Defrost Efficiency Analysis of PMMA Rear Window

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Abstract

As a potential material for lightweight vehicle, polymethyl methacrylate (PMMA) has proven to perform well in optical behavior and weather resistance. However, the application in automotive glazing has seldom been studied. This paper investigates the defrost performance of PMMA rear window using both numerical and experimental methods. The finite element analysis (FEA) results were found to be in good agreement with the experimental data. Based on the validated finite element model, we further optimized the defrost efficiency by changing the arrangement of heating lines. The results demonstrated the frost layer on the vision-related region of PMMA rear window can melt within 30 minutes, which meets the requirement of defrost efficiency.

Introduction

Polymethyl methacrylate (PMMA), known as acrylic or organic glass, serves as an important lightweight material applied in automotive industry for its excellent characteristic. PMMA has a density of 1.19g/cm3, which is a half the density of inorganic glass. It also has good optical performance and weather resistance and is a recyclable thermoplastic material. Compared to inorganic glass, PMMA has lighter weight, better formability and better impact resistance. Although it is comparatively brittle and not good for scratch and abrasion resistance than inorganic glass, the hard coating can improve its scratch and abrasion resistance significantly and, hence, meet the requirement of ECE R43 [1]. Meanwhile, PMMA performs better in terms of abrasion resistance, light transmission, weathering resistance than other common plastic, such as PC (Poly Carbonate) [1]. Therefore, PMMA is a promising substitute for inorganic glass and other plastic materials. It has been mainly used in interior and exterior trims, taillights and triangular windows. The potential application in side window was also studied by Gao et al. [2]. However, limited use to date has been found in the rear window. Considering its large size, the lightweight effect is very promising if the traditional inorganic glass substitutes for the lightweight PMMA glazing. However the silver paste technique for PMMA is challenging and the defrost performance of the PMMA rear window requires further study. The defrost performance is of crucial importance considering the visibility of the driver and passenger which will not only affect comfort but also safety.

For the abovementioned reason, many studies have been conducted on defrost efficiency of traditional automotive window. In this regard, Jahani and Beigmoradi [3] proposed a variety of modification methods to reduce the time of deicing process for windshield by using computational fluid dynamic (CFD) simulation. Goldasteh et al. [4] studied the defrost mode of windshield based on the numerical model of a car cabin with full heating, ventilation, and air-conditioning (HVAC) system using Star-CCM+, which demonstrated that the CFD simulation results matched the experimental results by accessing with the correlation coefficient method. Aroussi et al. [5] compared the defrost/demisting performance of system defroster and electrically heated windshields, which demonstrated that the electrically heated windshield has better clear patterns and reduces the defrost time. However, few of them cover the defrost efficiency of heating line and did not mentioned the plastic glazing. In fact, the heating line defrost method is an efficient way and need to be further investigated by experimental and numerical methods. When considering the new substitution material, PMMA, the defrost efficiency of the rear window need to be further studied.

Therefore, the objective of this paper is to adopt both simulation and experiments to evaluate the defrost performance of rear window and evaluate if PMMA rear window can meet the requirement of standard and how to improve the defrost efficiency by optimizing the arrangement of the heating lines. In addition to PMMA glazing, the defrost performance of inorganic glass is also considered for comparison purpose.

1. Experimental Study

1.1. Test Conditions

The rear windows of inorganic glass and the PMMA glazing with sintering silver paste were used as the test subjects. The PMMA glazing has the same size and same heating line arrangement with the inorganic glass rear window. The details of the test conditions are described as follows:

1. Equipment: Low temperature environmental chamber (Fig. 1), ARBIN electronic load test system, temperature measuring probe, etc.
2. Constraining method: As shown in Fig. 2, the rear window was obliquely fixed by the three points in the low temperature environmental chamber.
3. Temperature: The test environmental temperature kept -10°C.

Figure 1. Low temperature environmental chamber

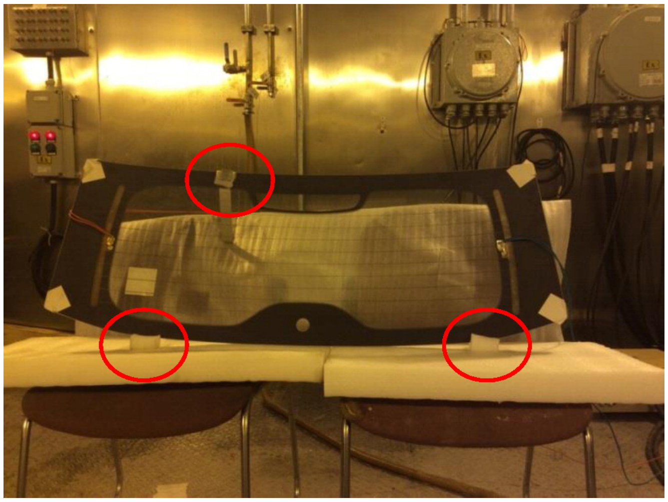

Figure 2. The test constraint method

1.2. Test Procedure

1. Clean the rear window with an alcohol solution and wipe dry with a cotton cloth;
2. Make sure the heating lines of glazing are connected well using multimeter;
3. Fix the test article in the environmental chamber and connect the circuit as shown in Fig. 2;
4. Adjust the output voltage to 12 V for inorganic glass and 21 V for PMMA glazing and the temperature of chamber to -10°C. The chamber maintained at this temperature for more than 4 hours;
5. Measure the area of rear window to calculate the amount of water for generating ice layer. Measure the water with volume of 200 mL by using a graduated cylinder. Spray water to test object with spray gun. In order to spread the water uniformly, the opening of spray gun should be vertical to test object at a distance of 200 to 300 mm and the spraying pressure was 350 kPa ± 20 kPa. A layer of frost with the thickness of 0.044 g/cm^2 is generated on the face of PMMA glazing and inorganic glass rear window as shown in Fig. 3.
6. Maintain the rear window at the above mentioned temperature for 30 min to generate an ice layer on the inner side of the window.
7. Record time using stopwatch as soon as the de-frosting test begin. Record the defrost status of the rear window utilizing the camera at the interval of 5 min for PMMA glazing and inorganic glass rear window.

a. PMMA glazing

b. Inorganic glass

Figure 3. Rear window with a layer of frost

2. Simulation Analysis on the Defrost Efficiency of PMMA and Inorganic Glass Rear Window

The software Star-CCM+ was employed to simulate defrost performance of PMMA and inorganic glass rear window. Tables 1 list all the material properties and temperature used for solving the distribution of frost thicknesses at different time for both PMMA and inorganic material. For simplification, we establish the plane with the same size to replace the shaped rear window geometry. Multiple mesh regions were used in order to accommodate different mesh sizes for heating line and rear window. The ice layer is established by using the ice layer element in the software.

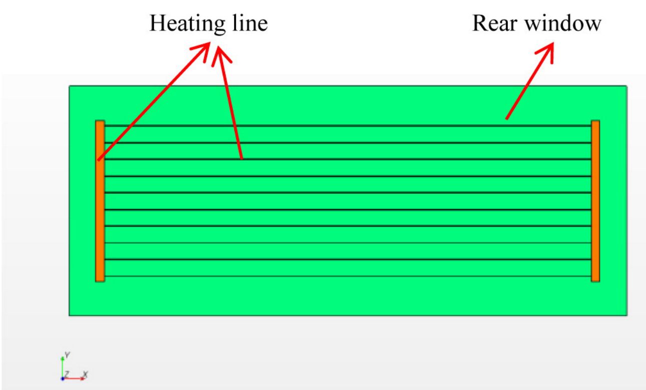

Figure 4. Finite element model for PMMA and inorganic glass rear window

Table 1. The simulation parameters.

Material of plate	inorganic	PMMA
The thickness of plate	3.2 mm	4 mm
Input power	146.5 W	74.4 W
Initial temperature of plate	263 K	263 K
Ambient temperature	263 K	263 K
heat transfer coefficient	100 W/m^2-K	50 W/m^2-K
Density of plate	2500 Kg/m3	1190 Kg/m3
Thickness of frost layer	0.44 mm	0.44 mm

3. Results and Discussions

Melting contours are measured by the experimental method and predicted by the numerical method every 5 minutes. The comparison results for test and simulation results for PMMA glazing and inorganic rear window are further discussed in the following.

3.1. Simulation and Test Results of Inorganic Rear Window

As shown in Fig. 5, the contours of ice thickness obtained from numerical simulation agree well with the test data in environmental chamber. Furthermore, for the inorganic rear window, the frost can melt within 30 minutes under the voltage of 12 V, which meets the requirement of the standard.

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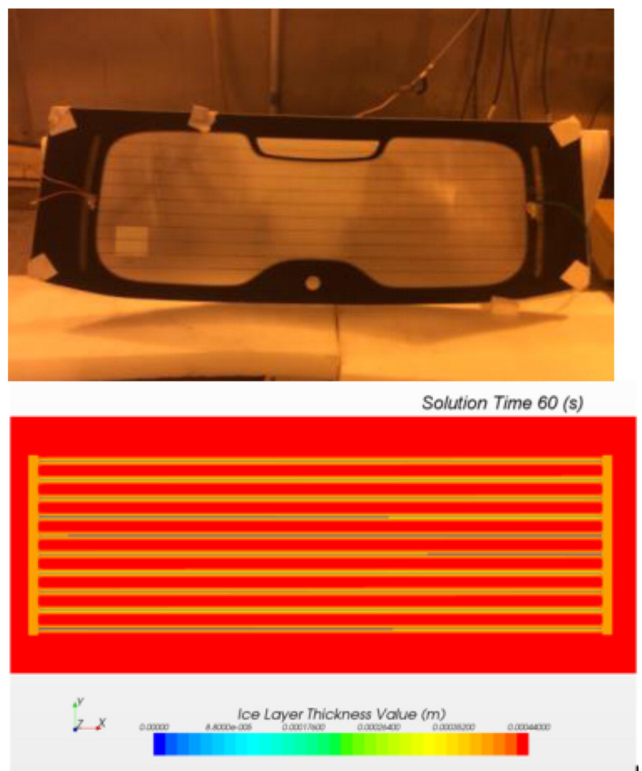

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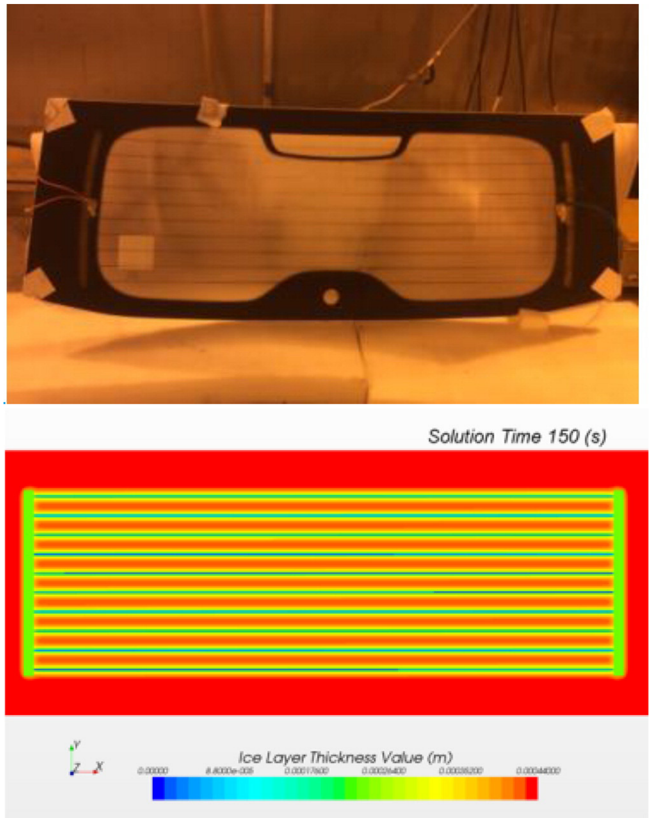

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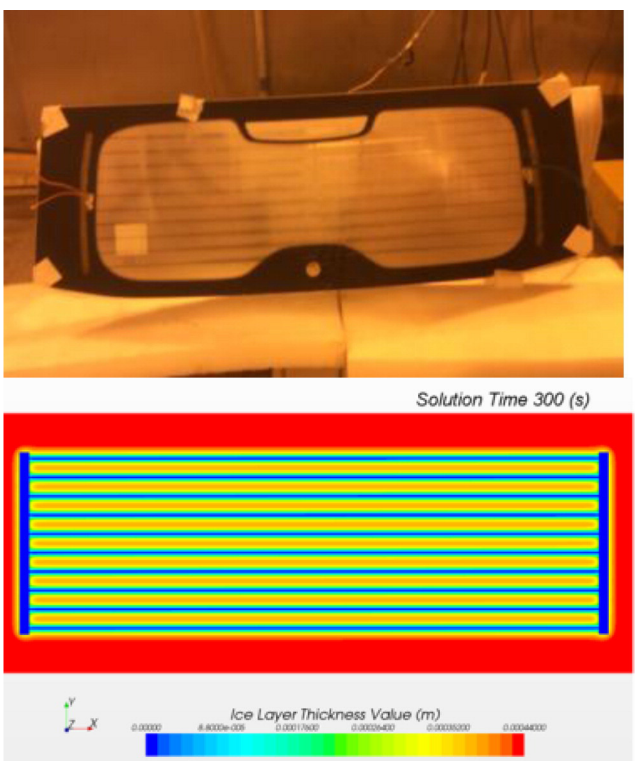

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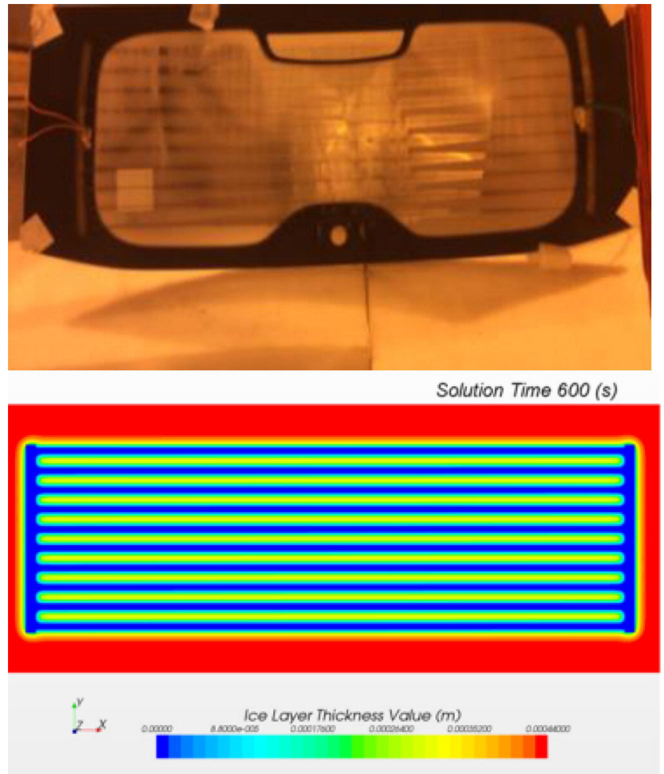

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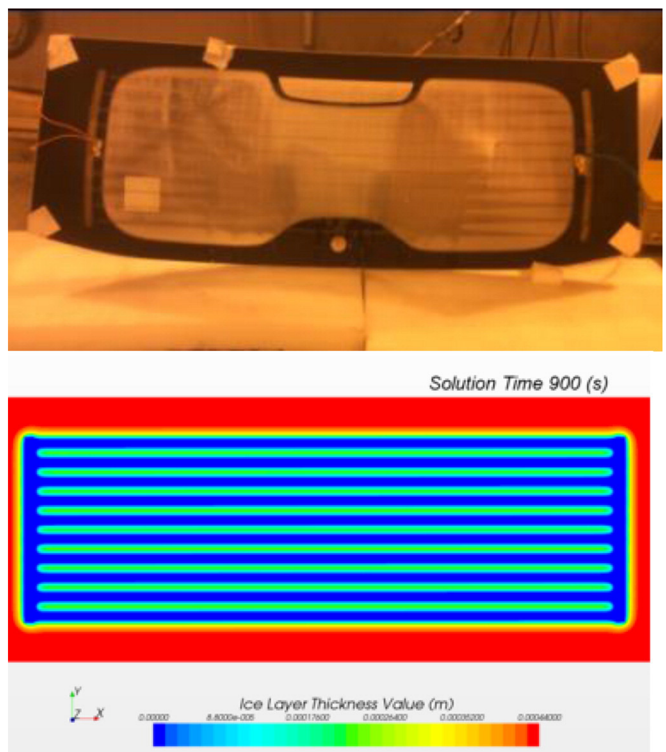

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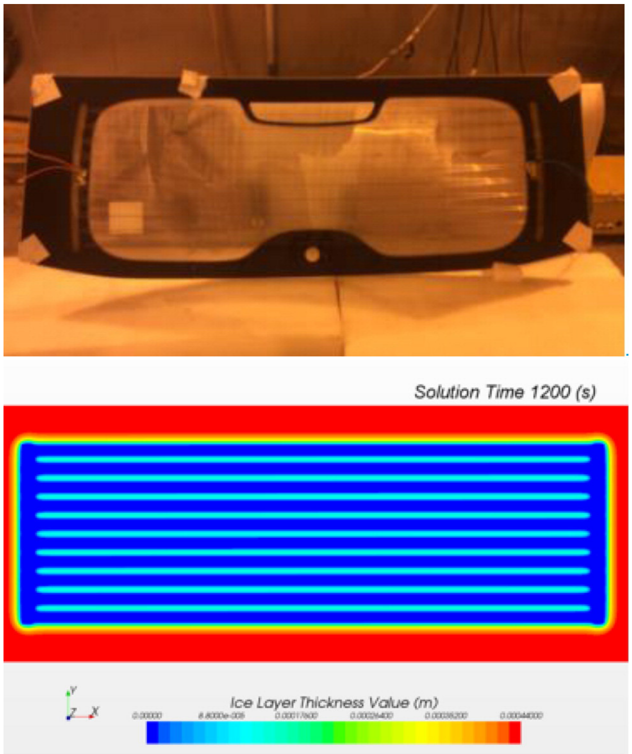

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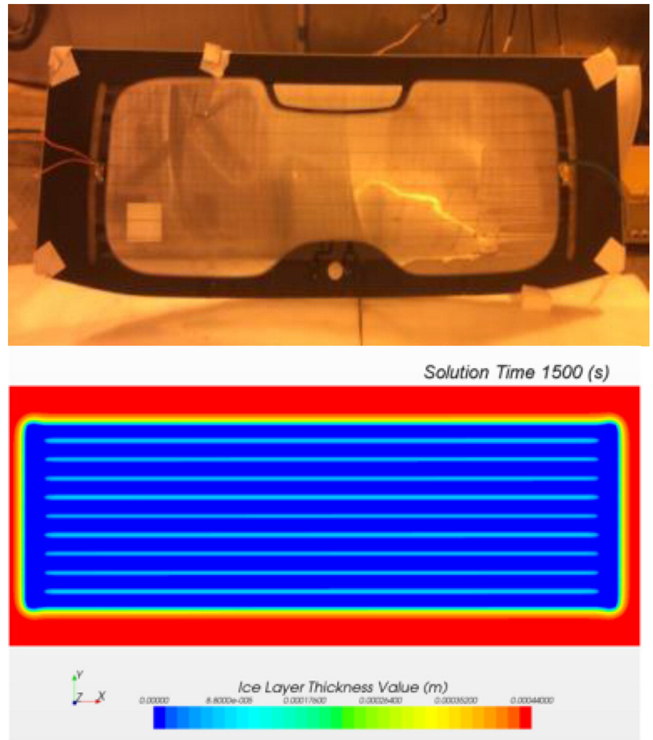

25 min.

30 min.

Figure 5. Test and simulation contours of ice layer thickness value over inorganic rear window at different times

3.2. Simulation and Test Results of PMMA Glazing

As depicted in Fig. 6, simulation results and test results for the PMMA glazing coincide well with each other. Besides, for PMMA glazing, the frost can melt about 30 % after 30 minutes under the voltage of 21V, indicating that the requirement cannot be satisfied. The aforementioned FE model will be used for optimizing the arrangement of heating line of PMMA rear windows to meet the requirement of the standard.

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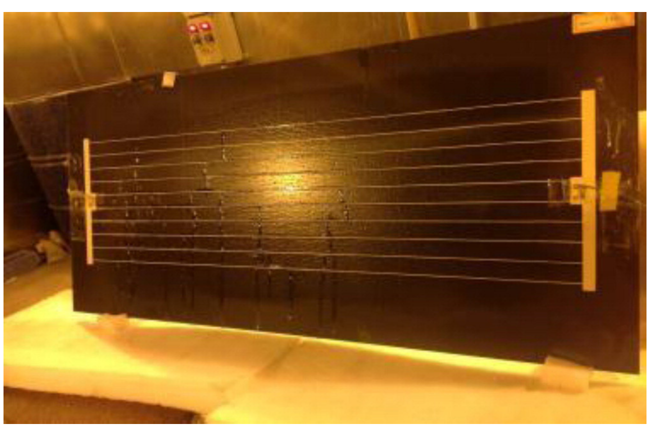

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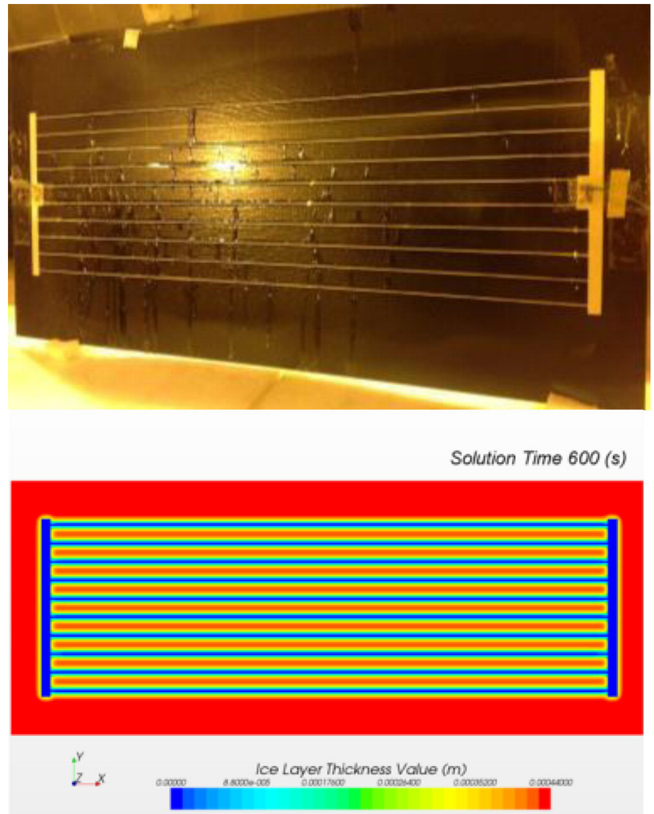

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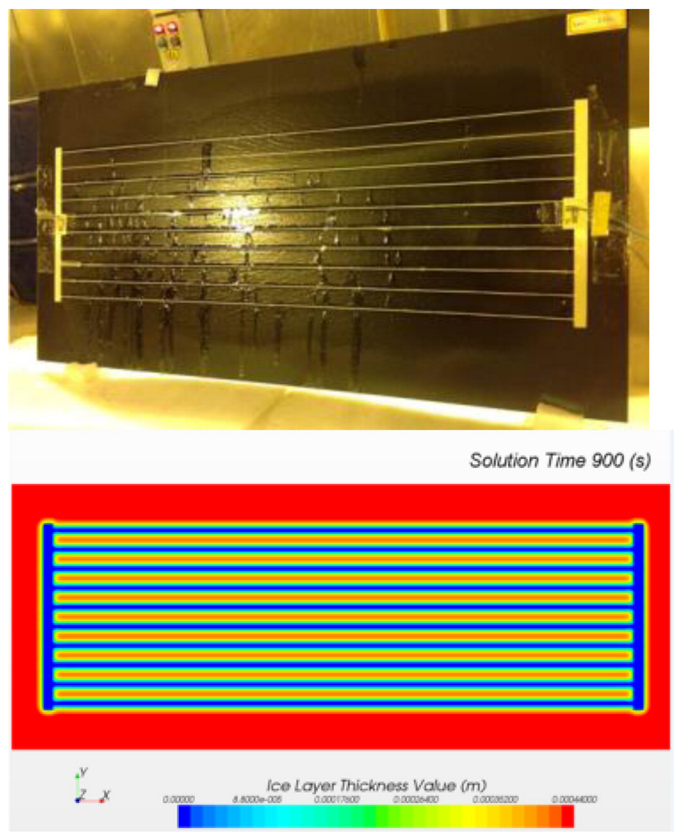

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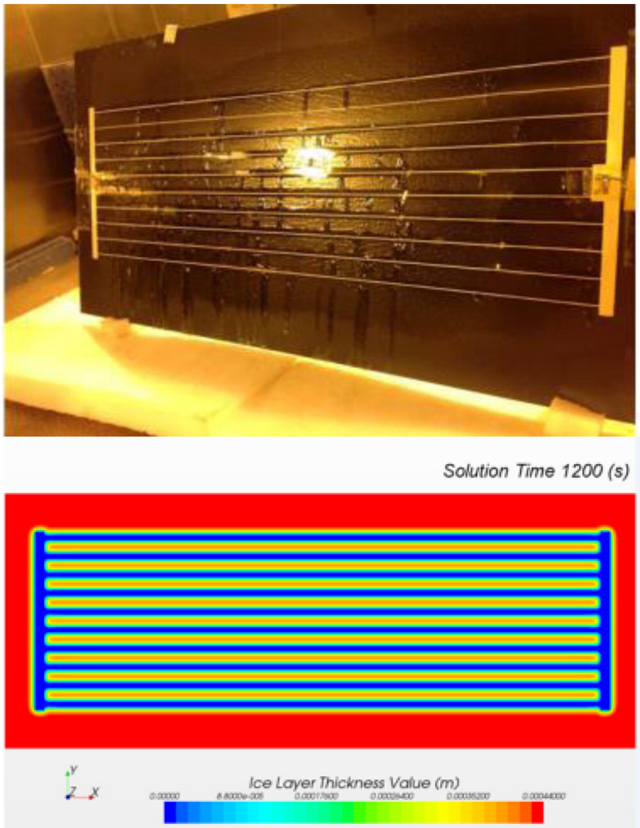

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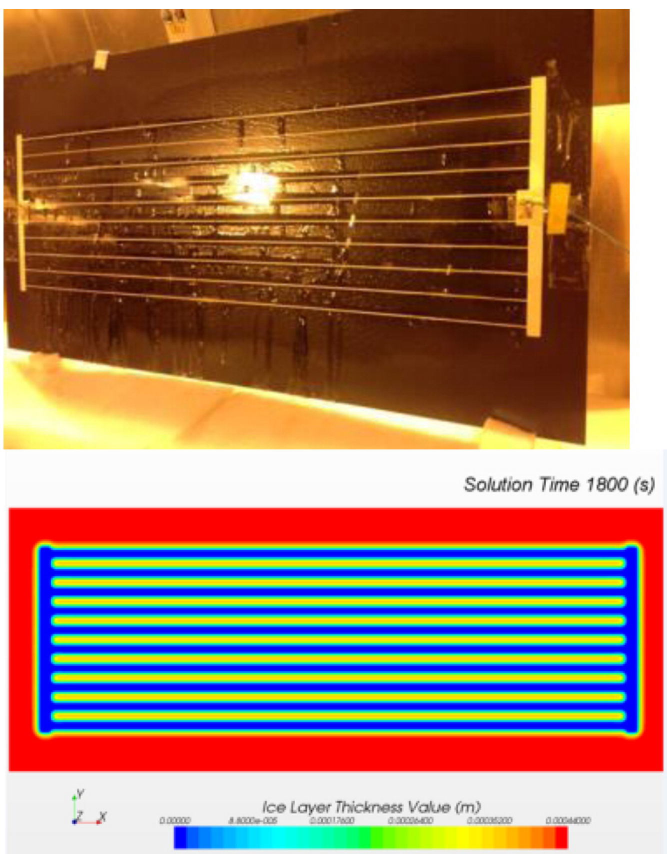

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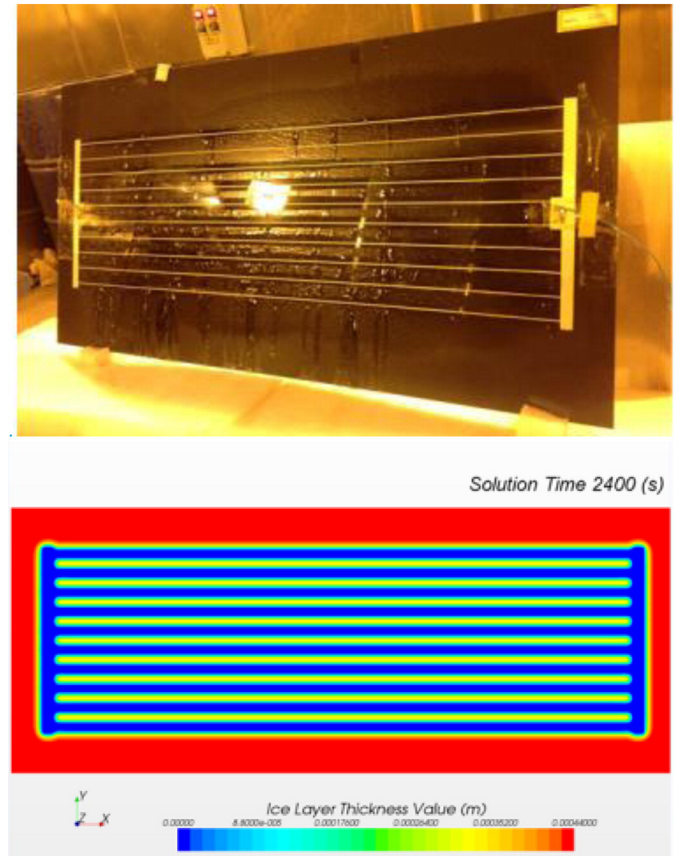

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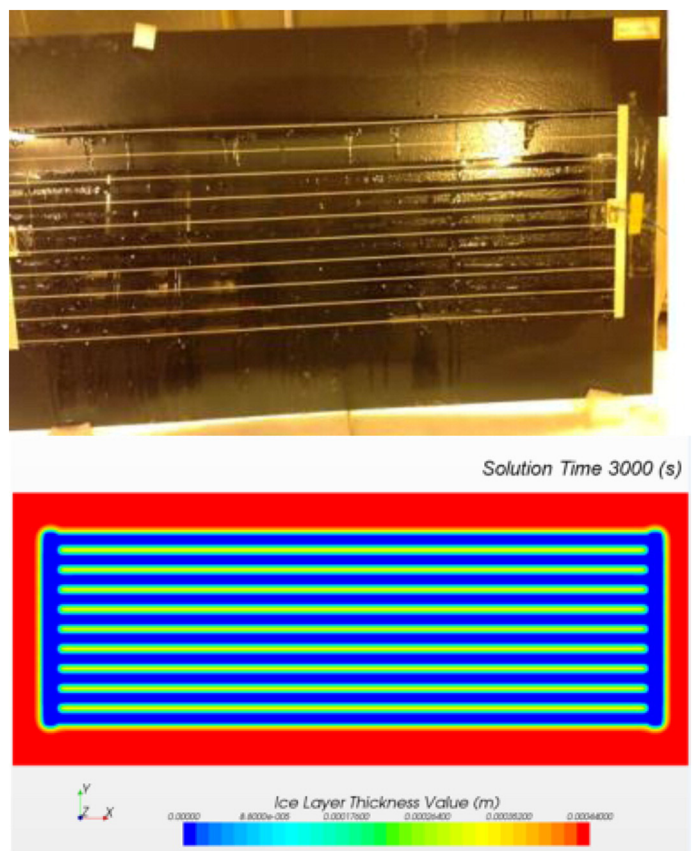

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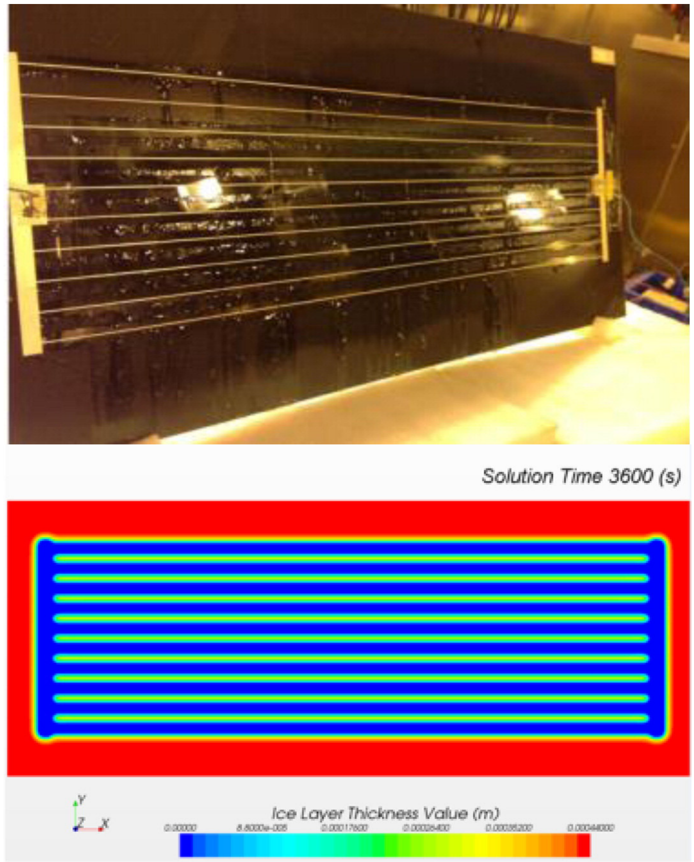

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Figure 6. Test and simulation contours of ice layer thickness value over PMMA rear window at different times

3.3. Defrost Efficiency Improvement of PMMA Glazing

3.3.1. Changing the Voltage to Improve the Efficiency of PMMA Glazing

With the predicted shift to use 42 V in the vehicles [5], the large voltage has the potential to be used to improve the efficiency of PMMA glazing. Besides, according to standard JC/T 672-1997[6], the maximum temperature on the surface of rear window should be below 70°C while the circuit is connected. Therefore, the maximum voltage was determined based on the requirement of maximum temperature test. Then the selected voltage was used to conduct the defrost efficiency test again and check if PMMA glazing under this load can meet the requirement. The procedure of maximum temperature test is described as follows,

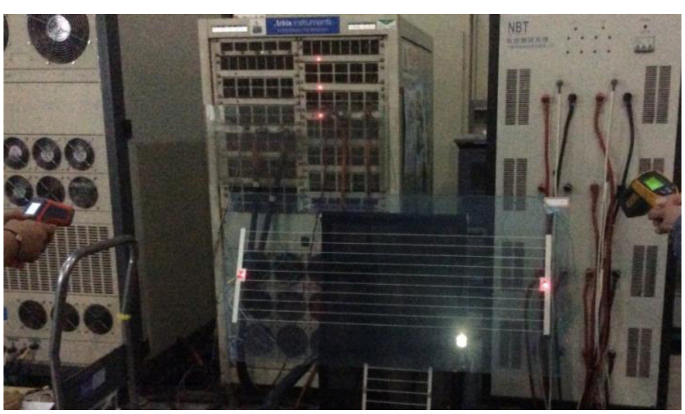


Figure 7. Maximum temperature test

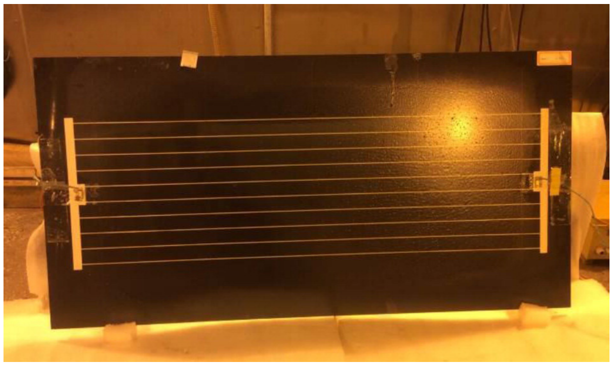
1. Connect the circuit and measure the voltage between two ends using multimeter. Adjust the voltage to 12V.
2. The maximum temperature on the whole surface of PMMA glazing is recorded by temperature measuring probe while the circuit is connected for 20 min.
3. First, cool down the glazing to room temperature. Then adjust the voltage to 12, 18, 20, 21, 23, 25, 26, 27 respectively and repeat step 2 and 3. The recorded temperatures under different voltages are shown in table 2.

Table 2. Maximum temperature under different voltage

Test number	Voltage/V	Maximum temperature/°C	Location of maximum temperature
1	12	30	Thin heating line
2	18	39	Thin heating line
3	20	49	Thin heating line
4	21	53	Thin heating line
5	23	55	Thin heating line
6	25	55.6	Thin heating line
7	26	65	Thin heating line
8	27	68	Thin heating line

When the circuit connected for 40 min with the voltage of 26 V, the maximum temperature on the surface of PMMA glazing is 65 °C. The maximum temperature should be less than 70°C according to the regulation of JC/T 672-1997 [6]. When the circuit was connected for

3 min with the voltage of 27 V, the maximum temperature on the surface of PMMA glazing is 68 °C and the temperature is still increasing. So the voltage of 27 V is not proper for the test and we finally choose the voltage of 26 V in the test. Then the defrost efficiency test was conducted under the voltage of 26 V. As shown in Fig. 8, after 30 minutes, the frost on the surface of PMMA is clear, thus meet the requirement of the standard. It shows that increasing the voltage is a good way to increase the defrost efficiency.



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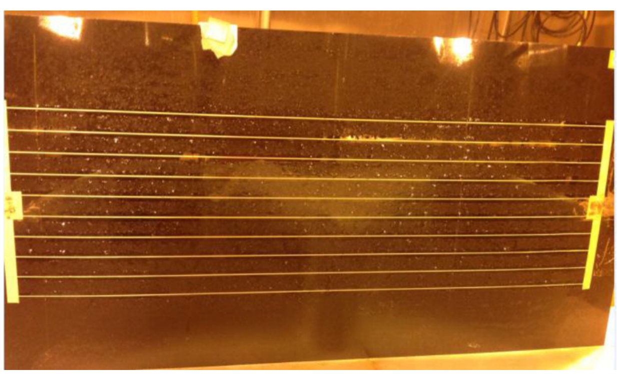

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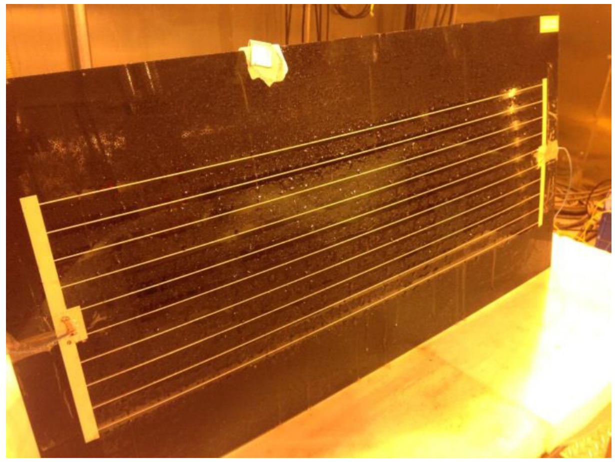

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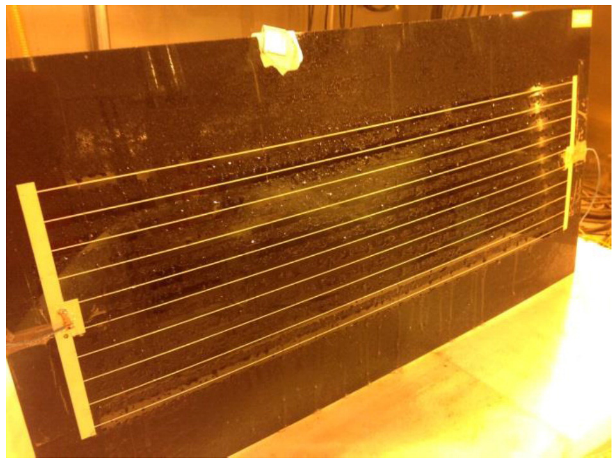

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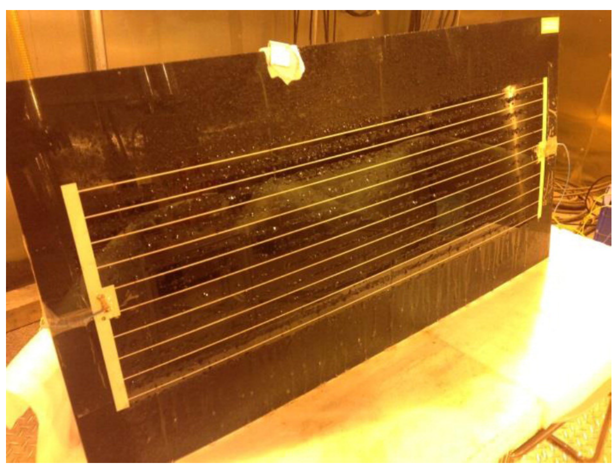

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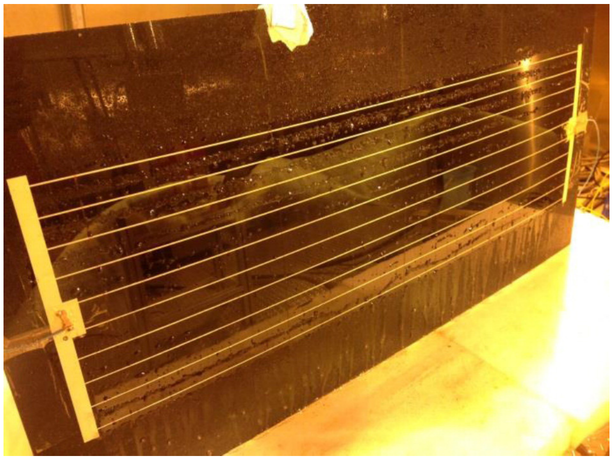

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30 min.

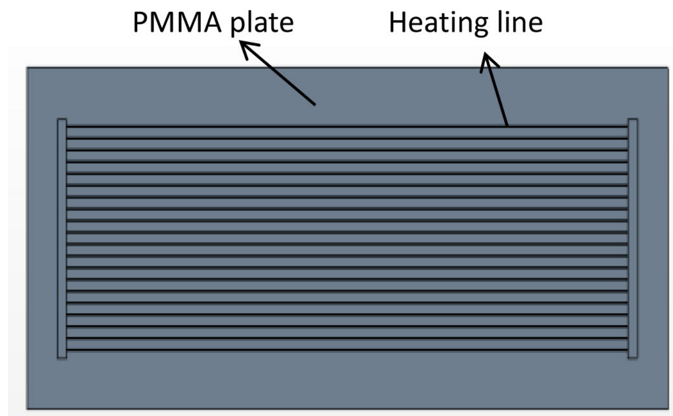
Figure 8. New plan to improve the defrost efficiency of PMMA glazing

3.3.2. Changing the Heating Line Arrangement to Improve the Efficiency of PMMA Glazing

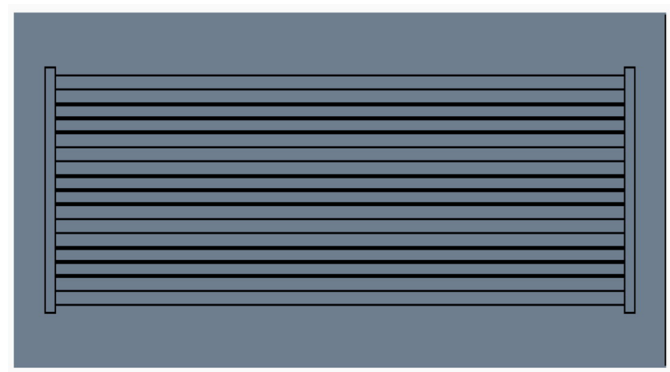
Optimum arrangements of heating line for PMMA glazing is required to meet the defrosting requirement under the voltage of 12V. The width or the number of the heating lines need to be increased to improve the defrost efficiency and not increase the defrost area. By changing the arrangement of heating lines, we found that two plans described in Table 3 and Fig. 9 can meet this demand. Plan 1 maintains the same width with the original plan and decreased the interval of heating line to 13.7 mm, whereas plan 2 increases the width of heating line to 2 mm and changed the interval of that to 16.3 mm.

Table 3. Two heating line arrangements for PMMA rear window

Material of plate	Plan 1	Plan 2
Size of plates	1000*500*4 mm^3	1000*500*4 mm
Number of heating	20	15
Length of heating	875 mm	875 mm
Width of heating	1 mm	2 mm
Interval of heating	13.7 mm	16.3 mm



a. plan 1

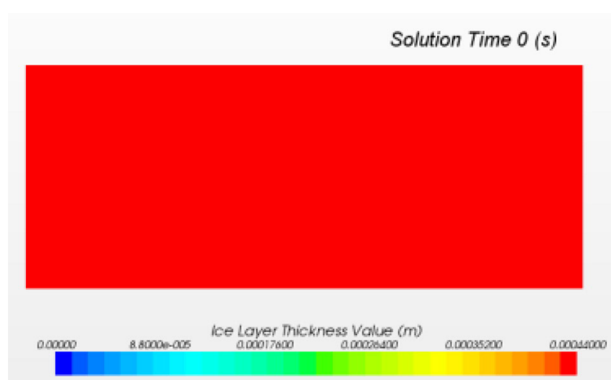


b. Plan 2

Figure 9. New plan to improve the defrost efficiency of PMMA glazing

For plan 1, the defrost efficiency is 95% and the thickness of remaining frost layer is close to 0 after 30min as depicted in Fig. 10(a), which demonstrated that PMMA glazing can meet the requirement of defrosting performance with this arrangement of heating line.

For plan 2, the defrost efficiency is 95% and the thickness of remaining frost layer is close to 0 after 25min as displayed in Fig. 10(b). And after 30min, the defrost efficiency is 100%. So with this arrangement of heating line, PMMA glazing can meet the requirement of defrosting performance.



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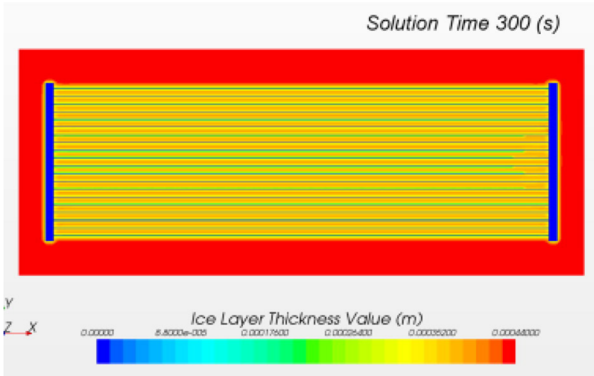

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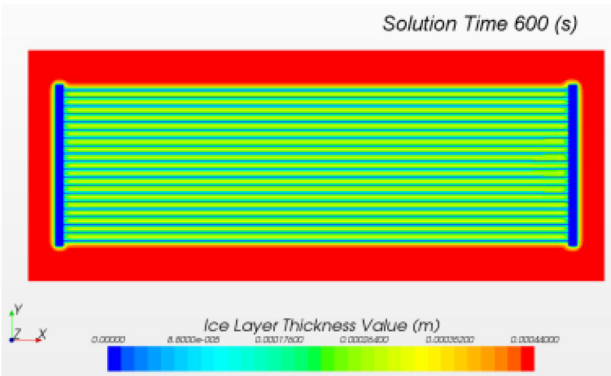

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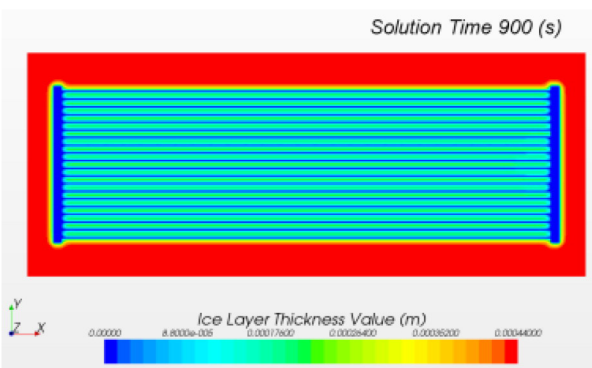

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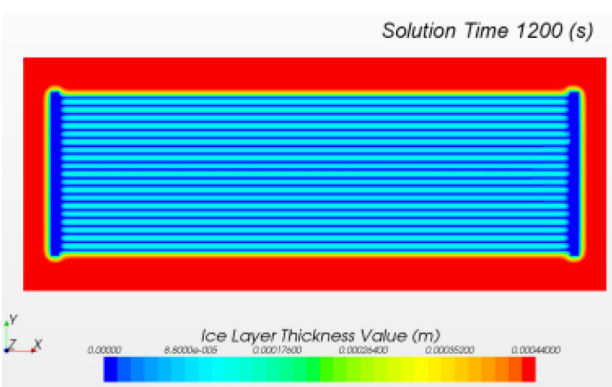

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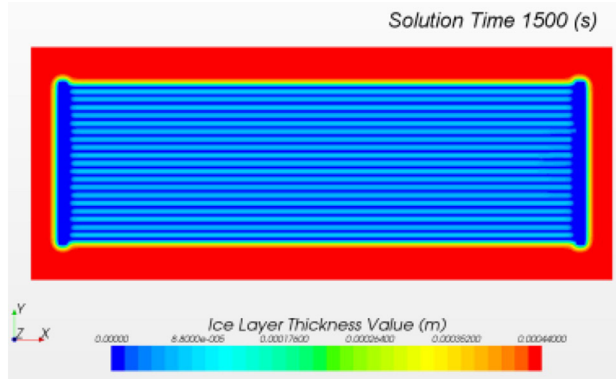

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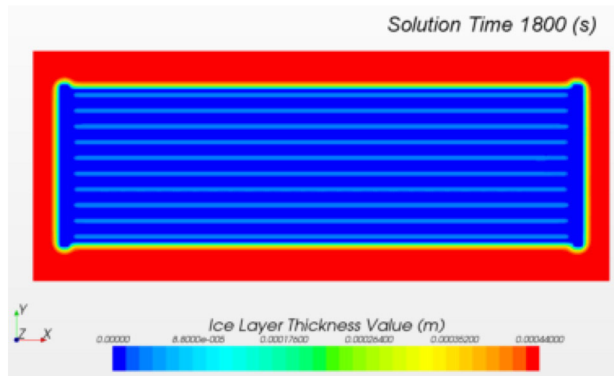

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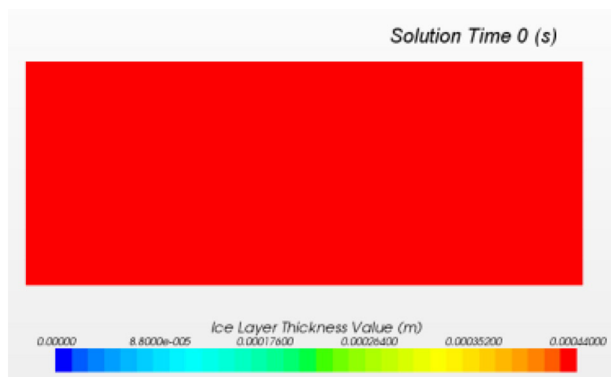
a. Plan 1



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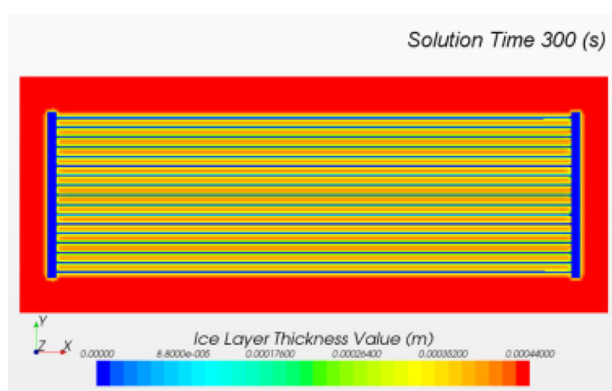

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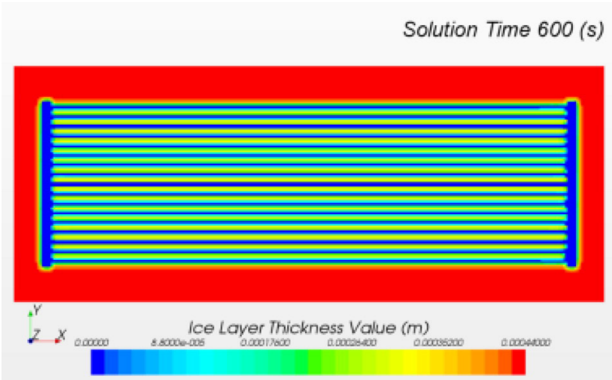

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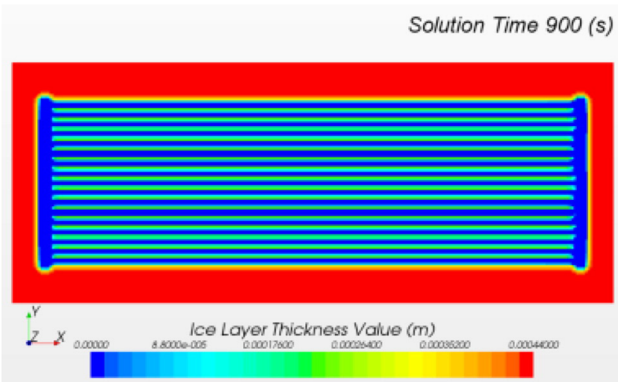

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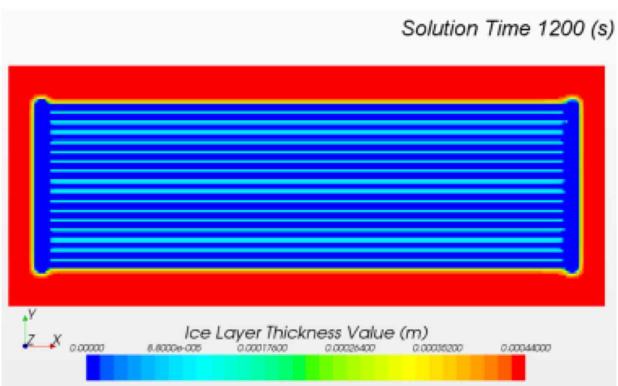

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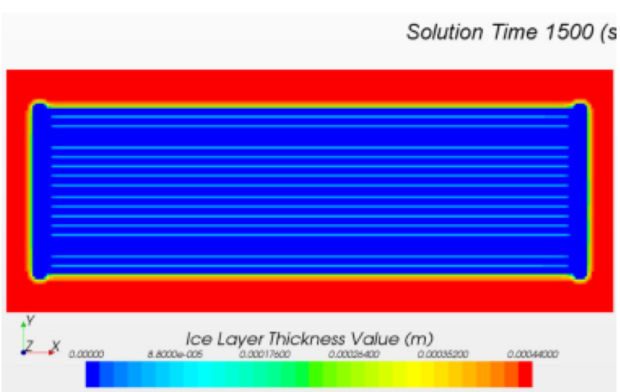

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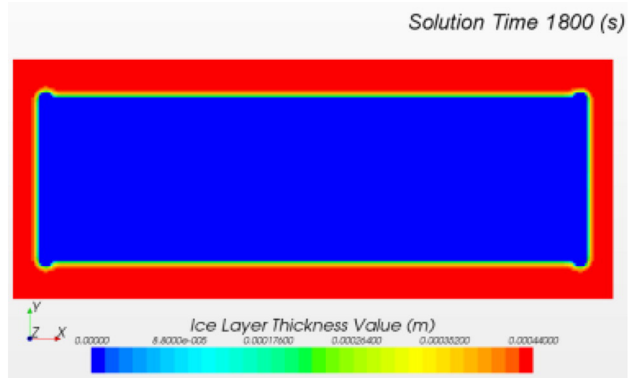

30 min.

b. Plan2

Figure 10. Simulation results for two new plans

4. Conclusions

In this paper, the defrost performance was studied for the rear window of inorganic glass and the PMMA glazing with sintering silver paste for comparison purpose. The PMMA glazing has the same size and same heating line arrangement with the inorganic glass rear window. The details of the main conclusions are described as follows:

1. As shown in Figs. 5 and 6, the simulation results agree well with the experimental results. It can be seen that the frost melts fast at first and slows down gradually in the tests, whereas, the frost melts stably in the simulation. This happened because in the simulation the heat are transferred under the desirable conditions and the effects of environment variables in the chamber were not considered. All these factors can affect the results. But PMMA glass has worse defrost performance than the inorganic glass. PMMA glass has lower heat transfer coefficient than inorganic glass rear window, thus it takes more time to melt the frost during heating on PMMA glazing.
2. The defrost efficiency of PMMA measured by test method is lower and cannot meet the requirement of melting within 30 minutes, as shown in Figs. 5 and 6, indicating that PMMA glazing has poor defrost performance. However, the defrost efficiency can be significantly improved by either increasing the voltage or designing the new arrangement of heating line. Specifically, PMMA under the voltage of 26 V or with the two proposed arrangement of heating lines described in the section 3.3 can melt ice layer within 30 minutes and meet the requirement of the standard.

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