RESPONSE TO ANONYMOUS REVIEWER #1
TO MANUSCRIPT tc-2020-56-RC1

Title: Liquid-water content and dielectric properties of wet snow using microwave heating

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We thank the anonymous referee #1 for his constructive comments and suggestions. All line numbers correspond to the discussion paper and all added texts to the discussion paper are marked red.

ANONYMOUS REVIEWER #1

The authors developed an experimental setup to investigate the liquid water and dielec- tric properties of snow and reported on the cold room experiment results using their experimental setup. In this manuscript, they classified the heating process of the snow into three phases: Dry snow, Wet snow, and Water percolation based on the charac- teristics of electric properties. They also showed the potential of micro-CT analyses for wet snow science. I think the manuscript is designed well and its scientific content is enough for publication in The Cryosphere. Before acceptance, several points, which are shown in comments, should be considered.

Comment #1: L33: Please add several concrete explanations how to help your result for the interpretation of the snow melt run-off of spring snow.

> ***[ANSWER]*** *We changed the sentence to:*
>
> L33: "These findings are pertinent to the interpretation of the snow melt run-off of spring snow as the restrained amount of water in the snowpack can be extracted and the expected amount of water run-off into the rivers can be calculated."

Comment #2: L76 and L 82: The authors used the sentences "water retention curve of snow from right(left) side", but it is hard to image what is right(left) side. Please add several detailed explanations for right(left) side.

[ANSWER] *We changed both sentences to:*

L76: "… water retention curve of snow (Yamaguchi et al., 2010) from the wetting curve"

L82: "… water retention curve of snow (Yamaguchi et al., 2010) is approached from the dry curve."

Comment #3: L120: "surface-to-volume ratio" means "Specific surface area"?

[ANSWER] *Yes, we changed it accordingly.*

Although the sentence of micro-CT experiment was named "2.1 Topography experiments", the first sentence to show the measurement experiment of dielectric properties of snow during heating is not named. I recommend to name the fast sentence likely the sentence of micro-CT part.

[ANSWER] *We changed the sentence in L128 to:*

L128: "… and a photo of the high voltage part of experimental setup and the micro-CT sample holder is shown in Fig. 2."

And change Fig. 2 to:

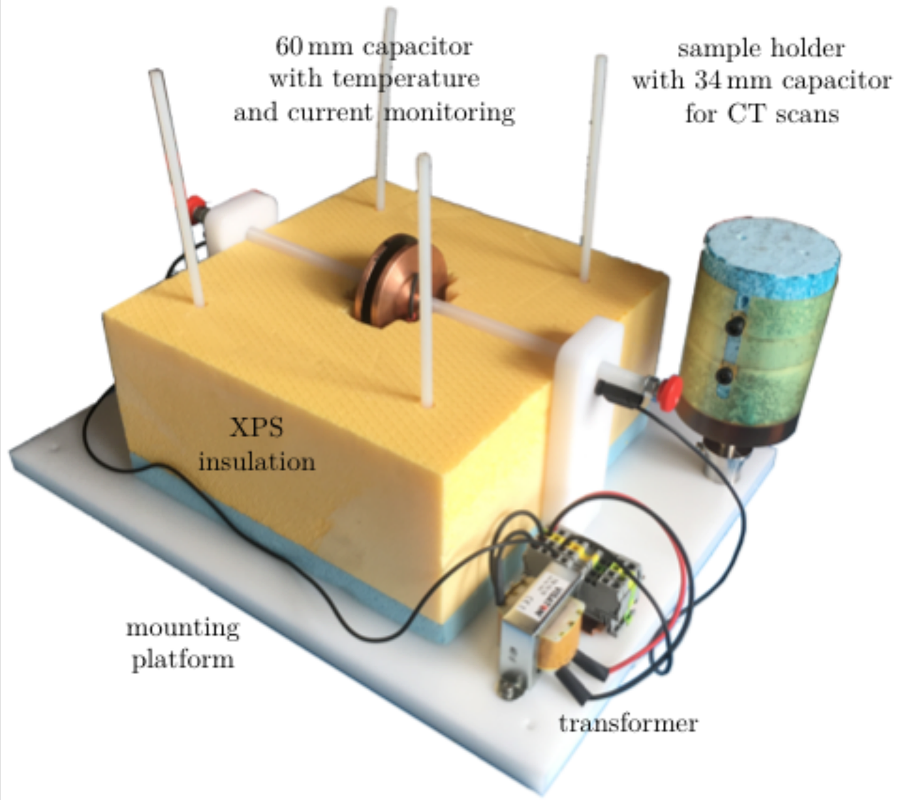

Figure 2: An illustration of the inner part of the box is shown. It illustrates the high voltage parts with the 60 mm capacitor. Additionally, the micro-CT sample holder with the 34 mm capacitor is shown.

Comment #4: L165: How to estimate the uncertainties of measurements? Please add more detail explanations.

[ANSWER] *The uncertainties of measurement are given by the measurement equipment and its measurement channel configuration. The current and voltage are measured with the high-speed channel of the Red Pitaya STEM 125-14, but with different channel configurations. The temperature is measured with an NTC attached to a linearization circuit (page 1076 of Tietze, Schenk, Gamm: Halbleiter-Schaltungstechnik 14.Auflage, ISBN:978-3-642-31025-6) with integrated low pass filter and then measured via low speed adc channel on Red Pitaya STEM 125-14. The other parameters are the calculated form these measurement values.*

Detailed information:

Measurement error voltage:

Diff probe 100-fold attenuation (manufacturer and type unknown)

DC Offset at HV is ±5 mV

(https://redpitaya.readthedocs.io/en/latest/developerGuide/125-14/fastIO.html)

With 100-fold attenuation the result is: ±500 mV

Measurement error current:

±0.5 mV at LV; measured resistor is 10Ω

$\Delta I = \Delta V \cdot R = \pm 0.5\ mV \cdot 10\ \Omega = \pm 0.05\ mA$

Measurement error power:

$\Delta P = \Delta U \cdot \Delta I = \pm 500\ mV \cdot 0.05\ mA = \pm 25\ mW$

Phase accuracy:

Depending on measuring frequency and signal frequency

Measuring frequency: 125000000 Hz / 64=1'953'125 Hz

Signal frequency: 18000 Hz

Samples pro 360° = f_{sample} / f_{signal} = 1953125 Hz / 18000 Hz = 108.507

$\Delta\varphi = \pm 0.5$ Samples = $0.5 \cdot 360° / 108.507 = 1.659°$

Measurement error temperature:

The uncertainty of ±0.05 °C of the temperature sensor was measured in ice water.

Measurement error density:

The uncertainty of the scales was around 0.7 gr.

$\Delta\rho = 0.7\ gr / (\pi \cdot r^2 \cdot h) = 0.7\ gr / (\pi \cdot (30\ mm)^2 \cdot 13\ mm) \approx \pm 20\ kg\ m^{-3}$

We added following sentences to L165:

L165: "The uncertainties of the temperature T(t) (measured in ice water), current I_{RMS}(t), voltage U_{RMS}(t), phase shift φ (t), total power consumed P_{RMS}(t), and mass of the snow sample measured by weighting are: ±0.01 °C, ±0.05 mA, ±0.5 V, ±1.66 degrees, ±0.025 W and ±0.001 kg. The uncertainties of measurement are given by the measurement equipment and its measurement channel configuration. The current and voltage are measured with the high-speed channel of the Red Pitaya STEM 125-14, but with different channel configurations. The temperature is measured with an NTC attached to a linearization circuit with integrated low pass filter and then measured via low speed adc channel on Red Pitaya STEM 125-14. Further uncertainty calculations are based on these uncertainties (see Appendix). "

Comment #5: L198 and L201: η should be heating efficiency, please clearly indicate what is η in the text.

***[ANSWER]** We changed the sentence:*

L198: "The heating efficiency η is an important factor to evaluate the heating process and is the fraction of energy that is absorbed by the sample."

Comment #6: L 224-L226: The authors say that Table 1 shows that "The higher the snow density and the water content in snow was, the stronger the measured electrical properties were affected. But I can't agree to their argument because Table 1 does not show any information of water contents. To clear the evidence of their argument, please add the information of water content in Table 1 or add several explanations in the text how to get the information of water content from the information of the current version of Table 1.

***[ANSWER]** We changed the sentence:*

L224: "The measured electrical properties between the two copper-plates were strongly influenced by the temperature and density of the snow sample. The higher the snow density in the snow was …"

Comment #7: L229-L230: Although text specifies the range of temperature from -1 to 0 °C, the temperature range in Fig. 3 is from -0.4 to 0 °C. The range description should be unified between text and figure.

***[ANSWER]** We changed it accordingly:*

L229: "… increasing from -0.3 °C up to 0 °C."

Comment #8: L237-L237: Although the authors insist on that "After this maximum the current started to decrease with time", I can't agree to their argument because the current graphs of 438 kg m-3 and 917 kg m-3 do not show such trends, namely they only seem to increase during the period in Fig. 3.

***[ANSWER]** The value 438 kg m^{-3} was wrong. We had to change it to 427 kg m^{-3} and changed Figure 3a and 4a. We also added a sentence about the values for ice (917 kg m-3) and added a new picture to Figure 10.*

L241: " The ice sample (917 kg m^{-3}) already broke into pieces (Fig. 10 (right)) before reaching the maxima and minima in the current and phase shift measurements.”

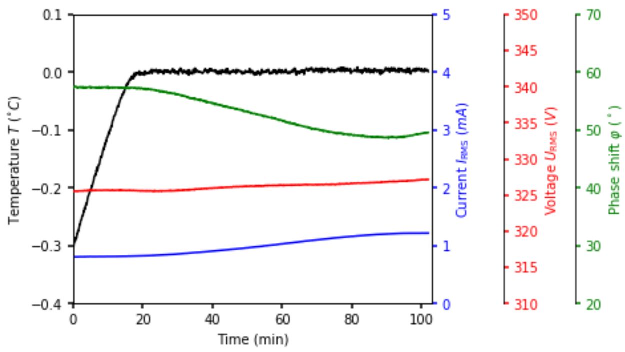

Figure 3a

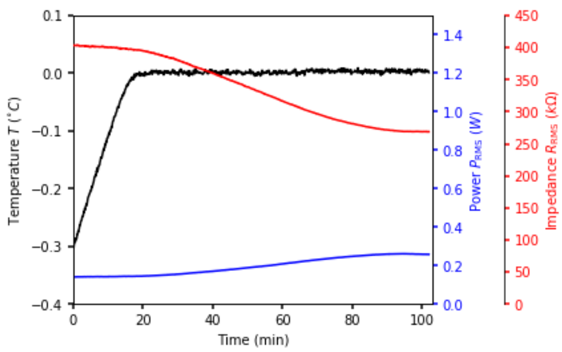

Figure 4a

Figure 10: (Left) Visualization of water percolation after an experimental run for a snow sample. The sample holder was aligned vertically between the capacitor plates. Water percolated in the upper part of the sample and accumulated at the bottom of the sample holder leading to an inhomogeneous

mixture of the sample affecting the heating process of the sample. (Right) Picture of the ice sample (917 kg m^{-3}) after an experimental run. Before the point of water percolation was reached, the ice sample broke into pieces.

<u>Comment #9:</u> L238-L239: Although the authors insist on that “Both parameters decrease with time and increased afterwards again”, I can’t agree to their argument because voltage and phase shift of 917 kg m-3 does not show such trends, namely they only seem to decrease during the period in Fig. 3.

[ANSWER] *We added a sentence about the values for ice (917 kg m-3) and added a new picture to Figure 10.*

L241: " Again, the ice sample (917 kg m^{-3}) already broke into pieces (Fig. 10 (right)) before reaching the minima and maxima in the impedance and power measurements.”

Figure 10: (Left) Visualization of water percolation after an experimental run for a snow sample. The sample holder was aligned vertically between the capacitor plates. Water percolated in the upper part of the sample and accumulated at the bottom of the sample holder leading to an inhomogeneous mixture of the sample affecting the heating process of the sample. (Right) Picture of the ice sample (917 kg m^{-3}) after an experimental run. Before the point of water percolation was reached, the ice sample broke into pieces.

Comment #10: L248-L252. Although the authors insist on that "The impedances of 38 kg m-3 and 917 kg m-3 reached minimum values after 80 min and 9 min respectively, I cannot agree to their argument because the impedance graphs of 438 kg m-3 and 917 kg m-3 still seem to continue decreasing during the period in Fig. 4.

[ANSWER] See answer to the last two comments.

Comment #11: The number of Discussion part should be 5.

[ANSWER] We changed the number:

Comment #12: L295-L297: Please add the description how to calculate the deviations.

[ANSWER] We calculated the deviation of the liquid water mass fraction based on

$$\Delta x_{\mathrm{mass}} \approx \left|\frac{\partial x_{\mathrm{mass}}}{\partial \eta}\right| \cdot \Delta\eta + \left|\frac{\partial x_{\mathrm{mass}}}{\partial P_{\mathrm{RMS}}}\right| \cdot \Delta P_{\mathrm{RMS}} + \left|\frac{\partial x_{mass}}{\partial m_{\mathrm{s}}}\right| \cdot \Delta m_{\mathrm{s}}$$

and the deviation of the liquid water volume fraction based on:

$$\Delta x_{\mathrm{vol}} \approx \left|\frac{\partial x_{\mathrm{vol}}}{\partial \rho_{\mathrm{s}}}\right| \cdot \Delta\rho_{\mathrm{s}} + \left|\frac{\partial x_{\mathrm{vol}}}{\partial x_{\mathrm{mass}}}\right| \cdot \Delta x_{\mathrm{mass}}$$

We added an Appendix containing following paragraph:

Appendix:

The experimental measurements have uncertainties due to measurement limitations (e.g. instrument precision) which propagate to the combination of variables in the total result. Each extracted parameter has different variables in their calculations (e.g. *a*, *b*, *c*, …) and can be written as a function of these variables

$$z = f(a, b, c, \dots) \qquad \text{(A.1)}$$

Neglecting correlations or assuming independent variables yields a common formula among engineers and experimental scientists to calculate the maximum uncertainty from the error propagation

$$\Delta z \approx \left|\frac{\partial f}{\partial a}\right| \Delta a + \left|\frac{\partial f}{\partial b}\right| \Delta b + \left|\frac{\partial f}{\partial c}\right| \Delta c + \cdots \qquad \text{(A.2)}$$

Therefore, the uncertainty measurement of the heating efficiency, water mass and volume fraction are given by:

$$\Delta\eta \approx \left|\frac{\partial\eta}{\partial m_s}\right| \cdot \Delta m_s + \left|\frac{\partial\eta}{\partial T}\right| \cdot \Delta T + \left|\frac{\partial\eta}{\partial P_{\mathrm{RMS}}}\right| \cdot \Delta P_{\mathrm{RMS}} \tag{A.3}$$

$$\Delta x_{\mathrm{mass}} \approx \left|\frac{\partial x_{\mathrm{mass}}}{\partial\eta}\right| \cdot \Delta\eta + \left|\frac{\partial x_{\mathrm{mass}}}{\partial P_{\mathrm{RMS}}}\right| \cdot \Delta P_{\mathrm{RMS}} + \left|\frac{\partial x_{mass}}{\partial m_s}\right| \cdot \Delta m_s \tag{A.4}$$

$$\Delta x_{\mathrm{vol}} \approx \left|\frac{\partial x_{\mathrm{vol}}}{\partial\rho_s}\right| \cdot \Delta\rho_s + \left|\frac{\partial x_{\mathrm{vol}}}{\partial x_{\mathrm{mass}}}\right| \cdot \Delta x_{\mathrm{mass}} \tag{A.5}$$

The measurement uncertainties are given in Table A1.

Table A1: Measurement uncertainties of the experimental setup: current ΔI_{RMS}, voltage ΔU_{RMS}, power ΔP_{RMS}, phase shift $\Delta\varphi$, mass Δm, and temperature ΔT.

	Uncertainty
ΔI_{RMS}	±0.05 A
ΔU_{RMS}	±0.5 V
ΔP_{RMS}	±0.025 W
$\Delta\varphi$	±1.66 °
Δm_s	±0.001 kg
ΔT	±0.1 °C

We also changed Table 3 and added the measurement uncertainty:

Table 3: Density of the snow samples and the corresponding heating time and the water mass and volume fraction where water starts to percolate. The uncertainty measurement of the mass and volume fraction is given in the brackets.

Density (kg m^{-3})	Heating time (min)	Mass fraction (%)	Volume fraction (%)
427	94.5	4.1 (±0.4)	3.3 (±0.5)
438	81.1	6.4 (±0.5)	5.2 (±0.8)
465	51.2	4.3 (±0.4)	4.1 (±0.7)
465	55.2	4.6 (±0.4)	4.2 (±0.7)
539	58.2	5.8 (±0.4)	7.3 (±0.9)
612	54.5	7.5 (±0.5)	12.9 (±2.0)
917	8.79	0.3 (±0.0)	0 (+2.1)

Comment #13: L308-L309: It is difficult to understand the sentence that "at higher density the structural connections between ice crystals were less destructed by the pore volume". Please add more detailed description.

***[ANSWER]** We changed the sentence:*

L308: "… density the snow structure had more intergranular bonds increasing the permittivity (Evans, 1965)."

Comment #14: L337: The range of mass water volume when water percolation started in Table 3 is from 4.1 to 7.5 %, therefore, the description in the text (5-8%) had better be 4 - 8 %.

***[ANSWER]** We changed it:*

Comment #15: L545: URMS should be RRMS.

***[ANSWER]** We changed it:*

Minor revisions were made throughout the revised manuscript.

We thank Anonymous Referee #2 for his insight, suggestions and recommendations.

The authors