temperature sensors located on the wing leading edge (TC1-TC3) and the upper surface (TC4 and TC5 - see Fig. 4). The total recording time of every flight did not exceed 3300 s. Several vertical flights of the altitude 120, 400, 500 m and the aircraft velocity 300, 400, 450, 500, 550 km/h were performed as well as one ascending flight up to 3100 m. The raw digital data collected during the flights was processed, analysed and compared with the pilot's reports.

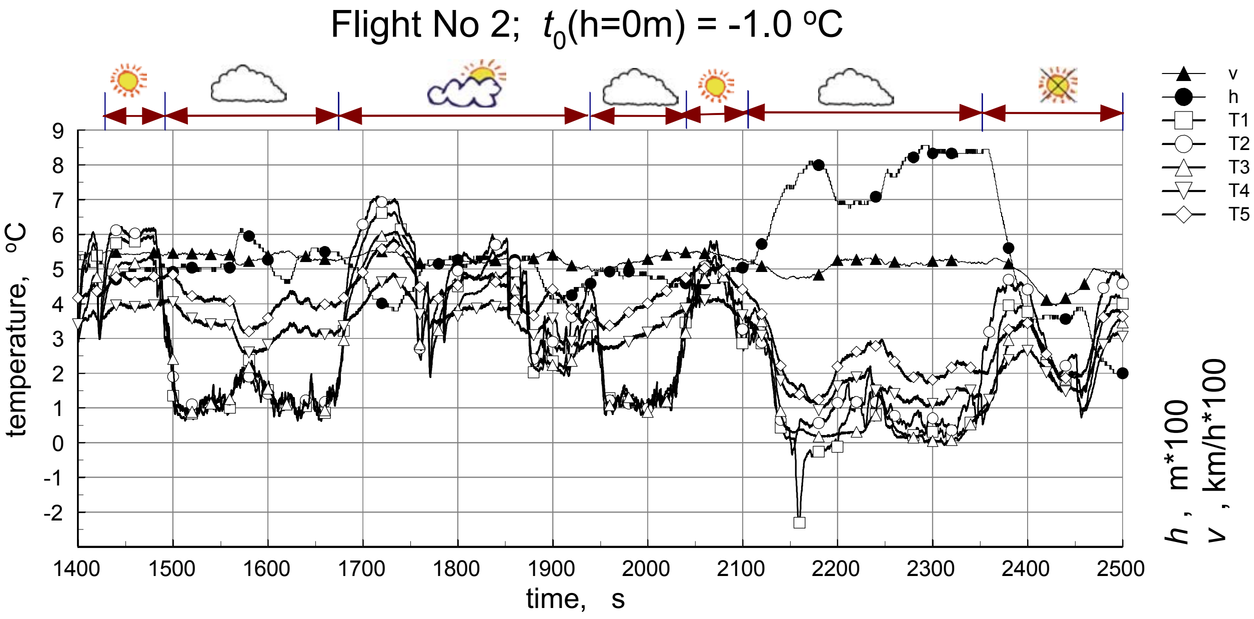


Figure 6: Selected results of the temperature (T1 – T5), the aircraft velocity and altitude recordings from the second test flight.

The details of all experiments are discussed in [6]. In general, the obtained results were in agreement with theoretical predictions (comp. e.g. [3]). However, there were also interesting phenomena revealed and some questions from the theoretical analysis [4] were still left open. Problems that remained can be discussed in view of typical results shown in Figure 6 (more experimental data is provided in [5]). There are displayed results form measurements of the flight No 2 performed in the atmosphere of the ground temperature $t_0(h=0\text{ m}) = -1.0\ ^{o}\text{C}$. Analysing the data one can observe a strong effect of thick clouds crossing. Recordings illustrate stabilisation of the airfoil surface temperature in a few seconds after the cloud entering or leaving. The changes were the most significant for the leading edge TC sensors. The recorded temperature changed for even more then 8 ^{o}C. Strangely enough, the changes for the upper surface thermocouples (T4, T5) were not only smaller but the temperature recorded was greater than the leading edge temperature while passing the cloud. This is just opposite to theoretical predictions – the aerodynamic heating is most significant at the trailing edge and the temperature increase was supposed to be greater than 7.5 ^{o}C [4]. During a climb after 2100 s of flight icing of the leading edge occurred. The temperature measured by the first temperature sensor $T1$ fell down to below -2 ^{o}C (2160 s). At this moment, independently, the ice formations were also noticed by the pilot. The observed changes of the temperature records can be explained by complex phenomena of heat and mass transfer. Just after entering the cloud the airfoil temperature decreases due to the ambient temperature decrease and due to interception of water from a cloud. The collected water evaporates from wet surfaces which results in additional temperature decrease up to the freezing point of the water. The temperature stabilisation at 0 ^{o}C can be attributed to the heat of crystallisation release of the supercooled water droplets. This heat compensates intensive heat flux of evaporation and sublimation. As a result the ice temperature, even for below 0 °C atmospheric air temperatures, stabilises at 0 °C. A rapid temperature drop recorded by sensor number 1 can be explained by breaking of the ice cover by aerodynamic forces. The thermocouple hot junction was exposed for a certain time to intense psychrometric cooling effects. The temperature of the upper airfoil surface was not affected so much because almost the whole water is collected by the leading edge – the water droplets collection efficiency for that part of the airfoil is almost zero.

Despite that the temperature recordings from sensors T1, T2, T3 and T5 were sensitive to splashing of the inner surface with fuel on the aircraft taxing, the fuel temperature did not affected the temperature of the wing surface during the flight. The thermocouples were reacted to changes of the air flow conditions almost independently of the fuel temperature. It was in agreement with theoretical prediction from [4]. However, because some controversial assumptions and weakness of the inner fluid flow theory these observations needed additional verification.

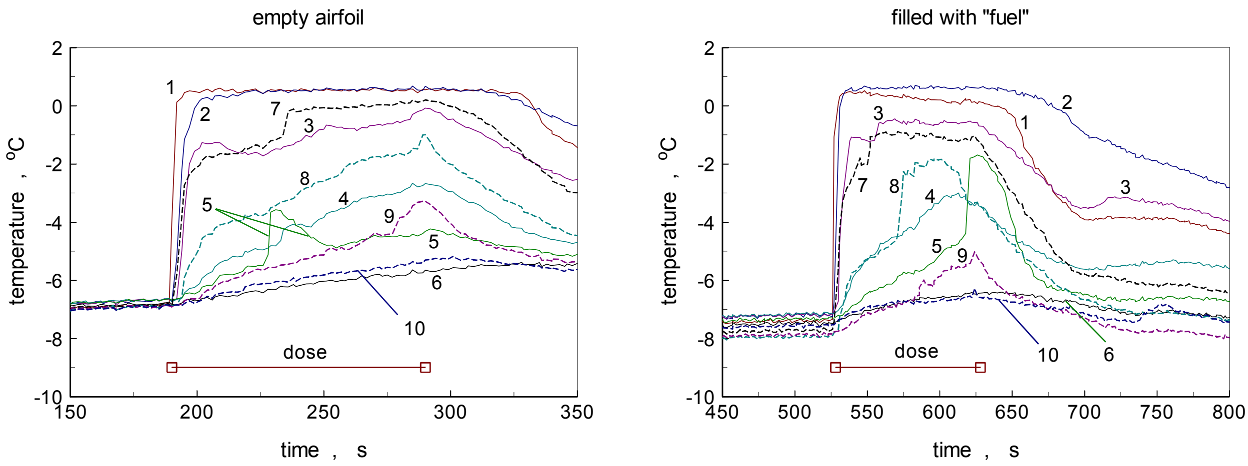
3.2 Results of IRT Investigations of the Model NACA 0012 Airfoil

In the course of the IRT investigation several experiments were performed. They were focused on the issues discussed above. From the huge amount of the collected data only selected results are presented here. Conditions of the appropriate experiments performed on the model NACA 0012 airfoil are listed in Table 1. The airfoil angle of attack, referred to the airflow, was adjusted to 0 deg. The inner fluid presence was studied both in dry and wet flow conditions including the airfoil icing. The fluid modelled the fuel moving inside the inner tanks due to the aircraft motion. The medium, which was an ethanol, has been supplied from a low temperature Lauda RL6CP thermostat.

The results from measurements performed on the airfoil without and with fluid modelling the fuel are compared in Figure 7. Numbers of the curves agree with numbers of thermocouples (see Fig. 5). The icing manifested itself in increasing temperature due to the heat release of supercooled liquid water solidification (crystallisation). The observations agree with predictions based on the Messinger's model of icing [4], [3]. The icing was the most intense on the cutting edge of the airfoil where the water collection efficiency was the biggest. The differences between traces from the points located back from the cutting edge reflect irregularities of the airflow over the object. The comparison of the two cases revealed that the influence of the "fuel" presence is minor. The observation agrees with qualitative prediction based on the extended Messinger's model [4]. This complements results of in flight measurements which have been presented in the previous paragraph. Despite rather intense inner fluid flow the differences were limited mostly to the stationary part before the water spraying and to some slight dissimilarities in the temperature courses after aerosol application (channels 5, 8 and 9).

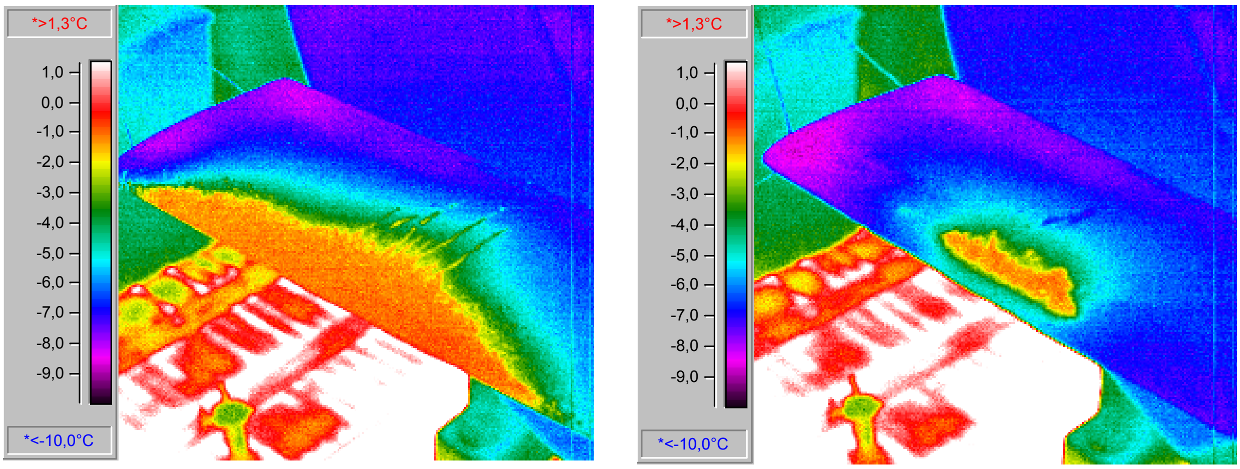
Table 1: Conditions of IRT experiments

IRT parameters				Data acquisition		Case description / Figure No
Air flow speed, $m \cdot s^{-1}$	Air temperature °C	Relative humidity, %	Doses duration, s	Type	Sampling rate (all ch.), Hz	
38.7	-8	99	100	NI4350	0.6	Empty airfoil / 7a
38.7	-8	99	100	NI4350	0.6	Inner –10 °C fluid flow of 16 $kg \cdot s^{-1}$ / 7b
38.6	-10	80	15	SCXI	1000	Empty airfoil



a) b)

Figure 7: Traces from IRT investigations of the model airfoil NACA0012: a – with the empty inner space, b – with the inner space filled with a flowing ethanol which models the fuel.



a) b)

Figure 8: IR images of the iced airfoil (comp. Fig. 5): a – during splashing with a supercooled water aerosol just before turning the dose off, b – about 30 s after turning the 100 s dose off.

In addition to the multichannel temperature data acquisition the experiments were recorded applying a digital video camera and an infrared (IR) camera. Typical results of the IR recordings are depicted in Figure 8. The illustrations shown confirm conclusions from the in-flight and IRT results analysis.

3.3 Comparison Between In-Flight and Icing Wind Tunnel Tests

As it has been shown above the results of experiments of both kinds are in agreement. However, from the consistency of the results one can not conclude that the experiments may be substituted. It is because of certain limitations. In the case of in-flight tests the most important are flight safety limitations. The same, the range of icing situations which can be investigated without endangering the aircraft crew is very narrow [2]. In the case of wind tunnel laboratory investigations the limitations are mostly due to limitation of the apparatus performance in modelling the icing atmosphere and icing conditions. The experiments of both kinds complements each other. Moreover, they complement results of theoretical predictions. In the discussed case such a complex analysis, including theory, in-flight and laboratory tests enabled to confirm results of reasoning based on relatively weak assumptions concerning the heat exchange between the fuel and the airfoil surface in the fuel tank zones [4].

4.0 CONCLUSIONS

The investigations presented here are a part of a wider research programme of the aircraft icing phenomena studies. In this particular case the attention was focussed on developing and testing the technique for transient temperature measurements during experimental investigations. Two types of experiments were considered: in-flight tests and laboratory icing research wind tunnel investigations. Specific experimental conditions: low temperature, high humidity and liquid water presence in a high speed airflow caused certain problems to overcome. In the case of test flights the additional problems arose due to applying a regular aircraft, not designed for such experiments.

The measurements performed created a good opportunity not only for testing and optimising the developed technique but for gathering very interesting experimental data as well. The analysis of the obtained results contributes to better understanding of aircraft icing phenomena.

During investigations some interesting phenomena have been revealed and analysed. Significant results from the tests are that the effects of supercooled fuel are minor if the fuel temperature is only slightly below the water freezing temperature (comp. [4]). Despite the fact that the discussion has been limited mostly to qualitative aspects of the observed phenomena the results have been used also as a base for calculation of some specific parameters and characteristics. They are being employed in analytical and numerical modelling of icing phenomena.

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