Real-time aerosol chloride deposition measuring device using a conductivity sensor

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Title

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Abstract.

This study proposes a new monitoring method to measure real-time aerosol chloride deposition. The concept of a water candle device is introduced, and the device is manufactured. By continuously generating a thin water film in combination with a conductivity sensor, the device is capable of measuring aerosol chloride deposition in all directions and has a compact design. The water candle device was fully tested in the laboratory and applied to monitor on a bridge. For the laboratory tests, the transport of aerosol in an area near the seashore was simulated to evaluate the accuracy and responsiveness of the device according to the variable wind speed and source salt concentration. For monitoring in the field, the device was implemented at the Thuan Phuoc Bridge, Vietnam, for seven days with a short recording frequency of a few hours. A set of wet candle devices were placed next to the water candle device to compare the results of the two methods. The results of the laboratory test and field monitoring demonstrated a high accuracy and responsiveness of the water candle device to variations in the wind speed and salt concentration of the source. Further, there were only very small differences between the results from the wet and water candle devices.

Keywords.

Real-time aerosol chloride deposition measurement, wet candle method, bridge, aerosol transport, conductivity sensor

1. Introduction

Corrosion is a significant issue for structures, especially in coastal areas. Chloride ions are one of the main factors that cause corrosion (Ahmad, 2006; Revie et al., 2008; Corvo et al., 1995; Silman et al., 1972). High amounts of chloride accumulated on the surface vastly accelerate the corrosion of metal or concrete structures (Corvo et al., 1995; Britton et al., 1976; Foley et al., 1970). Therefore, chloride deposition monitoring is crucial for the proper maintenance of structures. Chloride deposition monitoring is mainly used for the measurement of aerosol chloride deposited on a certain area. Aerosol chloride is generated from diverse locations such as forest, urban area, marine and coastal area. In forest, agricultural areas, aerosol chloride contains in fine particles in biomass burning plumes (Pratt et al., 2011). In industrialized urban areas, metal chlorides contribute as much as 73% to the fine particles emitted in industrial smoke (Moffet et al., 2008a). In marine and coastal area, aerosol chloride is contained in small particles generated from the ocean (Meira et al., 2008; Meira et al., 2006; Hossain et al., 2009; Fitzgerald et al., 1991; Spiel et al., 1996). These particles are transported onto land by the wind and deposited onto structures (Hossain et al., 2009; Gustafsson et al., 2000; Meira et al., 2007; Lee et al., 2006; Delalieux et al., 2006; Meira et al., 2017; Feilu et al., 1999).

There are many methods for monitoring chloride deposition, such as the dry gauze (JIS Z 2382, 1998), DOKEN (N. Kazuhiro and D. Yoshiki 1993), K3 (Lee and Moon 2006), and wet candle (ISO 9225, 2012) methods. The dry gauze, K3, and DOKEN methods utilise a dry gauze to cover a flat surface or a stainless plate to capture the aerosol chloride. The dry gauze method requires a large area of 2 m×2 m and is therefore difficult to install on bridges. The DOKEN and K3 methods have smaller consuming areas of ~0.5 m×0.4 m but have dry gauze or stainless plates installed in a box with one opening. Hence, these methods can collect aerosols mainly coming from one direction perpendicular to the opening. The wet candle device, with a consuming area of 0.5 m×0.5 m, uses a gauze wrapped around a pipe, enabling the collection of aerosols from all directions.

The wet candle method has been applied to aerosol chloride monitoring (Meira et al., 2006; Meira et al., 2017; Anwar Hossain, Easa and Lachemi, 2009). Studies have been conducted by long-term monitoring with monthly or longer sampling frequencies (Lee and Moon, 2006; Meira et al., 2006; Anwar Hossain, Easa and Lachemi, 2009; Morcillo et al., 2000). However, chloride deposition significantly increases in unfavourable weather events, such as typhoons, atmospheric depressions, or even strong winds (Morcillo et al., 2000; Pham et al., 2019; Meira et al., 2007), which usually last for a short time of a few days. Therefore, long sampling frequency data cannot be used to determine the rapid accumulation of aerosol chloride.

The shorter the sampling frequency, the better the chloride deposition evaluation; hence, appropriate maintenance of a structure may be performed. In a recent study (Pham et al. 2019), we carried out the long-term measurement of aerosol chloride in Da Nang city, Vietnam, with a weekly sampling frequency using the wet candle method. The monitored data contained the details of the rapid accumulation of aerosol chloride in a short period of an unfavourable weather event. However, typhoons and depressions can last a week or even a day, and therefore daily or shorter sampling frequency monitoring is required to determine the mechanisms responsible for aerosol chloride accumulation during these weather events. To the best of our knowledge, no study exists on the real-time monitoring of aerosol chloride deposition; hence, it is of great interest to obtain real-time monitoring of chloride deposition.

Measurements using wet candle devices require many operation steps. In the preparation step, each part of the wet candle device is washed to remove any chloride, and the device is carefully covered to avoid contaminants when transported to the site. After the monitoring period, the gauze is carefully collected and placed in distilled water for 24 h before extraction into a small cell for chloride analysis by the adsorption spectroscopy method. The whole measurement process and chloride content analysis requires expert personnel to avoid contamination and to obtain accurate results. Conversely, real-time monitoring requires less operation steps during monitoring and can be conducted by unskilled personnel.

This study proposes a real-time aerosol chloride measuring device. The device collects aerosol chloride, similar to the wet candle device, by a thin water film instead of wet gauze. A conductivity sensor is installed in the device to measure the aerosol chloride in real-time. The device is named a “water candle”, analogous to the wet candle device. The accuracy and responsiveness of the device was tested in a laboratory. In addition, it was successfully implemented in the field in Da Nang city, Vietnam, and the measured results showed good agreement with those of the wet candle device.

2. Methods

2.1 Device concept

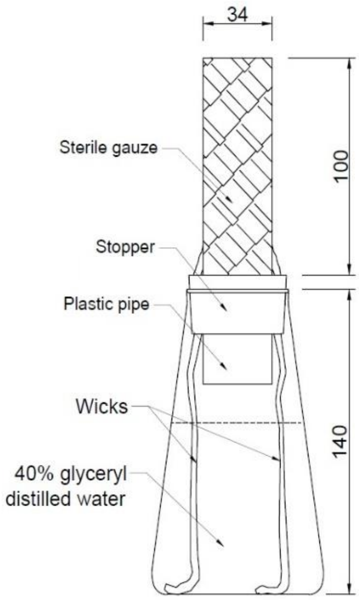

Figure 1 Wet candle device (Pham et al.,2019)

The wet candle method has been employed to measure aerosol chloride (Meira et al., 2006; Meira et al., 2017; Anwar Hossain, Easa and Lachemi, 2009). **Fig. 1** shows the assembly of a wet candle device, which consists of two parts. The upper part includes a plastic pipe covered by gauze to capture the aerosol chloride, and the lower part contains a reservoir of glyceryl-distilled water to maintain the wet condition of the gauze. Because the gauze is kept wet and wrapped around the pipe, it can capture aerosols blown from all directions. After the designated monitoring period, the gauze is placed into a new 600 mL beaker. The glyceryl-distilled water is poured into the same beaker. After rinsing the pipe, flask, and stopper with distilled water, and adding it to the beaker, the contents are adjusted to 500 mL and kept for at least 24 h before the chloride content analysis. The gauze is then wrung to drain water into the beaker. The remaining content is extracted to a small cell for the chloride content analysis by the absorption spectroscopy or chromatography methods.

As described above, the treatment and analysis process for a wet candle sample includes many operation steps, and the cumulative errors from each step can result in large errors of the final analysis result. Therefore, the measurement and chloride content analysis of a wet candle sample requires expertise to obtain accurate results.

This study proposes a new device that replaces the gauze with a thin water film to capture and dissolute aerosols. In this way, the device is applicable to real-time chloride deposition monitoring without any further human intervention after the preparation is completed. This therefore reduces analysis errors and treatment steps, compared with conventional analysis methods. As shown in **Fig. 2**, water is circulated through the device. To perform the chloride content analysis, a conductivity sensor is immersed into the reservoir to record the changes in the conductivity caused by dissolved aerosol chloride ions. Although this concept consumes electricity to maintain the water film, it can eliminate almost all of the disadvantages of the wet candle method.

Figure 2 shows the assembly of the new device consisting of a cylinder glass pipe; beaker containing distilled water and 40% glyceryl; 12 W pump to circulate the solution from the beaker to the glass pipe, and back to the beaker to form a thin water film around the surface of the pipe; conductivity sensor to monitor the change in the conductivity of solution; and stopper to support and fix the sensor and pipe. Moreover, the glass pipe is connected to the pump through a small plastic tube. A rubber plug is attached to the top of the glass pipe to modify the run-out water to produce an equal-distribution of the water film (the so-called floating plug). The surface of the glass pipe was brushed by sand-paper, No. 80, to maintain an equal distribution of the water film. The thickness of the water film is minimal due to the dispersal by strong wind. The thickness can be adjusted by the pumping speed of the pump via a valve. If the out-put rate is high, the thickness of water film becomes too large, causing water film easily blown out by strong wind. On the contrary, if the out-put rate is low, the run-out of water splits into small individual water streams and unable to keep uniform water film overall the surface of the glass pipe. Preliminary measurement showed that the width of water film was appropriate at 1 – 1.5 mm. As a result, the water out-put rate was chosen at 25 mL s^{-1}.

Before starting the new device, all components were washed with distilled water, and the pump was fixed to the bottom of beaker. The solution in water candle device was circulated through the pump until there is no change of conductivity (about 2 hours). This is to ensure there are no contaminants effecting the conductivity. A volume of 400 mL of 40% glyceryl distilled water is placed in beaker, and the connecting pipe is attached to the pump by a plastic tube and fixed to the stopper. The stopper is adjusted to fix it to the beaker wall. The conductivity sensor is attached to and carried by the stopper and merged into the solution. The accuracy and responsiveness of the device were tested in the laboratory and implemented in the field at Thuan Phuoc Bridge, Da Nang city, for seven days.

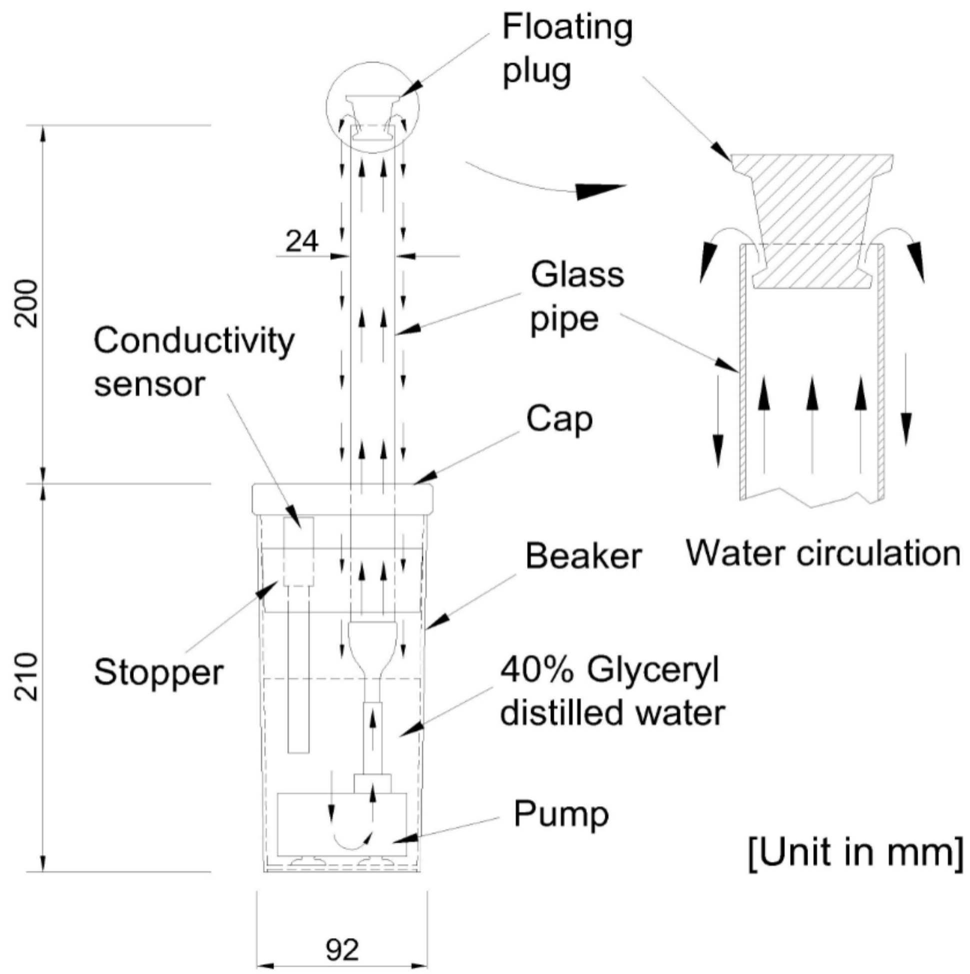

Figure 2 Real-time aerosol chloride measuring device

2.2 Calibration of the conductivity sensor

2.2.1 Conductivity sensor

In this study, a conductivity sensor was applied to measure changes in the conductivity of the solution with a low chloride content. The components of conductivity sensor include a conductivity cell which consists of two electrodes, and a conductivity meter to record the signal from conductivity cell. When the conductivity sensor is immersed into the solution, an alternating voltage signal (*V*) at 1 kHz is applied to the cell. The response electrical current (*I*) is measured and conductance (*I/V*) calculated. The conductivity meter utilises the cell constant, and the conductivity of the sample is finally determined. In this study, the conductivity electrode (model 9382-10D; Horiba Techno Company, Japan) and a conductivity meter (model ES-14; Horiba Techno Company, Japan) was used. The sensor contains a 3-pole cell with a cell constant of 100 m^{-1}.

2.2.2 Calibration of conductivity sensor

Before the conductivity sensor calibration was conducted, the sensor was conditioned in distilled water for 1 h. During the calibration test, the sensor was simultaneously immersed into solutions of sodium chloride with concentrations ranging from 10^{-6} to 10^{-4} M. This chloride concentration range is based on chloride deposition data of a recent study on long-term aerosol chloride monitoring with weekly sampling frequency in Da Nang city, Vietnam (Pham et al. 2019). All measurements were conducted with a stirred solution in chamber conditions at 18 °C, 32% Rh. The measurement results were recorded when the conductivity of solution becomes constant.

The calibration of the conductivity sensor is shown in **Fig. 3**, with a perfect linear relationship between the conductivity and chloride concentration of the test solutions. Therefore, the sensor can be used to measure samples with a low chloride content (10^{-6} to 10^{-4}M).

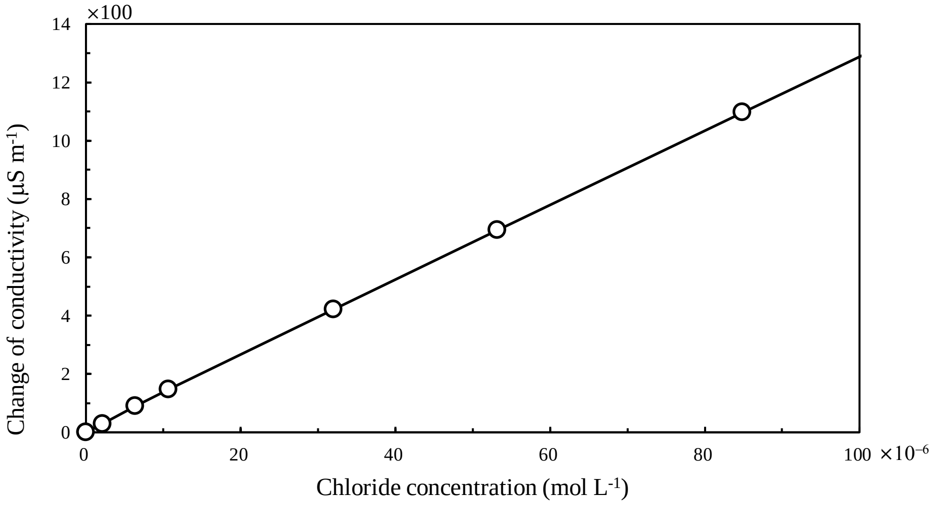

Figure 3 Relationship between conductivity and chloride concentration

The conductivity meter used in this study has a high measurement resolution of 0.01 μS cm^{-1}, and thus can detect small changes in chloride ion concentrations, up to 0.1×10^{-6} mol L^{-1}. In our recent research study on long-term monitoring of chloride aerosol (Pham et al. 2019) with a weekly sampling frequency, the absorption spectroscopy method was applied for the chloride analysis. The Absorption spectroscopy device (mode Lamda-9000; Kyoritsu chemical-check Lab., Corp., Japan) and reagent LR-Cl (containing Ag_2SO_4) were used with measurement resolutions of 0.6×10^{-6} mol L^{-1}. Therefore, the conductivity sensor in this study can detect more detailed changes in the chloride ion concentration, compared with those obtained by the absorption spectroscopy method.

3. Test

3.1 Laboratory test

The salt aerosol entrainment in an area near the seashore was studied, as salt aerosol generated from the sea is stirred up and entrained inland by wind (Centre, 1996; Spiel and De Leeuw, 1996; Leeuw, 1986). To examine the accuracy and responsiveness of the proposed device, laboratory tests were conducted that simulate salt aerosol entrainment. The tests were composed of three main parts: a salinity aerosol supplier, a wind generator, and the water candle device, as shown in **Fig. 4**.

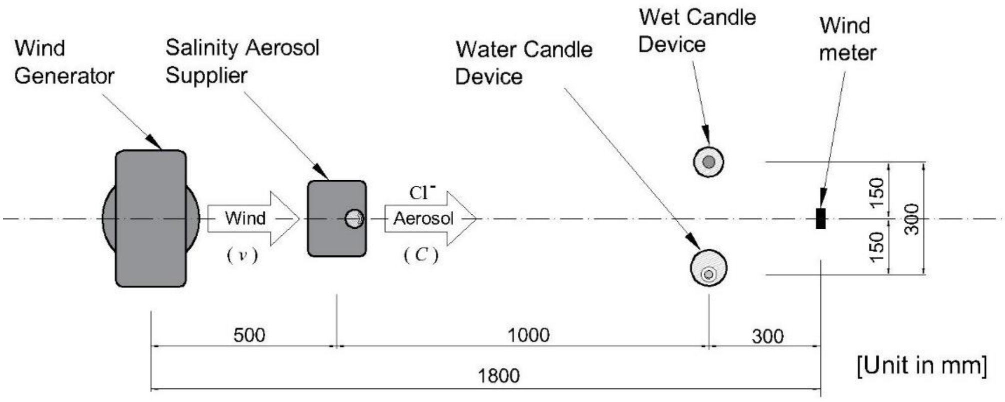

Figure 4 Layout of laboratory test

Figure 4 shows the laboratory test layout. An atomiser (mode 450CH; Levoit Company, USA) with an aerosol output rate of 45 ml h^{-1} was used as the aerosol supplier. An electrical fan (mode AM06DC30WS; Dyson Company, Japan) with stable and adjustable 10-level wind speed output was utilised as the wind generator. The output wind speed ranged from 0.7 to 2.2 m s^{-1}. In every test, a wet candle device was placed next to the water candle device to compare the measured deposition rates by both methods. A wind meter (mode Kestrel 5500-link; Mistral instruments Company, USA) was placed behind the two measuring devices to record the wind speed. Before measuring with the proposed device, a preliminary test was conducted to determine the best positions of the components for which the wind speed was stable. All of the equipment and meters were placed at a height of 1.5 m from the ground. All tests were conducted in a room with constant temperature and a humidity of 18 °C and 32% Rh without any other airflow. The deposited salinity amount was calculated using the solution conductivity inside the beaker and calibration graphs.

3.1.1 Accuracy test

The device accuracy was tested using certain values of the wind and source salt concentrations. Three different source salt concentrations were used: 3.5%, 17.5%, and 35%. The output wind speed of an electrical fan was adjusted to two levels: levels two (~1 m s^{-1}) and ten (~2 m s^{-1}). Each test was conducted for 60 min. The conductivity and wind speed were recorded every 1 min and 5 s, respectively. After each test, the wet candle device was treated and analysed based on the standard (ISO 9225, 2012).

3.1.2 Responsiveness test

The tests were aimed at evaluating the device responsiveness due to changes in the wind speed for different source salinity concentrations. The tests were conducted with two salinity sources with salt concentrations of 3.5% and 35%. For each salinity source, two tests were performed with ascending wind speeds from wind levels one to ten, and descending wind speeds from levels ten to level one. The ascending and descending steps were 10 mins, thus each test took 100 min.

3.2 Field test

After the laboratory tests, the device was implemented in a bridge to test the applicability in the field. The device was applied to the monitoring of the Thuan Phuoc Bridge in Da Nang city, Vietnam (**Fig. 5**). Thuan Phuoc Bridge is the longest suspension bridge in Vietnam, with a main span length of 405 m and deck

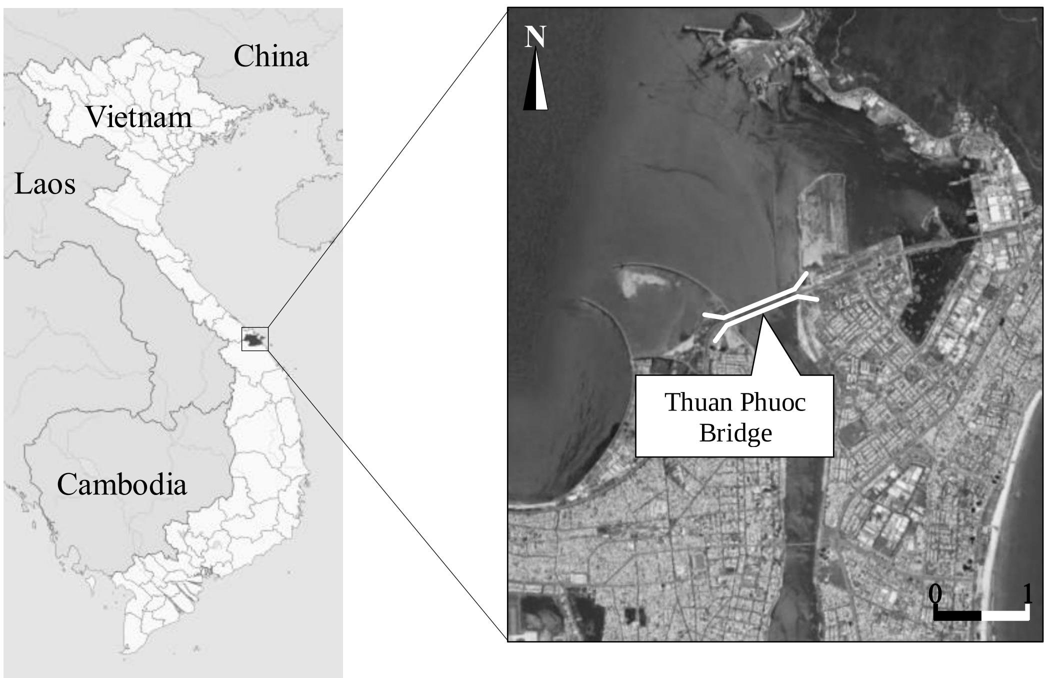

Figure 5 Location of Thuan Phuoc Bridge

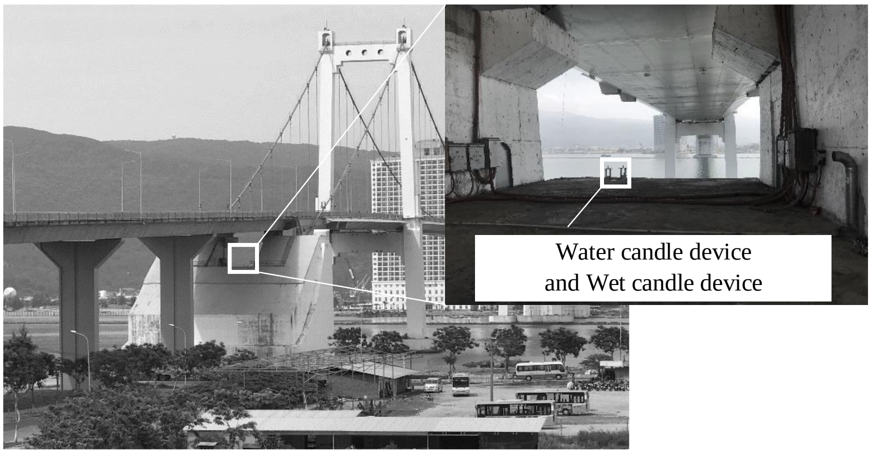

Figure 6 Install location of wet and water candle device

elevation of 27 m. The bridge is located far from the industrial zone, at the river mouth of the Han River. Therefore, the corrosive impact of the marine environment is one of greatest maintenance issues of this bridge. The measurement system was set on the anchor in front of cable fixing room of Thuan Phuoc Bridge. This zone is most important part of a suspension bridge. The height of anchor is 27 m from sea level. The device was placed into a wooden device holder, as shown in **Fig. 7**. The whole apparatus was placed on the South abutment of the bridge at an elevation of 20 m (**Fig. 6**). A wet candle device was also placed next to the device to compare the resulting data.

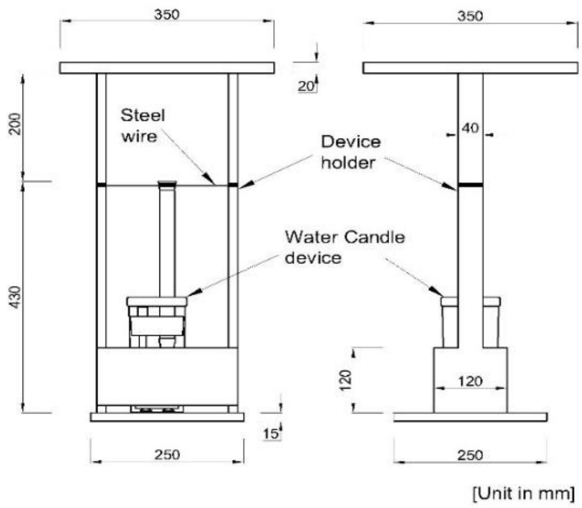

Figure 7 Assembly of water candle

In order to keep water film evenly distributed on the surface of the glass pipe in all condition of unfavorable weather events such as strong wind, typhoon, strong gust etc., the horizontal balancing of the supporting frame was checked and adjusted by a horizontal balance ruler prior to the initial of measurement; the supporting frame and the floating plug were fixed on concrete ground by steel wires to immobilize the device during strong wind (**Fig.7**).

The measurements were conducted over seven days from May 8, 2018 to May 15, 2018, which is during the early period of the dry season. The data were recorded at 6:00, 10:00, 13:00, 16:00, 19:00, and 23:00 every day. Due to the considerable evaporation of water, 50 mL of 40% glyceryl- distilled water was poured into the beaker every day. The chloride amount was calculated by the calibration line of the conductivity sensor, and the volume of the solution was calculated from the solution height. The meteorological data, such as the temperature, relative humidity, and wind speed, of Da Nang city during the monitoring period, obtained from a local meteorological station were used for the analysis.

4. Results and Discussion

4.1 Laboratory Measurements

4.1.1. Accuracy test

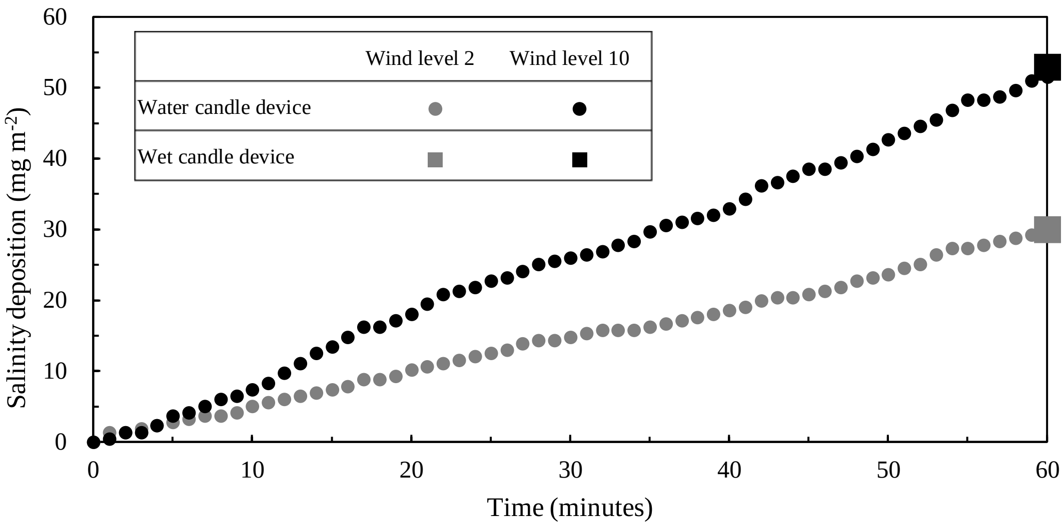

Figure 8 Variation of salinity deposition with time at wind speed levels 2 and 10 (source salt 3.5%)

Figure 8 shows the measured results of the salinity deposition and wind speed of the tests 3.5–2 and 3.5–10. The salinity deposition is calculated using the ratio of the total deposited salinity and total aerosol collecting area of the water or wet candles. In **Fig. 8**, there is an almost linear increase in the salinity deposition in both tests. The wind speeds in the tests 3.5–2 and 3.5–10 were 1.0 and 2.1 m s^{-1}, respectively, and both had average ±0.1 m s^{-1} variations. The salinity depositions measured by the water candle device in the tests 3.5–2 and 3.5–10 were 30.2 and 51.5 mg m^{-2}, respectively. The salinity depositions measured by the wet candle device in the tests 3.5–2 and 3.5–10 were 30.0 and 52.9 mg m^{-2}, respectively. Therefore results from the water candle device are in good agreement with the results of the wet candle device.

Table 1 Comparison of measured results of salinity deposition by the wet and water candle devices

Salt concentration	3.5%		17.5%		35.0%
Wind level	2	10	2	10	10
Wet candle device (WeCD) (mg m^{-2})	30	53	152	253	523
Water candle device (WaCD) (mg m^{-2})	30	52	147	250	526
Difference rate of WaCD to WeCD (%)	0.7	-2.5	-3.0	-1.1	0.7

The results using the water and wet candle devices of other tests are listed and compared in **Table 1**. This table shows the same results for the salinity deposition measured by both devices, with small differences from 0.7% to 3.0%.

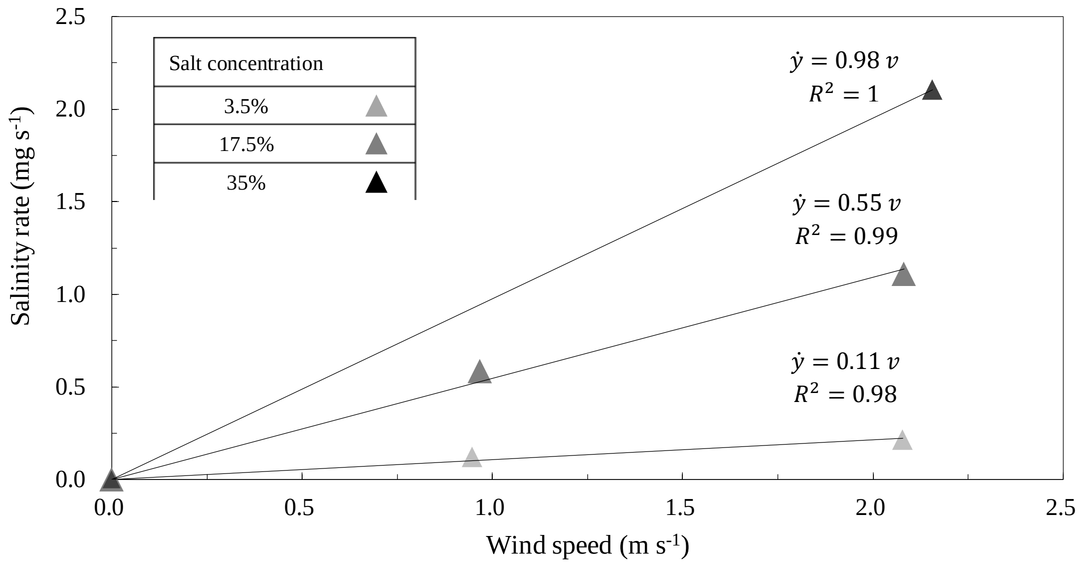

Figure 9 Salinity rate as a function of wind speed

Table 2 shows the salinity rates [salinity deposited per time unit ($\dot{y}$)] for varying average wind speeds (levels 2 and 10) for five tests. The average level 2 wind speeds were 0.95 and 0.97 m s^{-1} for salt concentrations of 3.5% and 17.5%, respectively. The average level 10 wind speeds were 2.08, 2.08, and 2.16 m s^{-1} in the tests with salt concentrations of 3.5%, 17.5%, and 35% respectively, which were almost double those of the level 2 wind speeds. The salinity rates ($\dot{y}$) in the level 10 wind speed tests were almost double those of the level 2 wind speed test, which were 0.12 mg s^{-1} and 0.21 mg s^{-1} (salt 3.5%); and 1.11 and 0.59 mg s^{-1} (salt 17.5%). **Fig. 9** shows the linear relationship between the salinity rate (α) with the wind speed (v) for each salt concentration:

$$\dot{y} \propto v. \qquad (1)$$

Table 2 Salinity rates ($\dot{y}$) due to wind speed and source salt concentration

Salt concentration (%)	3.5%		17.5%		35.0%	
Wind Level	Average wind speed (m s^{-1})	Salinity rate (g s^{-1})	Average wind speed (m s^{-1})	Salinity rate (g s^{-1})	Average wind speed (m s^{-1})	Salinity rate (g s^{-1})
2	0.95	0.12	0.97	0.59		
10	2.08	0.21	2.08	1.11	2.16	2.11

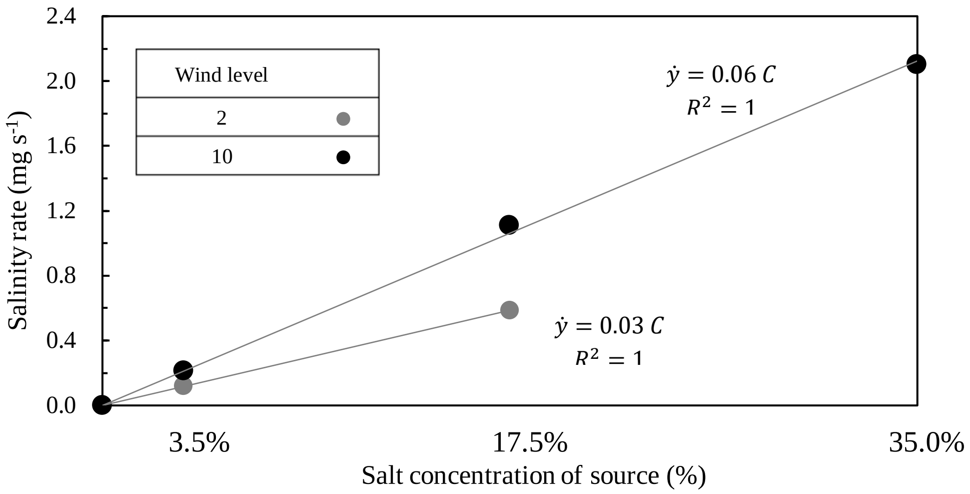

Figure 10 Salinity rate as a function of the source salt concentration

For the level 10 wind speed, the measured salinity rate for a salt concentration of 3.5% was 0.21 g s^{-1}, which was ~5 and ~10 times lower than those of the 17.5% and 35% cases; 1.11 and 2.11 g s^{-1}, respectively. This tendency is also clearly observed in **Fig. 10**, which shows that the salinity rate is proportional to the salt concentration source:

$$\dot{y} \propto C. \qquad (2)$$

Using equations (1) and (2), the salinity rate can therefore be expressed as follows:

$$\dot{y} = \beta v\, C \qquad (3)$$

where y is the total deposited salinity on the measuring device (mg); $\dot{y}$ is the salinity rate (mg s^{-1}); v is the wind speed (m s^{-1}); C is the salt content of the salinity source (%); and β is the distribution coefficient (mg m^{-1}).

The distribution coefficient (β) was calculated for five tests using equation (3). The calculated results are shown in **Table 3**. Identified β by each test condition are not so much different each other (0.0029 – 0.0038) and not so much different from the identified β by all test data (0.0032). β can be considered as a constant and identified value by all tests is used following analysis.

Table 3 Distribution coefficient (β) calculated for five tests using equation (3)

	Salinity concentration of source (%)				
	3.5%		17.5%		35.0%
Average wind speed (m s^{-1})	0.95	2.08	0.97	2.08	2.16
Distribution coefficient (β) (mg m^{-1})	0.0038	0.0029	0.0036	0.0029	0.0029
β identified by all data (mg m^{-1})	0.0032				

The total deposited salinity for a test time T is obtained by integrating equation (3):

$$y = \int_{t=0}^{T} \dot{y} dt = \beta \int_{t=0}^{T} Cv dt \ . \quad (4)$$

4.1.2 Responsiveness test

An analysis of the deposited salinity amount was carried out to compare the results of the responsiveness tests. As each ascending/descending step was 10 min, and there were ten wind speed levels in total, the deposited salinity amount, as defined by equation (4), was calculated for each wind speed level with time intervals of 10 min, as follows:

$$y = \sum_{i=1}^{10} y_i = \beta \sum_{i=1}^{10} Cv_i \Delta t, \quad (5)$$

where i is the time interval order, y_i is the amount of salinity deposited (mg) in the i-th time interval, v_i is the average wind speed (m s^{-1}) in the i-th time interval, and β is salinity distribution coefficient (mg m^{-1}) (see **Table 3**).

Table 4 Average wind speed and standard deviation for the two cases, ascending and descending, with 10 min intervals (salinity source: 35%) (Unit in m s^{-1})

Wind level		1	2	3	4	5	6	7	8	9	10
Ascending	Average	0.8	0.9	1.0	1.2	1.3	1.4	1.6	1.7	1.9	2.0
	Max	0.8	1.0	1.1	1.3	1.4	1.5	1.7	1.8	2.0	2.1
	Min	0.7	0.8	1.0	1.1	1.2	1.3	1.5	1.6	1.8	1.9

Wind level		10	9	8	7	6	5	4	3	2	1
Descending	Average	2.1	2.0	1.8	1.7	1.5	1.4	1.3	1.1	1.0	0.8
	Max	2.3	2.1	2.0	1.8	1.6	1.5	1.4	1.2	1.1	0.9
	Min	2.0	1.9	1.7	1.5	1.4	1.3	1.2	1.0	0.8	0.7

Table 4 shows the average, maximum, and minimum wind speeds for the two cases; ascending and descending, for 10 min intervals (salinity source: 35%). The scatter of each wind level was small with variations of ±0.1 to ±0.2 m s^{-1}.

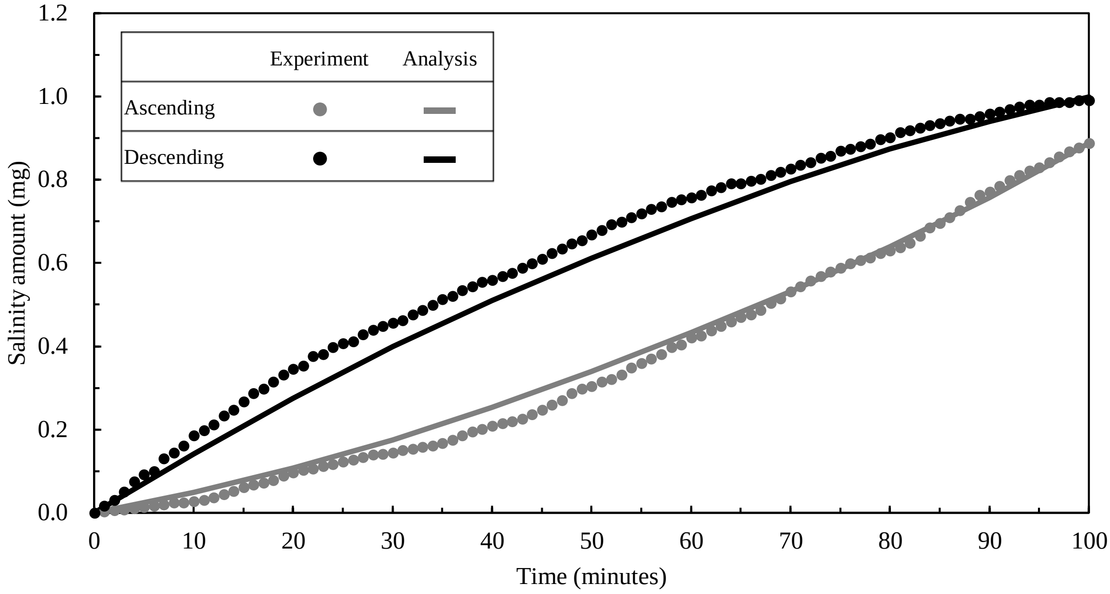

Figure 11 Variation of salinity deposition amount with ascending and descending of wind speed (Salt source 3.5%)

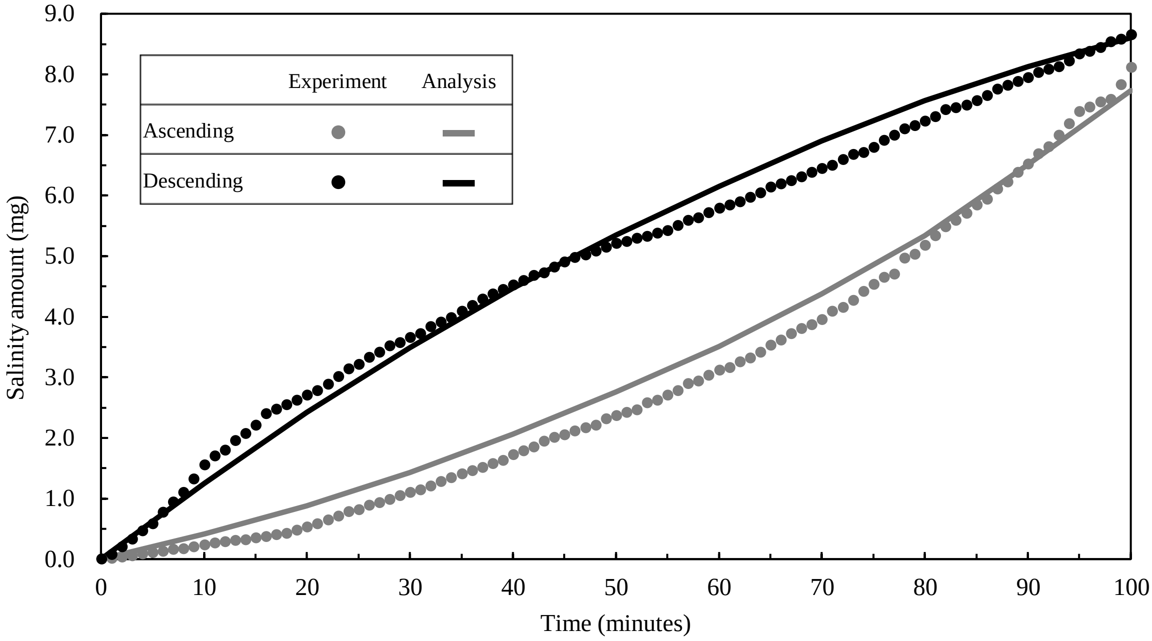

Figure 12 Variation of salinity deposition amount with ascending and descending of wind speed (Salt source 35%)

Figures 11 and **12** show the analysis and measurement results of the deposited salinity amounts for ascending and descending wind speeds for the 3.5% and 35% salt concentrations, respectively. For the 3.5% salt concentration, the deposited salinity amounts of the ascending and descending wind speeds were 0.90 and 0.99 mg, corresponding to analytically calculated values 0.89 and 1.00 mg, respectively. For a salt concentration of 35%, the deposited salinity amounts of increasing and decreasing wind speeds were 8.12 and 8.65 mg, corresponding to analytically calculated values 7.73 and 8.60 mg, respectively. There were small differences between experiment data and analysis data during the measuring period. This may be due to two main causes. One of them is wind velocity, for analysis it was assumed that the wind speed was constant during whole one segment of time. But in reality, wind velocity had time lag to reach set velocity and had fluctuation. Another cause is time lag after aerosol reach to the capturing water film and dilute into bottle of water then detected by the conductivity sensor. In analysis this is not considered.

The plots showed good agreements between the analysis and measurement results. For the ascending wind speed case, the accumulated salinity followed a polygonal line, with increasing steepness with time. Conversely, the steepness of the polygonal line was more gradual with time for the descending case. This is because for increasing/decreasing wind speeds, the salinity rate also increases/decreases, leading to a different rate of increase for the deposited salinity. Therefore, the device is capable of responding to changes in the salinity deposition rate due to wind speed variations.

Table 5 Comparison of the deposited salinity amounts of the wet and water candle devices after 100 min for increasing and decreasing wind speeds (Unit in mg m^{-2}).

	Condition	Water candle (mg m^{-2})	Wet candle (mg m^{-2})	Difference (%)
Salinity concentration 3.5%	Ascending	60	56	6.6
	Descending	67	66	0.2
Salinity concentration 35%	Ascending	555	579	4.1
	Descending	586	563	4.0

Table 5 provides the salinity deposition (mg m^{-2}) measured by the water candle device compared with that of the wet candle device. There were only small differences in the results of the two devices, with differences in the rate ranging from 0.2% to 6.6%.

In conclusion, the accuracy and responsiveness of the water candle device were confirmed in the laboratory test. In the accuracy test, the aerosol entrainment condition was fixed and constant, and as a result, the measured data exhibited a linear increase in the cumulative salinity amount. The results of this test agreed with those of the wet candle device, with only small differences of 0.2% to 3%. While in the responsiveness test, the device was tested with a constant salinity source and varying wind speed, and as a result, the measured data exhibited a polygonal increase corresponding to the wind speed level, providing a good fit with the calculated results. The difference between the water of the wet candle device in this test was as small as 6.6%.

4.2 Application to monitoring in the field

The device worked well without pausing or malfunctioning in the controlled conditions of the laboratory tests. However, in the uncontrolled conditions of the actual environment, the device may malfunction. Moreover, in the field the entrainment of the salinity aerosol is affected by many factors, such as wind, temperature, relative humidity, atmospheric pressure, and rainfall. These factors fluctuate largely and are more complicated than the controlled conditions in laboratory. Therefore, monitoring in the field is necessary to confirm the operation, accuracy, and real-time responsiveness of the water candle device.

Figure 13 shows hourly data of the temperature, relative humidity, atmospheric pressure, and wind speed recorded at a local weather station during the monitoring period. This is typical meteorological data for the early period of the dry season of Da Nang city. There was no rainfall observed in this period. The hourly average temperature, relative humidity, and atmospheric pressure ranged from 24 to 38 °C, 44% to 94%, and 1004 to 1013 hPa, respectively. The temperature and humidity reached peaks near 12:00 AM and dropped to their lowest values near 5:00 AM. The atmospheric pressure peaked near 10:00 AM and 10:00 PM every day. The wind speed fluctuated during the day, with the lowest speed in the early morning and highest speed (~6 m s^{-1}) after noon. These meteorological data showed greater variations in the temperature, relative humidity, and wind speed compared with the laboratory tests.

Meteorological factors, such as temperature, humidity, atmospheric pressure, and wind, contribute to the fluctuation of aerosol chloride deposition (Cole, Paterson and Ganther, 2003; Fitzgerald, 199; Gustafsson and Franzén, 2000). While the effect of temperature, relative humidity, and atmospheric pressure is not clear according to the salinity deposition data, the influence of wind speed seems to prevail to other meteorological factors. This agrees with recent researches on the transport of aerosol salinity (Exton et al.1985, Fitzgerald et al.1990). This is because the aerosol salinity is produced from the agitation of sea surface which is due to the wind (Fitzgerald et al.1990, Monahan et al.1971). Also, the wind is major meteorological factor transporting aerosol salinity in land (Morcillo et al.1999; Meira et al.2008). On the other side, other meteorological factors such as relative humidity, rainfall, temperature etc., contribute as additional effect to the motion and concentration of particle (Cole et al.2003).

Figure 14(a) shows the measured cumulative salinity during the monitoring period. The salinity deposition measured in this period was ~202 mg m^{-2}. This result only differed by 6.8% from that of the wet candle device. **Figure 14(b)** shows the incremental salinity deposition of two continuous recording times. The largest and smallest increments of the salinity deposition measured by the device were ~23 and 1 mg m^{-2}, corresponding to 0.5×10^{-6} and 11.5×10^{-6} M, respectively. These values occur in the range of the calibration graph in **Fig. 3**. According to **Fig. 14(b)**, the device detected the deposited salinity in a short time of a few hours.

Figure 14(c) shows the average wind speed corresponding to sampling frequency of water candle device during the monitoring period. The grey bands in **Fig. 14** indicate day light. During this monitoring period, the sunrise and sunset were near 5:00 and 19:00, respectively. The wind speed tended to increase after sunrise and decrease after sunset and, reached a peak between 14:00 and 15:00. This is due to the

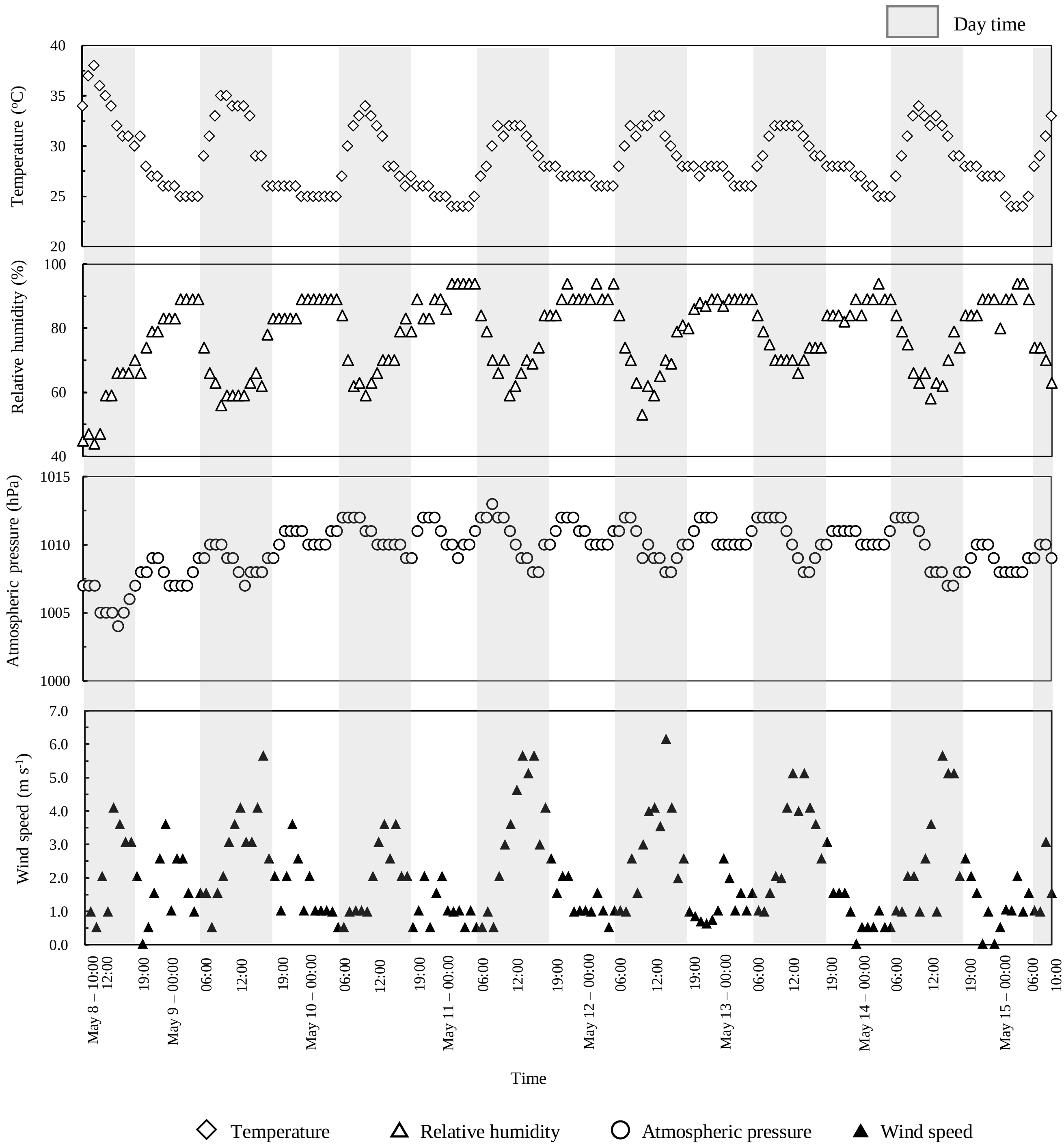

Figure 13 Data of meteorological factors in monitoring period

different heating abilities of the sea, earth surface, and air. The measured peak increments of the salinity deposition were 8, 22, and 10 mg m^{-2} corresponding to wind speeds of 4.1, 5.8, and 5.5 m s^{-1} which are peak wind speeds in the day. Hence, this demonstrates good functioning of the device for coping with variations in the wind speed, which cannot be monitored by a wet candle device. Therefore the water candle device is not only able to measure the salinity deposition with reasonable accuracy compared to the wet

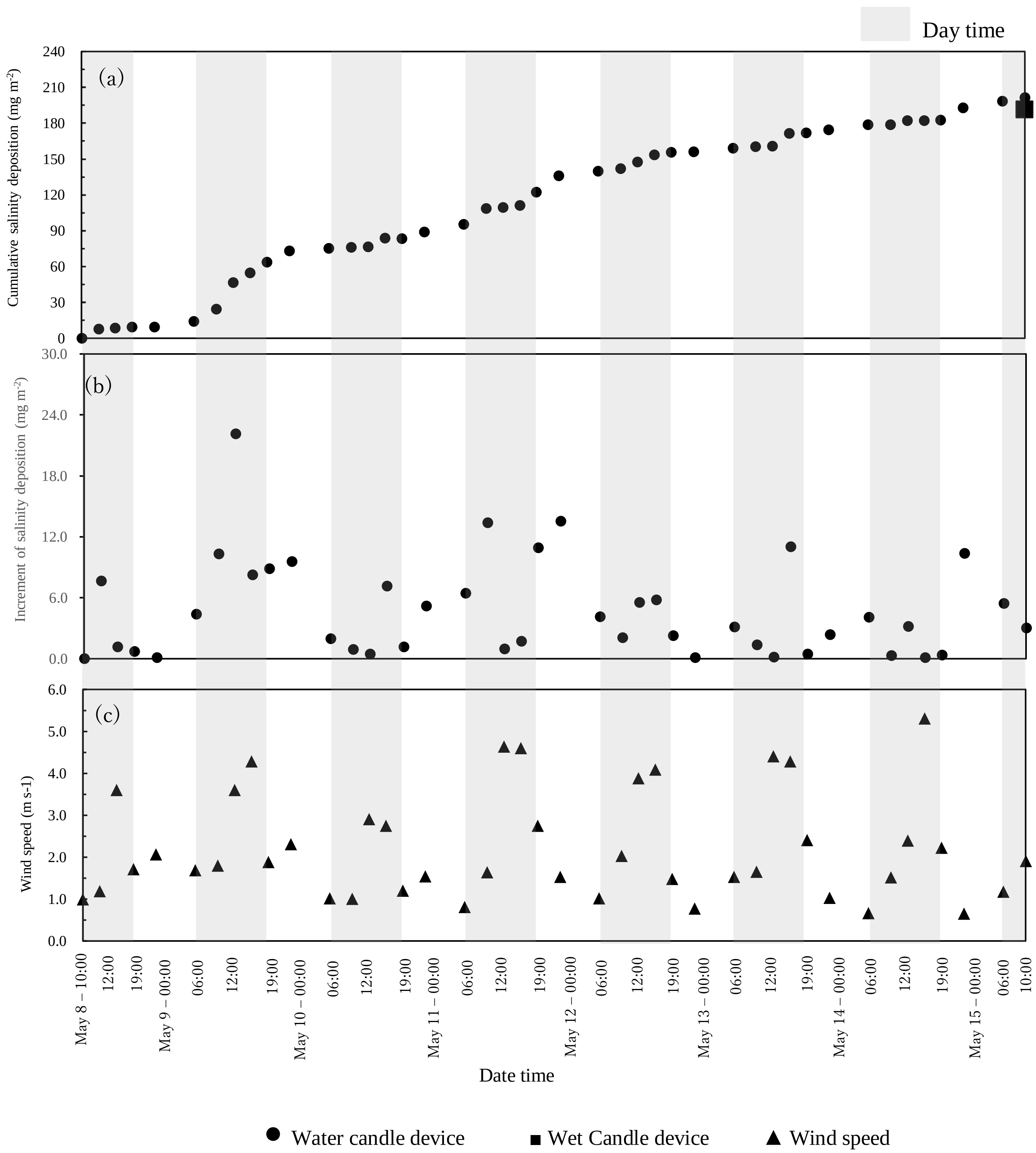

Figure 14 Monitoring results of salinity deposition in Da Nang city and wind speed records

candle device, but it is also capable of demonstrating temporal increments in the salinity deposition in real-time.

In laboratory test, since the salinity source contains only sodium chloride, there is no other ion dissolved in the solution. In monitoring at the field, other ion may dissolve in the solution and effect the conductivity. However, in this study, since the implemented place of water and wet candle devices were near the shoreline and far from sources of other ions (industrial zone nor forest), the effect of chloride ion on conductivity was predominant and other ion's influence on the conductivity was relatively small. This can be confirmed in comparison between monitored results of water and wet candle devices. However, further study is needed to eliminate the effect of other ions.

5. Conclusion

A real-time aerosol chloride measuring device was proposed and tested in the laboratory and in the field. Conditions were set in the laboratory tests to simulate the actual transport of aerosols in area near the seashore to evaluate the accuracy and responsiveness of the device. For monitoring in the field, the device was implemented on the Thuan Phuoc Bridge, Da Nang city for seven days with a short recording frequency. A wet candle device was also placed next to the water candle device to compare the results of both methods. The major conclusions of this study are presented below.

1. In the accuracy tests, the measured data exhibited a linear increase in the cumulative salinity amount corresponding to a varied wind speed with a constant salinity source, or varied salinity source with a constant wind speed. The measured result differences between the water and wet candle devices were as small as 0.2% to 3%.

2. In the responsiveness test, the measured data exhibited a polygonal increase corresponding to the wind speed level. The analytical calculation of a simple salinity entrainment model was conducted, showing a good agreement with the measured results. Therefore, the water candle device responded well to changing wind speed. The measured result differences between the water and wet candle devices were as small as 6.6%.

3. In the field, the device worked well without malfunctioning. The differences in the cumulative salinity deposition measured by the water and wet candle devices were small. The peak increment of the salinity deposition in the day may match the daily peak of wind speed. The results demonstrated the good measuring abilities of the water candle device in the field.

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Data Statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.