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ICE THICKNESS MEASUREMENT METHOD FOR THERMAL ENERGY STORAGE UNIT

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Abstract: The aim of this study is to develop a measurement method to determine the solidification front in a thermal energy storage unit. The electrical conductivity of a phase change material (PCM) changes dramatically in solidification/melting process and the proposed measurement method is based on observation of electrical conductivity of PCM. This system utilizes a microprocessor and a multiplexer unit to observe medium via multiple nodes. The experimental results show that the accuracy of this method is nearly 3%, in comparison with the traditional photography method. The most important advantages of this method are elimination of the heat gain, caused by opening a cover in the insulation at specific time periods, compared to the with photography method and ease of observation of solidification fronts electronically which results wider application area where photography method cannot be exploited.
Keywords: Ice measurement method, Solidification, Phase change.

ISIL ENERJİ DEPOLAMA ÜNİTESİ İÇİN BUZ KALINLIĞI ÖLÇÜM YÖNTEMİ

Özet: Bu çalışmanın amacı, ısıl enerji depolama ünitesindeki katılaşma ara yüzeyinin belirlenmesi için bir ölçüm yönteminin geliştirilmesidir. Faz değişim malzemesinin (FDM) elektriksel iletkenliği katılaşma/erime işleminde önemli oranda değişmektedir. Bu sebeple önerilen ölçüm yöntemi, FDM'nin elektriksel iletkenliğinin gözlenmesini esas almaktadır. Ortam içerisinde birden fazla noktada gözlem yapılabilmesi için özel bir prob tasarlanmış ve ölçüm noktalarından alınan veriler, bir gömülü işlemci vasıtasıyla kaydedilmiş ve bilgisayara aktarılmıştır. Deneysel sonuçlar, geleneksel fotoğraflama yöntemiyle karşılaştırılmıştır. Yöntemin göreceli doğruluğu yaklaşık %3 olarak belirlenmiştir. Bu yöntemin en önemli avantajları, fotoğraflama yönteminde belirli zamanlarda kapağın açılmasından kaynaklanan ısı kazançları yok etmesi ve fotoğraflama yönteminin kullanılamayacağı uygulamalarda, elektronik olarak katılaşma ara yüzeyinin gözlenmesini sağlamasıdır.
Anahtar Kelimeler: Buz ölçüm yöntemi, Katılaşma, Faz değişimi.

INTRODUCTION

Thermal energy storage (*TES*) systems are widely used in air conditioning systems for its benefits on energy conservation. The most important advantages of TES are the ability of increasing the energy efficiency and decreasing the capacity for cooling demand (Dinçer and Rosen, 2002; Zalba et.al, 2003; Farid et.al, 2005). TES systems are mainly divided into two: *sensible* and *latent*. In the former one, energy is stored by means of the temperature difference of the storage medium and in the latter one energy is stored via using the phase change energy of the storage medium. In comparison with the other TES methods, there exists many advantages of the latent thermal energy storage (*LTES*), such as, having high ratio of energy/volume and less phase change material usage to store high amount of energy within a narrow temperature band.

In a typical LTES unit, energy storage process is provided with the phase change of the storage material. The rate of energy stored in a LTES depends on the volume variation of liquid and solid phases of the PCMs in time, rather than the temperature difference. Hence, the volume measurement of liquid and solid phases is very important in the calculation of latent energy storage. Shi et al. summarize all of the possible measurement methods for an ice storage system and show the accordance of electronic measurement method with based on the difference of electrical characteristics of liquid and solid phases of the PCM (Shi and Wang, 2005).

Electrical conductivity characteristics of liquid and solid phases of water vary noticeably. This fact allows designing an indicator system for monitoring phase for a specific point. The electrical conductivity measurement methods, which can be used for monitoring ice formation, are generally represented as following setups,

- *Resistance based measurement setups:* the amperometric method (Palleschi and Biagiotti, 2008) and the potentiometric method, which implement Ohm's law on alternating and direct current circuits (Mark, 2009),
- *Inductance based measurement setup*, which uses a toroid shape inductive probe (De Jong et.al, 1979),
- *Capacitance based measurement methods*, which utilizes dielectric effect of ice between probes (Daily and Ramirez, 2004).

Last two methods exploit frequency based modeling and analysis of measurement setups since both require AC input voltage. Measurement outputs are then received as periodic steady state signals. Amplitude and phase shift in output signal is utilized to identify system parameters which are an inductance or a capacitance parallel or series to a resistance. Resistance based measurement systems are relatively simpler to analyze because there exists only a proportional relationship referring to electrical circuit formed. The difference between the amperiometric and potentiometric method is that the potentiometric method uses alternating voltage as input and calculates the ratio between output and input signal amplitudes. Potentiometric method implements Ohm's law to calculate resistance of the system with DC input voltage. A major fallback of DC input voltage is that electrolysis occurs between probes.

This study focuses on designing a measurement setup for monitoring whether a specific spatial point (*measurement node*) is inside the *solid* or *liquid* phases of the water. Measurement method is based on the observation of electrical conductivity of medium, since electrical conductivity of water changes dramatically while it freezes (Knight and Cox, 2006; Xiaoping et.al, 2007; Li et.al, 2001; Jay and Lehr, 2005).

ELECTRICAL CONDUCTIVITY MEASUREMENT METHOD

Electrical conductivity, the reciprocal of electrical resistivity, is the ability of a medium to conduct electric current. In order for anything to conduct electricity, matter must have charge carriers. In metals, they are weak-bounded electrons; and in solutions ionic contents. The electrical conductivity is used to monitor the characteristics of a medium concerning the changes in it. [Phase change (Knight and Cox, 2006), purity (Palleschi and Biagiotti, 2008), etc.]

Pure water is an excellent insulator but water is also a good solvent and it often has some solute dissolved in it. If water has any amount of an impurity, it conducts electricity. Since impurities (such as salt) separate into free ions in aqueous solution by which an electric current can flow. As can be seen in Figure 1 and Figure 2, electrical conductivity is also affected by temperature. As the temperature rises, the viscosity of water decreases and ions movement become easier. (Xiaoping et.al, 2007; Li et.al, 2001)

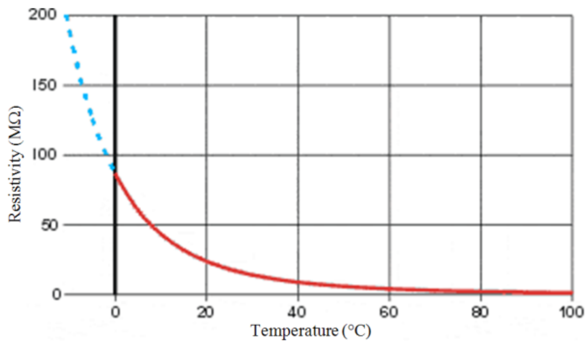


Figure 1. The variation of resistivity of water with temperature (Light et.al, 2005).

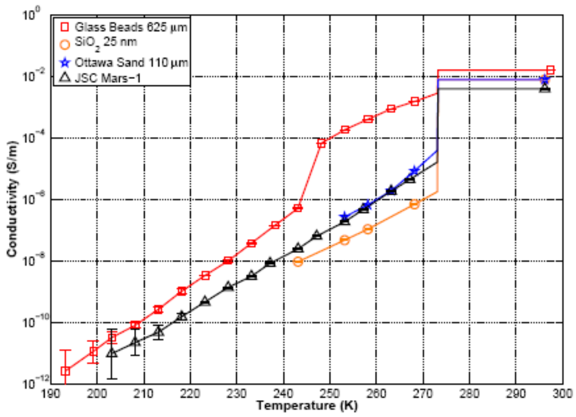


Figure 2. The decrease in the resistivity of impure ice (with silicate) via temperature (Stillman and Grimm, 2007).

The variation of electrical conductivity with temperature is given as;

$$S = d\sum \lambda_i c_i \qquad (1)$$

where S is conductivity, and c_i is the concentration of the i^{th} ion, since λ_i (*equivalent ionic conductance of ion i*), and to a lesser degree, d (*density of the water*) (Jay and Lehr, 2005) are temperature dependent. Different kinds of water conductivity and resistivity values are listed in Table 1 as examples.

Table 1. Typical conductivities of different kinds of waters.

	Conductivity	**Resistivity**
	(S/m)	(Ω/m)
Ultra pure water	5.5E-6	181818.18
Drinking water	0.005 – 0.05	200 – 20
Sea water	5	0.2

While water freezes into ice, ice becomes more pure than water. This is because of the crystal lattice of the ice, which tries to form a very uniform structure and this uniform structure force the impurities out (Tori et.al, 2006). Therefore result the conductivity of ice decreases. When ice becomes de-ionized, the molecules and ions cannot move anymore (Tori et.al, 2006). Even if the liquid water initially has charge carriers, during the freezing process, the mobility of these carriers become significantly diminished, thus the conductivity drops dramatically during the phase change (Figure 2).

The basic electrical conductivity measurement methods, which can be used for monitoring ice formation, can be detailed as follows,

In amperometric measurement setup, the probe is used to measure the conductivity with two electrodes spaced apart from each other and protrude inside the media. The amperometric method applies a known voltage value to the pair of electrodes and measures the current. According to Ohm's law, monitoring current allows recovery of conductivity of medium (Palleschi and Biagiotti, 2008).

The potentiometric method employs four rings: the two outer rings is used to apply an alternating voltage and induce a current loop in the solution, while the inner rings measure the voltage drop induced by the current loop. This measurement is directly dependent upon the conductivity of the solution (Mark, 2009).

Another method of conductivity measurement is using an inductive probe. The sensor is a toroid on a stick. The advantage of this technology is measurement without any electrical contact between the electrode and the process medium. The probe uses two toroidal transformers which are inductively coupled side by side and encased in a plastic sheath. The measurement is made by applying a high frequency reference voltage to generate a strong magnetic field. As the media in toroid shaped probe changes, current flows through sensing windings proportional to the voltage induced by the magnetic field. The conductance is proportional to the specific conductivity of the fluid and a constant factor determined by the geometry and installation of the sensor (De Jong et.al, 1979). Although this method is used widely in industrial applications, it does not provide data referring to a specific point because of the geometry of the sensor.

One inverse approach, for estimating conductivity of medium to define its current state, is to measure the dielectric effect of probes, which are basically have the same setup with amperiometric measurement (Daily and Ramirez, 2004). The term dielectric is used when considering the effect of alternating electric fields on the substance. As conductivity of the medium reduces, dielectric effect of the probes become dominant and the capacitance value of the system increases. Hence the phase of the output signal shifts.

EXPERIMENTAL APPARATUS

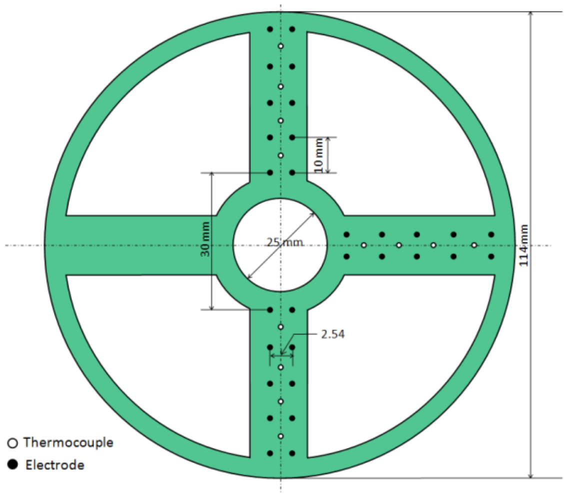
The probe dimensions and the positions of the electrodes on the board are illustrated in Figure 3. Electrodes on the printed board are designed as small circular pads with the diameter of 1 mm. Generally in ampreimetric measurement setups, the electrodes protrude inside the medium and this causes capacitive effects on the system, because conductivity decreases and they become capacitors rather than resistors (Shi and Wang, 2005). These quasi 2D electrodes have no parallel plate arrangement in measurement setup and the capacitive effect on measurement is omitted.

The distance between the pair of electrodes is 2.54 mm (0.1 inch) and 10 mm in radial directions. Therefore, the measurement uncertainty occurring from geometry is 0.38 mm. As it is intended to measure the time dependent thickness of ice formation, it is necessary to use several nodes for measurement. There are five measurement nodes on three radial lines and fifteen electrodes on each probe. In thermal energy storage system, three probes are placed to observe the solidification front from inlet to outlet and totally 45 nodes are used from three different sections. Furthermore, there are also four thermocouples mounted on one direction of a probe and 36 thermocouples are used to establish the temperature distribution of PCM. The T type thermocouples with an accuracy of ±0.5°C are calibrated in constant temperature bath between -15°C and +20°C range.

PIC 16f877 microcontroller is used as the main processor unit. It has three peripheral circuits; *measurement circuit*, *serial communication circuit* and *multiplexers*. Measurement circuit has a pre resistance (R_p) of 1KΩ to limit the current in the above mentioned probe design. Multiplexers are used to direct input output node connections to analog to digital (A/D) converter pin and digital output pin. Communication circuit is an IC to convert levels of voltages of microcontroller and computer (Figure 4).

Microcontroller operates in timer driven routines at a specific operation period of which a digital output port becomes active for 20 ms. This evokes an A/D measurement and the program records the read values to a summing register. A/D measurement is repeated 50 times. The sum of all the values is then transferred to a computer to create a log (Figure 5).

The described measurement loop is repeated for all 45 measurement nodes. Scanning method for measurement is as follows: First, the nodes on the same radial level closest to the pipe are scanned. Afterwards this scan continues to distant nodes. Microcontroller uses timer interrupts for providing consistency in sampling time and also controls multiplexers to enlarge input output ports.



(a)

(b)

Figure 3. Layout of the nodes on the measurement probe (a) Technical drawing, (b) Photography.

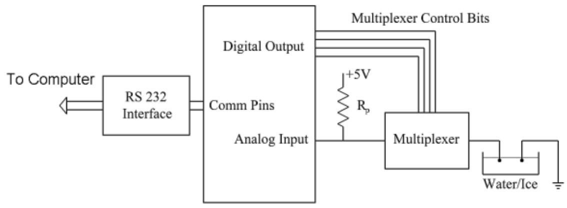


Figure 4. Measurement circuit.

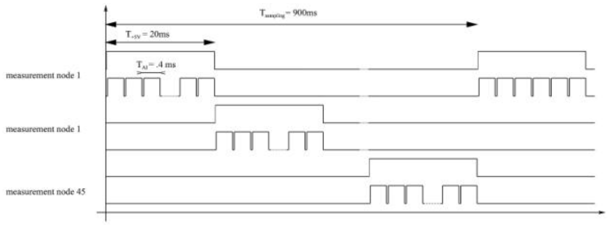


Figure 5. Timing diagram.

Since there exists 45 measurement points to construct instantaneous ice formation data and only one microprocessor is used and it is not possible to measure all points at the same time, measurements are done synchronously (Figure 5). Concerning slow time response of ice formation system (which has time constant of a few seconds), microprocessor based measurement system with time constant in milliseconds satisfies Nyquist frequency criterion for constructing real signal from sampled values (Proakis and Manolakis, 1996).

The electrolysis on measurement nodes is an important issue of concern, when planning sampling times, because ion deposition on the electrodes due to electrolysis can vary the resistance and can also cause corrosion which leads to defected probes. Therefore, the measurement system is designed to avoid electrolysis effects; it applies input voltage only during measurement period (Figure 5).

Before the installation of the experimental apparatus, the characteristic of voltage variation with temperature of the pair of electrodes in used in experimental setup was determined experimentally. Experimental result given by Figure 6 can be evaluated via concerning Figures 1 and 2. As time passes, temperature on measurement medium decreases and the monitored voltage (proportional to resistance between electrodes) decreases. That is why the more conductance decreases, the less current flows through water.

Monitored signal changes dramatically when ice is formed at the nodes, since the circuit becomes open, electrically. This result verifies that implemented measurement system can act as an indicator to provide discrete data that the current phase of the measurement point is ice or water.

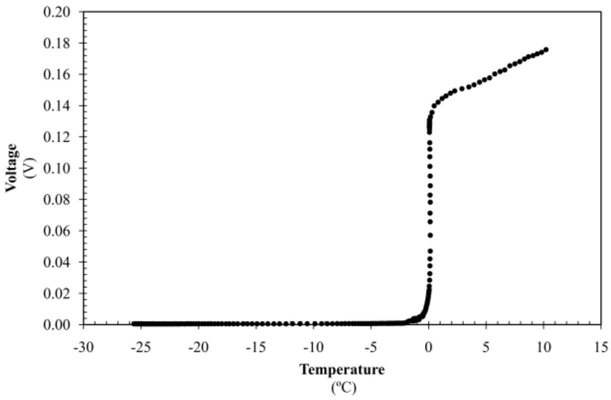


Figure 6. Voltage variation in single probe with temperature. (Supply Voltage: 5 V, Current Limiter (R_p) 1KΩ).

EXPERIMENTAL STUDY AND VALIDATION

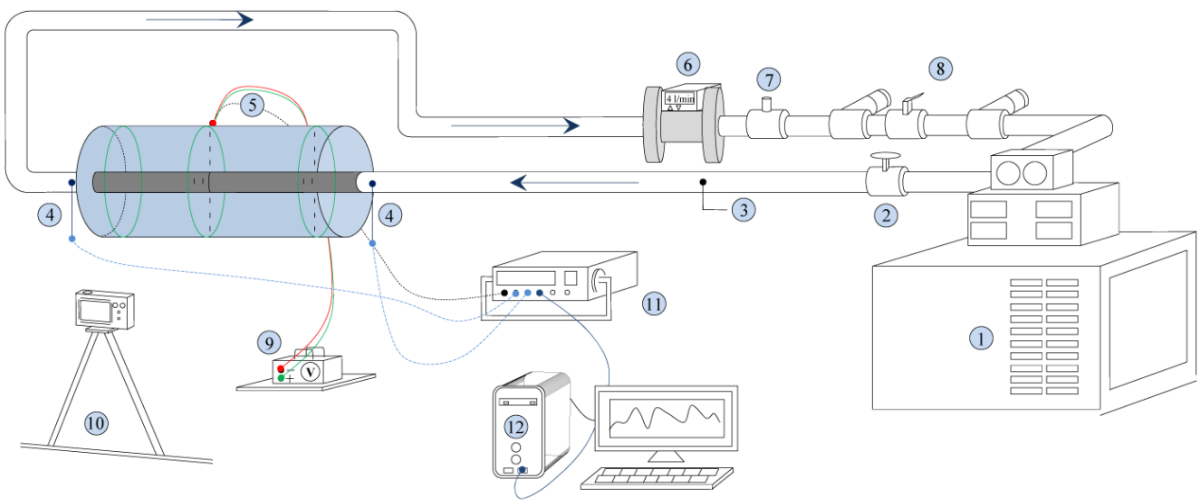
This study is mainly focused on designing a measurement setup for monitoring the solidification front of an ice-on-coil latent energy storage system. Latent energy storage system and its components are illustrated in Figure 7. Refrigerated bath pumps chilled brine (*40% ethylene glycol-water solution by volume*) through the TES unit inside a long pipeline, with a certain temperature and flow rate. While the coolant brine flows inside the tube side, water as used PCM fills the shell side of the TES unit. The inlet and outlet temperatures of the coolant brine are measured with Pt-100 sensors and the temperature distribution inside the PCM unit is determined from the thermocouples, which are located at 40 different points. In order to control and regulate the flow rate, electromagnetic flow meter and electronically controlled valve are integrated to the system.

The probes are settled at three different sections of the storage tank; *inlet*, *middle* and *outlet*, to observe the solidification front variation through the flow direction, as shown in the Figure 8. Plexiglas is used as a shell material with D_s = *114mm* inner diameter and polyethylene tube is used as the heat transfer fluid carrier with D_o = *25 mm* outer and D_i = *15 mm* inner diameters.

In earlier experimental studies, the solidified volume in a closed TES unit was calculated by taking photographs at different time periods (Erek, 1999 and Erek et.al, 2005). The suitability of the measurement method is validated with comparison of photography results. A camera is located in front of the middle section and solidification front is both determined from the measurement probe and photographs. The ice radii of top and bottom directions are scaled from photographs with the aid of a pipe diameter, as illustrated in Figure 9.

Comparisons between photograph and measurement probes are obtained for two different experiments with inlet conditions of T_{in} = *-5°C, V = 2 l/min* and T_{in} = *-5°C, V = 4 l/min*. In both experiments, to eliminate the natural convection effect, the initial temperature of the PCM (*water*) is dropped under 0.5°C. In each experiment, solidification is observed until the 4th nodes penetrate in the ice.

In Figures 10 and 11, the radii calculated from the measurement probes are given as a function of time, in comparison with photography. Four different curves can be seen in each figure, which are; *top* and *bottom* radius values obtained from both photography and measurement probe methods. In the Figures, hollow triangles and circles illustrate the photography data and the solid ones denote the measurement probe data. A dynamic curve fitting method (*Exponential Rise toMaximum – Double – 5 Parameter*) is applied to 4 nodes of the measurement probe data to obtain the tendency curve, and is shown as dashed lines. From Figures 10 and 11, it can be seen that there is a good agreement between two methods, for both top and bottom directions, and the solidification tendencies are nearly the same. On the other hand, to observe the relative error between two methods, numerical values



(1) Refrigerated bath, (2) Valve, (3) Pipeline, (4) Pt-100 sensor, (5) Measurement probes, (6) Electro-magnetic flow meter, (7) Electronically controlled valve, (8) Valve, (9) Electrical conductance measurement device, (10) Camera, (11) Datalogger, (12) Computer

Figure 7. Ice-on-coil latent energy storage system.

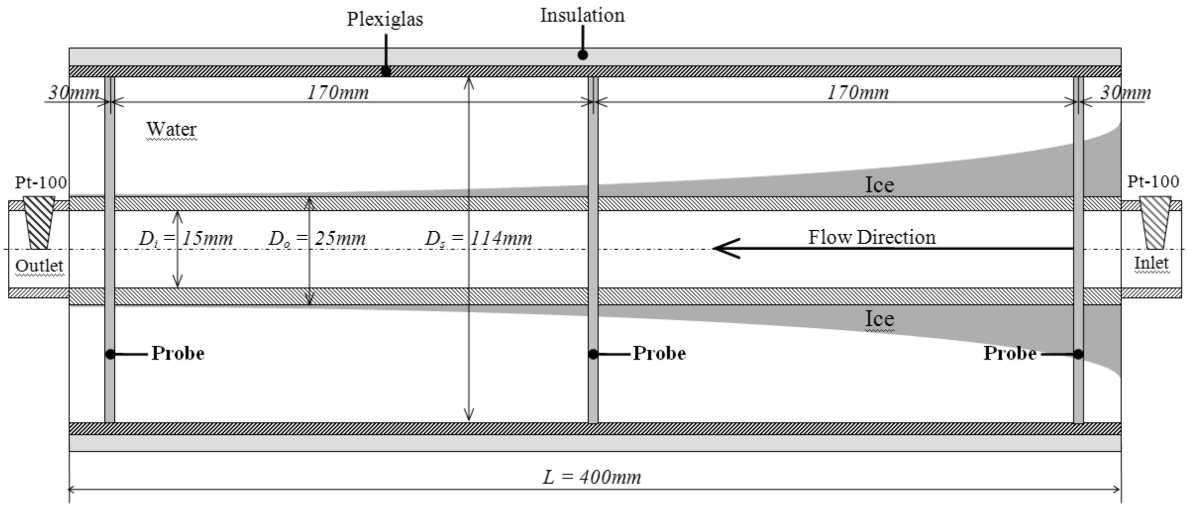


Figure 8. Layout of the measurement cards inside storage tank.

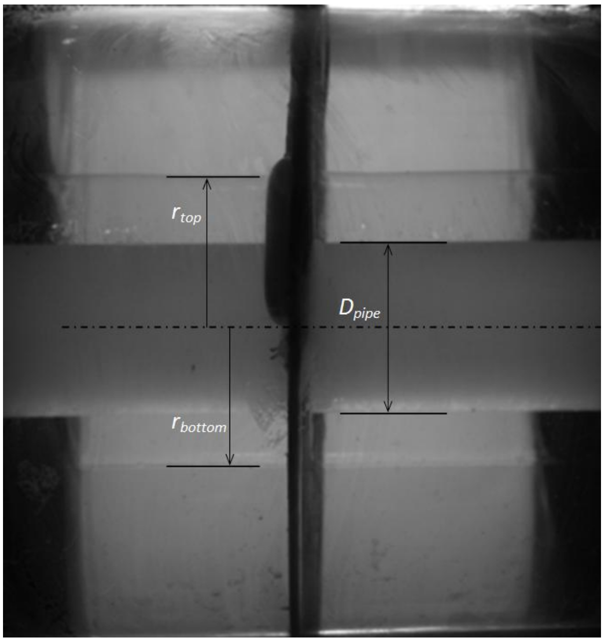


Figure 9. Scaling top and bottom radiuses with the aid of pipe diameter.

and errors are given in Tables 2 and 3. At the beginning of the solidification there appears to be relatively big difference, but the average is about 3%. As an average, the difference between photography and measurement probe is less than 1mm. This difference is acceptable for the calculation of the volume of ice in TES systems.

After verification of the measurement method, solidification front can be determined with the aid of three probes, at each section and downstream. As an example, for T_{in} = *-5°C, V = 2 l/min*, the solidification front variation from inlet to outlet of the storage tank is illustrated in Figure 12, for *t = 60 min., 120 min., 180 min., 240 min.,* and *300 min.*. Unsurprisingly, the radius of the ice decreases in flow direction because of the reduction of fluid temperature. Meanwhile, as seen in Figure 13, due to the thermal stratification, the solidification interface also varies around the pipe, from bottom to top side. Hot water with higher density drops down to the bottom of the storage tank and slows down the ice formation.

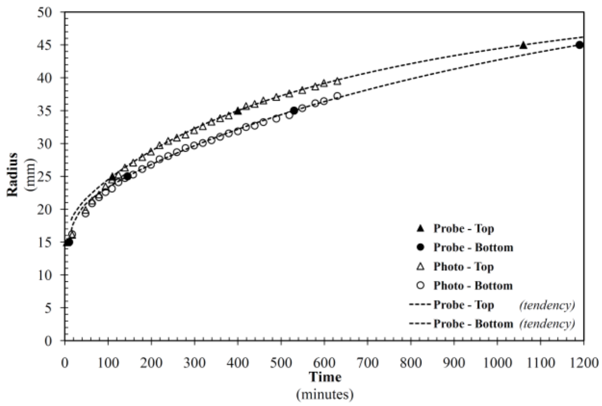


Figure 10. Comparison of solidification front for middle section (T_{in} = -5°C, V = 2 l/min).

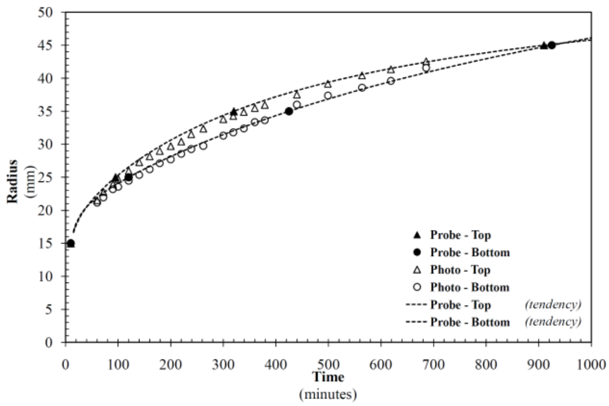


Figure 11. Comparison of solidification front for middle section (T_{in} = -5°C, V = 4 l/min).

Table 2. Comparison of measured radius with relative errors (T_{in} = -5°C, V = 2 l/min).

Time	**Top**				**Bottom**			
	Photography	**Probe**	**Difference**	**Difference**	**Photography**	**Probe**	**Difference**	**Difference**
(minute)	(mm)	(mm)	(mm)	%	(mm)	(mm)	(mm)	%
17	18.71	16.09	2.62	16.25	17.25	16.20	1.05	6.48
48	21.52	19.89	1.63	8.20	20.75	19.36	1.39	7.16
63	22.47	21.31	1.16	5.44	21.63	20.89	0.74	3.55
79	23.39	22.23	1.16	5.23	22.42	21.81	0.61	2.79
94	24.19	23.46	0.74	3.13	23.07	22.61	0.47	2.07
109	24.95	24.52	0.43	1.75	23.68	23.14	0.54	2.34
124	25.67	25.27	0.41	1.60	24.25	24.10	0.15	0.63
139	26.36	26.33	0.03	0.11	24.79	24.73	0.06	0.23
158	27.19	27.07	0.11	0.42	25.44	25.27	0.18	0.71
179	28.05	27.93	0.13	0.46	26.14	26.12	0.02	0.07
199	28.84	28.78	0.06	0.21	26.77	26.76	0.01	0.05
219	29.58	29.73	0.15	0.51	27.38	27.61	0.23	0.83
239	30.29	30.39	0.10	0.31	27.97	28.09	0.12	0.42
259	30.97	30.88	0.09	0.28	28.54	28.68	0.14	0.48
279	31.62	31.36	0.26	0.84	29.09	29.31	0.21	0.73
299	32.24	32.01	0.22	0.69	29.63	29.69	0.06	0.20
319	32.83	32.64	0.19	0.59	30.16	30.07	0.09	0.29
339	33.40	33.32	0.08	0.25	30.67	30.49	0.18	0.59
359	33.95	33.84	0.11	0.32	31.17	31.01	0.16	0.51
379	34.47	34.26	0.21	0.62	31.66	31.54	0.12	0.39
400	35.00	34.99	0.01	0.03	32.16	31.85	0.31	0.97
419	35.46	35.69	0.23	0.65	32.60	32.50	0.10	0.31
439	35.93	36.01	0.08	0.23	33.05	32.71	0.34	1.05
459	36.38	36.54	0.16	0.45	33.50	33.24	0.25	0.77
489	37.03	37.07	0.05	0.13	34.15	33.78	0.37	1.10
519	37.64	37.61	0.03	0.09	34.77	34.31	0.47	1.36
549	38.22	38.14	0.08	0.22	35.38	35.37	0.01	0.03
579	38.77	38.67	0.10	0.27	35.97	36.12	0.15	0.40
599	39.13	39.20	0.07	0.19	36.35	36.44	0.08	0.22
630	39.66	39.50	0.15	0.39	36.93	37.24	0.30	0.81

Table 3. Comparison of measured radius with relative errors (T_{in} = -5°C, V = 4 l/min).

Time	**Top**				**Bottom**			
	Photography	**Probe**	**Difference**	**Error**	**Photography**	**Probe**	**Difference**	**Error**
(minute)	(mm)	(mm)	(mm)		(mm)	(mm)	(mm)	%
60	22.39	21.51	0.88	4.10	22.15	21.15	1.00	4.71
72	23.36	22.75	0.61	2.69	23.05	21.94	1.11	5.06
90	24.66	23.95	0.71	2.98	23.81	23.19	0.62	2.66
100	25.33	24.75	0.58	2.33	24.51	23.55	0.96	4.07
120	26.57	25.96	0.62	2.37	25.17	24.46	0.71	2.90
140	27.71	27.28	0.43	1.57	25.80	25.35	0.45	1.78
160	28.75	28.15	0.60	2.13	26.57	26.20	0.37	1.42
179	29.68	28.99	0.68	2.36	27.37	27.11	0.27	0.99
200	30.63	29.71	0.91	3.08	28.11	27.71	0.40	1.46
220	31.47	30.40	1.07	3.53	28.82	28.55	0.27	0.95
239	32.23	31.52	0.71	2.26	29.51	29.27	0.24	0.81
262	33.08	32.36	0.73	2.24	30.17	29.75	0.42	1.41
300	34.37	33.80	0.58	1.70	30.81	31.31	0.50	1.60
319	34.97	34.28	0.69	2.01	31.44	31.79	0.36	1.12
339	35.56	34.88	0.68	1.96	32.04	32.39	0.35	1.08
360	36.15	35.48	0.67	1.90	32.63	33.35	0.72	2.16
379	36.66	35.96	0.70	1.95	33.21	33.64	0.44	1.30
440	38.14	37.52	0.62	1.65	33.77	36.00	2.23	6.19
499	39.38	39.17	0.21	0.55	34.34	37.37	3.03	8.11
564	40.58	40.43	0.15	0.38	34.84	38.57	3.73	9.66
619	41.48	41.37	0.11	0.27	35.36	39.60	4.24	10.70
686	42.45	42.57	0.11	0.27	35.87	41.57	5.71	13.72

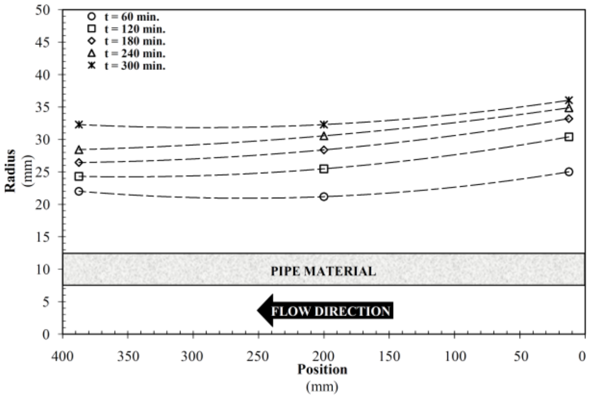


Figure 12. Variation of solidification front from inlet to outlet.

CONCLUSION

This study aims to develop and apply a measurement method to determine the solidification volume in a TES system. The electrical conductivity of a phase change material (PCM) changes dramatically in solidification / melting process and the proposed measurement method is based on observation of electrical conductivity of PCM. The experimental results show that the accuracy of the method is nearly 3%, in comparison with the traditional method of photography. The most important advantages of this method are elimination of the heat gain, caused by opening a cover in the insulation at specific time periods, compared to the with photography method and ease of observation of solidification fronts electronically which results wider application area where photography method cannot be exploited.

This system also has the advantage of implementing the measurement method on a microprocessor. Although the given experimental results represent continuous changes in the medium, they also show that it is also possible to implement fully digital input output measurement system. This future system will enable higher spatial resolution (closer nodes) and faster sampling rates.

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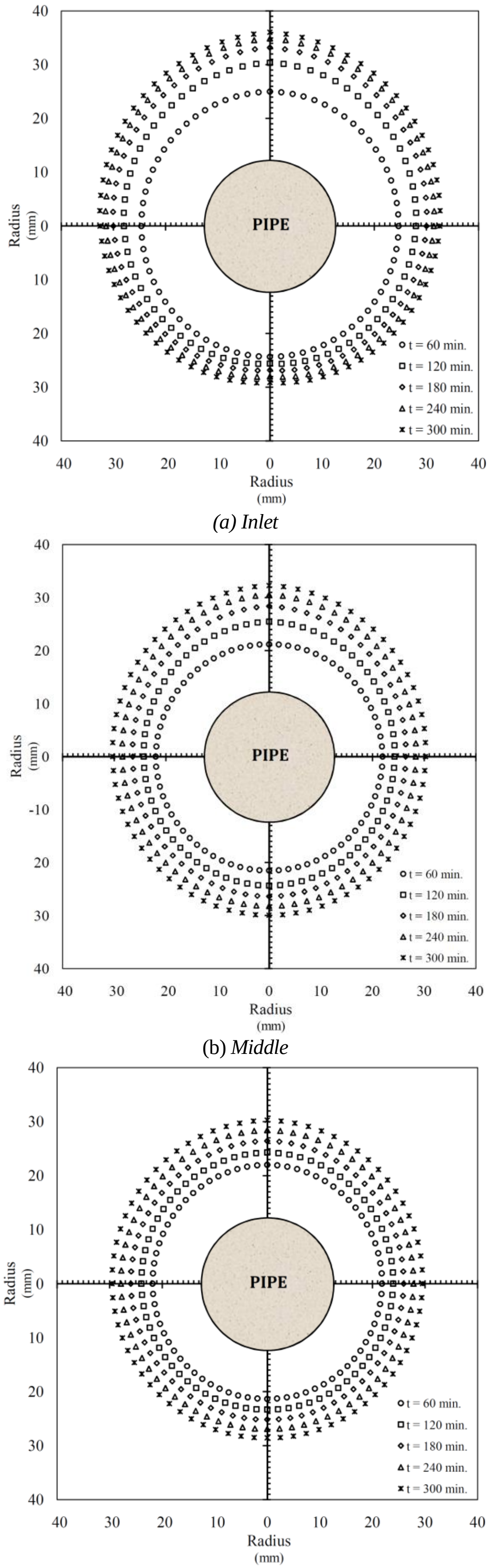

(a) *Inlet*

(b) *Middle*

(c) *Outlet*

Figure 13. Ice-water interface for *inlet*, *middle* and *outlet* sections of tank.

REFERENCES

Daily W., Ramirez A., Electrical resistance tomography, *The Leading Edge* 23, 438–442, 2004

De Jong E., Ballantyne A.K., Cameron D.R., Read D.W.L., Measurement of Apparent Electrical Conductivity of Soils by an Electromagnetic Induction Probe to Aid Salinity Surveys, *Soil Sci. Soc. Am. J.* 43**,** 810–812, 1979.

Dincer I., Rosen M.A., *Thermal Energy Storage: Systems and Applications*, John Wiley & Sons, Chichester, 2002.

Erek A., Phase change around finned horizontal cylinder: a conjugate problem, PhD Thesis, Dokuz Eylül University, Turkey, 1999.

Erek A., İlken Z., Acar M.A., Experimental and numerical investigation of thermal energy storage with a finned tube, *International Journal of Energy Resources* 29, 283–301, 2005.

Farid M.M., Khudhai A.M., Razack S.A.K., Al-Hallaj S., A review on phase change energy storage: materials and applications, *Energy Conversion and Management* 45, 1597–1615, 2005.

Hori T., Kako, H. Hayashi, Relationship between static electrical conductivity and unfrozen water content in food products, *Journal of Food Science* 47, 1254–1256, 2006.

Jay H., Lehr J.K., *Water Encyclopedia,* John Wiley & Sons, 2005.

Knight P.C., Cox G.A., The Electrical Conductivity and Crystal Phase Change in d-Camphor, *Physica Status Solidi (b)* 37, K39–K41, 2006.

Li Q., Li T., Wu J., Electrical Conductivity of Water/Sodium Bis(2-ethylhexyl) Sulfosuccinate/n-Heptane and Water/Sodium Bis(2-ethylhexyl) Phosphate/n-Heptane Systems: The Influences of Water Content, Bis(2-ethylhexyl) Phosphoric Acid, and Temperature, *Journal of Colloid and Interface Science* 239, 522-527, 2001.

Light T.S., Licht S., Bevilacqua A.C., Morash K.R., The fundamental conductivity and resistivity of water, *Electrochem. Solid-State Lett.* 8, E16-E19, 2005.

Mark B., A technique for in situ measurement of the conductivity of water in `triple point of water' cells, *Meas. Sci. Technology* 10, L33–L36, 1999.

http://www.iop.org/EJ/article/0957-0233/10/7/101/mt10007l1.html (Accessed in February 2009)

Palleschi G., Biagiotti V., Study of amperometric sensors for the determination of nitrite and ammonia in drinking water, Ph.D. thesis, Università degli Studi di Roma, 2008.

PIC16f87x Microcontrollers Data Sheet, Microchip inc.

Proakis, J.G., and Manolakis, D.G., Digital signal processing: principles, algorithms and applications, Macmillan, 1996.

Shi W., Wang B., Li X., A measurement method of ice layer thickness based on resistance-capacitance circuit for closed loop external melt ice storage tank, *Applied Thermal Engineering* 25, 1697–1707, 2005.

Stillman D.E., Grimm R.E., Laboratory Measurements of the Electrical Properties of Water Ice-Silicate Mixtures and Implications for Dielectric Spectroscopy and Radar on Mars, *Seventh International Conference on Mars*, 3311-3314, Pasadena, California, 2007.

Xiaoping S., Spitzer P., Sudmeier U., Novel method for bulk resistance evaluation in conductivity measurement for high-purity water, *Accreditation and Quality Assurance* 12, 351-355, 2007.

Zalba B., Marin J.M., Cabeza L.F., Mehling H., Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Engineering* 23, 251–283, 2003

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