Droplet Size Distribution and Liquid Water Content Monitoring in Icing Conditions with the ICEMET Sensor

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Abstract— **Field measurement results from a novel optical cloud droplet monitoring sensor designed for icing conditions monitoring are presented. The sensor has been demonstrated at two sites in northern Finland; first at Global Atmosphere Watch Station in Pallas together with a reference icing sensor and secondly mounted on a wind turbine nacelle in eastern Finland in 2017. Test runs in an icing wind tunnel have been made where more severe icing conditions were generated.**

The ICEMET sensor measurement principle is based on capturing the images of cloud droplets and ice particles. Droplet properties, such as droplet size distribution (DSD) and median volume diameter (MVD), are acquired by means of image analysis of the captured images. The images and the calculated features (size, location, shape descriptors) of all the found particles are saved in a database.

A volume of 0.5 cm3 is imaged in a single frame. The liquid water content (LWC) is calculated based on this known sample volume in combination with the droplet data acquired from the image analysis of the found and filtered particles (droplets only).

The sensor is typically freely rotating – it aligns itself against the wind by a wing on the backside. In the rotating configuration, the maximum sampling rate is 3 cm^3/s. The movement of the particles inside sample volume is frozen in the images by a nanosecond scale light flash, making the sample volume independent of the wind speed. The maximum wind speed tested in a wind tunnel with the sensor is 40 m/s. The cloud droplet sizes from 5 to 200 microns are measured by the ICEMET sensor.

In this paper LWC and MVD measurement results from the field tests and the wind tunnel tests with the sensor are presented and discussed.

The webpages for the sensor can be found at https://www.oulu.fi/icemet.

Keywords— ***LWC, MVD, Icing Measurement, Cloud Droplets, Image analysis.***

I. INTRODUCTION

Instruments for the measurement of both droplet size distributions (DSD) and liquid water content (LWC) have been commercially available for years, but still there is no standardized way of measuring these parameters needed for the modelling of icing [1]. Instruments capable of measuring these both parameters in icing field conditions are typically optical instruments based either on light scattering from the droplet and particles or shadow imaging with digital cameras [2]. In icing modelling applications, the interest is to know the median volume diameter (MVD), a calculated droplet diameter which divides the water content of the total droplet distribution in half [3].

We have developed an optical shadow imaging instrument and system for the in situ measurement of DSD and LWC during icing conditions [4]. In this paper, we present the background and user interface of the ICEMET-system, and go through results from both laboratory and field environment tests as well as discuss possible future actions.

II. ICEMET SENSOR AND SYSTEM

The ICEMET-system consists of an ICEMET-sensor, Fig. 1, and separate computer, either local or remote, where the image data from the sensor is sent for analysis. Additional minimum parameters needed for the evaluation of the icing condition and rate are the temperature and the wind speed who are not measured by the ICEMET-sensor itself.

A. Sensor specifications

The ICEMET-sensor is a freely rotating construction, Fig. 1. It aligns itself against the wind by the wing on the back of the sensor. The sensor is mounted from the bottom and the height is 53 cm without a mount. The weight of the sensor is 8 kg and the maximum measurement speed is 3cm^3/s.

The anti-icing of the sensor is implemented with heating elements with total maximum power of 500 W. The anti-icing is controlled by an adjustable digital thermostat together with overheating protection thermostats. Droplet and particle sizes are measured from 5 to 200 microns, also larger particles up to approx. 1 mm size range can be measured.

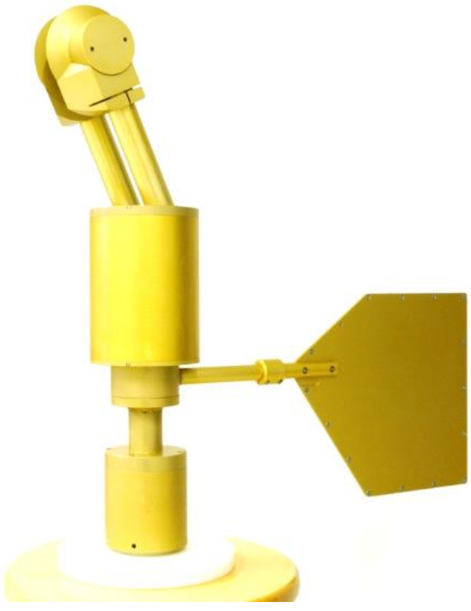


Fig. 1 The ICEMET-sensor unmounted.

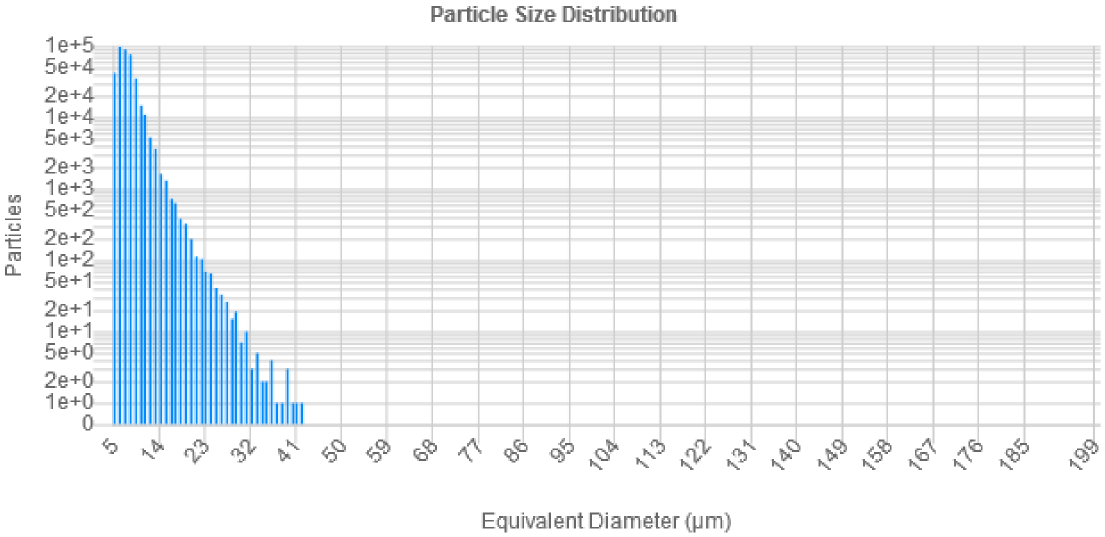


Fig. 2 The DSD histogram from the web interface, first four hours of 17th February measurement from Fig. 3 shown.

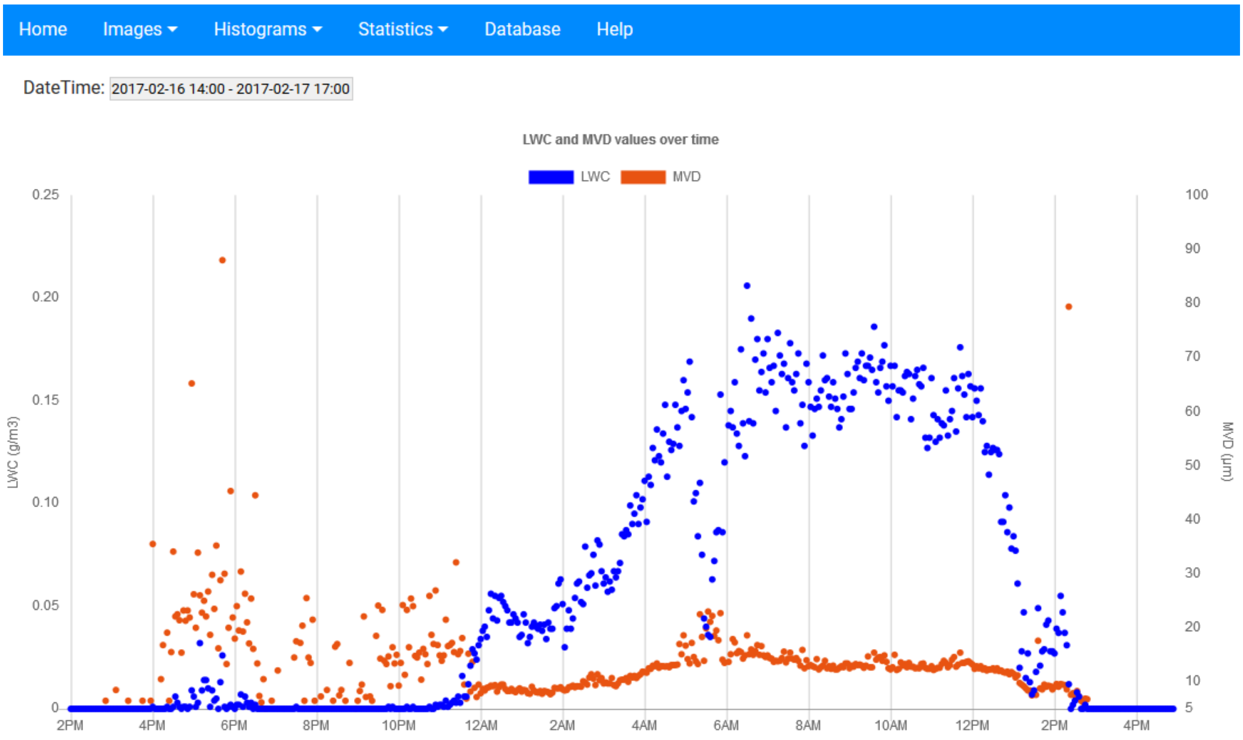
B. *Data processing*

The image processing and particle analysis software ICEMET Server was developed for processing of the image data from the ICEMET sensor. The software has been designed with performance and usability in mind using modern C++ and OpenCV image processing libraries. The most expensive computations are performed on GPU with OpenCL GPGPU framework. Data processing has been split into various logical steps which are executed in multiple simultaneously running threads.

Features such as the equivalent diameter, the Heywood circularity factor, the dynamic range and spatial coordinates are extracted from reconstructed particles. From the measured droplet diameters, the LWC and MVD values are calculated over time as the measurement volume and number of frames are known. Other shape features are used to distinguish droplets from unwanted objects such as ice crystals.

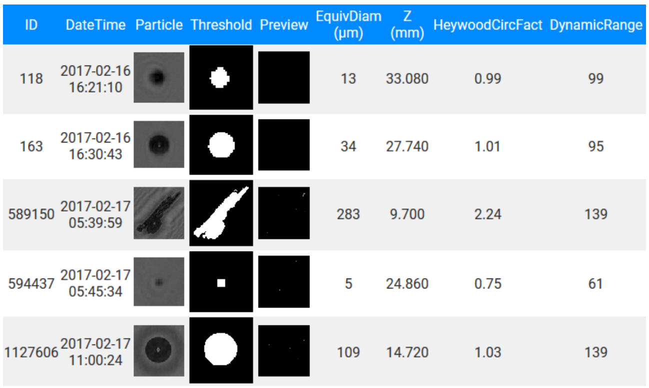
C. *User interface*

ICEMET Server writes all its particle data and statistics to SQL database. Focused particle images are also saved. The data can be accessed using any SQL client or ICEMET web interface software. The web interface provides an easy way to view size distributions Fig. 2, LWC and MVD statistics over time Fig. 3, and particle images with measured properties Fig. 4.



DateTime: 2017-02-16 14:00 - 2017-02-17 17:00

Fig. 3 LWC and MVD statistics display on the web interface. Values shown measured at Kivivaara-Peuravaara starting at 14.00 UTC+0 on 16th and ending at 17.00 UTC+0 on 17th February 2017. The outside temperature varied between -0.5 and -4 °C during this period.



ID	DateTime	Particle	Threshold	Preview	EquivDiam (µm)	Z (mm)	HeywoodCircFact	DynamicRange
118	2017-02-16 16:21:10				13	33.080	0.99	99
163	2017-02-16 16:30:43				34	27.740	1.01	95
589150	2017-02-17 05:39:59				283	9.700	2.24	139
594437	2017-02-17 05:45:34				5	24.860	0.75	61
1127606	2017-02-17 11:00:24				109	14.720	1.03	139

Fig. 4 Measured properties of each particle in the web interface

III. RESULTS FROM FIELD TESTS AND ICING TUNNEL TESTS

The tests during the ICEMET-project were done first with a proof-of-concept (PoC) sensor, a modified version of the SAKU II sensor, which was originally designed for ground plane hydrometeor measurements [5]. With the experience gained from the Pallas site, a totally new design for the cloud droplet and ice crystal measurement was made. Anti-icing heating and mechanics were designed to operate in harsh icing conditions in high wind speeds.

A. PoC-sensor tests on Pallas Global Atmosphere Watch station

The very first PoC testing of the DSD and LWC measurement by shadow imaging technique was done at Pallas GAW Station starting at the beginning of 2016, see Fig. 5. Two different icing detection references were installed; a commercial icing detector (Labkotec LID-3300IP Ice Detector) and a 30 mm diameter, 1 m long steel rod as an icing object monitored from one side with the on-site surveillance camera. The rod was fitted with a 90 W/m power heating cable controlled by a GSM power socket to allow melting the ice from the rod on demand.

The results in Fig. 6 compare the signals from the reference icing detector, and the LWC and MVD measurements from the PoC sensor. In Fig 6, the value 100 from the LID-3300IP ice signal corresponds to the maximum ice signal value which corresponds to a situation where no ice is detected. The factory pre-set alarm level for ice detected alarm is 60, meaning that when a level of 60 or below is measured, an icing alarm is given and the sensor starts an automatic reset function by warming the sensor to remove the accumulated ice. This is the reason in the Fig 6. where multiple successive signal drops during a single icing event can be seen. The detected rises in LWC-values during freezing temperatures from the PoC-sensor and the drops in the ice signal from the LID-3300IP sensor correlated very well during the whole test period. The small rises in the LWC-level measured with the PoC-sensor were observed typically from 5 to 60 minutes before the change on the ice signal of the LID-3300IP. The timing difference was estimated to depend on the intensity of the icing conditions.

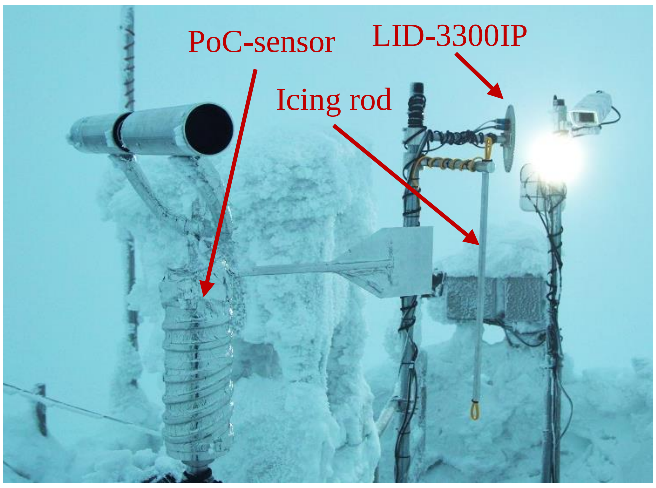


Fig. 5 The PoC-setup on Pallas GAW station

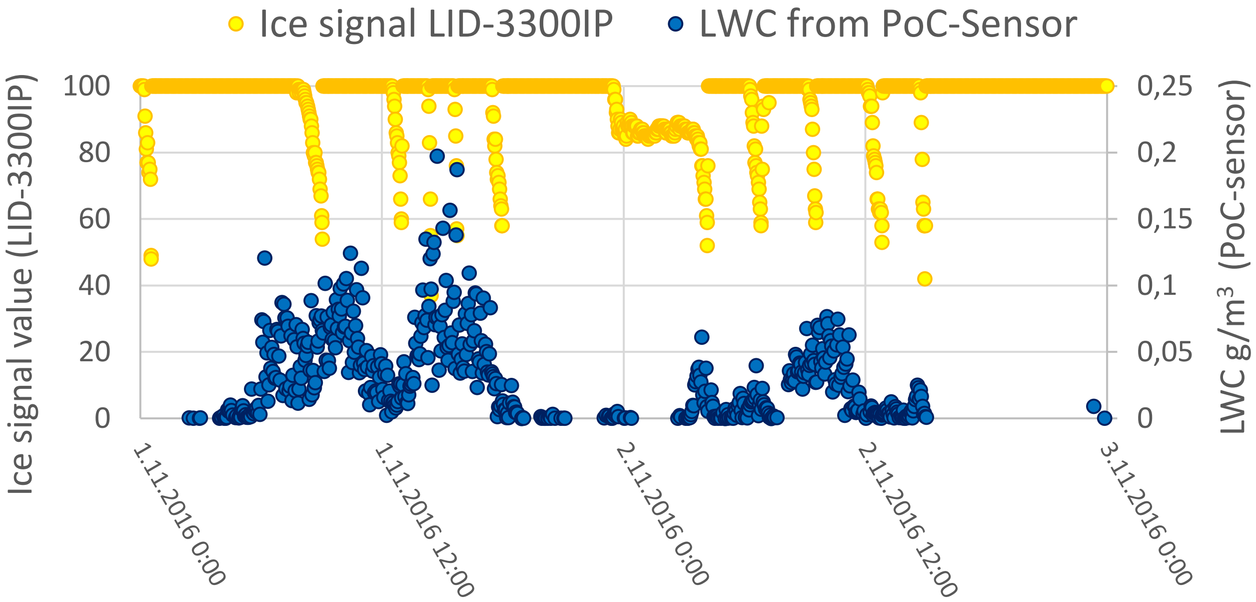


Fig. 6 The ice signal from LID-3300IP and non-zero LWC values measured with the PoC-sensor on Pallas GAW-station. Temperature varied between -1 and -4.5 °C during these icing events.

Fig. 7 A thermal camera image of the sensor inside an icing wind tunnel while anti-icing heating is active.

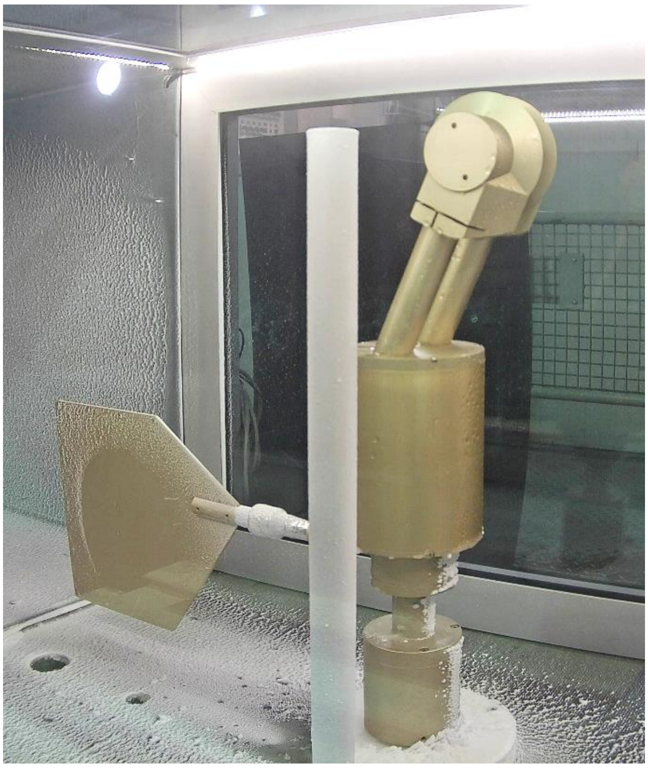


Fig. 8 Sensor anti-icing testing, temperature -15°C, wind speed 10 m/s, measured LWC 0.3 g/m^3, photo taken right after a 10 minute run. Upper part fully ice-free, the lower part and the tail wing have gathered some ice as expected.

B. Icing wind tunnel

After the PoC-tests at Pallas, the ICEMET-sensor prototype was build. The ICEMET-sensor prototype was tested in an icing wind tunnel in the autumn of 2016 at VTT Espoo, Finland. Tests were made for evaluating the anti-icing properties of the sensor in varying icing conditions. A thermal camera image from the wind tunnel shows the distribution of heating power on the sensor surface, the upper parts where the droplets are measured have a higher heating power compared with the lower part of the sensor Fig. 7. The lower part where ice was formed, in Fig. 8, is heated by the heating element in the support arm which is missing in the tunnel, but seen in Fig. 9. Based on the tests made in the icing wind tunnel tests, it was shown that the ICEMET-sensor could be used even in harsh icing conditions without ice accumulation on the parts sensitive to the droplet measurement. Most intense icing conditions tested were at the temperature -15°C, wind speed 10 m/s and LWC 0.3 g/m^3. The result after a ten-minute run shown in Fig. 8.

C. Wind turbine measurements

The first field tests with the ICEMET-sensor in icing climate conditions were done on a wind turbine nacelle of a modern wind turbine in Kivivaara-Peuravaara wind park. The ICEMET-system test configuration consisted of the ICEMET-sensor, a temperature and humidity sensor (Vaisala HMS112), 4G mobile router with an external antenna for data transfer and a control box including power supplies and a windows pc for controlling the measurements and buffering the data if the mobile network connection would be lost.

The sensor was mounted on the top of a nacelle, on the radiator support structure, so that the sensor was approx. 1 m outside the edge of the nacelle top. The nacelle installation and images before and during an icing event are shown in Fig. 9. Two photos shown in the Fig. 9 are taken before and during the measured icing event in Fig. 3.

A benefit of using an imaging system to determine the DSD and LWC values is that it is possible to analyse the shapes of the measured particles to discriminate between cloud droplets, ice crystals and other particles, such as dust if their shapes or optical properties differ. As seen in Fig. 4 on the third row, an ice particle has been measured. This needle type of ice crystal can be effectively filtered out from the results solely based on the non-spherical shape, described here as the Heywood Circularity Factor, “HeywoodCircFact” as the column headline in the Fig. 4. The Heywood Circularity Factor has a value of 1 for spherical shapes and larger or smaller for other shapes. In order to determine realistic LWC values in mixed clouds, it must be possible to identify between the cloud droplets and ice crystals.

During the field test on the wind turbine lasting over 1 year period, the only malfunctions observed were overheating alarms with the anti-icing active at temperatures above 0°C. The temperature controller was updated after these alarms, and no over temperature alarms were recorded after the update.

As an example of the other particles than cloud droplets that were measured during the field campaign by the ICEMET-system, an ice crystal is shown in the Fig. 10. The diameter of this crystal is larger than the set limit of 200 microns for cloud droplets.

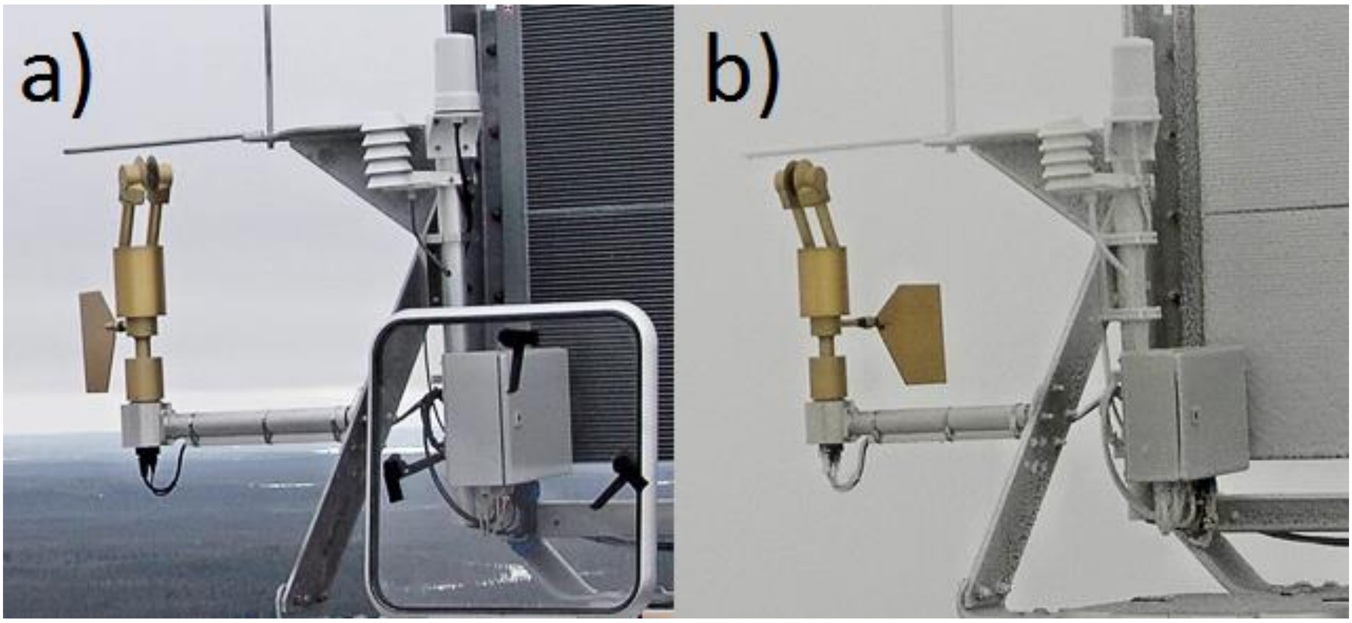


Fig. 9 The ICEMET-sensor installed on a wind turbine nacelle. Photo a) taken on 16.2.2017 at 14.00 UTC+00 and photo b) on 17.2.2017 at 10.00 UTC+00 during an icing event, see Fig. 3 for the measured conditions.

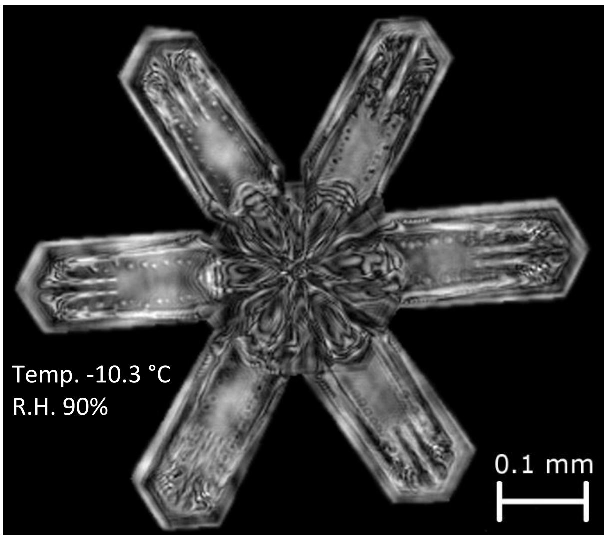


Fig. 10 An ice crystal imaged in Kivivaara-Peuravaara on 11.2.2017 at 07.45 UTC +00. The background has been removed.

IV. CONCLUSIONS

Two instruments capable of measuring cloud droplet sizes in icing conditions were presented. The PoC-sensor proved the measurement principle to be suited for icing condition monitoring, and based on the experience on Pallas, the ICEMET-sensor was developed and tested both in a icing wind tunnel and in natural icing cold climate field conditions in Kivivaara-Peuravaara Wind Park. The ICEMET-sensor was found to have adequate anti-icing properties both in the icing wind tunnel tests and in natural cold climate conditions. No concerning faults with the first sensor prototype during the field test were observed.

The benefit of using an image based instrument is that in data analysis it is possible to distinguish between droplets and ice particles (snowflakes) by shape analysis, thus making it possible to make more realistic evaluations on the LWC values and ice build-up on structures.

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REFERENCES

[1] Krenn, A., et al. "Available technologies for wind energy in cold climates." *International Energy Agency Wind Task 19*, 2016.

[2] Black, David Lee, Mardson Queiroz McQuay, and Michel P. Bonin. "Laser-based techniques for particle-size measurement: a review of sizing methods and their industrial applications." *Progress in energy and combustion science*, vol. 22, pp 267–306, 1996.

[3] Finstad, Karen J., Edward P. Lozowski, and Lasse Makkonen. "On the median volume diameter approximation for droplet collision efficiency." *Journal of the atmospheric sciences,* vol. 45, pp. 4008-4012, 1988.

[4] Kaikkonen, V., Mäkynen, A., Arstila T., Kananen, T. 2018,”Freezing of structures caused by cloud droplets,” WO patent application 2018220268, retrieved from Espacenet, viewed 20 April 2019.

[5] Kaikkonen, V.A., Makynen, A. J., “A hologram imager instrument for ground plane measurements of hydrometeors,” *Proceedings of the 5th IMEKO TC19 Symposium on Environmental Instrumentation and Measurements*, pp. 113–117, 2014.