Numerical simulation and analysis of pressure distribution and airflow speed around an airborne cloud microphysics measurements instrument

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Abstract: *Clouds have an important impact on Earth’s energetic balance, so measuring accurately the microphysical parameters and using them in research has become one important step in atmospheric studies. Regarding the fact that light scattering probes convert the flow rate to concentration, any wrong assumption or measurement of the flow rate can lead to incorrect results. Applying numerical simulation to an airborne cloud microphysics measurements instrument can provide information that can be measured in any point of the sampling volume, and further used in determination of microphysics parameters, providing more accurate data. Taking this into consideration, in this paper are presented the results of numerical simulation applied to Cloud Aerosol and Precipitation Spectrometer and the comparison with results reported in literature.*

Key Words: *numerical simulation, pressure distribution, airflow speed, cloud microphysics, airborne measurements*

1. INTRODUCTION

The changes in the Earth’s atmosphere have become a topic addressed by many researchers, whether is about air pollution, weather forecasts or the determination of long-term climate change. Atmospheric measurements, especially airborne measurements, have been a source of information in order to study atmospheric changes. One important aspect of the airborne measurements is to determine the parameters of cloud microphysics. Thus, with the development of new equipment dedicated to this type of measurements, their limitations were also discovered, not only the ones about the integration on the aircraft but also for the *in-situ* acquisition process.

Clouds have a considerable impact on the radiative balance, climate and weather. They represent a key element which contributes to mean temperature adjustment. In this manner, clouds can contribute both to the cooling process because they reflect a certain amount of radiation from the Sun, but they also contribute to warming process due to the effect of greenhouse gases, but also due to the fact that they cause the diffusion of solar radiation on the

Earth's surface [1]. Considering this aspect, any change in the cloud's surface or location can lead to climate changes, other than the expected ones caused by greenhouse gases, anthropogenic aerosols or other factor associated with global wide changes.

2. AIRBORNE INSTRUMENT FOR CLOUD MEASUREMENTS

In-situ airborne instruments for cloud microphysics measurements are usually electro-optical spectrometers using measuring techniques developed by Knollenberg [2]. In order to have an overview of cloud properties and to understand the impact on the environment, there were designed airborne instruments which can measure directly the size, shape, optical properties and the mass of cloud particles [3].

There are many instruments which use light scattering for the detection process: FSSP-100 (Forward Scattering Spectrometer Probe Model 100), CAS (Cloud and Aerosol Spectrometer), CAS-DPOL (Cloud and Aerosol Spectrometer with Depolarization), SID1 and SID2 (Small Ice Detector) [3]. The operating principle of the instruments listed above is based on the concept that the intensity of scattered light is directly proportional to the particle size and can be deduced theoretically if the shape, particle refractive index and incident light wavelength are known.

CAPS (Cloud, Aerosol and Precipitation Spectrometer) is an airborne equipment designed to study the atmosphere: aerosols and particle properties in clouds [4]. It consists of two components: CAS (cloud and aerosol spectrometer) and CIP (cloud imaging probe). In addition, the instrument is also equipped with a liquid water content sensor and a Pitot tube for determining the air speed, a temperature and relative humidity sensor [4].

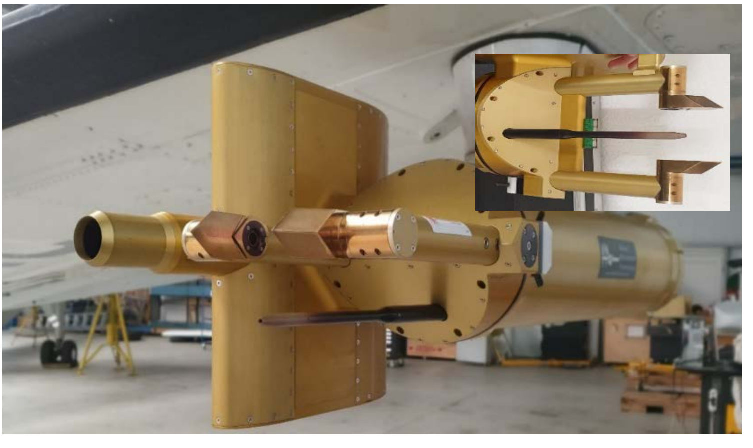

Fig. 1 – DMT Cloud Aerosol and Precipitation Spectrometer mounted on INCAS's aircraft

The operating principle of the CAS instrument is based on the light scattering on individual particles, thus obtaining their diameter, assuming that the particle is considered spherical.

In addition, since the refractive index of the particle and the wavelength of the incident light are known, the Mie scattering theory can be applied [3]. Also, during the flights, images collected through the CIP instrument and concentration of particles from clouds and their size can be measured.

In addition, the values of thermodynamic parameters such as: dynamic pressure, static, humidity and temperature are also provided.

3. FLOW-INDUCED ERRORS IN AIRBORNE MEASUREMENTS

From the beginning of atmospheric measurements with airborne probes, a single goal was pursued: to measure the atmosphere's parameters accurately.

Thus, by successive attempts it was desired to determine the factors that can lead to errors and their correction methods.

After several studies, it was concluded that these factors that lead to the deflection of parameters can be classified in several types: factors that depend on the structure of the aircraft and the positioning of the sensors on the aircraft, those related to the environment in which the measurements are performed and factors regarding the measurement methods.

Airborne instruments such as optical spectrometers and probes provide detailed information on the horizontal and vertical distribution of aerosols and cloud properties. Thus, since the instruments are located outside the aircraft, errors caused by fluid flow, in this case air, can have direct effects on the concentration of particles detected and can cause deformation and/or break of droplets during the measurement process [5].

Because the airflow is converted to a concentration using the air flow rate, the errors associated affect directly the calculation of concentrations. For example, too low air flow rates will lead to higher concentrations of particles.

Because the aircraft can influence the air flow, particle distortion, changes in temperature, pressure and density measurements can occur.

For example, a higher density will result in a higher concentration of aerosol particles if they are small enough to follow the path of the air flow. In addition, larger particles can be deformed or shattered during flights at high speeds due to aerodynamic forces acting on the surface of the droplets [5].

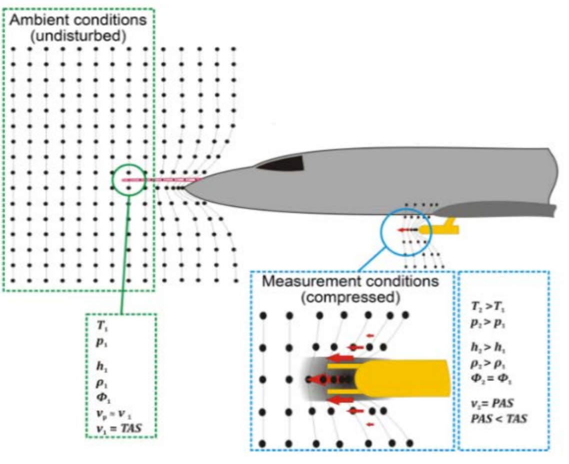

Fig. 2 – Compressibility effect caused by aircraft's geometry and by underwing probes [6]

The design represents the intermediate stage in numerical simulations. The CAPS instrument and a wing section were modelled three-dimensional in order to study the impact of air circulation on its profile.

Thus, the design was realized in order to perform the simulations with the initial conditions as close as possible to the atmospheric conditions and in this manner the results will reflect the phenomena that take place during atmospheric flights.

From a constructive point of view, all components of the instrument have been designed so that the pressure distribution and air flow can be calculated as accurately as possible.

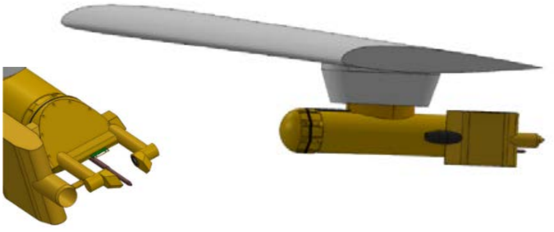

Fig. 3 – 3D model of Cloud Aerosol and Precipitation Spectrometer

4. NUMERICAL SIMULATION AND CONCLUSIONS

For the numerical simulations section, several variants were chosen for the input parameters, these representing scenarios in which the flight through the cloud and outside it is simulated. Thus, two pressure values were chosen: 90000 Pa, 65000 Pa being suitable for three altitude levels. Temperatures were also chosen according to pressure and altitude: 10°C, 0°C, -10°C. In addition to these parameters, two speeds were also introduced: 140 m/s being the maximum cruising speed of the aircraft on which the instrument is mounted and 80 m/s travel speed during research flights. The humidity selected in these simulations was 80% for flight simulation outside the cloud and 100%, corresponding humidity inside the clouds [7].

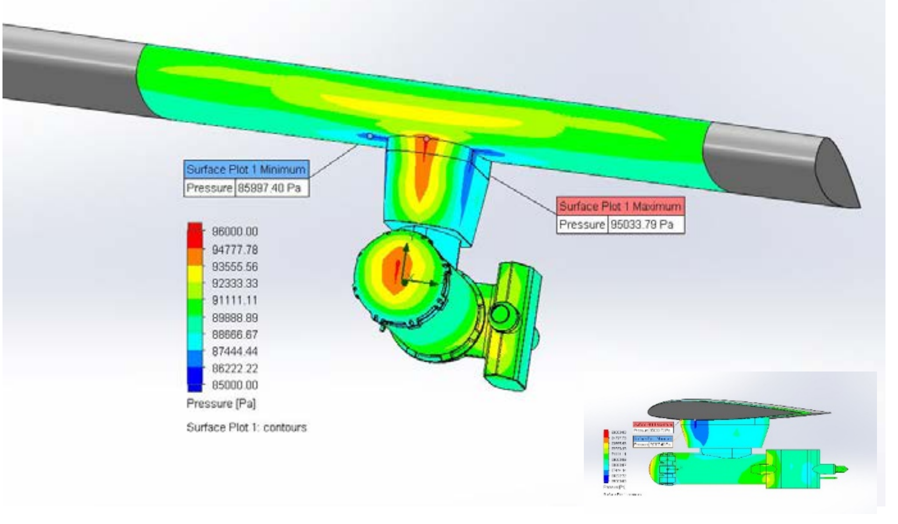

Fig. 4 – Pressure distribution on CAPS instrument (input: 90000 Pa, 0°C, 80 m/s, relative humidity 100%, turbulent flow)

Figure 4 shows the pressure distribution for the CAPS instrument mounted underwing of the Beechcraft King Air C90GTx aircraft. It can be seen that under the conditions of the chosen input data, the area where the maximum pressure value is found is at the top of the instrument canister and the area where the pressure is minimal is the area where the instrument support is attached to the wing.

It can also be observed that the pressure is evenly distributed on the top of the canister, being a gradual decrease. This happen because the airflow is decelerated on impact with cannister's tip. Thus, given the value of the input pressure as input parameter: 90000 Pa, it can be observed that the sampling area of the instrument, the pressure is higher, resulting in the detection of a lower concentration of particles.

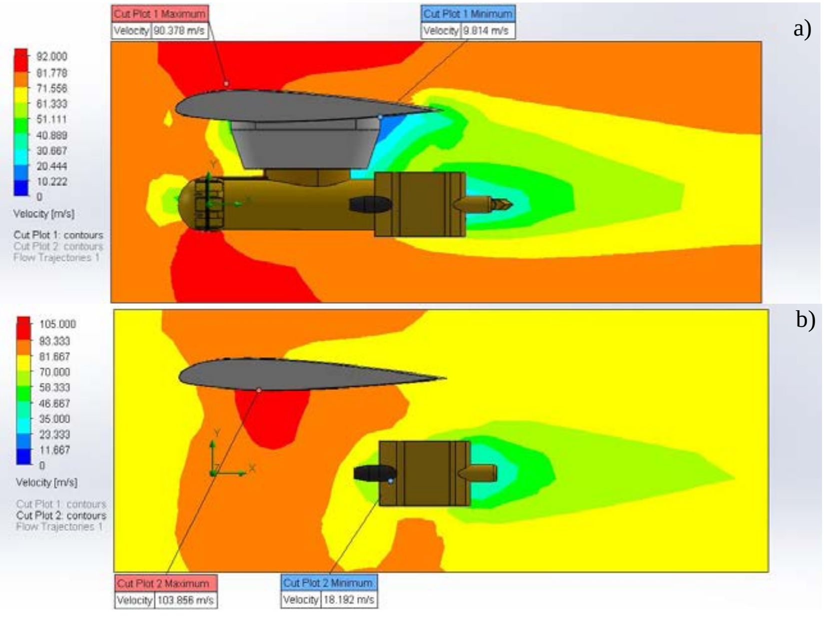

Fig. 5 – Airflow distribution on canister's (a) and CAS's (b) longitudinal sections (input: 90000 Pa, 0°C, 80 m/s, relative humidity 100%, turbulent flow)

Figure 5 illustrates the distribution of airflow velocities on the canister and the CAS instrument. It can be observed that although the speed selected as input parameter was 80m/s, there is an area where the speed exceeds 90m/s, but also there is an area where the speed is considerably reduced.

Thus, if the speed measured by the Pitot tube is used, the concentration will be different. In consequence, because the velocity is inversely proportional to the concentration in the computational, from a lower velocity in the sampling volume will result a higher particle concentration.

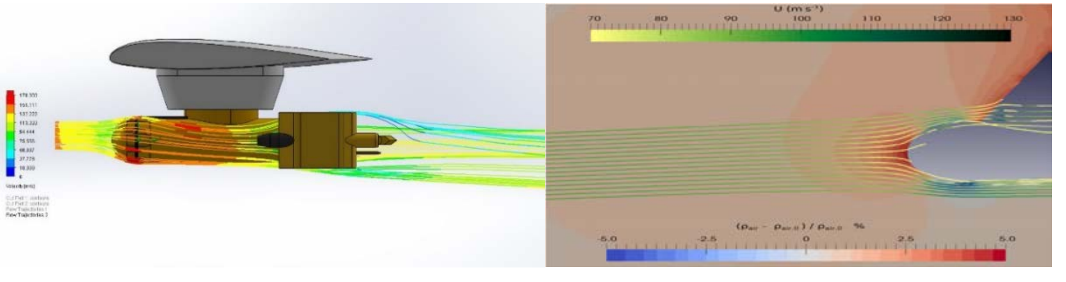

Fig. 6 – Particle trajectories obtained in numerical simulation (left) and from literature (right) [5]

Figure 6 highlights the air flow trajectories along the instrument canister. As specified in the previous section, in the sampling volume the air flow rate is much lower than the particle travel speed.

Thus, the speed calculated by means of the pressures measured with the Pitot tube will not be equal to the speed in the sampling volume.

By comparing the results obtained from numerical simulations with those obtained in the literature (Figure 6 – right) [5], it can be observed that the speed has the same flow character on the surface of the instrument even if the 3D model of the instrument is more detailed.

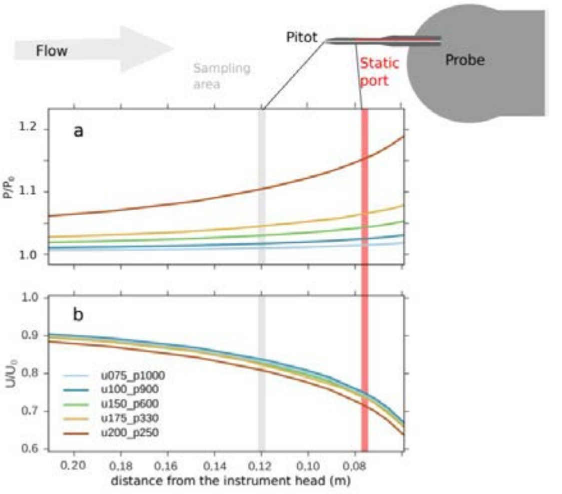

Fig. 7 – Graphical representation of static pressure and velocity normalized by free stream values calculated from the instrument head mounted on Falcon aircraft [5]

Figure 7 illustrates the simulations performed on the simplified three-dimensional model of the canister and the wing of the Falcon aircraft, highlighting the degrees of compression or decompression (Figure 7 a) and the degree of acceleration or deceleration of the air around the simplified model (Figure 7 b) [5].

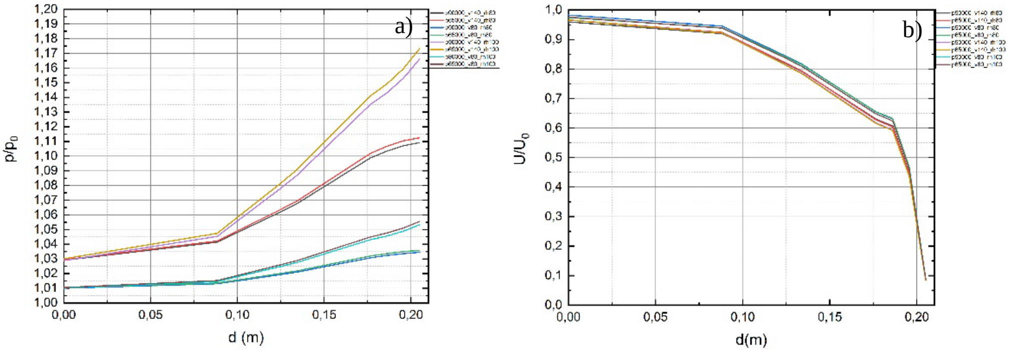

Fig. 8 – Normalized values of static pressure and velocity by free stream conditions as a function of the distance from the instrument's head

Figure 8 a) illustrates the increasing trend of the ratio between the measured pressure and the undisturbed flow pressure as a function of the distance from the tip of the canister. Thus, compared to Figure 7, the same trend can be observed, point 0 being corresponding to the area where the air is not disturbed by the interaction with the canister.

Figure 8 b) highlights the effect of air compressibility on the ratio between the measured speed and the value introduced as an input parameter.

If in the case of an incompressible flow the U/U_0 ratio is independent of the air flow speed, in the case of the compressible flow, the value of the ratio changes with the change of the U_0 velocity value [5].

The same trend is highlighted in Figure 7, where for different values of pressure and speed, the ratio between the speed determined in the simulation and the speed selected as input parameter decreases depending on the distance from the top of the canister.

Thus, the determination of dynamic parameters: speed and pressure at any point in the computational field, offers the possibility to improve data quality after the post-processing process, because currently, for the calculation of cloud microphysics parameters, dynamic parameters determined by external measurements, for example: Pitot tube, are used. Thus, by analyzing the air flow inside the sampling volume, differences in pressure and velocity values given by the phenomenon of air compression around the instrument were determined. The exact determination of these parameters on a three-dimensional model and in various simulation conditions, offers the possibility to determine and compare the parameters of cloud microphysics in different flight scenarios.

The comparison with the results obtained in the literature on a simplified model of the canister [5], offers the certainty that both the three-dimensional model and the simulations were performed correctly and reflects that the results obtained can be used in post-processing data from research flights.

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