The ice and water condition detecting sensor based on the physical characteristics differences among the air, ice and water and its application in the detecting process of river ice

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Abstract: This paper discusses the resistance characteristics of ice during its formation, growth and melting life cycle based on our experimental research. We discovered that the resistance of ice falls into the low and high resistance zones as the temperature changes. We therefore established our new research theory of 'ice status measurements based on the equivalent resistance difference among air, ice and water'. Our 'R-T（Resistance and Temperature） ice and water measurement sensor' structure design is based on this new theory. Field researches have been conducted in both the Yellow River basin in North China and in the Heilongjiang River in North East China. Data have been collected with the 'R-T ice and water measurement sensor' and analyzed. Our analysis approved the influences of ice structure on the equivalent resistance difference of ice. Our research provides an applicable solution to the real engineering practices.

Keywords: air; ice; water; temperature; equivalent resistance; sensor

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1. Introduction

In the high latitude regions where it always freezes in winter, a continuous monitoring and fully understanding on the ice status change during the whole freezing period is completely important in the fields of hydrological information collection, water-power engineering and safe operation of hydraulic structure, river transportation in winter time, the monitoring of the ecosystem, ice jam flood control and meteorological monitoring etc. Affected by the complex and unpredictable geographical environment and the adverse weather condition in most High Latitude and cold inland regions, continuous automatic monitoring of river ice is a very challenge subject in water engineering. There is yet a good measurement method that need to be studied. Since 2000, the author 1 and his research group have started their field research in this area based on the differences of the physical characteristics between ice and water. We studied the resistance characteristics of ice during its formation, growth and melting life cycle based on many of our experience researches. We established our research theory of 'ice status measurements based on the equivalent resistance difference among air, ice and water'. Our 'R-T（Resistance and Temperature） ice and water measurement sensor' structure design is based on this theory. The application of sensor in Heilongjiang River in the Mohe (Heilongjiang province in China) is briefly introduced.

2. Theory of continuous fixed-point measurement of ice based on the differences of the physical characteristics among air, ice and water

2.1 Capture of the equivalent resistance difference between ice and water

During the analysis of the physical processes of ice and water status change due to temperature changes, the equivalent resistance is the most explicit physical parameters that can be measured electronically (or through circuit method) . For example, if we insert a pair of detection electrodes into ice or water and connect the electrodes with a fixed resister to form a piece of series circuit- potential divider of resistance, it is fairly easy to measure the equivalent resistance value of the ice and water within the tested area under different temperatures and measurement environments.

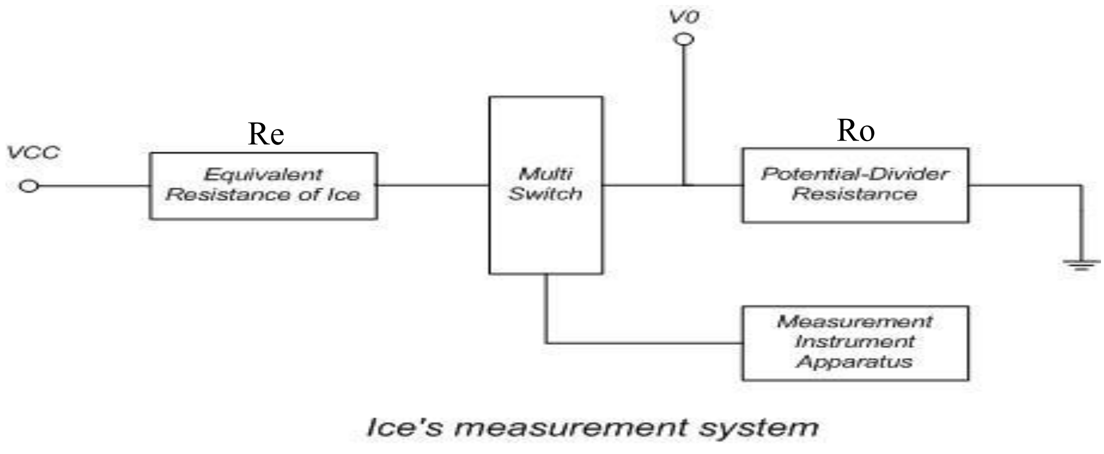


Figure1. The equivalent circuit of measuring for equivalent-resistance

In figure 1. *Re* represents the equivalent resistance value of the measured medium (here referring to either ice or water) through detection electrodes with certain geometrical structure and material. It is worth to point out that when there is change on the geometrical structure and material of the detection electrodes, different equivalent resistance values will also be detected; R_o in figure 1 represents a fixed resister, the resistance of which is known; while Vcc , V_0 represents the applied voltage and the voltage on the two sides of the fixed resister respectively. According to the Series pressure formula, it is easy to come up with formula 1:

$$V_0=Vcc\ R_o/(R_o+Re) \quad \textbf{[1]}$$

If Vcc and R_o are assigned with fixed values during the system design, then they can be treated as constants in formula 1; while the voltage on the two sides of the fixed resister (V_0) varies as the equivalent resistance of the measured medium (Re) changes. Formula 1 can also be written as formula 1a:

$$V_0=f(Re)=Vcc\ R_o/(R_o+Re) \quad \textbf{[1a]}$$

If the value of V_0 in formula 1a can be detected, we can then calculate the equivalent resistance of the measured medium (Re):

$$Re= R_o(Vcc/V_0 - 1) \quad \textbf{[2]}$$

If we analyze formula 1a or formula 2, we can conclude that when the equivalent resistance of the measured medium varies within the range of ∞ Ω, the voltage on the two sides of the fixed resister will also change accordingly within the range of Vcc ~ 0 V. In practice since V_0 can be more easily measured through circuit method, we monitor the value change of V_0 via the analysis of the equivalent resistance of the measured medium (Re).

2.2 Experiences and analysis of the equivalent resistance variation according to temperature changes during the formation, growth and melting life cycle of ice

Lots of factors have been found that can influences the change of the equivalent resistance of ice and water. Our laboratory and field work research data have approved the following factors including temperature, the concentration of the conductive impurities in the measured ice and water, the water flow and ice structure, and the performance of the circuit inside the measuring instruments etc. Temperature is one of the best known factor which was earlier discovered by us. Existing literatures have shown that when the concentration of the conductive impurities in the measured ice and water is known, as the temperature decreases, the equivalent resistance of water will increase monotonically. When the temperature reaches as low as 0℃, the physical form of water will change from liquid into solid ice. But there have been very few literature found on the change of the equivalent resistance of ice due to temperature changes. Therefore, we have designed a Ice/Water Equivalent Resistance-Temperature Gradient Synchrotron Automatic Measurement Instrument, the structure of which has been shown in figure 2. We have conducted experimental research in our laboratory with this is instrument on the study of the equivalent resistance change of ice against temperature changes during the formation, growth and melting life cycle of ice.

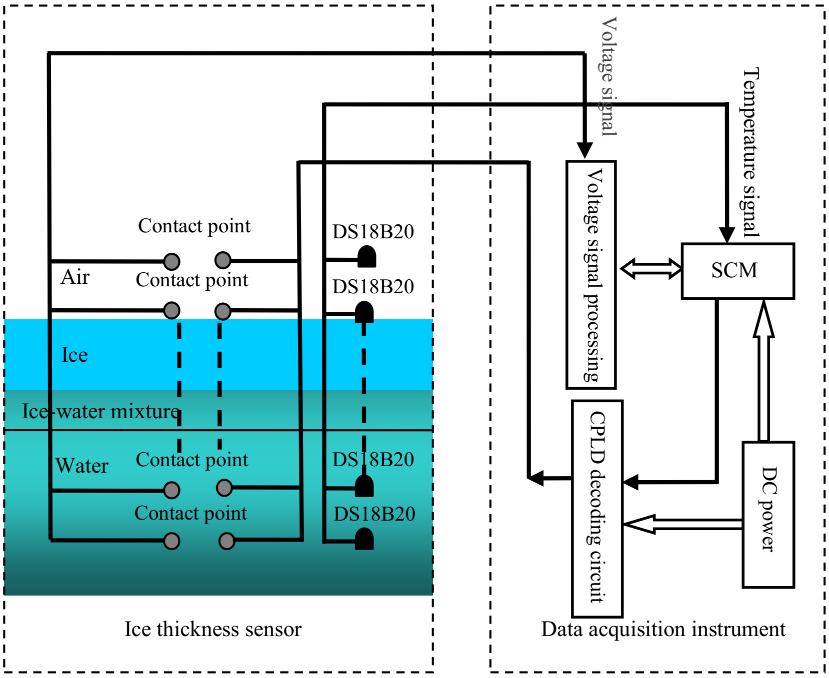
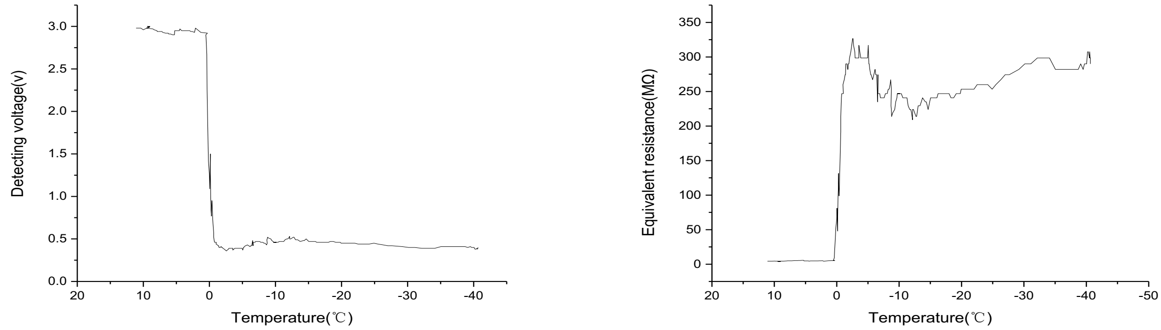


Figure2. The circuit structure of the ice and water equivalent resistance measurement

As has been illustrated in figure 2,the measurement circuit of our experimental instrument is composed of two groups of metal contacts with good conductivity at a vertical interval of 1cm and horizontal distance of 1.5 cm. Stands vertically in parallel is the temperature gradient synchrotron measurement circuit composed of IC-DS18B20. By controlling the Single Chip Microcontroller (SCM) through programs, we can switch on the different on-off circuits of the equivalent resistance measurement instrument at different time points; measure the equivalent resistances Re of each pair of the metal contacts, and simultaneously detect the temperature of the measured medium at the same height of the metal contacts.

During our experiments, we placed the measurement instrument as shown in figure 2 inside a plastic container full of tap water. We then placed the plastic container in a temperature-controllable test unit, where we froze and unfroze the tap water repeatedly. Data of the voltages among all metal contacts of the corresponding temperature collected during this experiment have been stored. Figure 3(a) reflects the typical trend of changes of the voltage (V_0) on the two sides of the fixed resister as the temperature fluctuates between -60℃~+10℃. Figure 3(b) shows a typical trend of changes of the equivalent resistance of ice Re corresponding to the temperature changes based on Formula 2.



（a）Curve of changes of V_0 in -60℃~+10℃ (b) Curve of changes of Re in -60℃~+10℃

Figure3. Curve of Re-t changes during the growth and melting cycle of ice when R_o=40MΩ

A thorough analysis on the experimental data shows that the equivalent resistance of the natural water (including rainfalls, river water, lake water, seawater and tap water etc) has the following characteristics:

1）Firstly, the lower the temperature is the higher the equivalent resistance will be under the room temperature. The equivalent resistance falls into the range between several KΩ and several hundred KΩ .

2) Secondly, the temperature is close to 0℃ when ice crystal (a mixed status of ice and water) are found in the water as it decreases.

3) Thirdly, when the temperature decreases till 0℃, the physical form of water will change from the mixed status of ice and water into solid ice; meanwhile the Re value will be found with significant changes. The value is an order of magnitude higher (from KΩ to MΩ). The value falls into the range of between several MΩ and several dozens of MΩ . An obvious knee can be seen in the Re-t curve. As the temperature inside the ice continuously decreases, the Re value increases in fluctuations and stays below 100 MΩ

4) Last but not least, as the temperature inside the ice continuously decreases, the Re value shows a significant growth exceeding 100 MΩ at a specific temperature level.

The distribution of the temperatures inside the ice can be summarized as:

The temperature of the water bodies at the bottom layer of the ice is greater than or equal to 0℃. The temperature of the mixes of water and ice is close to 0℃. The average temperature inside the ice is below 0℃. As to the top layer of the ice , because the heat exchange of the top layer of the ice happens mainly between the ice top layer and the air above the ice surface; the temperature of the higher part of the ice will gradually increase approaching the temperature of the air above the ice surface; On the other hand, the heat exchange of the bottom layer of the ice happens mainly between the ice and the water below the ice; therefore the temperature of the lower part of the ice gradually approaches 0℃.

These characteristics and rules have offered theoretical foundations and tremendously support for the development of a new type of ice measurement sensor and lead us to a new way for automatic monitoring of ice during its formation, growth and melting life cycle.

2.3 Ice measurement theory based on the differences of physical properties of air, ice, and water

Based on many laboratory researches, the author1of the paper has proposed "The theory of Ice measurement based on the differences of physical properties of air, ice, and water" in 2005. In this theory the author has described that the vertical cylindrical space of the fixed ice observation point contains 3 types of to-be-measured mediums: air, ice and below-ice water (the below-ice water can be further categorized as the mixes of ice and water and liquid water). Many physical parameters (including the equivalent resistance) of these three types of to-be-measured mediums show large differences in values. Suppose certain physical parameters (such as resistance, capacitance, temperatures etc) of the contact points along the horizontal section of the aforementioned vertical cylindrical space can be measured with certain detecting circuit, it is very possible to tell the physical status (solid ice or liquid water) of the measured medium based on the analysis of the data; based on which it is further possible to infer the boundary between ice and air and the boundary between ice and water and finally it is possible to calculate the thickness of the ice layers and the height of the water below the ice. This method is suitable to the measurement of continuous monitoring of ice physical status, ice thickness and water levels below the ice at a fixed observation spot in the rivers, reservoir, lakes and glaciers. This theory is explained by figure 4.

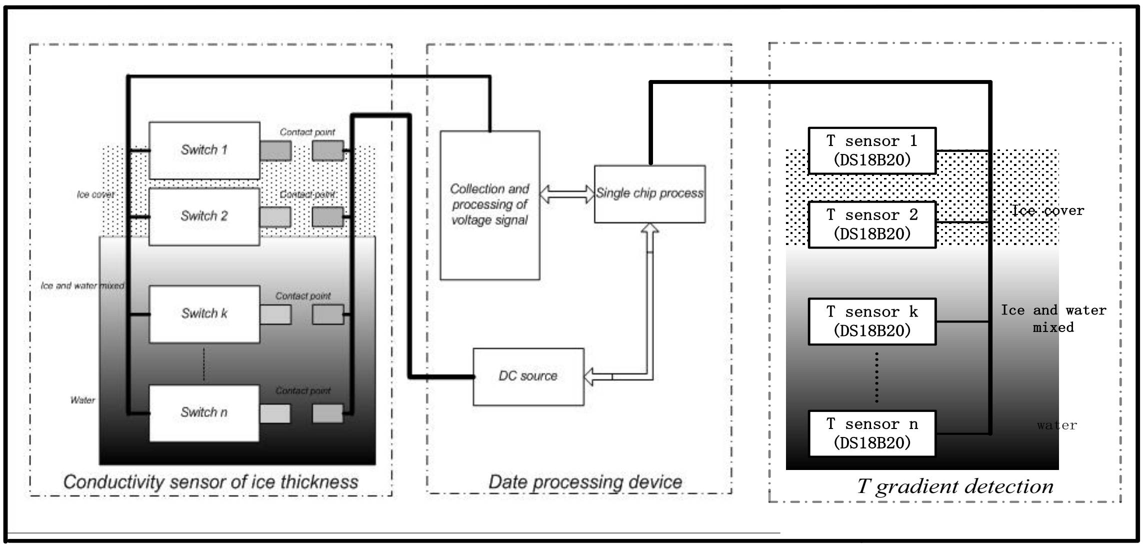


Figure4. Ice measurement theory schematics

3. 'R-T Ice Automatic Measurement Sensor' and its data processing system

Based on the theory explained by figure 4 and the structural design as illustrated by figure 2, we developed our 'R-T Ice Automatic Measurement Sensor' with a maximum measurement range of 200cm. The picture of the actual sensors is shown in figure 5. In the actual production of sensor, two types of sensor designs can be adopted. The first type of sensor can detect both the equivalent resistance and gradient temperature values as shown at the bottom part in figure 5. The sensor displays as accurate as to ±1cm for the equivalent resistance and to ±5cm/±10cm for the gradient temperature respectively. Another type of sensor is a highly accurate temperature only ice measurement sensor composed of the integrated temperature sensors DS18B20 as shown on the top part in figure 5. The sensor displays as accurate as to ±1cm.

Figure 5. The picture of the actual R-T Ice Automatic Measurement Sensors

We also composed the ice thickness calculation algorithm based on the working theory of the R-T Ice Automatic Measurement Sensor and its applicable situations in the field work research. For further readings, please refer to reference 9.

4. 'R-T Ice Automatic Measurement Sensor' and its field work applications

We have installed both types of the 'R-T Ice Automatic Measurement Sensors' as shown in figure 5 in Heilongjiang River in the Mohe (Heilongjiang province in China). Continuous monitoring on the ice thickness changes and the gradient temperature changes have been conducted for these rivers in the freezing period in the winter for these segments of the rivers. Sensor Set parameters: Vcc=3.3V ; R_o=15MΩ; Range：200cm.

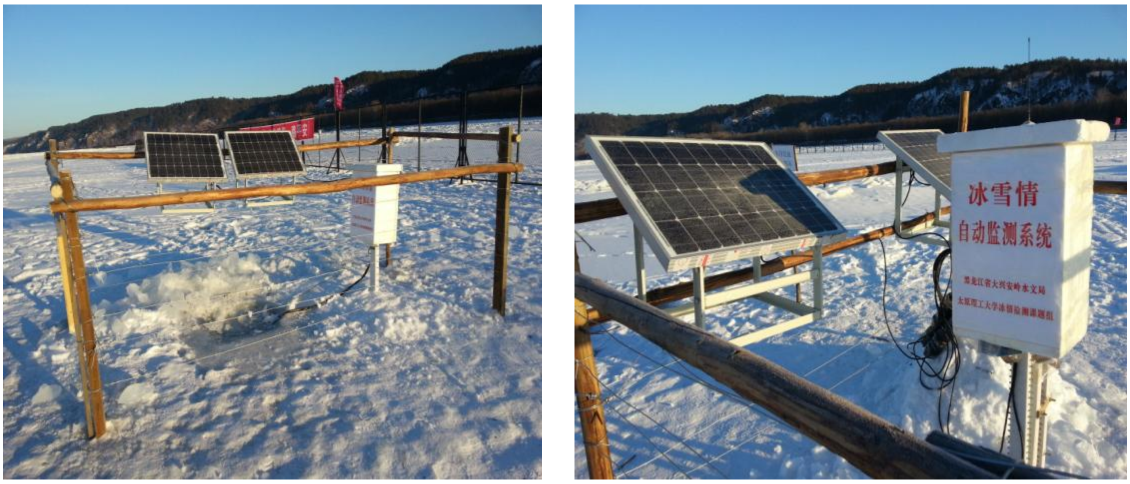
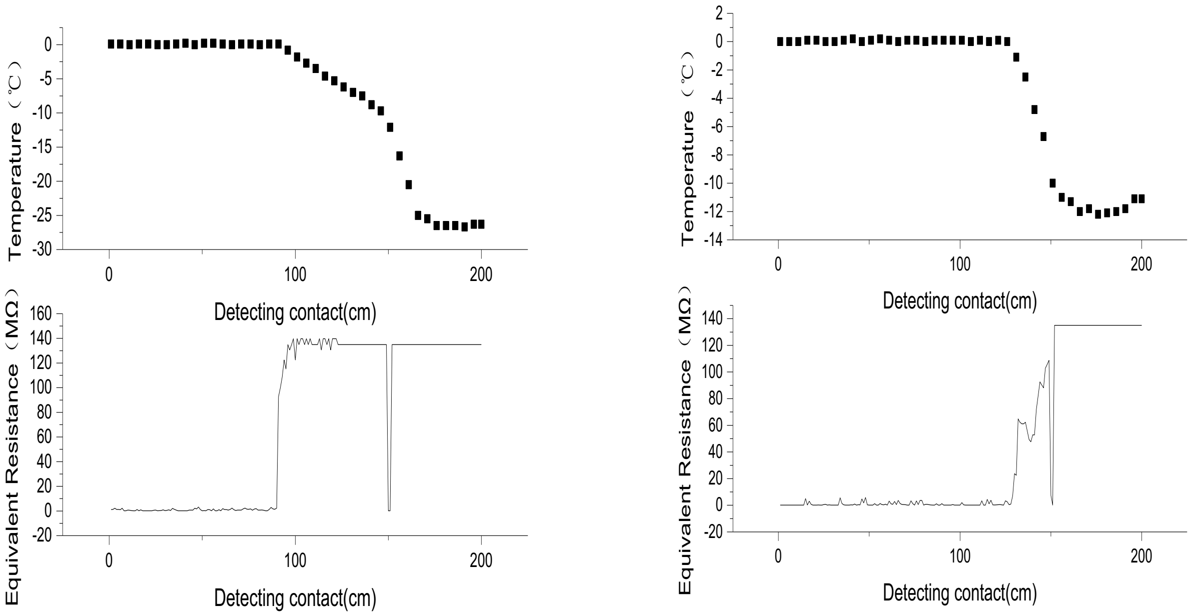


Figure6. The R-T Ice Automatic Measurement Sensor installed in Mohe , Heilongjiang river

Figure 7(a) (b) shows real-time data collected originally from automatic measurement sensors in the field of Mohe, Heilongjiang river in the dimension of equivalent resistance and temperature, at 5 o'clock ,6th, Jan., 2014 and at 5 o'clock, 1st, Apr., 2014 respectively.



(a). Data: Jan. 06,2014 Time: 05:00 (b). Data: Apr.01, 2014 Time: 05:00

Figure7. Distribution curve of Re-t in the field of Mohe, Heilongjiang river

In figure 7, Re reaches the peak at the location of 150cm by manual short circuit. The value can be used as judging point of upper ice level in actual engineering field. Comparing figure 3 with figure 7, we find that data in lab is similar to data in real field. The data in figure 7(a) indicates that ice is generating in Mohe, Jan., due to low environment temperature. The inner structure of ice is hard, which results the sharp change point of temperature was close to freezing point. The zone of low value resistance is relatively narrow. In Spring (Apr. 01, 2014), ice is melting due to increase of environment temperature. The value of equivalent resistance drops sharply. The zone of low value resistance is relatively broad, and the inflection point moved to the right.

Acknowledgments

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