https://dx.doi.org/10.22161/ijaers.5.4.11 *ISSN: 2349-6495(P) | 2456-1908(O)*

# Numerical & Experimental Investigation of Solidification Thickness around Cylindrical Surfaces for HVAC Cold Storage Systems

Jamal Youssef Al Abbas, Hussein Ali Tina, Bassam Edmond Badran

Department of MEE, Damascus University, Damascus, Syria

***Abstract—*** *Thermal Ice Storage System (TISS) is an innovative way of storing night-time off-peak energy for daytime peak usage. In many locations, demand for electrical power peaks during summer time. Air-conditioning equipment are the main reason accounting for as much as half of the power demand during the hot mid-day hours when electricity is most expensive. Since utilities have spare electrical generating capacity at night, electricity generated during this "off-peak" is much less expensive. In this research a numerical model for Latent Heat Storage (LHS) cylindrical tank has been obtained from a numerical package, ANSYS software ver. 15, and compared to an experimental data gathered from similar tank. The data showed good agreement with the experimental data with an error of 9%. The numerical model can be used to estimate ice thickness and tank geometries for any future work.*

***Keywords— ANSYS, Phase Change Materials (PCMs), Latent Heat Storage, Thermal Ice Storage System, Thermal Storage Systems.***

## I. INTRODUCTION

Thermal Ice Storage Systems (TISS) are used in the HVAC systems for their benefits in reducing the consumed electrical power in building and hence reducing cooling loads needed [1, 2, 3]. Those systems uses Latent Heat Storage (LHS) phenomena to absorb or release large amount of heat (heat of fusion) when they change phase from solid to liquid and vice versa [4]. Habeebullah et al. [5] presented an experimental results of ice growth rate on the outside of cooled copper tubes. The tubes, which were immersed in water in an insulated vessel, were internally cooled by circulating glycol through them. He found that axial growth rate of ice is distinct at low values of the coolant Reynolds number and short freezing times. The slope of the ice thickness with axial distance showed moderate dependency on time but varied with coolant flow rate, and with Stanton and Biot numbers. A key result from the experiments is the abrupt ice thickness enlargements on the surface of tube bends. This anomaly may be attributed to internal flow disturbances of the coolant, and creation of local eddies inside the bends that enhance growth of ice. The effect was evident for a low Reynolds number ($Re \geq 251.9$ and $Bi < 1$), and fades out for large Reynolds number flows. Sait et al. [6, 7] investigated experimentally ice formation on cold vertical banks of horizontal tubes subjected to falling-film, jet mode. In the charging and discharging process, a set of internally cooled vertical banks of horizontal tubes of brine was subjected to a falling film of water. The formed ice was periodically observed, photographed and measured in falling-film jet mode at specific internal coolant (ethylene–glycol solution) flow rates and temperatures. The maximum gained ice has a thickness that is approximately equal to half of the tube spacing between the tubes utilized, which is formed in approximately 45 min and released in 12.5 min. Hosseini et al. [8] studied experimentally and numerically the role of buoyancy driven convection during constrained melting of commercial paraffin (RT50) inside a shell and tube heat exchanger. A series of experiments is conducted to investigate the effect of increasing the inlet temperature of the heat transfer fluid (HTF) on the charging process (melting) of the PCM. The computational results show that by increasing the inlet water temperature to 80 °C, the total melting time is decreased to 37%. Yingxin et al. [9] Studied the melting of an unrestrained phase change material (PCM) around a horizontal tube arises in many applications such as ice storage for HVAC (Heating, Ventilating and Air Conditioning) systems. The instantaneous heat transfer rate during the melting process must be known for optimal system design and operation of the application. A series of experiments on internal melting of unrestrained ice around a fixed horizontal tube were reported. The validation results show that the model accurately predicts the solid PCM melting rate. Yari et al. [10] developed a numerical method for solving energy equation and describing solidification phenomenon around a circular pipe. The results have shown that the effect of decreasing pipe surface temperature is more than the effect of decreasing initial water temperature. Ismail et al. [11] validated a numerical study by experimental

https://dx.doi.org/10.22161/ijaers.5.4.11 ISSN: 2349-6495(P) | 2456-1908(O)

measurements on the solidification of PCM along a horizontal tube by using the boundary immobilization technique. Liu et al. [12] performed a charging transient simulations based on a two dimensional numerical model, the melting processes of the storage units with staggered tube bundle structure and parallel tube bundle structure are compared with that of flat plate structure. Sugawara et al. [13] investigated a freezing/melting of water/ice around a horizontal cylinder placed in a square cavity of the inner side length numerically.

In this research, a Computational Fluid Dynamic (CFD) software, ANSYS Package, is used to estimate the geometry of the latent storage tank, the suitable parameters of the Heat Transfer Fluid (HTF), and the ice thickness around a cooper tubing (charging process) based constant cooling load and specific working hours (8 working hours). The obtained numerical data is compared with experimental data to verify the CFD model chosen.

## II. NUMERICAL MODEL ASSUMPTIONS

Specific and logical assumptions are going to be used in the numerical model to obtain the ice thickness of the LHS for our experiment. The assumptions are:

1. Insulated cylindrical heat storage tank with evenly distributed copper tubing inside it, Fig. (1), transporting the Heat Transfer Fluid (HTF) from the cooling source. The diameter of the tank will be determined based on the ice thickness around the copper tubing.
2. Regular water is the phase change material inside the tank surrounding the copper tubing.
3. The working hours of the cooling source, which is a chiller, is eight night hours only.
4. The temperature of the Heat Transfer Fluid is (258.15 K) from the cooling source and it is a constant temperature. The HTF is water with 40% Ethylene Glycol (EG) [14].
5. An internal diameter bigger than (2 cm) has little effect on the ice thickness around the copper pipe [15].

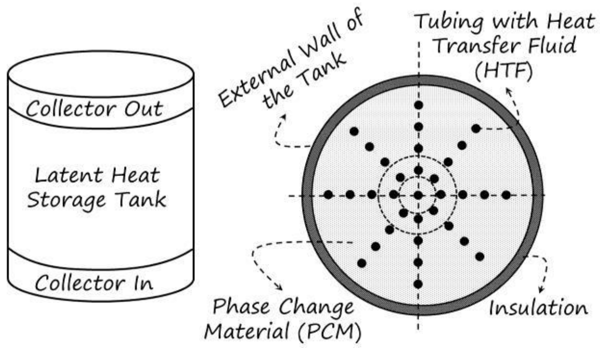


*Fig.1: Conceptual ice storage tank.*

## III. NUMERICAL MODEL METHODOLOGY

In order to determine the diameter of the storage tank experimentally, firstly, a big tank filled with regular water and **one copper pipe** for a specific Internal diameter, Fig. (2), will be tested based on the data shown in Table (1).

*Table.1: Input data for the numerical Model.*

| | |
|---|---|
| PCM Properties | |
| PCM Initial Temperature | 298.15 K |
| Thermal Conductivity | 1.88 W/m K |
| Density | 1000 kg/m$^3$ |
| Heat of Fusion | 334 kJ/kg |
| Copper Tube Properties | |
| Thermal Conductivity | 110 W/m K |
| Internal Diameter | 2 cm |
| Thickness | 0.1 cm |
| Heat Transfer Fluid (HTF) | |
| Volumetric Concentration | 40% |
| Initial Temperature | 258.15 K |
| Velocity | 1 m/s |

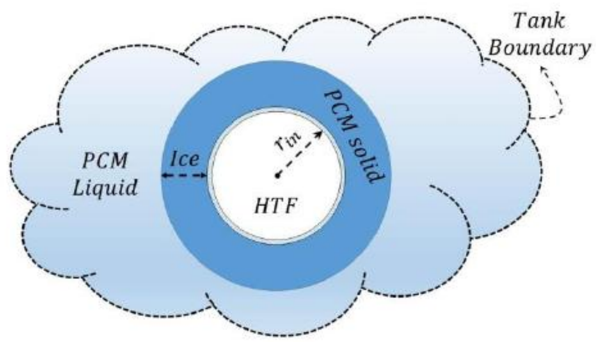


*Fig.2: One Copper Pipe in a storage Tank.*

After running the cooling source for about eight hours, which correspond to constant temperature of the external surface of the copper pipe, some essential parameters will be obtained such as the ice thickness around the copper pipe. Secondly, based on the data obtained from the first run which will define the diameter of the storage tank, a specific diameter tank will be tested with evenly distributed copper tubing to show the piping effect on each other's.

## IV. NUMERICAL MODEL FOR A COPPER PIPE

The effect of the HTF temperature and also the PCM initial temperature will be studied on the ice thickness around the pipe in the ice storage tank. A tank with a diameter of (15 cm) and a height of (100 cm) will be used in the numerical analysis, the tank has only one copper pipe with the thermos-physical properties shown in Table (1). Table (2) shows that data obtained from the numerical run after eight hours of work for every hour.

https://dx.doi.org/10.22161/ijaers.5.4.11 **ISSN: 2349-6495(P) | 2456-1908(O)**

The maximum ice thickness was (3.5 cm). Fig. (3) shows the trend on the ice thickness with time based on the data from Table (2). It shows that data obtained from the numerical run after eight hours of work for every hour. The maximum ice thickness was (3.5 cm).

*Table.2: Output data for the numerical model.*

| Time (hours) | Ice Thickness (cm) |
|---|---|
| 1 | 1.2 |
| 2 | 1.8 |
| 3 | 2.1 |
| 4 | 2.5 |
| 5 | 2.8 |
| 6 | 3 |
| 7 | 3.3 |
| 8 | **3.5** |

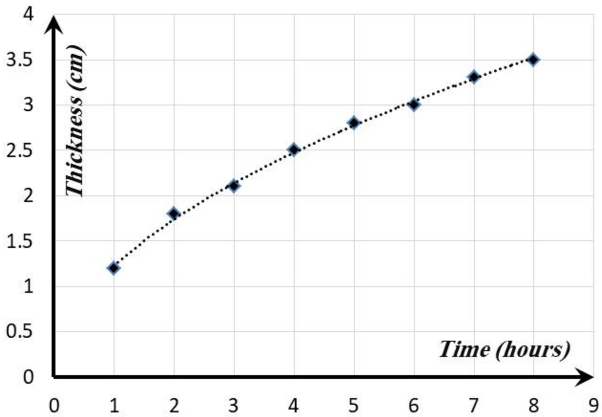


*Fig.3: Ice thickness with respect to time numerically.*

Fig. (4) shows temperature distribution from the surface of the one copper pipe outward after eight hours of work. Red color indicates a temperature of (274 K) and blue color indicates a temperature of (258.15 K) which is equal to the temperature of the HTF. The Figure shows also that the ice thickness in uniform along the length of the pipe.

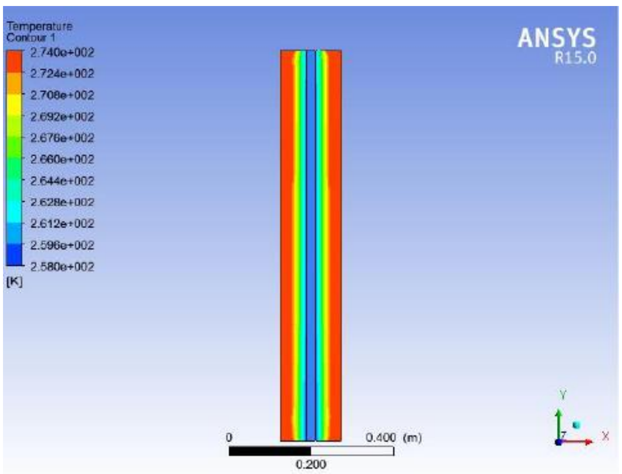


*Fig.4: Temperature distribution along the diameter of the copper pipe.*

Fig. (5) shows the effect of the HTF temperature ($T_\infty$) on the ice thickness ($\delta$) with a pipe length of (100 cm) on the final hour (eighth hour) only. The Figure reassures that increasing the HTF temperature decrease the ice thickness formed around the tube and vice versa decreasing the HTF temperature increases the ice thickness.

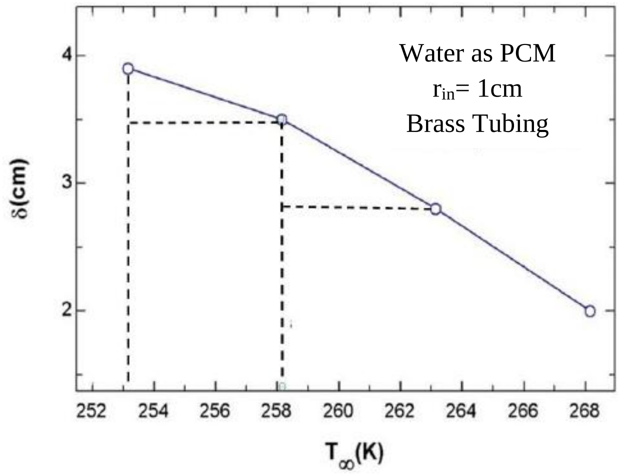


*Fig.5: The relationship between ice thickness & HTF temperature on the eighth hour.*

The Fig. (5) also shows that decreasing the HTF temperature below (258.15 K) reduce the ice thickness (slop is decreased). Working below that temperature will increase the electrical power consumption on the cooling source which reduces the efficiency of the whole system. Fig. (6) shows the effect of the length of the copper pipe on the ice thickness around the copper pipe. It shows that a pipe length longer than (200 cm) will decrease the ice forming around the pipe. Using several storage tanks with (200 cm) length connected in parallel could be the solution for this states. The data in this Figure is obtained at the final hour (eighth hour) of work.

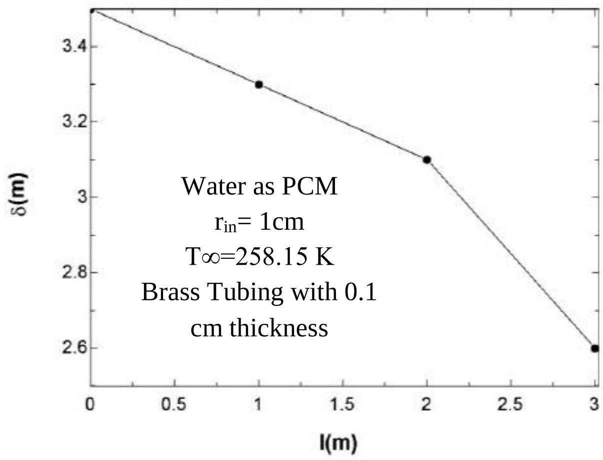


*Fig.6: The relationship between Ice thickness and pipe length on the eighth hour.*

https://dx.doi.org/10.22161/ijaers.5.4.11 **ISSN: 2349-6495(P) | 2456-1908(O)**

To study the effect of PCM initial temperature ($T_{initial}$) on the ice thickness, several numerical tests were conducted based on the data shown in Table (3).

*Table.3: PCM Initial Temperature Tests*

| No of Tests | PCM Initial Temperature |
|---|---|
| 1 | 298.15 K |
| 2 | 293.15 K |
| 3 | 288.15 K |
| 4 | 283.15 K |
| 5 | 278.15 K |
| 6 | 273.15 K |

Fig. (7) shows the results obtained from the previous tests. It indicates the relationship between the ice thickness and the PCM initial temperature on the final hour (eighth hour) of work.

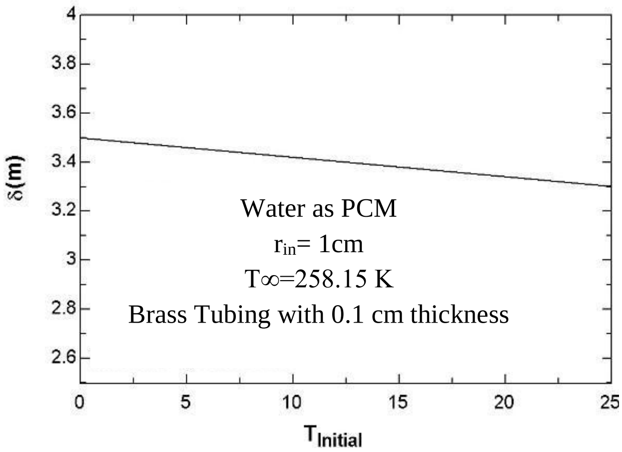


*Fig.7: The relationship between Ice thickness and PCM initial temperature on the eighth hour.*

The Fig. (7) shows that the effect of the PCM initial temperature is negligible, decreasing the PCM temperature will increase the ice thickness about 5.7% (0.2 cm) only. The sensible load removal by dropping the PCM temperature has little effect of the ice thickness. Based on previous data, the ice storage tank can be selected to have PCM with initial temperature of (298.15 K), length less than (200 cm) and HTF temperature more than (258.15 K). These finding will lead numerically to a maximum thickness of (3.5 cm) around the copper tube.

## V. NUMERICAL MODEL FOR SEVERAL COPPER PIPES

Previous obtained data will be used to study the effect of implementing several copper pipes in the storage tank. The optimal distance between the pipe will be measured numerically which specify at the end the diameter of the storage tank. Fig. (8) shows the numerical solution of a storage tank with a diameter of (32 cm) and height of (100 cm) which contains (7) cylindrical copper pipes on the final hour (eighth hour) of work. The distance between the center of pipes has been calculated to be (9.4 cm) based on the previous data. As mentioned before, red color indicates a temperature of (274.15 K) and blue color a temperature of (258.15 K) which is equal to the temperature of the HTF. The Figure shows regions interference between the solid and the liquid which can be explained by decreasing the amount of liquid between the pipes which leads to an increment in the ice thickness at the final hour. Table (4) reveal the ice thickness obtained hourly numerically.

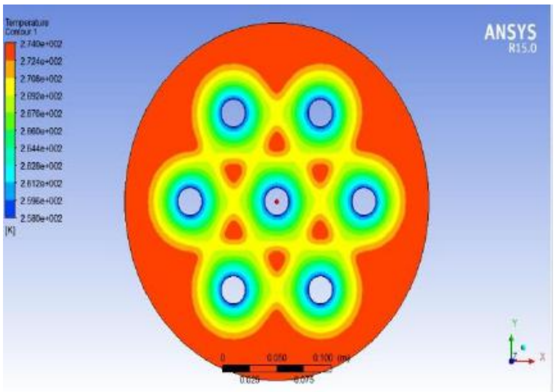


*Fig.8: Temperature distribution along the diameter of the copper pipe.*

*Table.4: Numerical data output for several pipes.*

| Time (hours) | Ice Thickness (cm) |
|---|---|
| 1 | 1.2 |
| 2 | 1.8 |
| 3 | 2.1 |
| 4 | 2.5 |
| 5 | 2.8 |
| 6 | 3 |
| 7 | 3.3 |
| 8 | **3.7** |

The table shows the same data obtained for one pipe test but the ice thickness increased at the final hour and became (3.7 cm) instead on (3.5 cm). To verify this finding, several test numerically were done on the same storage tank with different HTF temperatures as per Fig. (9). The Figure gives the optimal space between the pipes with relation to the HTF temperature at the final hour (eighth hour) of work.

*https://dx.doi.org/10.22161/ijaers.5.4.11* *ISSN: 2349-6495(P) | 2456-1908(O)*

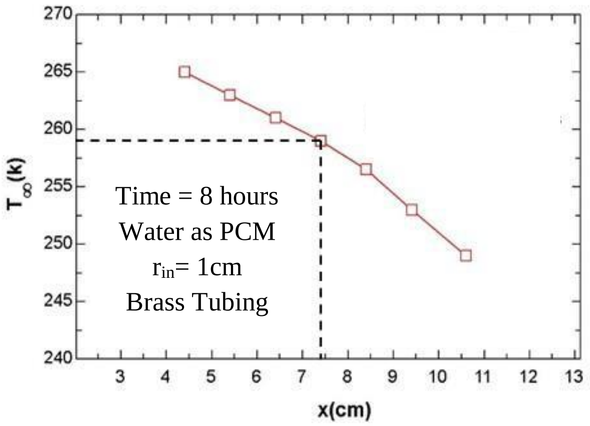


*Fig.9: The relation between HTF temperature and optimal pipe spacing for eighth hour.*

Fig. (10) shows the numerical solution of a storage tank with a diameter of (100 cm) and height of (100 cm) contains (61) cylindrical copper pipes on the final hour (eighth hour) of work for the same data before. Also the interference between regions is clear.

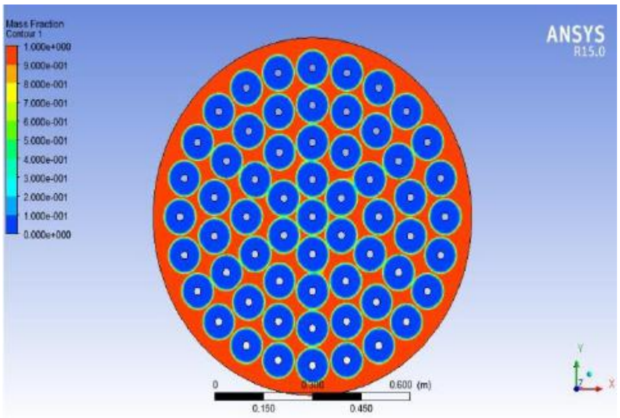


*Fig.10: Temperature distribution along the diameter of the copper pipes in a storage tank.*

Fig. (11) shows the numerical solution of a storage tank with a diameter of (100 cm) and height of (150 cm) contains (37) cylindrical copper pipes on the final hour (eighth hour) of work for the same data before where the space between the pipes were increased to be (13.6 cm). No interference was found.

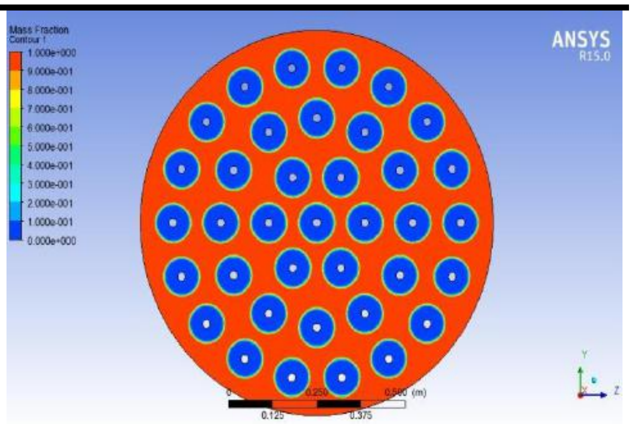


*Fig.11: Temperature distribution along the diameter of the copper pipes in a storage tank.*

## VI. EXPERIMENTAL TEST AND RESULTS

In order to rely on numerical data obtained before, test experiment has been conducted. A storage tank with a diameter of (32 cm) and height of (40 cm) contains (7) cylindrical copper pipes was test. The PCM was a regular water, with an initial temperature of (298.15 K), HTF is 40% Ethylene Glycol (EG) with a temperature of (267.15 K) and velocity inside the tube is (1 m/s), copper tubing with an internal diameter of (2 cm) and thickness of (0.1 cm), eight hours of work. The numerical solution shown in Fig. (12) with hourly details data from Table (5). The final ice thickness was (2.2 cm).

*Table.5: Numerical data output for several pipes.*

| Time (hours) | Ice Thickness (cm) |
|---|---|
| 1 | 0.3 |
| 2 | 0.8 |
| 3 | 1.1 |
| 4 | 1.4 |
| 5 | 1.6 |
| 6 | 1.8 |
| 7 | 2 |
| 8 | **2.2** |

In Fig. (12) yellow color indicates a temperature below (274.15 K) as per the temperature scale on the Figure but no solidification phase, and blue color a temperature of (267.15 K) which is equal to the temperature of the HTF. Fig. (13) shows the actual storage tank insulated with a collector in and out ready to be tested.

Table (6) shows the **actual** ice thickness every two hours for eight hours of work. The table shows that the maximum ice thickness was (2 cm) which is shay by (0.2 cm) from the numerical model, the error was in the order of 9% only.

*https://dx.doi.org/10.22161/ijaers.5.4.11* *ISSN: 2349-6495(P) | 2456-1908(O)*

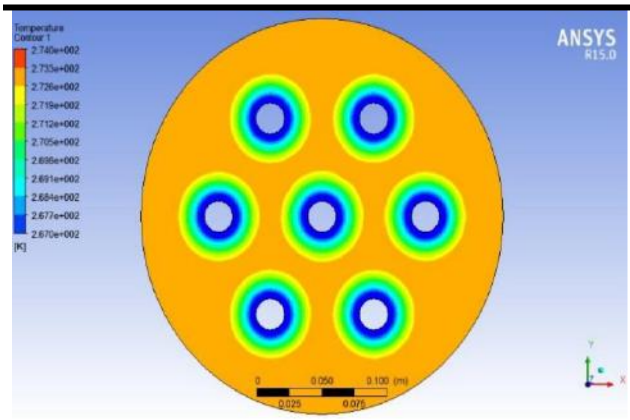


*Fig.12: Temperature distribution along the diameter of the copper pipes in a storage tank.*

*Table.6: Experimental data output for several pipes.*

| Time (hours) | Ice Thickness (cm) |
|---|---|
| 2 | 0.5 |
| 4 | 1.1 |
| 6 | 1.6 |
| 8 | 2 |

Figure (14) shows the formation of the ice at the eighth hour of work. It shows a uniform thickness around the pipe and along the pipe which verify the numerical model used.

*Fig.13: Actual storage Tank.*

*Fig.14: Actual ice thickness in the storage tank.*

Fig. (15) shows the comparison between the numerical data and the experimental data. The data shows that the error is small as stated before and the numerical model can be used in predicting the dimensions of different ice storage tanks.

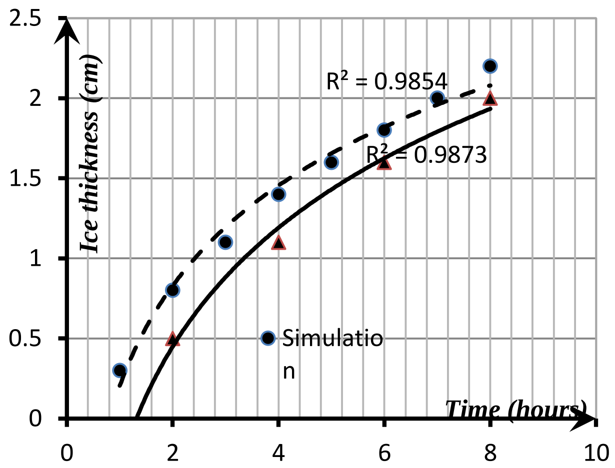


*Fig. 15: Comparison between numerical and experiment Results.*

## VII. CONCLUSION

The data obtained before stated that the speed of the interface between solid and liquid decreases with time because of the increase of solid thermal resistant. The ice thickness increases with decreasing of HTF temperature up to (259.15 K). No effect in changing the diameter of the copper pipes bigger than (2 cm) on the ice thickness. No effect of the copper pipe length which less than (200 cm) on the ice thickness. No effect on the PCM initial temperature (amount of sensible load) on the ice thickness. Good agreement between numerical and experimental data after eight hours of work with an error of 9%.

## REFERENCES

[1] Dincer, I. and Rosen, M., (2002). Thermal Energy Storage Systems and Applications. John Wiley and Sons, ISBN 0-471-49573-5.

[2] Zalba, B., Marin, J. M., Cabeza, L. F., Mehling, H., (2003). Review on Thermal Energy Storage with Phase Change: Materials, Heat Transfer Analysis and Applications, Applied Thermal Engineering 23, 251–283.
[3] Farid, M.M., Khudhai, A.M., Razack, S.A.K., Al-Hallaj, S., (2005). A Review on Phase Change Energy Storage: Materials and Applications. Energy Conversion and Management 45, 1597–1615.
[4] Evapco, (2007). Thermal Ice Storage, Application & Design Guide. Evapco Inc.
[5] Habeebullah, B. A., (2007). An experimental study on ice formation around horizontal long tubes. International Journal of Refrigeration, 30:789–97.
[6] Sait, H. H., Hussain, A, Selim, A. M., (2012). Experimental investigation on freezing of water falling film on vertical bank of horizontal cold tube. Journal of Thermal Science Eng. App., 4.
[7] Sait, H. H., (2013). Heat transfer analysis and effects of feeding tubes arrangement, falling film behavior and backsplash on ice formation around horizontal tubes bundles. Energy Convers Manage; 73: 317–28.
[8] Hosseini, M. J., Ranjbar, A. A., Sedighi, K., Rahimi, M., (2013). A combined experimental and computational study on the melting behavior of a medium temperature phase change storage material inside shell and tube heat exchanger. Int. Commun. Heat Mass Transf. 39 (9), 1416–1424.
[9] Yingxin, Z., Yinping, Z., Gang, L., Fengjun, Y., (2001). Heat transfer processes during an unfixed solid phase change material melting outside a horizontal tube. Int. J. Therm. Sci. 0, 1–14.
[10] Yari, M., Monsef, H., Zadegan, M. N., (2010). Numerical Analysis Of Water Solidification Around Horizontals Tubes Using For Ice Storage Systems. Journal of Economics and Engineering, ISSN: 2078-0346.
[11] Ismail, K. A., Fátima, A.M., (2014). Experimentally validated two dimensional numerical model for the solidification of PCM along a horizontal long tube. International Journal of Thermal Sciences, 75, 184-193.
[12] Liu, J., Xu, C., Ju, X., Yang, B., Ren, X., Du, X., (2017). Numerical investigation on the heat transfer enhancement of a latent heat thermal energy storage system with bundled tube structures. Applied Thermal Engineering 112, 820–831.
[13] Sugawara, M. Komatsu, Y., Beer, H., (2008). Melting and freezing around a horizontal cylinder placed in a square cavity. Heat Transfer Journal, 45:83.
[14] ASHRAE Fundamental Handbook, (2013). Physical properties of secondary coolants (brines). Chapter 31.
[15] Alaa, A., Badran, E. B., (2017). Analyzing the Moving Boundary Condition (solidification phenomena) of PCMs around cylindrical surface numerically and experimentally. M.Sc. Thesis, Damascus University.