Fixed spray type anti-ice deicing control system design

Wenjiang Liu 1, Yunquan Chen 2, Fujin Hou 3, Yucai Jing 4 and Jie Chen 1
1 Research Center for Road Safety, Emergency and Disaster Reduction Technology, Shandong Jiaotong University, Jinan 250357, China
2 Testing Department, Shandong Quanjian Engineering Testing Co., LTD, Jinan 250014, China
3 Shandong Hi-speed Construction Management Co., LTD, Jinan 250000, China
4 Shandong Hi-speed Qingdao Highway Co., LTD, Qingdao 266061, China

Corresponding author and e-mail: Jie Chen, 979656312@qq.com

Abstract. This paper takes intelligent control technology as the core technology, combines with meteorological and road freezing information collection technology and water supply and drainage technology. Firstly, this paper introduces the design of grading subsystem of fixed spray type anti-ice and snow removal control system, and proposes a new type of nozzle suitable for the viaduct at the same time, which can improve spraying effect of the deicing liquid while improving safety guarantee. Then based on analysis of collected on-site road conditions and meteorological actual data and combined with logic control algorithm, a live ice and snow early warning mathematical model is designed to predict the snowy condition of the road surface, and automatically control equipment to spray deicing fluid before or after road icing. It uses PID control technology to ensure pressure balance inside the spray pipe. The real-time field data is connected to the cloud server with 4G wireless transmission technology, and the existing data and current data are compared and analyzed through the recursive neural network, so as to further accurately predict the ice and snow situation, classify danger level according to national road safety standards, and release it to other platforms. Based on application of actual field, this paper designs a method that can be combined with prevention in advance and post-disposal to eliminate road icing and reduce risks of vehicle driving safety in severe weather.

1. Introduction
With the rapid development of technology, people's concept of de-icing and snowmelt is also undergoing major changes, from the passive form of handling after the occurrence of ice and snow to the active form of prevention in advance. Prevention in advance can reduce the freezing point of road liquid under the condition of water on the road surface or lay a layer of protection on the road surface to prevent snow and ice from directly adhering to the road surface to improve the efficiency of de-icing snow. Therefore, it is an urgent problem to improve the road ice and snow warning and disposal capacity. Nowadays, China mainly uses mechanical vehicles to clean accumulated ice and snow or spread snow melt agent. However, in some remote areas such as long longitudinal slope and other special road sections where snowplow cannot reach quickly, we can only rely on relatively mature fixed spray type anti-ice and snow control system to achieve unmanned automatic disposal of road accumulated ice and snow [1]. Other de-icing methods (conductive abrasion layer, chemical anti-ice
coating, thermal conductivity pipe) are still in experimental stage of the road section, and have not been widely promoted.

2. Design of the system hardware structure

With the rapid development of technology and economy, automatic control system has been widely used in all walks of life, including road maintenance. In order to achieve the purpose of timely and rapid automatic disposal of road ice and snow, the main hardware design of this system includes: road and weather detection subsystem, spray subsystem, control subsystem and support subsystem. Schematic diagram of system structure is shown in Figure 1 and Figure 2.

![Figure 1. Schematic diagram of system structure](image1)

![Figure 2. Structure drawing of control system](image2)

2.1. Design of road and weather detection subsystem

In practical engineering applications, road and weather sensors should not only be able to accurately measure road and weather data, but also be able to be used under special working conditions.

In order to achieve accurate measurement and cost saving and to facilitate construction, it is necessary to integrate the measurement sensor used for measured data into a single device, so as to reduce the volume of the measurement instrument and facilitate installation and transportation [2-3].

This system adopts the passive road sensor IRS31-UMB of Lufft and the active road sensor ARS31-PRO as shown in Figure 3, which make the measurement of data more accurate and at the same time assist the WS-600 weather sensor as shown in Figure 4.

![Figure 3. Passive and active sensor](image3)

![Figure 4. Weather sensor](image4)
Lufft road sensors adopt unique capacitance detection technology, microwave radar technology, and combine with multi-parameter fusion algorithm. Through detecting sensors to monitor the state of different materials: capacitance values of the condition of freezing, ice thickness, water, and integrate temperature detection and temperature compensation technology to monitor freezing and ice thickness.

IRS31-UMB passive sensor is an embedded sensor. By using two kinds of shell composition, the surface is hard wear-resistant plastic and others are hard alloy material, which make the sensor package more compact, better durability, and stronger stability. It can detect the freezing point of chloride solution, road temperature, road condition, road water film thickness and other parameters.

ARS31-PRO active road sensors utilize active cooling technology to directly cool the road surface when set conditions are met until icing, and then increase the heat to melt, in the process the real ice temperature can be obtained. This method is not affected by the influence of the snowmelt agent composition, it is the ideal freezing point detection device.

The WS-600 weather sensor measures relative humidity through the capacitive sensor element. Using accurate negative temperature coefficient components (NTC), it measures the temperature. 24 KHz Doppler radar is adopted to perceive each drop and each snowflake. At the same time, precipitation types are distinguished according to different falling speed of raindrops and snowflakes, and the amount of precipitation and precipitation intensity are calculated by using the falling speed and size of raindrops (snowflakes). Ultrasonic transmitter receiver is used to detect wind speed and direction.

2.2. Execution part: the design of spray subsystem

2.2.1. Main supply circuit design
The main liquid supply loop is divided into two parts with the shunt as the node. The front end is composed of liquid storage tank, manual ball valve, electric valve, filter screen, flow meter and pipe connector. The back end is composed of water pump, pressure gauge, check valve, buffer pressure tank, relief valve and connecting pipe fitting. The small pressure tank can absorb the sudden increase of pressure in the pipeline to prevent "water hammer effect", which increases the pressure stability of the pipeline, and prevents the damage caused by high pressure to the pipeline.

When selecting the main material, the main material shall be determined according to the physical and chemical characteristics of the working liquid of the system and the working pressure of the system. In general, the main material in the pump station shall give priority to using the metallic materials and when metallic materials are not applicable, consider non-metallic materials; steel pipes are preferred for metallic materials, and non-ferrous metals are considered later. Due to short distance of the main liquid supply circuit, the corrosion resistant stainless steel material is generally selected.

The material of liquid storage tank can choose polyethylene.

2.2.2. Design of spray circuit
Spray main pipe consists of main infusion pipe, solenoid valve, spray water hose, nozzle and its accessories. In order to be suitable for the rolling and bending road trend of construction road section and make installation convenient and standardize production and processing, the main infusion pipe had better adopt the pressure-resistant rubber hose which is easy to bend.

Among them, fish and bird sprinkler head and fan-shaped sprinkler head are widely used in de-icing system. The spraying distance of fish and bird sprinkler head is relatively long, but there are spray blind areas, which leads to uneven proportion of the sprayed road solution, and reduces the effect of road de-icing. At the same time, the protruding protrusion of the fish and bird sprinkler head will also cause a safety hazard to the vehicle. The fan-shaped sprinkler head orifice channel is large and smooth. Although the blocking phenomenon is reduced, the spray solution is relatively wasted in practical application. At the same time, its spray distance at the same height of the same pressure is much shorter than that of the fish and bird sprinkler head, and the spray coverage area is relatively small.
In order to improve the safety of sprinklers to work, improve the utilization rate of deicing medium and improve the sprinkler spray distance, improve the system running timeliness, we design a new type of nozzle, which is compact and has a smooth surface that can be embedded in the concrete barrier basting reduces the safety impact on moving vehicle. The water outlet is composed of a plurality of orifices of different sizes. The upper large hole ensures the spray distance. The lower holes ensure uniform spraying. The inner arc-shaped curved surface reduces the water hammer effect of the nozzle to further increase the spraying distance and uniformity of spraying. The object of the new nozzle is shown in Figure 5.

Figure 5. New type of nozzle

2.2.3. Design of solenoid valve controller
In order to improve system construction efficiency, modular production and cost saving, solenoid valve controller is designed by us. In addition to the basic I/O port controller, the terminal design is divided into power inlet and outlet terminal, signal inlet and outlet terminal and solenoid valve power supply terminal. In construction as long as the wiring is correct, it can be quickly connected. The power supply adopts safe DC 24V. RS-485 interface is adopted for data transmission. And they are sealed in a water drain box.

Among them, the connecting party of the main controller and the solenoid valve controller had better adopt the "hand-in-hand" topological structure. Other topological structures are easy to generate reflected signals and affect communication quality. At the same time, the topological structure reduces the distance between the equipment and the main line and further reduces interference. 485 repeaters should be used if the distance between the main controller and the solenoid valve controller is long. The communication cable used must be twisted pair with shielding layer above double strands, which has strong anti-interference ability and is more conducive to differential mode of communication adopted by 485 communication. Meanwhile, all equipment should have good grounding to prevent outdoor lightning surge interference [3].

2.3. Design of control subsystem
In this system, the main body of the control subsystem is a set of relatively large electrical cabinets. It is divided into two parts: one is responsible for connecting the distribution area of external power supply lines, and the other is responsible for controlling the control area of external equipment. The touch screen, control knob and threading hole are embedded on the door panel corresponding to the electrical cabinet.

In general, the industrial control system can use the main controller of the single chip microcomputer and the peripheral circuit. The main controller of the programmable logic controller, the subsidiary module, and the industrial control computer are the core of the main controller.

In the spray type active anti-ice deicing system, the single chip microcomputer needs to complete the external circuit by itself. By displaying drive circuit, pulsing width modulation circuit, D/A conversion circuit, serial communication circuit, control relay circuit, etc., to complete the overall control function of the system.

In the spray type active anti-ice deicing system, only the model of PLC (Programmable Logic Controller) and its affiliated modules need to be selected and connected with other hardware devices
in the system by using power cord and signal cable. In general, there is no need to design peripheral circuits by us. Logical control program is used to control the operation of serial ports or I/O ports, so as to realize data detection and processing and spraying of the system [4].

In the spray type active anti-ice deicing system, IPC also only needs to use power cord and signal cable to connect with other hardware devices in the system, and generally does not need to design the peripheral circuit by itself. VB and other software programming can be used to control serial communication, data detection and processing and spraying of the system.

In the design and construction of spray type active anti-ice deicing system, the form of the main controller can be selected according to installation and construction environment of the system and the requirements of using. Generally speaking, PLC is widely used in the spray type active anti-ice deicing system because it does not need too much self-designed circuit in the process of using, which makes it easy to have strong reliability and can adapt to complex and harsh working environment [5].

3. Design of control algorithm

3.1. Spray decision control
In order to realize early warning and forecast accurately and simply, mathematical models are often established by using the relationship between various kinds of data in practical applications, and mathematical formulas which are easy to understand and operate are formed. In the prediction of road ice coagulation and snow cover, a mathematical model can be established after analyzing and extracting summarized laws of road ice coagulation mechanism, and the abstract experimental phenomena and principles can be converted into a concise mathematical formula that is easy to be applied in the early warning and control system. For example, the formula to predict the time of freezing snow and the amount of spray.

Formula of road water freezing time prediction:

\[ t_{jb} = \frac{(T_{L} - Q)}{V_{L}} \]  \hspace{1cm} (1)

Formula of the amount of spraying time required by a single nozzle to spray deicing liquid:

\[ X = \frac{L_{L} \cdot D_{P} \cdot D_{L} \cdot (T_{L} - T_{S})}{100000 \cdot n_{P} \cdot x_{P}} \]  \hspace{1cm} (2)

Time required for road surface snow prediction:

\[ t_{js} = \frac{1}{V_{L}} + \frac{1}{V_{Q}} + V_{F} \]  \hspace{1cm} (3)

Formula of the amount of spraying time required by a single nozzle to spray deicing liquid on road surface with snow:

\[ X = \frac{L_{L} \cdot D_{P} \cdot S_{XL} \cdot F}{1000 n_{P} \cdot n_{X}} \]  \hspace{1cm} (4)

Among them: \( t_{jb} \): Predicted freezing time; \( T_{L} \): The road surface temperature; \( Q \): Real-time freezing point; \( V_{L} \): Road temperature drop rate; \( D_{L} \): The water film thickness; \( D_{P} \): The spray width; \( L_{L} \): Laying length; \( T_{S} \): The freezing point of a deicing liquid in a storage tank; \( T_{S} \): The set temperature difference; \( n_{P} \): The number of nozzles; \( x_{P} \): Spray amount per unit time of nozzle; \( t_{js} \): Forecast snow cover time; \( V_{Q} \): Air temperature drop rate; \( V_{F} \): The wind speed; \( T_{D} \): Atmospheric temperature; \( S_{X} \): Snow rate; \( F \): Snow melting efficiency of deicing liquid.

For example: on December 27, 2018, the detection data of the automatic de-icing and snow removal system on er-huan south road in Jinan city are shown in Table 1.
As can be seen from Table 1, the storage time interval between the same data type is 5 minutes. A total of 12 pieces of data were selected for a total of 1 hour. In the table, as time goes by, the road surface temperature drops slightly. However, after the snowfall, the detected road surface temperature rises due to heat released from snowfall and the snow will cover the surface of the road sensor. After the spraying starts, the snow on the road starts to melt and absorb heat, and the road surface temperature starts to drop again. Curve of road temperature change is shown in Figure 6.

![Chart of road temperature change](image)

Figure 6. Chart of road temperature change

In the early stage of snowfall, the water film thickness of road surface is kept within the safe range. At this time, the change trend of atmospheric temperature and road surface is similar, and there will be a temperature rise phenomenon. The change curve of atmospheric temperature is shown in Figure 7.
The snow cover time predicted by the system early warning model at 13:20 is 16.34 minutes, the difference between the time of 13:35 and the time of the actual sensor to detect snow in the outlet area is less than 2 minutes. The change curve of road condition is shown in Figure 8.

In order to improve the efficiency of anti-ice and snow removal, the system will enter spraying state five minutes before the warning time to eliminate snow and ice hazards in advance. It can be seen from the change of the friction coefficient of road surface, the friction coefficient of road surface with thick snow will decrease rapidly when the road surface have snow, and the friction coefficient of road surface will gradually reach the safe range after the start of spraying as shown in Figure 9.

### 3.2. Design of pressure control

In this system, PLC executes PID function block by timing (according to sampling time) and takes the relatively ideal proportional-integral-differential value obtained through repeated experiments as the basic fixed set value according to PID operation rules. When the spraying is started, a fixed pressure value will be given for each nozzle to achieve the spraying effect when the system is running, and then the real-time pressure value detected by the pressure sensor in the pipeline will be used as the feedback value, and the voltage signal obtained after calculation is the output value. The output signal is connected with the corresponding input port of the frequency converter by cable and converted into controllable frequency (range 0~50 Hz), so as to achieve the purpose of constant pressure spraying.

However, in practical projects, the pipe wall and valve will cause losses to the pressure of solution in the pipe with the extension and increase of the number of pipes, the spray pressure away from the nozzle of the pump will decrease with the extension of the distance between the pipes under the condition of constant pump outlet pressure, making the spray effect impossible. Therefore, in the design of pipeline pressure control, the sprinkler head within each distance corresponds to different running frequency of water pump, and the end sprinkler head corresponds to the highest running frequency of water pump. In order to facilitate the control, the nozzles closest to the water pump are taken as NO.1, and the nozzles number increases successively with the extension of the distance. When designing the program, the nozzle number is used as the trigger signal to change the set pressure value of the input PID module in real time [6-7]. PID control output simulation is shown in Figure 10.
At the initial stage when the water pump started, the pipeline pressure gradually rises. After the control and adjustment of PID, the pipeline pressure is basically maintained within reasonable range of the set value of 0.5Mpa.

3.3. Road ice and snow warning

To solve this problem, "road safety warning and disposal platform” is designed by using cloud computing on the basis of intelligent anti-icing and snow removal control system, and 4G network is used to realize remote data docking. The cloud platform is embedded with icing snow warning function, and the recursive neural network icing snow warning model is used to combine the received local road meteorological data information with the local overall weather forecast information to predict the remaining occurrence time(greater than 5min) of icing or snow on the special road surface. At the same time with the combination of the controller in real-time decision tree of early warning function, danger level: high risk, medium risk, slight risk and no risk are divided. When there is no danger, the system does not execute action processing. In the case of slight danger, the system issues the speed limit signal to remind the driver and gives the reasonable driving speed. In the case of medium risk, the system turns on the spraying mechanism on the basis of the light dangerous action and sprays a small amount of deicing liquid for prevention. At high risk, the amount of deicing liquid would be increased to ensure the anti-ice ability of the road.

Using the cloud for big data analysis and advance the ability to learn quickly, and the host controller real-time logic control function of different risk measures the deicing snow removal function more detailed accurate. Rational use of the dosage of the deicing fluid can promote efficiency of road deicing snow melting, further efficiently solve icy roads of snow and prevent road problems of "black ice" and secondary icing [8].

4. Effect verification

Through the verification of the result of actual project, in winter when the road surface has accumulated water or snowfall due to rainfall, etc., when it is predicted that the snow accumulation time is less than 10 minutes, the spray will be automatically started, add a layer of "protective outerwear" before the road surface is frozen or snowy. After the road surface temperature dropped below zero degrees Celsius, the spray of the deicing fluid surface due to the increase of the thickness of water film is a decrease in the road surface friction coefficient, but generally no less than 0.45. The vehicle is not easy to appear skid sideslip phenomenon. The surface of the non-spray deicing fluid has already formed ice, and the friction coefficient of the road surface reaches 0.1. The vehicle is prone to have accidents under such road conditions. This system can respond quickly and prevent road icing in time. Below shows laying the overpass ramp of this system, five o’clock in the morning it began to snow, after 20 minutes the system automatically started to spray. Road of floating snow began to melt the outflow while other pavements still had snow. The snow continues. Freezing point system detected at half past seven in the morning the road solution and pavement temperature difference is less than the set value and the system opened a second spray, while other roads had up to two centimetres of snow, the sprayed road had no snow. The road maintenance department and environmental protection after other pavement, freezing point system detected the road solution maintained in a safe range from start. At this time, the system can detect the ice and snow condition of the road in real time to prevent the secondary icing phenomenon. Spray scene effect diagram are shown in Figure 11.
Acknowledgement
This work is supported by the Key Research and Development Foundation Project of Shandong under Grant 2017GSF220008; Science and Technology Project of Shandong Provincial Transportation Department under Grant 2017B33.

References
[1] Ren yi, Yuan tongsen, wan zhi, Qin min. Overview of the current situation of highway ice-prevention and de-icing technology at home and abroad [J]. Hunan traffic science and technology, 2014, 40(2): 71-75.
[2] Ou yan, Pu xiang, Zhou xuchi, Lu ye, Ren yi, sun guai. Research progress of pavement ice monitoring technology [J]. Highway, 2013(4): 191-195.
[3] Qu zhi, Liang jia, Zheng min. Referring to the ice monitoring system of xihan expressway-talking about the construction method of road ice monitoring system in shaanxi province [J]. Straits science and technology & industry, 2016(10): 95-96.
[4] Anburaj Muthumani, Laura Fay, Michelle Akin, Shaowei Wang, Jing Gong, Xianming Shi. Correlating lab and field tests for evaluation of deicing and anti-icing chemicals: A review of potential approaches [J]. Cold Regions Science and Technology, 2014, 97: 21-32.
[5] Fu zhen, Peng dan dan, sun guo qiang, qin juze. Application of fixed automatic spray snow and ice control technology in North America and Europe [J]. Highway engineering, 214, 39(4): 64-68.
[6] Wu lipu, Zhang long, Zheng changbing. Remote monitoring system for intelligent flyover snowmelt spraying [J]. Microcomputer and application, 2015, 34(2): 69-71.
[7] Tao Ma, Lei Geng, Xunhao Ding, Deyu Zhang, Xiaoming Huang. Experimental study of deicing asphalt mixture with anti-icing additives [J]. Construction and Building Materials, 2016, 127: 653-662.
[8] Wu chuanhong. Analysis on severe weather warning system of expressway [J]. China traffic informatization, 2016(2): 94-96.