Integration of PCM in Domestic Hot Water Tanks: Optimization for Shifting Peak Demand

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ABSTRACT

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Most of the current domestic hot water tanks store heat in sensible form. They use electrical heaters which have low efficiency of energy utilization. Latent heat storage systems have become popular recently, and they seem to be more efficient than existing storage systems. High latent heat of phase change materials and their compactness are the main reasons for their popularity in the thermal storage industry.

This thesis reports the outcomes of implementing PCM in a standard domestic hot water tank, on energy consumption and the discharge period and suggests a method for optimization of the tanks regarding their discharge time. Geometrical aspects of PCM containers and the amount of PCM inside the tank were design parameters of this study. TRNSYS was used to simulate the behavior of the tank. The results of 900 simulations were used to create an initial database for training an artificial neural network in order to find a correlation between design parameters of the tank and the discharge time. Genetic Algorithm was then used in order to find the optimum amount of PCM needed for a desired discharge time.

Finally, a comparison between an optimized tank and a regular water tank was done. It was concluded that an optimized tank is able to provide hot water while consuming less energy compared to a hot water tank without PCM. Furthermore, by placing a certain amount of PCM at the top part of the tank, electrical energy consumption could be shifted completely to off peak periods characterized by less power demand.

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LIST OF SYMBOLS

PCM	Phase change material
ANN	Artificial Neural Network
TRNSYS	Transient Energy System Simulation Tool
GA	Genetic Algorithm
Sol	Solid
Liq	Liquid
λ	Thermal conductivity [W m^{-1} $°C^{-1}$]
C_p	Specific heat [J $kg^{-1} °C^{-1}$]
ρ	Density [kg m^{-3}]
H	Enthalpy [J]
t	Time [s]
T	Temperature [°C]
h	Convection coefficient [W m^{-2} $°C^{-1}$]
Re	Reynolds number
Ra	Rayleigh number
Pr	Prandtl number
Nu	Nusselt number

1. INTRODUCTION

1.1 ESSENCE AND CHALLENGES OF THERMAL STORAGE

In order to balance energy demand and supply, energy storage should be used. The stored energy can be used in peak periods when there is a high demand for energy. Thermal storage systems can lower energy consumption and greenhouse gas emissions. Two main means of storing thermal energy are sensible and latent heat storage. Latent heat storage has some advantages over sensible heat storage. Some of which are its very slight change in temperature during phase transition and its high energy storage density. But most of the practical applications use sensible heat storage [1].

Some of the characteristics of PCMs such as their high latent heat and high density have made them popular in the thermal storage industry which uses water as a storage medium in most cases. Liquid-solid is the most preferable phase change transition in thermal storage systems due to very minor variations in volume of the storage medium. Solid-gas, liquid-gas transformation requires large space [2].

The most desired thermo-physical characteristics of PCMs are a high value of specific heat per volume, having a melting temperature suitable for the application, low vapor pressure at the working conditions and high thermal conductivity. In addition, the materials used in the system should not be poisonous, flammable and chemically unstable [3].

One of the most important drawbacks of PCMs is their relatively low thermal conductivity on which the charging time of PCM depends [2]. Several studies have focused on increasing the thermal conductivity of phase change materials. Shabtay and Black [4] suggested that the thermal conductivity efficiently increases by placing copper tubes or aluminum fins in a container filled with phase change materials. Fan et al. [5] used carbon and graphene nanoplatelets in order to increase the thermal conductivity of paraffin-based phase change materials.

Phase change materials have been used in a variety of applications in the past three decades from spacecraft thermal systems [6] to food production industry [7]. The current study focuses on the application of PCMs in domestic hot water tanks.

Current domestic hot water tanks usually use electrical heaters or gas. Zhu and Long [8] reported that sensible heat storage systems have low efficiency, and they cause large amount of greenhouse gas emissions. Several studies have focused on improving the thermal performance of domestic hot water tanks. Two popular methods are applying control strategies [9] and improving thermal stratification of the tank [10]. Using latent heat energy storage in hot water tanks has been one of the main topics of research in recent years. This thesis tries to investigate the advantages of placing PCM inside domestic hot water tanks.

1.2 OBJECTIVES

The main objective of this thesis is to find the minimum amount of PCM needed for completely shifting the operation time of electrical heaters to off peak period, when there is less power demand. For carrying out this task a 270-L North American standard domestic hot water tank was simulated with TRNSYS, and the results of the simulations were used in MATLAB for optimization. In addition, this study aims at finding the effects of design parameters, such as the location of PCM inside the tank and the diameter of PCM containers, on the thermal performance of the domestic hot water tank.

1.3. THESIS OUTLINE

Chapter 2: “Literature review” contains the previous studies regarding the implementation of PCM inside hot water tanks, their achievements and limitations.

Chapter 3: “Methodology” introduces the numerical model used in this thesis and outlines all the stages of training an ANN and performing optimization.

Chapter 4: “Results” is about the analysis of the results.

Chapter 5: “Conclusions and limitations of study” summarizes the results and suggests potential future studies.

2. LITERATURE REVIEW

2.1. LITERATURE REVIEW ON INTEGRATION OF PCMS IN HOT WATER TANKS

2.1.1 Previous studies

Cabeza et al. [11] developed a numerical model using the finite volume method to study the thermal performance of a domestic hot water tank integrated with PCM. They validated their model with experiments. They considered three different discharge scenarios for their parametric studies. 57 PCM containers were used in their model, and seven thermocouples carried out the task of observing the temperature of water inside the tank during simulation. They concluded that although the amount of water decreases because of the occupied volume of the PCM containers, the new system can provide hot water for longer period of time and that PCMs can be fully charged during off-peak periods. They also stated that the arrangement of PCM containers inside the tank is another important factor affecting the performance of the tank. When there are large number of container tubes inside the tank, the system is able to provide hot water for longer period of time in the first discharge but less in the next discharges. When the number of tubes is smaller and their diameter is bigger, the system is able to provide hot water in posterior discharges. They argued that this behavior is mainly due to the large amount of energy being transferred between the water and the PCMs when the surface area is increased as a result of a larger number of tubes. The study, however, does not give an accurate optimized arrangement for the PCM containers and the amount of PCM that is used.

Cabeza et al. [12] investigated the effects of adding PCM to the top layers of a stratified tank. They conducted experiments by making a solar plant. They used granular PCM-graphite consisting of 90 vol. % of sodium acetate trihydrate and 10 vol. % graphite in cylindrical containers. Their results suggest that PCM increases the storage performance of the tank. They reported that an increase of PCM from 2.1 kg to 6.3 kg resulted in an increase in the system's energy density from 40% to 66.7%. Their results suggest that using PCM can reduce the size of the hot water tanks. Their study does not specify the criteria for the quantity of PCM to be selected for the modules of the hot water tank.

Ibanez et al. [13] developed a new TRNSYS component called Type 60 PCM. In their model, they put two cylindrical PCM modules inside the tank, considered the cooling as well as reheating effect of the water inside the tank and validated their model. Their study still needs more consideration and design optimization to improve the model's performance.

Mehling et al. reported that when PCM is added to the upper layers of the tank, it can compensate for the heat loss from the top of the stratified tank [14]. They developed a model based on the explicit finite difference method. This model takes into account conduction from each layer to the other, heat transfer between phase change material and water and the amount of heat transferred between the water and PCM.

They carried out studies with two different types of PCM [14]. They replaced 1/16 of the volume of the tank with PCM and concluded that the average energy density increased by 20% to 45%. However, they did not consider convection in their model and they measured the temperature of PCM at its highest layer and assumed that PCM in the module is isothermal.

Mazman et al. [15] investigated the effects of placing PCM at the top layers of a domestic hot water tank. They conducted experiments with three different mixtures of paraffin. By placing paraffin at the top layers of the tank, they measured the temperature over time in charging and discharging processes. The PCM that was able to prolong the cooling time and shorten the reheating time was chosen as the best mixture of paraffin. Their study only considered 3 types of PCMs without exploring the effects of their arrangements and their amount inside the tank.

Nkwetta et al. [16] used TRNSYS to model a hot water tank with two heating elements and carried out parametric studies to investigate the influence of the type of PCM, its amount and its location inside the tank on the energy density of the hot water tank. Granulated Paraffin Wax, RT58-Rubitherm and sodium acetate trihydrate+ 10% graphite were used in their study. For their simulation they used three different real-life consumption of hot water profile. They reported that sodium acetate trihydrate+10% graphite is a better type of PCM than Granulated Paraffin Wax and RT58-Rubitherm. They concluded that placing the PCM at the top of the tank is more beneficial than placing it in the middle or at the bottom of the tank. They also reported that the conductivity of a PCM container plays an important role on the performance of the PCM. The higher the conductivity of the container, the quicker the PCM will be charged. Their study considered only three possible locations for the PCM inside the tank, and it did not discuss the effects of the geometrical parameters of the PCM containers, such as the number and diameter of the tubes.

Nkwetta et al. [17] used a validated TRNSYS model in order to study the effects of PCM in a hot water tank. They applied a control strategy so that the heaters work only during off-peak periods. They used real hot water consumption profile and concluded that the hot water tank with PCM was able to provide hot water for a longer period of time compared to the PCM-free tanks. They concluded that the peak power shift increases with the increase in the amount of PCM applied in the tank. They further stated that with control strategy and PCM, electrical energy consumption could be reduced.

Nabavitabatabayi et al. [18] numerically investigated the impact of some of the design and operational parameters such as the mass of PCM and concentration of nano particles and mass flow rate on the performance of a hot water tank. The results showed that enhanced PCM could be more beneficial and could shift the power demand more than pure PCM. They also reported that, due to its lower thermal conductivity, it takes more time for pure PCM to be completely solidified than the enhanced PCM.

Fazilati and Alemrajabi [19] investigated the effects of use of PCM on the performance of a solar water heater. They utilized commercial-grade paraffin wax with a melting temperature of 55 °C and placed it in 180 spherical capsules with a diameter of 38 mm. In order to increase the low thermal conductivity of the paraffin, a layer of copper was inserted inside each capsule. The researchers carried out experiments and reported that the energy storage density of the system could be increased by 39%; the discharge period was also increased by 25%.

Talmatsky and Kribus [20] simulated the thermal behavior of a storage tank for a period of one year. They considered different load profiles, PCM types, and volume fractions and they concluded that the use of PCM in the storage tank does not provide considerable benefits. They reported that the main reason why using PCM in a hot water tank was not beneficial is that heat loss from the tank increases during nighttime when the water is being reheated by PCM. They argued that their system works within a wide range of temperatures and the system could not benefit from PCM's large storage capacity in the form of latent heat when the temperature is far from PCM's melting range. In their study, they used RT42, a material that has a heat capacity smaller than water. Therefore, when the PCM operates in single phase, water is the main heat storage medium.

Kousksou et al. [21] carried out a new study on the abovementioned work of Talmatsky and Kribus [20] and proposed an improved alternative so that PCM could be beneficial in solar domestic hot water tanks. The system they used was a 120cm-high tank with a diameter of 40cm equipped with PCMs in cylindrical containers.

They developed a numerical model by assuming that the heat transfer takes place only in vertical direction so the problem is one-dimensional. They also assumed that the system is lumped because of high conductivity of the selected PCM. They concluded from the sensitivity analysis that optimization at the early stages of design may cause the PCM to be more beneficial for the hot water tank due to the high sensitivity of domestic hot water tanks towards design parameters such as the melting temperature of PCM.

Haillot et al. [22] tried to optimize a solar domestic hot water tank integrated with PCM. They tried to find a tank with the smallest possible volume for a required solar fraction. They conducted parametric studies under two different weather conditions. They chose the amount and type of PCM and the volume of the tank as their design parameters. They then optimized the problem using Genetic Algorithm. Their study does not account for user load profiles. It is also important to note that the limitation of experimental data: The experiment was performed only for two months.

Padovan and Manzan [23] optimized a storage tank using Genetic Algorithm. They chose geometry, melting temperature of PCM and insulation thickness as the design parameters of the problem and used modeFRONTIER as an optimization tool. It was concluded that the integration of PCM for this particular application is not beneficial. However, other design parameters play a key role on the performance of the tank. They reported that by changing the geometry and insulation diameter, the system could save more energy. They reported that the inefficiency of PCM might be because of the large variation in operational temperature, which nullifies the benefits of the significant latent heat of PCM. They suggested that some improvements could be made if paraffin is replaced with a higher-density PCM.

2.1.2 Summary and limitations of previous studies

The notable achievements of the previous studies regarding the integration of domestic hot water tanks with PCMs can be summarized as follow:

- Implementing PCM inside the hot water tank can increase the energy density of the system.
- Placing PCMs inside the tank could increase the discharge time of the domestic hot water tank.
- Thermo-physical characteristics of PCMs, such as the conductivity and melting point, have a great influence on performance of the tank.

However, there are some shortcomings in previous studies. These limitations can be listed as follow:

- Few studies used real-life consumption profiles. (The current study uses standard Quebecois withdrawal profile).

- The geometry and arrangement of PCM containers inside the tank were neglected in most of the cases. (Location and geometry of PCM containers are design parameters of this study).
- Optimizations were carried out with few parametric studies instead of using optimization tools. (The current study uses MATLAB for carrying out the two-objective optimization with Genetic Algorithm in order to optimize the performance of hot water tanks with PCM).
- In experimental cases, the meteorological conditions under which the experiments were carried out were ignored. (This study proposes a general method for the optimization of a hot water tank with PCM, which can be applied to any withdrawal profile).
- Energy density was the main objective in most cases. In order to choose an optimal system, various aspects need to be considered. (Energy consumption and discharge time were considered in this study).

2.2 LITERATURE REVIEW ON OPTIMIZATION

2.2.1 Multi-objective optimization problems.

A problem that aims to optimize more than one function is called "Multi-objective optimization problem". The multi-objective optimization problem cannot be solved in the same way as single objective optimization: In these cases, improvement towards the optimal value of one objective might worsen closeness to optimal value of the other objectives. Therefore, in these cases one should either considers weighing strategies or use multi-objective optimization algorithms [24].

A multi-objective optimization problem can be described as follow [25]:

Min $[f_1x(x), f_2(x), \ldots. f_n(x)]$

$x \in S$ and $n>1$,

where S is a set of constraints which x is subjected to.

The multi-objective optimization is based on the concept of pareto-optimality or non-dominance. The multi-objective optimization algorithms find solutions which are laid on the pareto frontier.

x is a pareto optimal vector if all other vectors which satisfy the constraints have a higher value for at least one of the objective functions.

A point x^* is a weak pareto optimum for a multi-objective optimization problem if there is no $x \in S$ such that $f_i(x) < f_i(x^*)$ for all $\in \{1,\ldots, n\}$.

A point x^* is a strict pareto optimum for a multi-objective optimization problem if there is no $x \in S$ such that $f_i(x) \leq f_i(x^*)$ for all $\in \{1,\ldots, n\}$.

2.2.2 Optimization algorithms

Attia et al. [24] categorized optimization methods as follow:

1. Enumerative algorithms.

2. Deterministic algorithms.

3. Stochastic algorithms.

Enumerative means choose the best solution after evaluating of all the possible candidates. If the evaluation functions of the problem are twice differentiable, this method carries out its search according to the gradient of the function. It starts from an initial value and then continues its search in a direction where the local gradient of the function is zero or very small. There are, however, major drawbacks of enumerative algorithms. First of all, the functions must be twice differentiable, which rarely happens in complex systems. Secondly, the algorithm might find a local optimal point instead of the global one. In order to avoid the barriers of gradient-based enumerative algorithms, one should use gradient-free methods in which several iterations are carried out in order to probe the entire search space. Hooke–Jeeves direct search [26] is one of the most famous forms of this kind of algorithms.

Mathematical programing or deterministic algorithm is a branch of optimization in mathematics and computer science which relies on linear algebra and the calculation of the gradient and Hessian. These methods can converge to the solution quickly, but since these algorithms search for the stationary points in response variables, they might get trapped in local optimum instead of global optimum. Since these algorithms require derivable evaluation functions, they might not be useful for complex systems [27].

In stochastic algorithms, the search for the optimum takes place in a random way, but at each level, at least one criterion controls the process; therefore, the randomness can be beneficial. These algorithms are perfect for dealing with nonlinear and high dimensional systems [28]. One of the greatest advantages of the stochastic algorithms is that they do not need many mathematical requirements [29]. However, in these algorithms it is impossible to predict the upper bound for computation time [24].

2.2.3 Genetic Algorithm

Recently, a great number of optimization problems have been solved using Genetic Algorithm. Genetic Algorithm is a form of stochastic optimization algorithm proposed by Holland [30]. It is based on Darwin's theory of evolution. Mitchell [31] suggests that GA is the most efficient stochastic algorithm when it comes to noisy cost functions and when the problem is not smooth. The GAs search for optimum points in all areas of search space, and because they do this task simultaneously, they reduce the chance of trapping in the local optimums [32].

The GA can be summarized in these steps:

1. Creation of random population consists of candidate solutions.

2. At each generation, candidates create new solutions known as offspring produced either by mutation or gene cross-over.

3. Candidate solutions are evaluated by evaluation function.

4. Production of new candidates and their evaluation is repeated at each generation until the termination criteria are met [33].

GAs have been used in wide variety of applications. Wright [34] suggests that GAs are capable of dealing with discontinuous and nonlinear functions. The main disadvantage of GAs is their long computation process due to high number of calls to the evaluation function [33].

3. METHODOLOGY

3.1 DESCRIPTION OF TRNSYS TYPE 860

3.1.1 Numerical modeling

In this study, TRNSYS type 860 is used in order to simulate a domestic hot water tank integrated with PCM. This model was developed by Bony and Citherlet [35]. Previously, TRNSYS type 60 was being used to simulate stratified hot water tanks, but that model cannot be used for a tank integrated with PCM. The current type 860 was based on type 60.

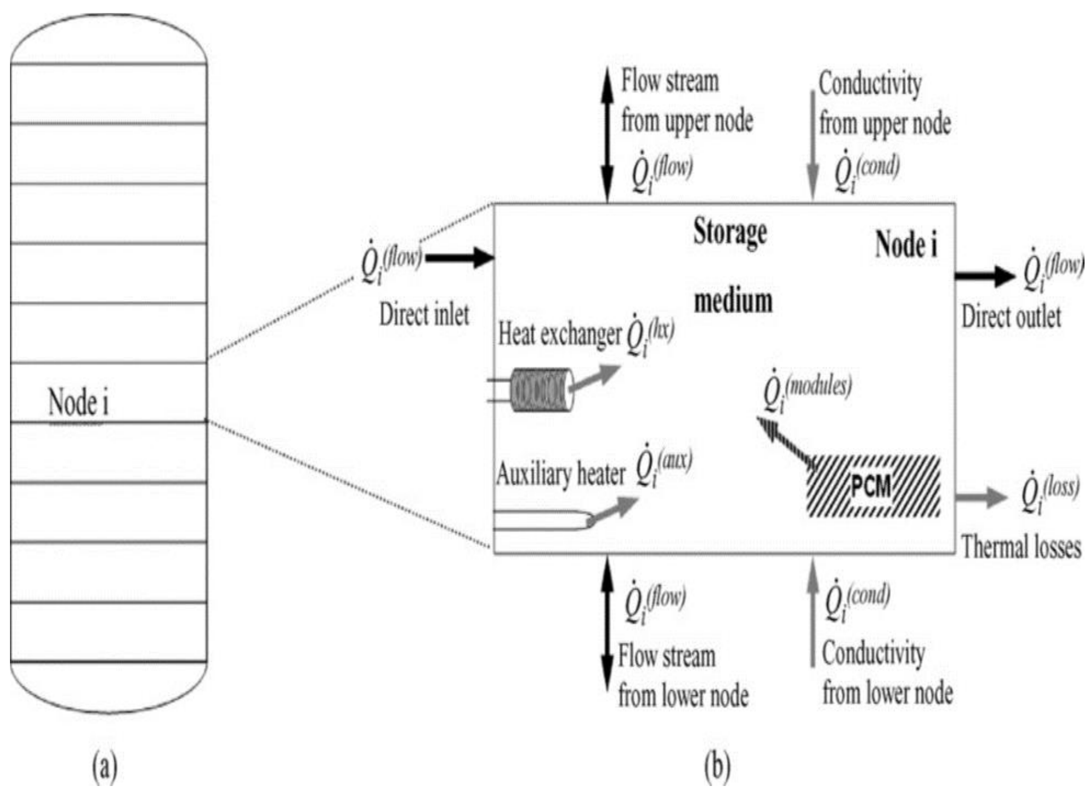

Figure 3-1. The modeling of a vertical hot water tank by Bony and Citherlet [35].

By assuming uniform temperature in each node, the energy balance for a node can be written as:

$$\dot{Q}_{storage(i)}=\dot{Q}_{flow(i)}+\dot{Q}_{heatflux(i)}+\dot{Q}_{heater(i)}+\dot{Q}_{conduction(i)}+\dot{Q}_{loss(i)}+\dot{Q}_{pcm(i)} \quad (1)$$

where,

$\dot{Q}_{storage(i)}$ is the energy that is stored in the ith node .

$\dot{Q}_{flow(i)}$ is the heat caused by fluid motion.

$\dot{Q}_{heatflux(i)}$ is the heat flux of the internal heat exchangers(if applicable).

$\dot{Q}_{heater(i)}$ is the energy provided by electrical heaters.

$\dot{Q}_{conduction(i)}$ is the heat transferred between the neighboring nodes via conduction.

$\dot{Q}_{loss(i)}$ is the heat loss from tank to the ambient.

$\dot{Q}_{pcm(i)}$ is the heat transferred between the PCM module and storage segment (see Eq. 2)

$$\dot{Q}_{pcm(i)} = -N(U_i A_{pcm,i}(T_i\text{-}T_{PCM,i})) \quad (2)$$

where N is the number of PCM containers. U_i is the coefficient of heat transfer between the water and PCM. $A_{pcm,i}$ is the surface area between the PCM container and water. $T_{PCM,i}$ is the temperature of the PCM container. Since Bony and Citherlet [35] used the enthalpy method, the temperature of the PCM container is derived from the enthalpy curve. The explicit method is used to solve the set of equation in TRNSYS type 860 [35]. The explicit method is not unconditionally stable. In order to avoid instability the time step Δt must be smaller than a certain limit, which is dependent on the size of the nodes and other parameters of the system.

The maximum suitable time step for the interior and interface nodes can be derived from:

For the interior nodes: $t \leq \frac{\rho x^2 C_p}{4\lambda}$ (3)

For interface nodes: $t \leq \frac{\rho x^2 C_p}{2\lambda(2+\left(\frac{hx}{\lambda}\right))}$ (4)

where h is the coefficient of the convection between the both sides of the surface and λ is the thermal conductivity of the inner side; c_p is the specific heat of the material, and ρ is its density and x is the distance between the two nodes. The model uses the maximum possible time step for solving the equations numerically.

3.1.2 PCM meshing

Assuming uniform temperature in each node, the energy balance equation for node i,kcan be defined as:

$$\frac{\Delta h^{t1}{}_{i,k}}{\Delta t} = \dot{Q}^{t1}{}_{i,k-1\rightarrow i,k} + \dot{Q}^{t1}{}_{i,k+1\rightarrow i,k} + \dot{Q}^{t1}{}_{i+1,k\rightarrow i,k} + \dot{Q}^{t1}{}_{i-1,k\rightarrow i,k} \quad (5)$$

where the first term on the right side of equation is the heat that transfers between two nodes:

$$\dot{Q}^{t1}{}_{i,k-1\rightarrow i,k} = \left(\frac{\lambda_{i,k}}{X_{i,k}} + \frac{\lambda_{i,k-1}}{X_{i,k-1}}\right) A_{i,k-1\rightarrow i,k} \left(T^{t0}{}_{i,k-1} - T^{t0}{}_{i,k}\right) \quad (6)$$

where i is the vertical axis, k is the horizontal axis, X is the distance between two nodes and λ is the thermal conductivity, A is the surface area between two nodes, and indexes 0,1 for time indicate the initial and final time.

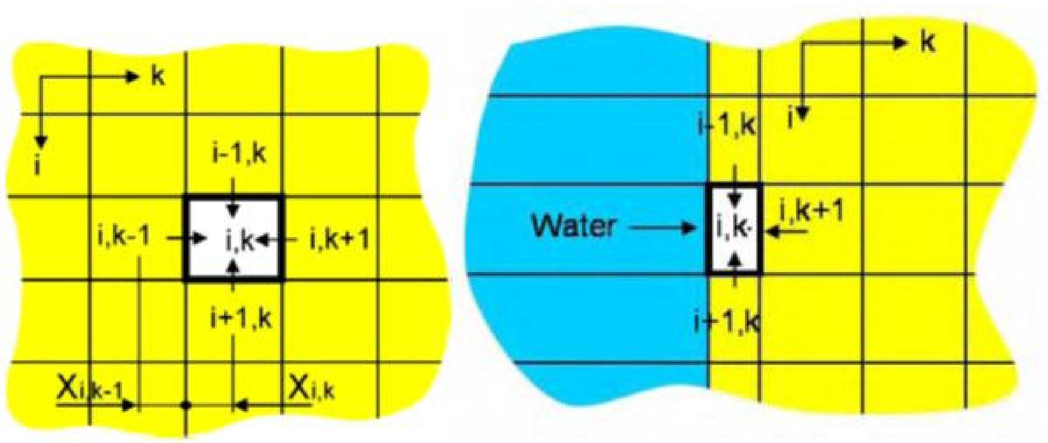

Figure 3-2. Meshing of PCM [35].

The enthalpy at the time 1 can be derived from:

$$H^{t1}{}_{i,k}=H^{t0}{}_{i,k}+\Delta h^{t1}{}_{i,k} \tag{7}$$

3.1.3 Thermal conduction inside PCM

In order to be able to find the thermal conductivity of PCM during phase transition, linear interpolation is used. The formula for the thermal conductivity of PCM during the transition is:

$$\lambda_{sol/liq}=\lambda_{sol}+\frac{\lambda_{liq}-\lambda_{sol}}{H2-H1}\left(H^{t}-H1\right) \tag{8}$$

where H^t is the enthalpy at the time step t and can be derived from Eq. (11).

3.1.4 Convection between water and PCM

The shape of the PCM containers is crucial factors in the computation of the convection between water and PCM. TRNSYS type 860 can be considered for three different types of PCM containers: spherical, cylindrical, and plate. Cylindrical containers were used in this study. Convection equations between water and PCM in this case are listed in table 3-1.

Table 3-1. Water/PCM convection equations[35].

Laminar/ Free	$Nu=\{0.825+\frac{0.378.Ra^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}}\}^2$
Turbulent/Free	
Laminar /Forced	$Nu_x=0.332.{Re_x}^{1/2}.Pr^{1/3}$ $Re_x < 5\times10^5$
Turbulent/ Forced	$Nu_x=0.0296.{Re_x}^{4/5}.\ Pr^{1/3}$ $5\times10^5 < Re_x < 10^7$

During the draw-off process, both forced and free convection exist. Therefore, in these situations, the convection coefficient should be calculated by Eq. (9):

$$Nu_{mixed}=({Nu^3}_{free}+{Nu^3}_{forced})^{1/3} \tag{9}$$

3.1.5 Validation of the model

Bony and Citherlet [35] validated their model using experiments. They used aluminum for the cylindrical PCM container with a diameter of 88mm, height of 150 mm and thickness of 0.3 mm. They poured liquid paraffin in the containers and monitored the temperature during the charging and discharging process. They concluded that by ignoring the convection within the

PCM, the model is not in a good agreement with experimental data. They argued that in PCMs which have high viscosity, the effect of internal convection can be neglected but in the case of paraffin-containing PCMs, the internal convection should be taken into account. In order to do so, they used the effective conductivity factor in their model:

$$\lambda_{effective}=\lambda Nu \quad (10)$$

In fact, after considering the effect of internal convection, the simulation result was in agreement with the experimental data. Nkwetta et al. [16] also validated the TRNSYS type 860. They investigated the charging of PCM inside a hot water tank and using experimental data of Ibanez et al. [13]. They reported good agreement between the simulation and the experimental data.

3.1.6 TRNSYS interface of the model

Figure 3-3 shows the TRNSYS studio of the model used in this study. As shown, the type 860 receives data regarding the draw-off profiles from excel reader type 62. Electrical heaters work by control strategy. In the model, each of the two heaters works according to the limits that are imposed on them with the purpose of reducing energy consumption during the peak hours. The TRNSYS model can plot the temperature at each node inside the tank during the charging and discharging process. It can also provide data for energy consumption and heat loss with respect to time.

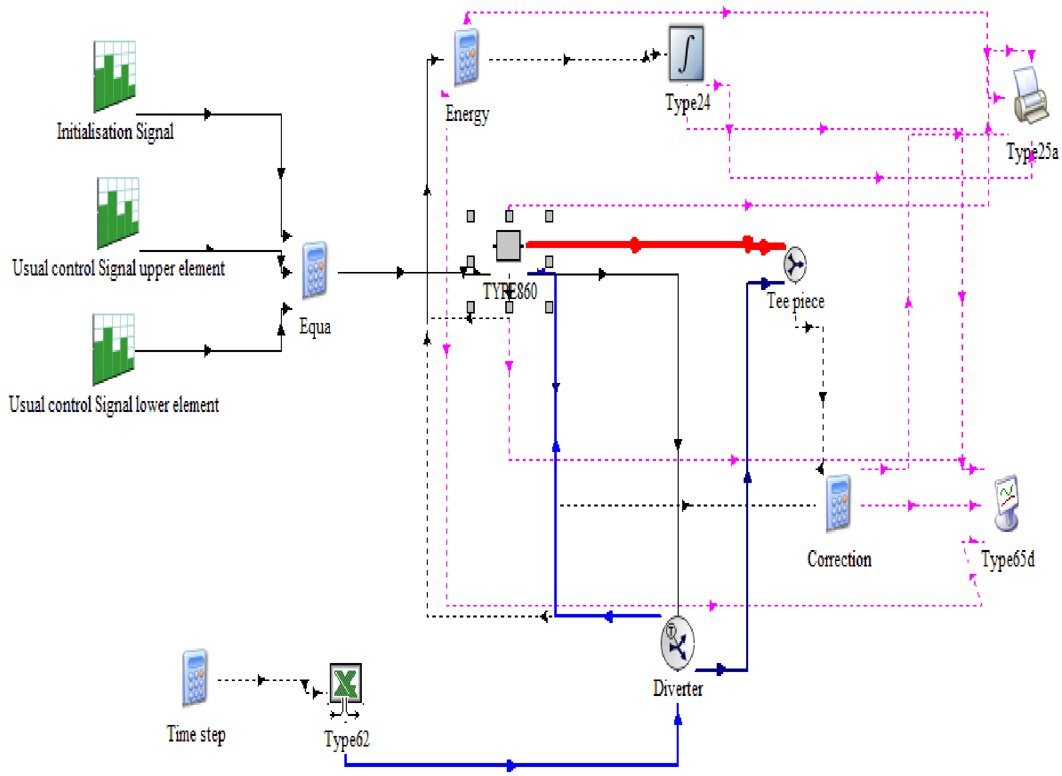

Figure 3-3. The TRNSYS interface of the model used in this study.

3.2 ARTIFICIAL NEURAL NETWORK

An artificial neural network with two hidden layers is used in this study in order to find a relationship between the design parameters of the domestic hot water tank and the discharge period. The network has a sigmoid activation function at the first hidden layer and a purelin at the second one. The number of neurons in first hidden layer was found 25 by trial and error. See Figure 3-4.

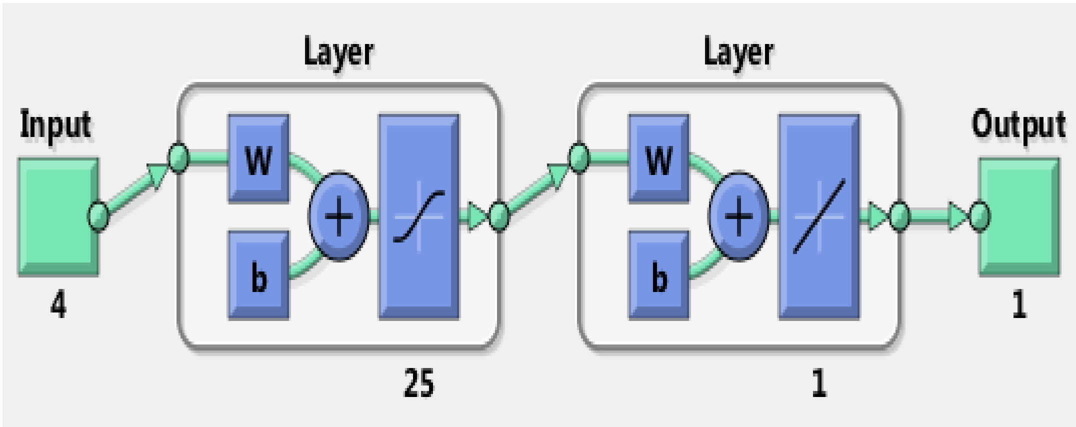

Figure 3-4. Schematic view of a two-layer neural network which has a sigmoid activation function at the first and linear transfer function at the second layer.

The sigmoid and purlin transfer functions are presented respectively in Eq.11, Eq.12.

$$Y_j = \frac{2}{(1+\exp(-2X_j))} - 1\text{: Sigmoid Activation Function} \qquad (11)$$

$$Y_j = X_j\text{: Purelin Activation Function} \qquad (12)$$

Levenberg-Marquardt algorithm was used for training the artificial neural network. According to neural network toolbox guide [36], this method is the fastest training algorithm for networks which have few layers.

X_i was selected as the input to the artificial neural network and Y_i as the output.

$$X_i = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \qquad (13)$$

where:

x_1 is the diameter of the PCM containers.

x_2 is the number of PCM containers.

x_3 is the length of PCM containers.

x_4 is the number of a node which indicates the location of the center of the PCM containers.

Y_i is the discharge time.

Initial database for training an artificial neural network was created by the results of several TRNSYS simulations in which the discharge period of the tank (output) was measured after changing the design parameters (inputs). The validated ANN was then used in MATLAB for the optimization.

3.3 DEFINITION OF THE PROBLEM

3.3.1 Geometry of the tank

Bony and Citherlet' model allows the users to simulate a domestic hot water tank by defining 174 input parameters [35]. These parameters include the geometry of the tank as well as the PCM containers, the physical properties of water, the PCM and the materials of containers.

Moreau reported that the standard type of domestic hot water tank in North America is either a 270-L or 180-L cylindrical tank. In Quebec, they represent 45% and 47%, respectively, of available tanks in the market [37].

In these domestic hot water tanks, cold water at the temperature of 15 °C enters the bottom of the tank and hot water is withdrawn from the top. A common tank has two electrical heaters: one at the top and one at the bottom. According to Moreau [37], electrical heaters have a maximum power of 4.2 kW. Each of these electrical heaters has its own thermostat; in this project, the set point temperature of the thermostats was chosen to be 70°C with a dead band of 10°C for the upper thermostat and 5°C for the lower one. The schematic view of the standard, 270-L tank with two heaters is given in Figure 3-5.

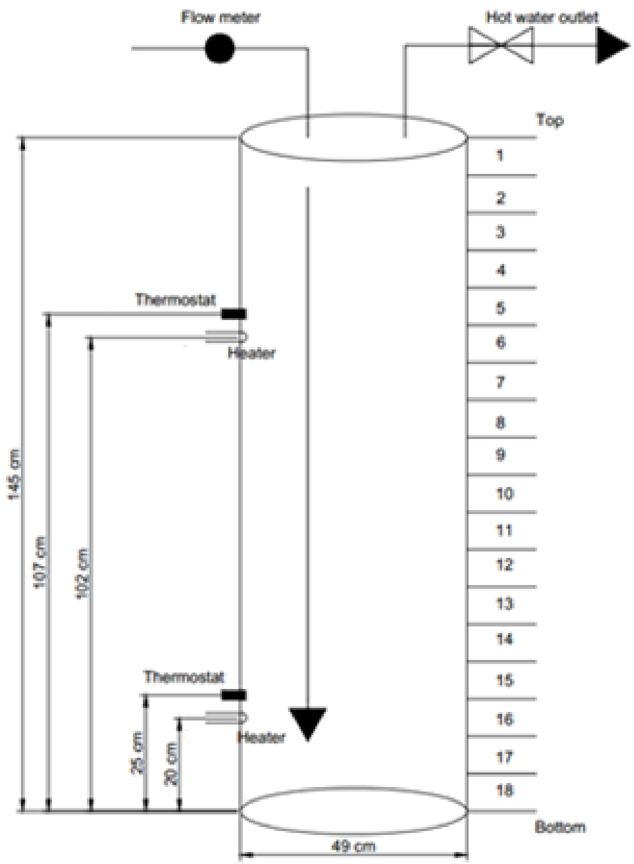

Figure 3-5. Standard hot water tank used in the study.

Table 3-2 gives the geometrical characteristics of the hot water tank used in this study:

Table 3-2. Geometrical characteristics of the tank

Tank volume	270 L
Tank height	145cm
Height of the upper heater	102cm
Height of the upper thermostat	107cm
Set point temperature of the upper heater	70°C
Dead band for the upper heater	10°C
Height of the lower heater	20cm
Height of the lower thermostat	25cm
Set point temperature of the lower heater	70°C
Dead band for the lower heater	5°C
Maximum heating rate of both heaters	4.2 kW

3.3.2 Control strategy for the heaters

Figure 3-6 shows the draw-off profile of the standard domestic hot water tank which used in this study in order to design an optimized hot water tank. This profile is provided by Hydro-Quebec [16]. As it can be seen in the figure, water consumption is particularly high in the morning between 6-8 and at night around 8-10. That means energy demand is too high during the peak periods. In order to avoid extra energy consumption during those hours, it is necessary to reduce the use of electrical heaters during these periods. To this effect, control strategies, which force heaters to work only during off-peak periods, are applied to them.

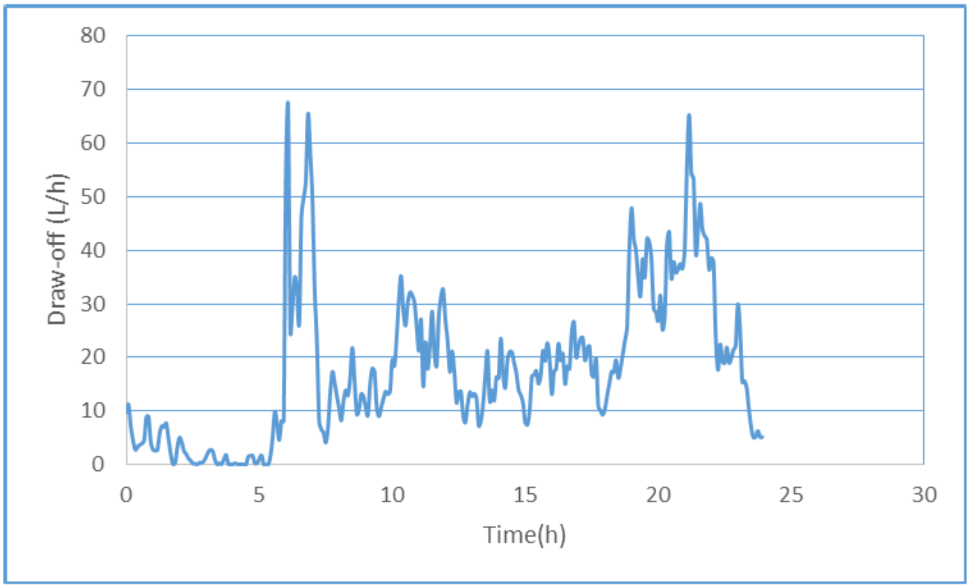

Figure 3-6. Hot water withdrawal profile of residential buildings [16].

In this study, heaters were turned on only during the first six hours of the day after which they could not be turned on even if the temperature fell below the dead band of the thermostats. The purpose of this study is to integrate PCM inside a tank so that the energy that heaters provide during the first six hours of the day will be enough to provide hot water for the rest of the day.

3.3.3 Properties of PCM used in this study

The system cannot benefit from PCM's large storage capacity in the form of latent heat when the temperature is far from PCM's melting range. When the PCM operates in single phase, water is the main sensible heat storage medium due to its high heat capacity. Therefore, the PCM inside the tank must have a melting point near the operation temperature. As Figure 3-7 clearly demonstrates, due to their high melting enthalpy, salt hydrates and eutectic mixtures are the best options for domestic hot water tanks which operate between 50°C-70°C.

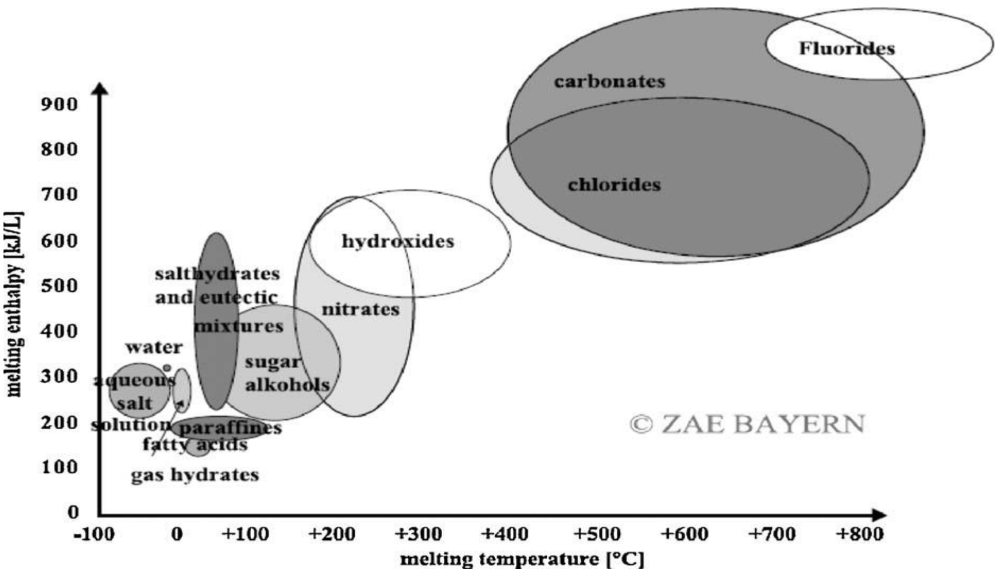

Figure 3-7. Melting enthalpy of different types of PCM [11].

Sodium acetate trihydrate+10% graphite is used as a PCM in this study. Previously, Nkettawa et al. [16] reported that Sodium acetate is able to store more energy than paraffin wax and RT58-Rubitherm due to its high thermal conductivity. The physical properties of sodium acetate are listed in the Table 3-3 [17]:

Table 3-3. Physical properties of sodium acetate trihydrate+10%graphite.

Density in solid state	1360 kg/m^3
Density in liquid state	1260 kg/m^3
Kinematic viscosity	$5\times 10^{6}\ m^{2}$/s
Liquid specific heat capacity	2505 J/kg.°C
Solid specific heat capacity	1900 J/kg.°C
Expansion coefficient in liquid phase	0.001
Solid conductivity	2.3 W/m.°C
Liquid conductivity	2 W/m.°C
Melting temperature	58°C
Melting enthalpy	180-200 kJ/kg

3.3.4. Properties of the PCM container

Several materials have been used for containers. Some of the most popular materials are aluminum, copper, and stainless steel. Although copper has greater conductivity, aluminum was chosen as the more appropriate material for the PCM containers because of its relatively light weight and low cost in comparison with copper [38]. Physical and geometrical characteristics of PCM containers are listed in Table 3-4.

Table 3-4. Physical and geometrical properties of PCM containers made of aluminum.

Density	2702 kg/m^3
Thermal conductivity	237 W/m.°C
Specific heat capacity	903 J/kg.°C
Thickness of containers	0.5mm

3.4 OPTIMIZATION

3.4.1 Introduction

In order to start the optimization process, it is necessary to define the function(s) which should be minimized. The objective is to prolong the discharge time with less amount of PCM.

In order to be able to define the discharge time as a function of design parameters, artificial neural network is used. To train an accurate ANN, it is necessary to provide sufficient data for the neural network. By choosing the diameter, length, location and number of containers, as the design parameters, simulations using TRNSYS were carried out to predict the discharge time.

900 simulations were done, and the amount of PCM inside the tank ranged from 5kg to 60kg. The diameter of tubes varied from 4mm to 160mm, and the number of tubes varied from 1 to 500. PCMs were placed at every part of the tank (from node 1 to 18). Results of the simulations are presented in Chapter 4 of this thesis.

3.4.2 Optimization problem

The objective was to prolong the discharge time as much as a whole day with the least amount of PCM. Therefore, two objective functions were defined; 1) to minimize the amount of PCM, and 2) to fix the discharge time around 24 hours.

Objective 1: Minimize the mass of PCM (M= $0.25 \times \pi \times {x_1}^2 \times x_3 \times x_2 \times \rho \times 0.08$), $X_i = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$

where:

x_1 is the diameter of PCM containers,

x_2 is the number of PCM containers,

x_3 is the length of PCM containers, and

x_4 is the number of a node which indicates the location of the center of PCM containers.

Practical concerns and the geometry of the system impose some constraints on the parameters of the problem. The constraints are listed as follow:

8mm≤x_1≤160mm,

which suggests that the diameter of the tubes cannot be smaller or bigger than a certain amount.

$1 \leq x_2 \leq 500$

This implies that the number of tubes cannot exceed a certain upper band.

$1 \leq x_3 \leq 18$

In TRNSYS type 860, two numbers define the length of PCM container. The first number represents the node at the top of the container whereas the second represents the number of a node at the bottom of the PCM containers. Since 18 nodes define the whole vertical height of the tank, the length of these PCM containers cannot exceed 18.

$0.5 \leq x_4 \leq 17.5$

$$x_4 + \frac{x_3}{2} \leq 18$$

$0 \leq x_4 - \frac{x_3}{2}$

These three constraints guarantee that the PCM containers fit inside the tank.

Objective 2: minimize (Abs (24- Y_i))

$Y_i = B_2 + SW \times Tanh\ (B_1 + FW \times X_i)$: (Discharge time)

where:

B_1= The first layer Bias matrix [25×1]

B_2= The second layer Bias matrix [1×1]

FW=The first layer Weight matrix [25×4]

SW=The second layer Weight matrix [1×25]

3.4.3 Optimization tool

Several optimization tools, which can deal with a large variety of problems, are in existence. Choosing an appropriate optimization tool is an important task that can make the results more reliable and the optimization process faster. MATLAB was used in this study. Some of the most popular algorithms, including Genetic Algorithms, are available in MATLAB's Toolbox. These algorithms are capable of dealing with nonlinear optimization and constrained optimization. MATLAB also can perform multi-objective optimization and handle discrete problems [24].

Multi-objective Genetic Algorithm function was used in this study ("gamultiobj"). The "gamultiobj" tries to develop a set of pareto optima for a multi-objective optimization. It uses a controlled elitist genetic algorithm. An elitist GA always acts in favor of individuals with higher fitness value while, a controlled elitist GA also favors individuals that are able to increase the diversity of the population in spite of having a lower fitness value. Maintaining the diversity of the population is important for convergence. Controlling the elite members of the population as the algorithm progresses does this. Two options 'ParetoFraction' and 'DistanceFcn' are used to control the elitism. The pareto fraction option limits the number of individuals on the Pareto front (elite members) whereas the distance function helps maintain diversity on a front by favoring individuals that are relatively far away on the front [39].

4. RESULTS

4.1 RESULTS OF THE SIMULATIONS

4.1.1 Introduction

In order to create the initial population for training an ANN, 900 simulations were carried out using TRNSYS. Design parameters were the mass of PCM inside the tank, diameter, length, number and location of the PCM containers. In each simulation, the discharge time was measured.

4.1.2 Impact of the amount of PCM

The findings show that the more PCM is used inside the tank, the longer the discharge time is. This can be attributed to the increase of stored energy caused by an increased amount of PCM inside the tank. Figure 4-1 shows the impact of PCM amount on discharge time.

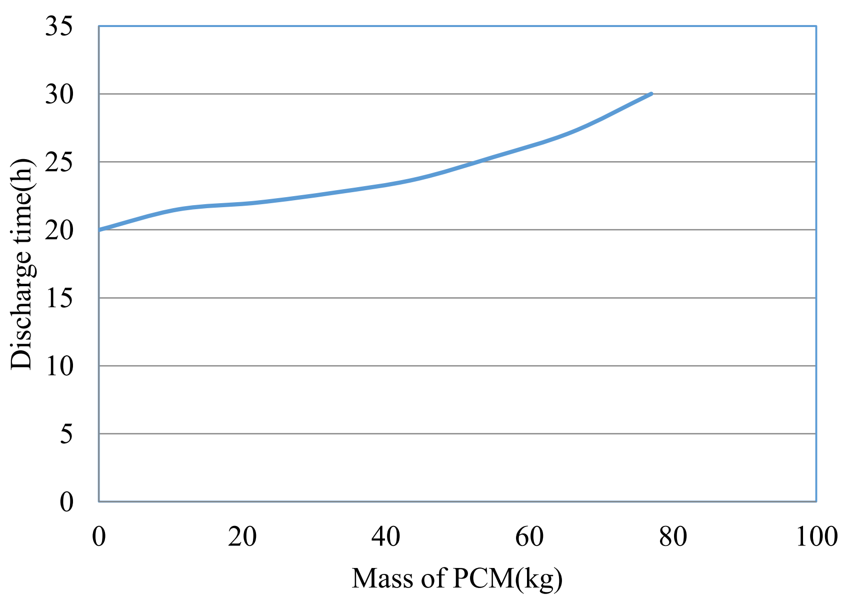

Figure 4-1. Impact of PCM amount on discharge time (tubes with a diameter of 16mm and length of 40cm were placed at the top of the tank).

It is not efficient to increase the discharge time by increasing the amount of PCM inside the tank as increasing the amount of PCM inside the tank also increases the time required for charging of the tank. Therefore, this leads to an increase in the electrical energy consumption as well. In addition, parametric studies show that other design parameters like the location of PCM containers and their diameter are important as well and can considerably increase the discharge period for certain amount of PCM. Figure 4-2 shows the impact of PCM amount on charging time.

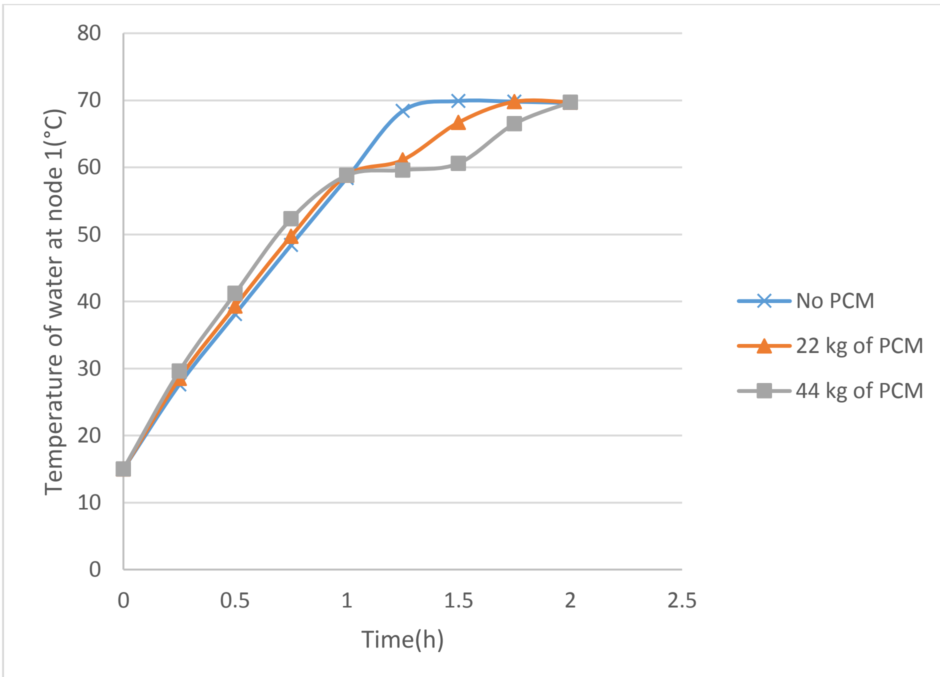

Figure 4-2. The impact of PCM on charging time of the tank.

Figure 4-2 shows that after reaching the melting point of the PCM (58°C), the temperature of water increases more slowly in PCM-containing tanks compared to pure-water tanks. By increasing the amount of PCM inside the tank, the charging time increases as well. The heat provided by heaters causes the PCM to melt, and the melting process delays the temperature increase of the water.

By placing PCM inside the tank, the amount of water inside the tank decreases. The specific heat of water is almost twice bigger than that of sodium acetate, and when sodium acetate inside the tank is in single-phase form, less energy is required to increase the temperature of a PCM-tank than that of a pure-water tank (see appendix A). The effect of the amount of PCM on electrical energy consumption of the tank during charging period is shown in Figure 4-3.

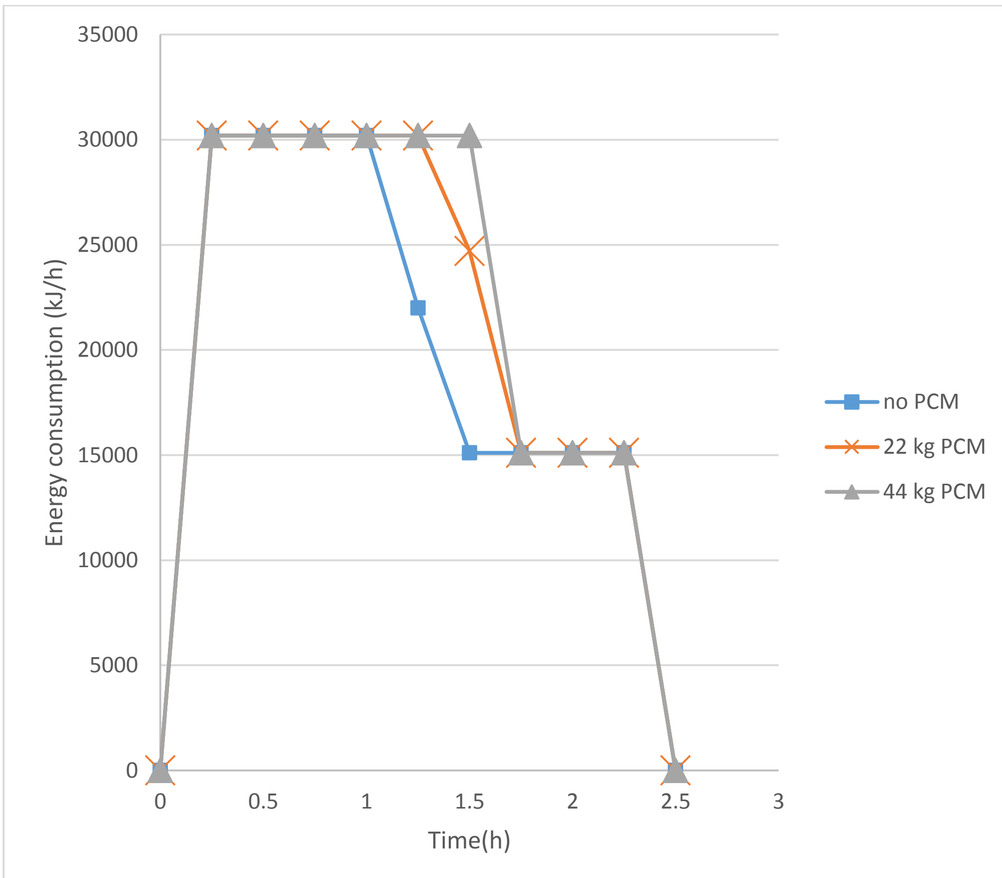

Figure 4-3. Impact of amount of PCM on the energy required to charge the tank.

4.1.3 Impact of the location of PCM containers

The tank is stratified; cold water enters from below and hot water is withdrawn from the top. Placing the PCM at the top or bottom of the tank can influence the system performance.

When PCM is placed at the bottom, it has more heat transfer as a result of the, cold water entering the tank from below and it loses its heat more quickly. Figure 4-4, shows the influence of the location of PCM containers on discharge time.

It can be seen from Figure 4-4 that the location of PCM inside the tank can notably change the discharge time for a certain amount of PCM. By placing 11kg of PCM at the center of the tank, the tank is able to provide hot water for 20.7 hours. By placing the PCM containers at the top of the tank, the discharge time increases by 50 minutes. It can also be seen from Figure 4-4 that discharge time decreases as we change the location of PCM containers from the top to the middle of the tank. That is mainly because of an increase in the heat transfer between the PCM and cold water which causes the PCM to transfer heat more quickly. However, by placing PCM containers at the bottom of the tank, an increase in discharge time can be observed. That is due to the close proximity of PCM containers to the electrical heater at the bottom of the tank which is on for longer periods of time due to its closeness to cold water entering the tank.

Manufacturers prefer tanks with PCM containers at the bottom [16]. However, in addition to shorter discharge time, one of the other disadvantages of placing PCM containers at the bottom of the tank is that the PCM does not fully melt. Figure 4-5 shows the temperature profile at different nodes of the tank while PCM is placed at the bottom of the tank. It can be seen that the temperature at lower parts of the tank (nodes 17, 18) does not reach the melting point of PCM when PCM is placed at the bottom. This is mainly because of the cold water that constantly enters the tank from below.

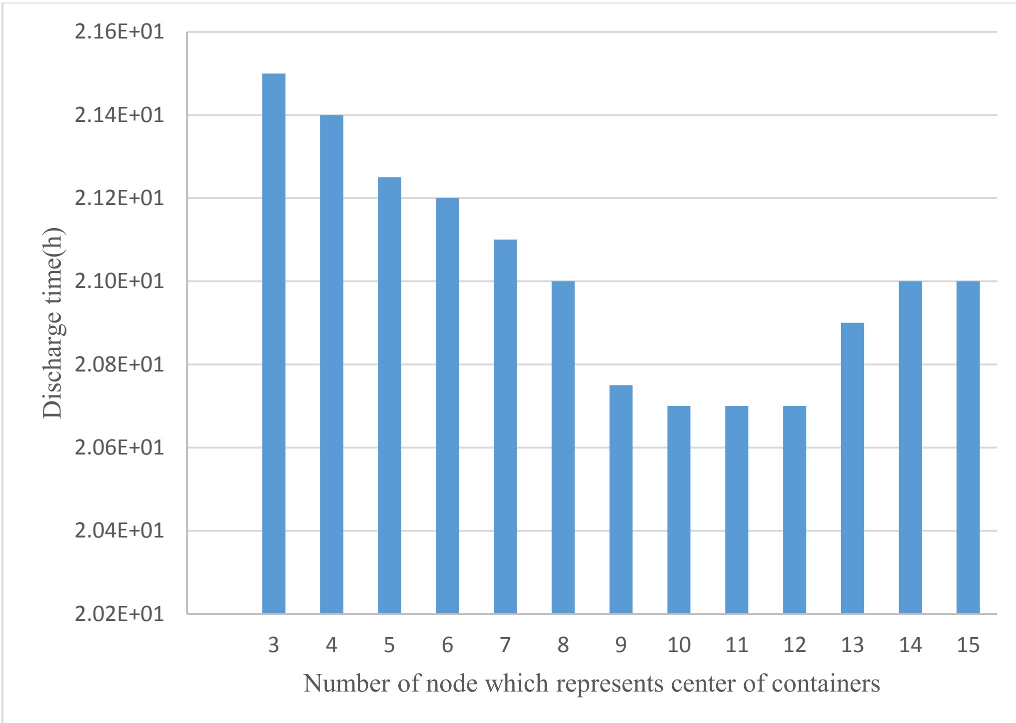

Figure 4-4. Impact of location of PCM containers on discharge time (100 tubes with diameter of 16 mm and length of 40 cm are placed inside the tank).

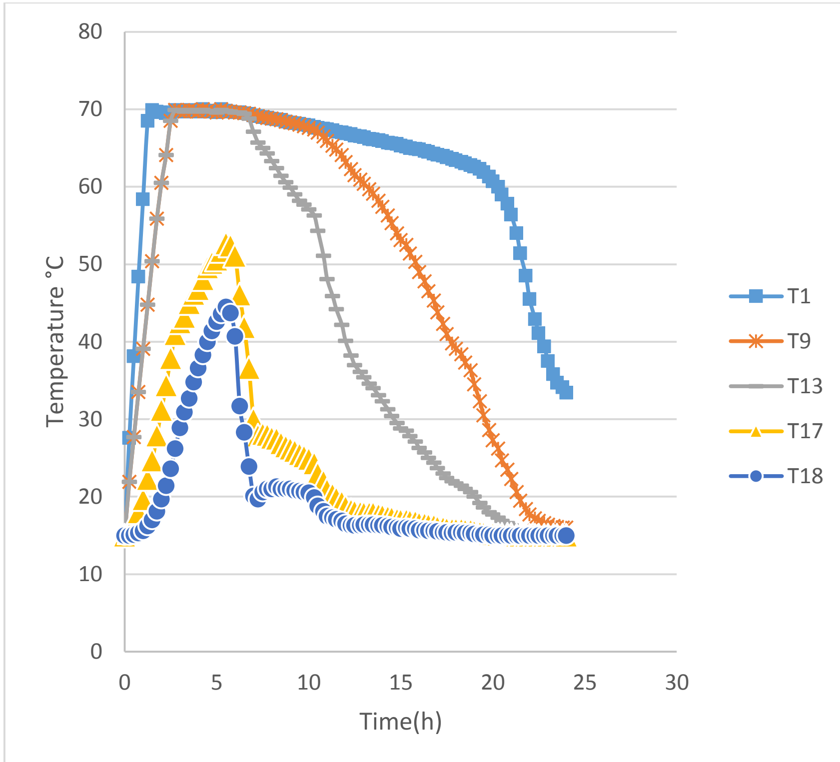

Figure 4-5. Temperature profile of the tank while 11kg of PCM is placed at the bottom of the tank (100 tubes with diameter of 16mm between nodes 14-18).

Figure 4-6 compares the performance of two heaters. Eleven kilograms of PCM is placed at the top of the tank. It can be seen from Figure 4-6 that the temperature of the upper thermostat reaches to its set point after about 90 minutes while the lower heater works for one more hour. After that the temperature of the upper thermostat never falls below the dead band during the first 6 hours of the day while the lower heater is being turned on three more times. That is due to the fact that cold water enters from below. The lower heater has a smaller dead band, and it turns on when the temperature falls below 65 °C.

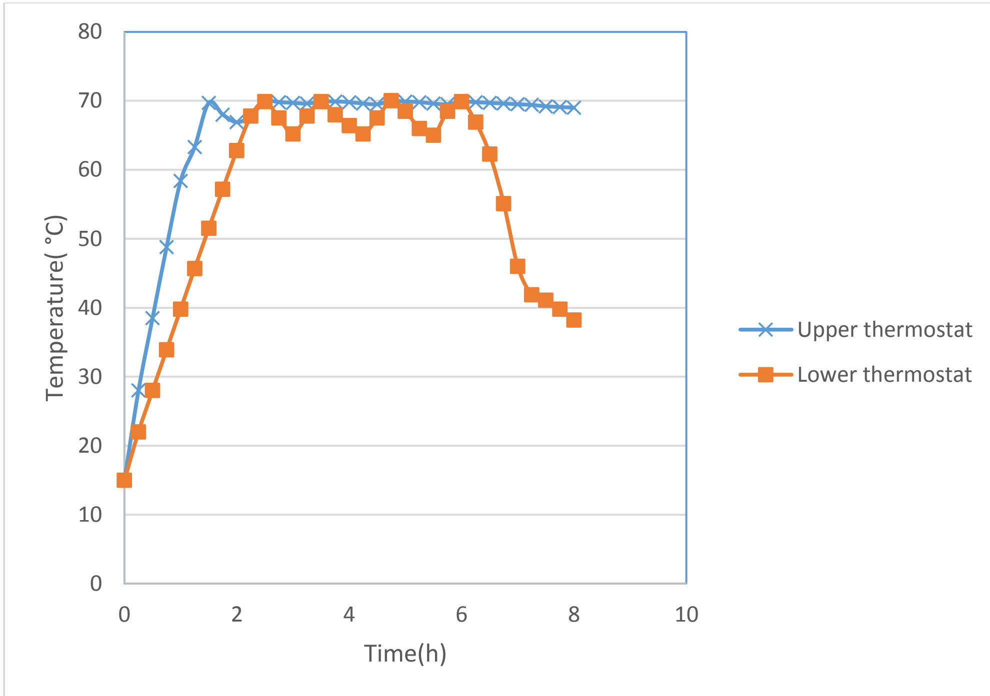

Figure 4-6. Comparison between performances of heaters during charging period.

Figure 4-6 shows that temperature at lower part of the tank sharply decreases after 6 am due to the high consumption while the temperature at the top part of the tank drops very slowly.

4.1.4 Impact of the diameter of PCM containers

Figure 4-7 shows the effect of the diameter of PCM containers on the tank discharge time. 40 kg of PCM, in tubes with a length of 40 cm, were placed at the top of the tank, and by changing the diameter and number of the tubes, the discharge time was measured. Figure 4-7 shows that increasing the diameter of the tubes increases the discharge time up to a specific value after which increasing the diameter of containers (reducing the number of containers) decreases the discharge time. This behavior could be attributed to the variation of heat transfer surface area between the water and containers and the amount of PCM which melts during charging period. By increasing the diameter of the tubes, surface area between water and PCM decreases. Decreasing the surface area causes the PCM to lose its stored heat to the water more slowly therefore; hot water is made available for longer periods of time. Yet, increasing the diameter of PCM containers reduces the fraction of melted PCM inside the tank which subsequently causes reduction in stored energy of the tank and discharge time.

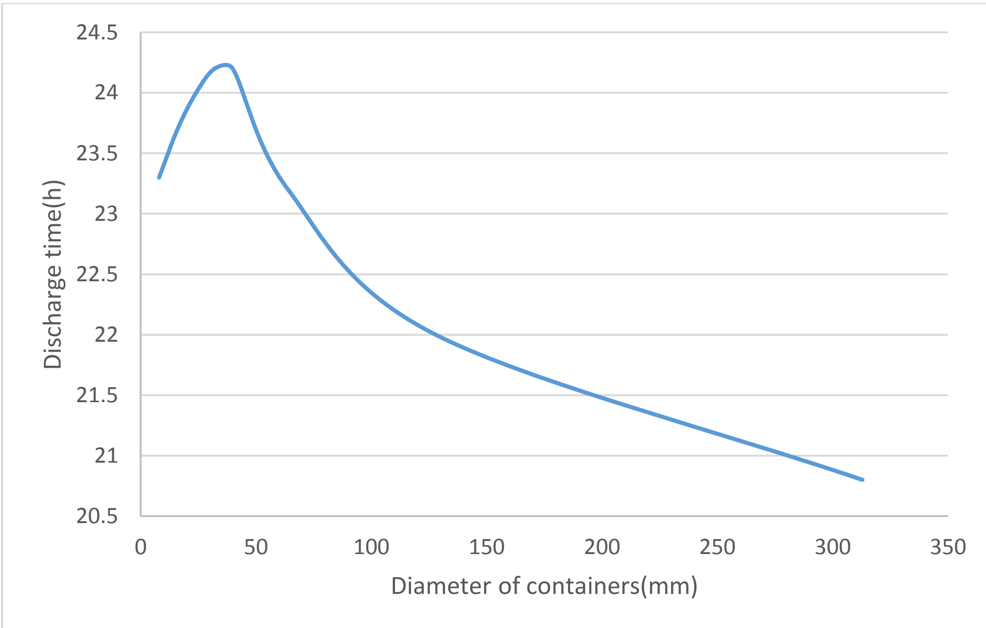

Figure 4-7. Impact of diameter of PCM containers on discharge time.

4.2 DISCUSSION ABOUT ARTIFICIAL NEURAL NETWORK

620 out of 900 simulations were used to train an artificial neural network. 160 samples were used to validate the network, and 80 samples were used for testing the network. In order to confirm the accuracy of the network and check the over-fitting phenomenon, the trained network was validated by the remaining 40 samples of the database. The results demonstrated that the average error of the network is less than 1%. In order to improve the generalization of the neural network, MSEREG was used as a performance function and the performance ratio of 0.9 was chosen. In order to secure higher efficiency, samples were scaled to [-1, 1] before training began.

Figure 4-8 shows the regression correlation coefficient between the outputs of the network and TRNSYS simulation results, which is very close to 1, suggesting a good correlation between ANN outputs and target values.

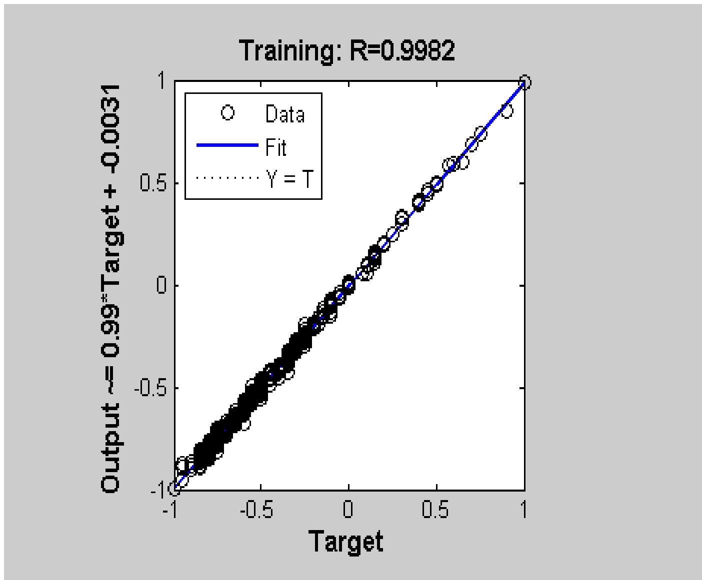

Figure 4-8. Regression of ANN outputs on scaled targets of training.

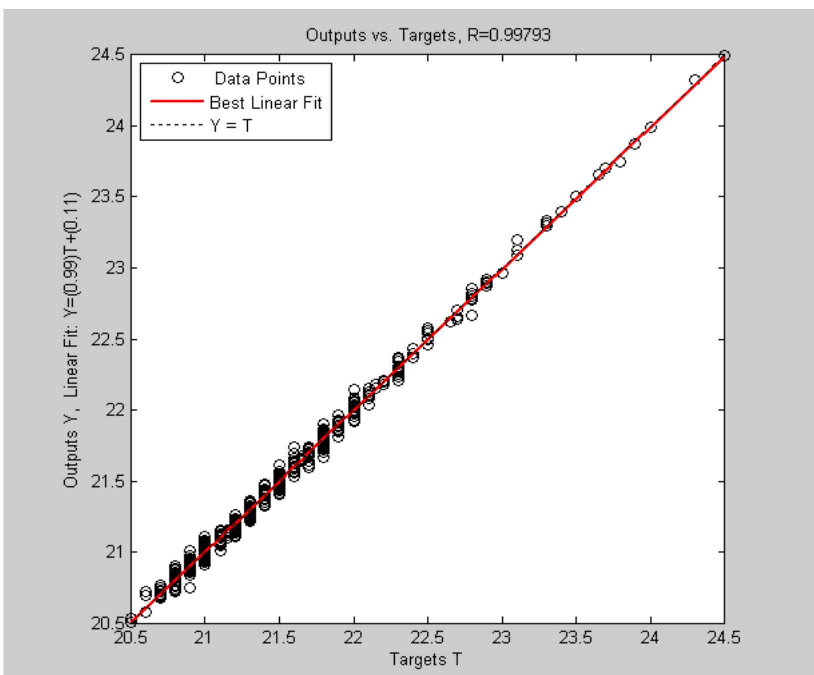

Figure 4-9. Regression of ANN outputs on targets.

Figure 4-10 shows the regression correlation coefficient between the outputs of the network and TRNSYS results (which were used for the validation and testing of the artificial neural network) is very close to 1, which suggests a good correlation between outputs and target values.

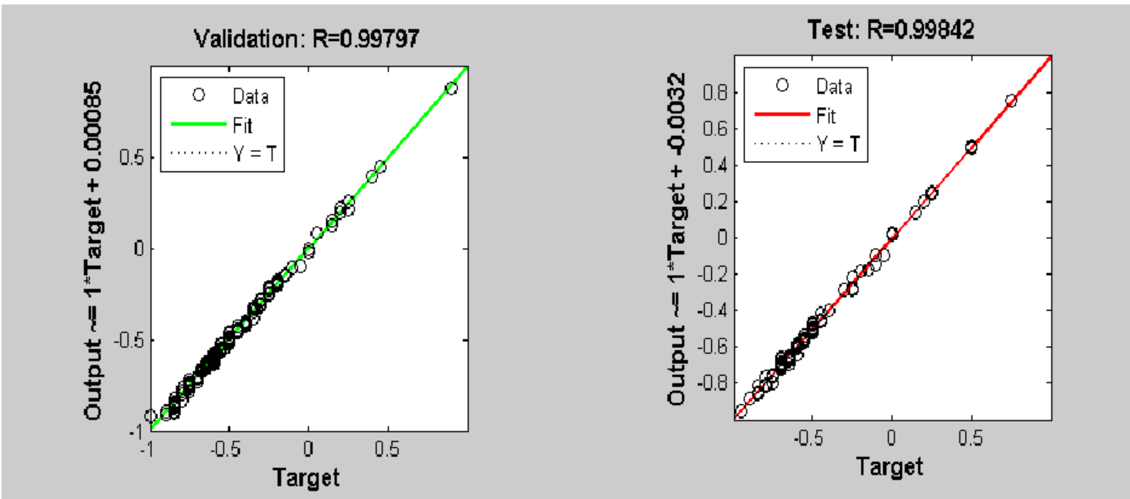

Figure 4-10. Regression of ANN outputs on scaled targets of validation and testing.

Increasing the number of neurons in hidden layers can increase the accuracy of the artificial neural network, but it might cause a phenomenon called over-fitting. In this case, error on the training set is very small but since the network is not equipped with dealing with new situations, the error is going to be large when new datasets are provided for the network. In order to check the over-fitting phenomenon another 40 samples were used to test the network. The average error of the network was found to be less than 1% and therefore, the trained ANN is accurate enough to be used in this study.

4.3 RESULTS OF THE OPTIMIZATION

Figure 4-11 shows the pareto front of the optimization. As shown in this graph, the optimum range of the amount of PCM inside the tank is between 32 to 36kg; with this amount of

PCM inside the tank, the discharge time changes between 23.3 to 24 hours, respectively. In order to validate the optimization, the points of pareto front must be checked with TRNSYS. The TRNSYS type 860 accepts integers for the diameter and length of the PCM containers. In order to make the comparison possible, a custom creation function, a custom mutation function and a custom crossover function that generate only integer outputs for the required variables were created. Points of pareto front in this case were simulated with TRNSYS, and the average error was found to be less than 2%. See appendix B.

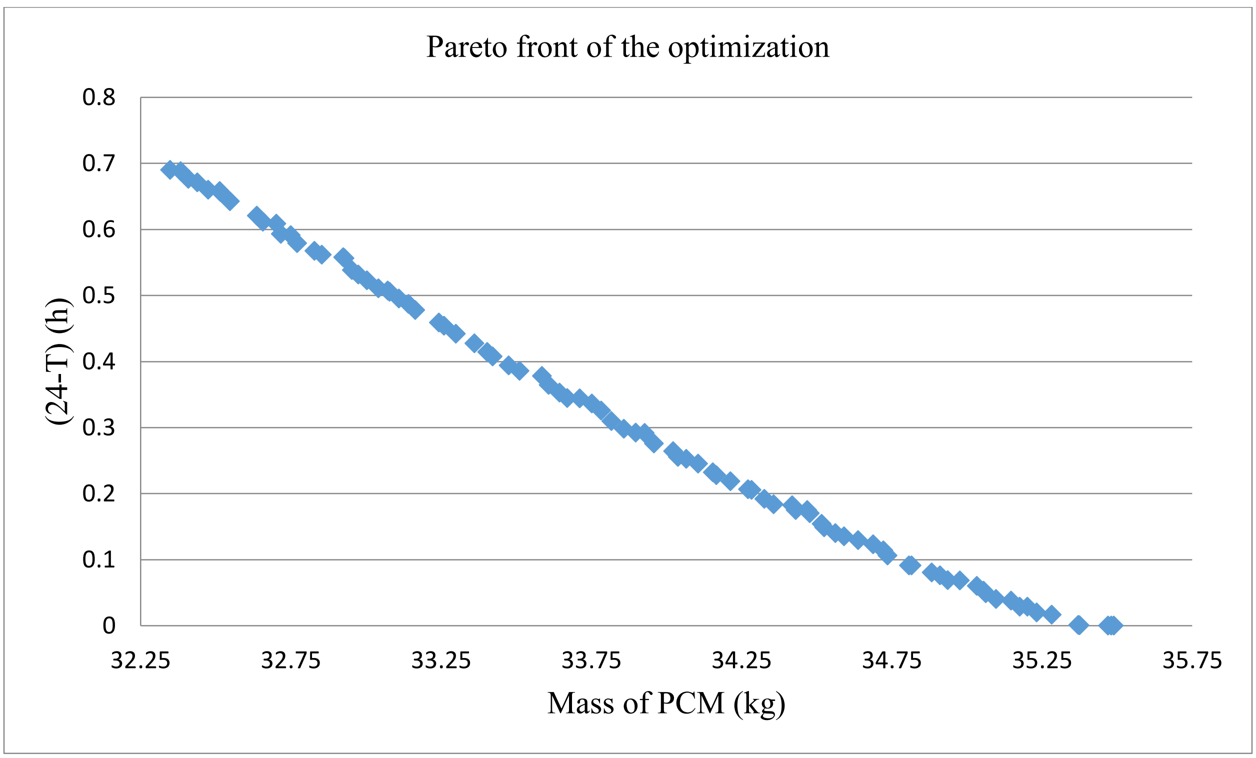

Figure 4-11. Pareto front of optimization.

Variable ranges in optimal solutions are listed in Table 4-1. One of the points, which represent a 35-kg PCM placed in 90 tubes with a diameter of 30 mm and length of 45 cm, was taken as an optimized solution in order to make comparisons between an optimized and a pure-water tank.

Table 4-1. Variable ranges in optimal solutions.

Variables	Range
Diameter of containers (mm)	[30-34]
Length of containers (cm)	[38-48]
Number of containers	[80-91]
Location of containers (number of the node representing the center of containers)	[3-4]

4.4 COMPARISON BETWEEN A PURE-WATER TANK AND AN OPTIMIZED TANK WITH PCM

It can be seen from Figure 4-12 that in the case of no PCM being placed inside the tank, the temperature of the water outlet falls below 50°C at around 8pm when hot water is mostly needed. In order to prolong the discharge time, the lower heater was turned on in the off-peak period in the afternoon between 2-4 pm. The outlet temperature in this case is presented in Figure 4-13.

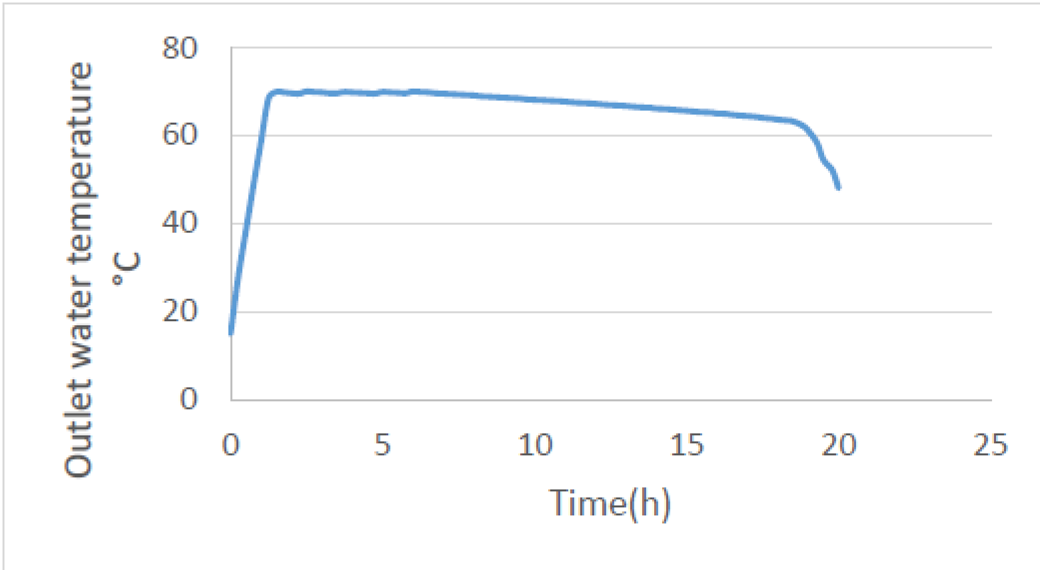

Figure 4-12. Outlet water temperature of pure-water tank

Figure 4-13 shows that the lower heater has to work for about 1.5 hours in order to keep the water warm for the rest of the day. The idea of using PCM is to store energy during off-peak and avoid the required extra electrical energy during peak, which is necessary for pure-water tanks so that they can provide hot water for the whole day.

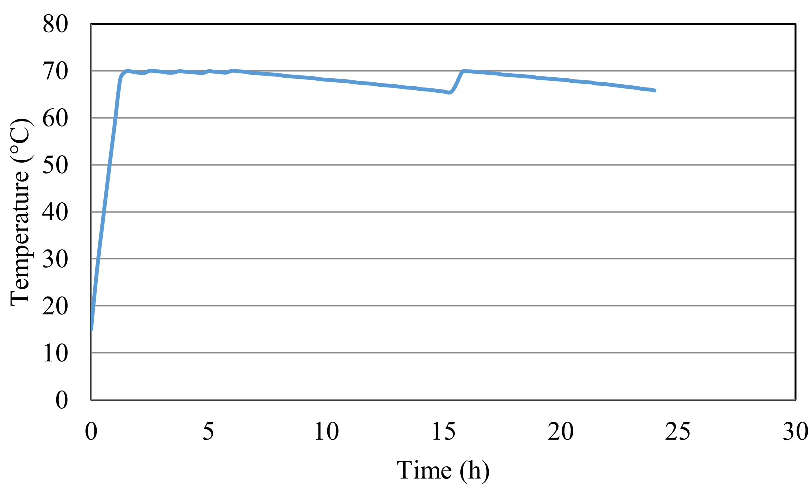

Figure 4-13. Outlet water temperature of pure-water tank when lower heater is allowed to be turned on in the afternoon

A comparison between an optimized tank with PCM and a pure-water tank regarding the electrical energy consumption during charging period is done in Figure 4-14. As can be seen, during the charging period, the tank with PCM requires almost 20000 kJ more energy to be charged; however, it is able to provide hot water for the rest of the day. In contrast, the pure-water tank (without PCM) has considerable energy consumption in the afternoon. See Figure 4-15. 6100 kJ energy can be saved each day if an optimized tank instead of a pure-water tank is used. Furthermore, the rate of heat loss to the ambient increases drastically after the lower heater starts to work in the afternoon. This suggests that electrical heaters are not efficient, and implementing PCM inside the tanks can improve the efficiency of the tanks. See appendix C.

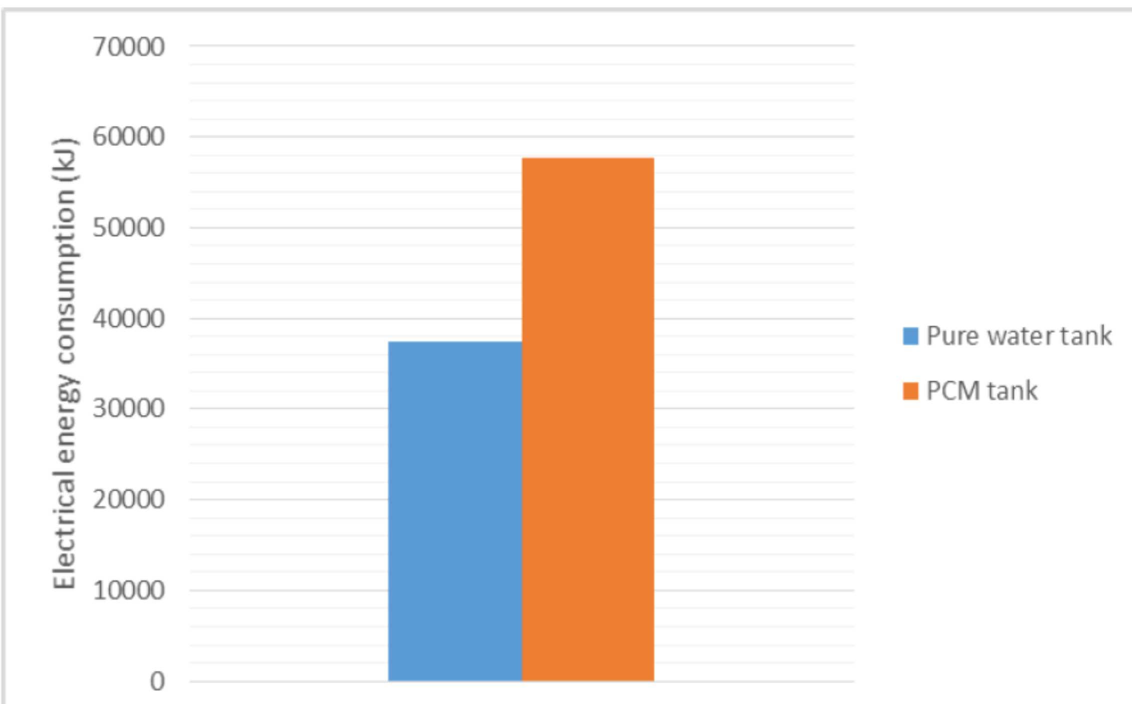

Figure 4-14. Comparison regarding the electrical energy consumption between an optimized tank and a pure-water tank during charging period

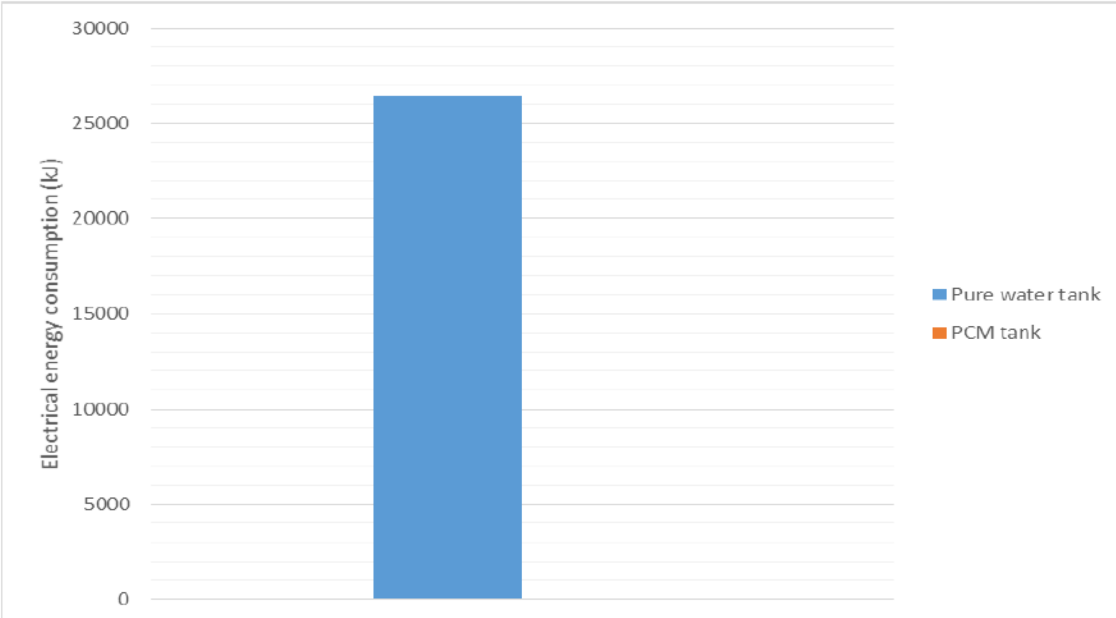

Figure 4-15. Comparison regarding the electrical energy consumption between an optimized tank and a pure-water tank during discharging period

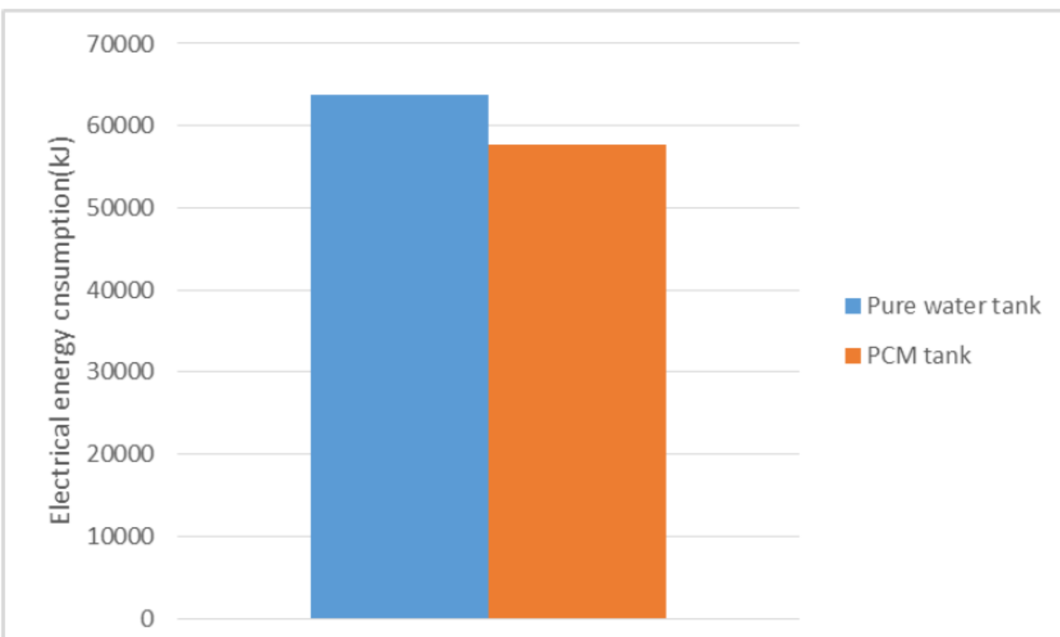

Figure 4-16. Comparison regarding the electrical energy consumption between an optimized tank and a pure-water tank during a whole day

5. CONCLUSIONS AND LIMITATIONS OF THE STUDY

5.1 CONCLUSIONS

Thermal energy storage systems can balance energy supply and demand by storing energy during off-peak periods. Storing heat in latent form seems to be more advantageous than sensible heat storage. This study has focused on the advantages and disadvantages of using latent heat in domestic hot water tanks.

The conclusions of this study can be summarized as follow:

- In order to benefit from PCM's high latent heat inside the domestic hot water tanks, the operation temperature of the system must be close to PCM's melting range. The heat capacity of water is greater than that of most commercial PCMs, and when PCM is in a single-phase form, water is the dominant storage medium. Therefore for a domestic hot water tank which operates between 15°C-70°C, an appropriate PCM should be chosen.
- The discharge time of a domestic hot water tank is very sensitive to the amount of PCM add it to the tank, diameter of PCM containers and location of PCM inside the tank.
- Increasing the amount of PCM inside the tank prolongs the duration of the availability of hot water on one hand and increases the electrical energy consumption on the other hand. Therefore, finding the minimum amount of PCM inside a tank that can satisfy the desired discharge time is necessary.
- The top part of the tank is the best location for PCM containers in which case the PCM loses heat more slowly as opposed to when PCM is placed close to the cold water emerging from below (in which case it loses heat faster).

- By increasing the diameter of PCM containers and decreasing their number inside the tank, the heat transfer surface area between the PCM and water decreases. Decreasing the surface area of the heat transfer causes the PCM to lose heat more slowly. Therefore, the discharge time increases. However, increasing the diameter of PCM containers over that certain limit reduces the fraction of PCM which melts during charging period which subsequently decreases the stored energy and discharge time.
- For a high Quebecer withdrawal profile optimization was done using a 270-L tank and sodium acetate trihydrate as a PCM placed inside cylindrical containers. It was observed that with 32-35 kg of PCM the tank is able to provide hot water for the whole day without its heaters being turned on after 6 am.
- An optimized tank can provide hot water for the whole day after its heaters are turned off at 6am while a pure-water tank needs extra 25800 kJ to be able to provide hot water for the rest of the day.
- Total amount of 6100 kJ is saved each day if an optimized tank is used instead of a pure-water tank.

5.2 LIMITATIONS AND POTENTIAL AREAS OF FUTURE INVESTIGATION

This study suggests a general approach towards the optimization of domestic hot water tanks regarding their discharge time. There are some limitations that need further study, which can lead to a more reliable and general results. Some of the areas of investigation are listed below:

- Optimization was done for a standard North American tank with a volume of 270-L. A high withdrawal profile was considered for optimization. The discharge time is heavily dependent on the withdrawal profile and, although the approach towards the optimization of the tank was a general one, the results of this study are not valid for tanks subjected to other withdrawal profiles.
- Sodium acetate trihydrate was chosen as the storage medium inside the tank for this study. Physical properties of the PCM inside the tank also influence its performance, and choosing another type of PCM as the storage medium might change the optimal solution.
- The shape of the PCM containers inside the tank is another factor that was neglected in this study. Cylindrical tubes were placed inside the tank, and simulations using spherical containers might change the results of this study as well.

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APPENDIX A: ENERGY CONSUMPTION APPROXIMATION FOR A TANK WITH 11KG OF PCM

Table A-1. Initial and final temperature (°C) at different parts of the tank during a whole day cycle

	T_{1i}	T_{1f}	T_{2i}	T_{2f}	T_{3i}	T_{3f}	T_{4i}	T_{4f}	T_{5i}	T_{5f}	T_{6i}	T_{6f}	T_{7i}	T_{7f}	T_{8i}	T_{8f}	T_{9i}	T_{9f}
No PCM	27.2	70	24.1	70	21	70	18.7	70	17.1	70	16.2	70	15.6	70	15.3	70	15	70
11 kg PCM	28.6	70	26	70	22.8	70	20.1	70	18.1	70	16.7	70	15.8	70	15.4	70	15.2	70

Table A-2. Initial and final temperature (°C) at different parts of the tank during a whole day cycle

	T_{10i}	T_{10f}	T_{11i}	T_{11f}	T_{12i}	T_{12f}	T_{13i}	T_{13f}	T_{14i}	T_{14f}	T_{15i}	T_{15f}	T_{16i}	T_{16f}	T_{17i}	T_{17f}	T_{18i}	T_{18f}
No PCM	15	70	15	70	15	70	15	70	15	70	15	70	15	62	15	34	15	20
11 kg PCM	15.1	70	15	70	15	70	15	70	15	70	15	70	15	62.8	15	28	15	17

Energy required for melting 11 kg of PCM= 11×200kJ=2200kJ

Sensible heat required to charge a pure-water tank = $\sum_{j=1}^{18} m_j\, c_{pw}(T_{jf}\text{-}T_{ji})$ =54230.4kJ

c_{pw} = specific heat of water

T_{jf} =Temperature of jth node at the end of the charging period

T_{ji}= Temperature of jth node at the beginning of the charging period

m_j=mass of jth node

Sensible heat required to charge a tank with 11 kg of PCM between node 1-5=

$\sum_{j=1}^{18} m_{jwater}\, c_{pw}(T_{jfpcm}\text{-}\, T_{ji}pcm) + \sum_{j=1}^{5} m_{jpcm}\, c_{ppcm}\, (T_{jfpcm}\text{-}T_{ji}pcm)$ =52860 kJ

c_{ppcm}= specific heat of PCM

T_{jfpcm} = Temperature of jth node at the end of the charging period when 11 kg of PCM is placed inside the tank.

$T_{ji}pcm$ = Temperature of jth node at the beginning of the charging period when 11 kg of PCM is placed inside the tank.

Heat loss from the tank with 11 kg of PCM during a day=6840 kJ

Heat loss from the tank without PCM during a day=6820 kJ

Total energy consumption for a tank with 11 kg of PCM =55060 kJ

Total energy consumption for a tank without PCM =54230 kJ

The 2% difference between the energy consumptions can be attributed to the variation of density and specific heat of PCM during transition, which the model takes in to account.

APPENDIX B: VALIDATION OF OPTIMIZATION

For validating the optimization results with TRNSYS, a custom creation function, a custom mutation function and a custom crossover function that generate only integer outputs for the required variables were created. Figure B-1 shows the results of optimization with integer constraints. Points of pareto front in this case were simulated with TRNSYS and the average error was found out to be less than 2%.

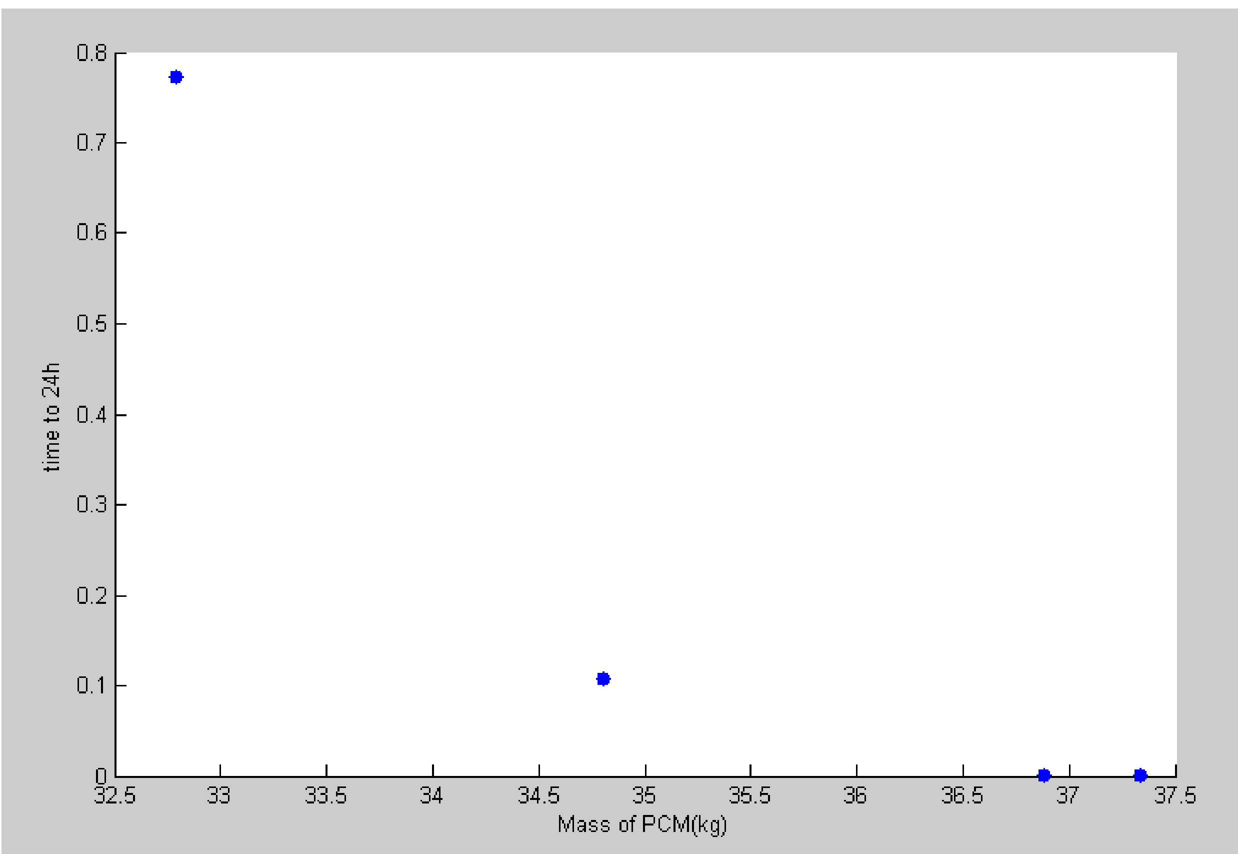

Figure B-1. Pareto front of optimization with integer constraints

APPENDIX C: COMPARISON BETWEEN TEMPERATURE PROFILE AND HEAT LOSS OF PURE-WATER TANK AND AN OPTIMIZED TANK

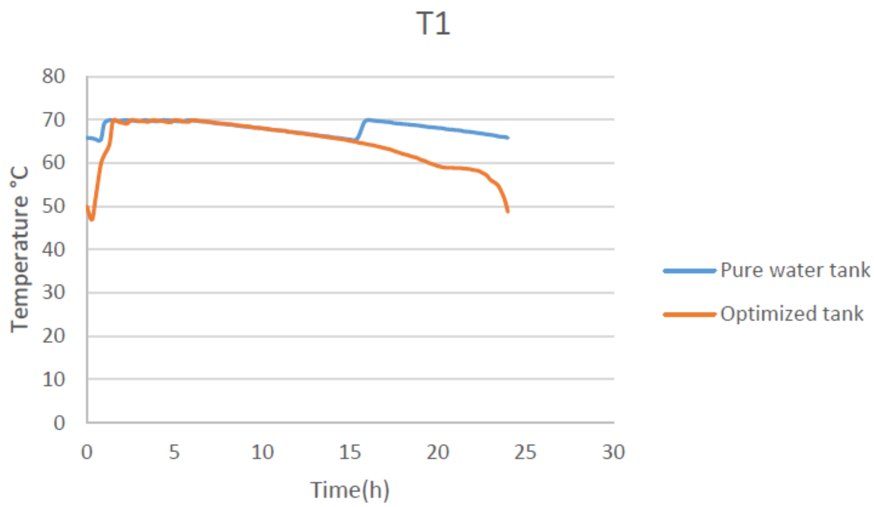

Figure C-1. Temperature at node 1 of the tanks

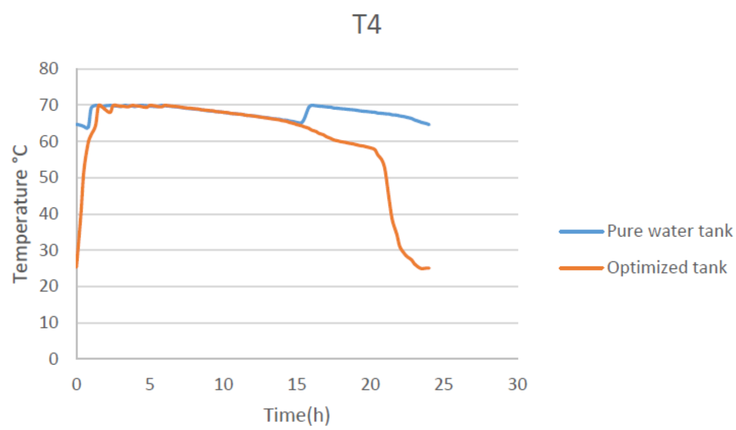

Figure C-2. Temperature at node 4 of the tanks

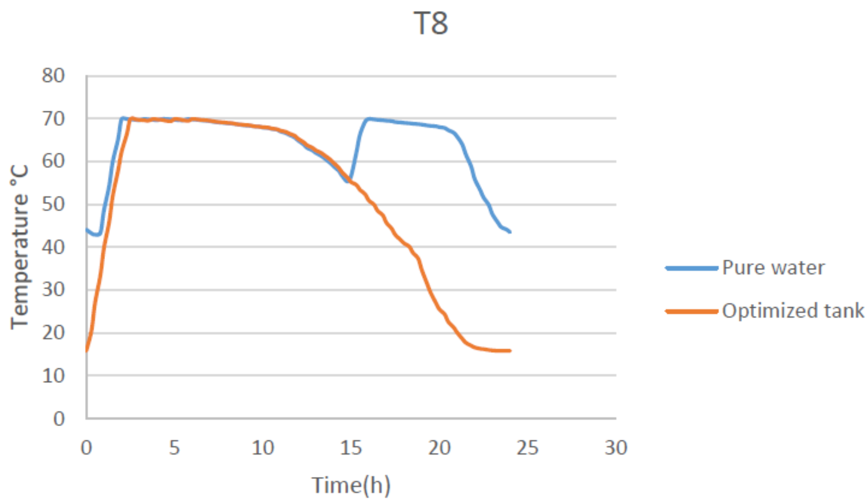

Figure C-3. Temperature at node 8 of the tanks.

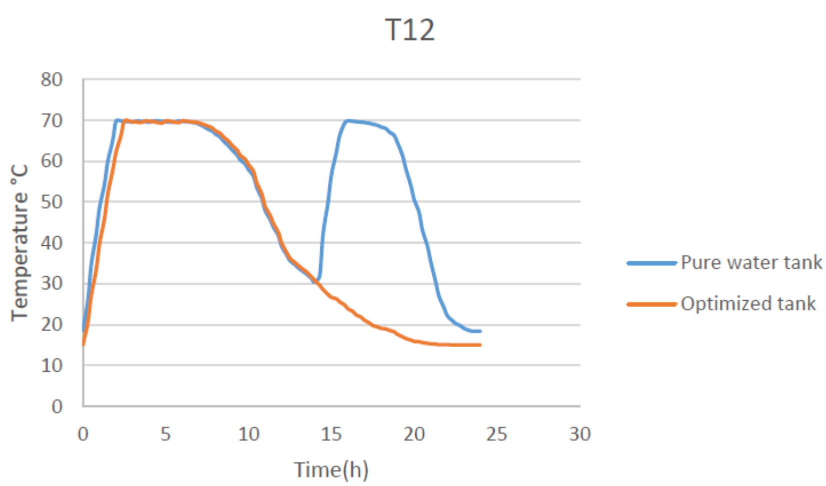

Figure C-4. Temperature at node 12 of the tanks

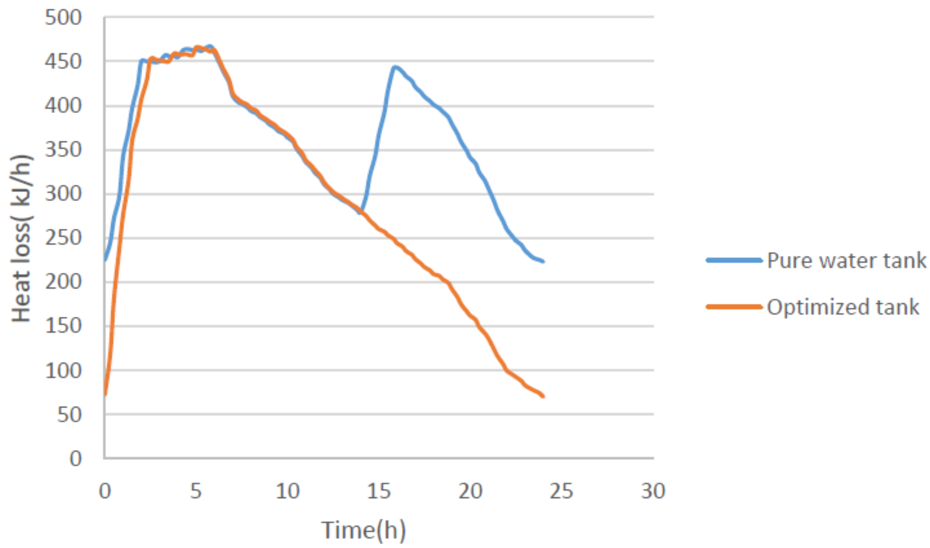

Figure C-5. Rate of heat loss of the tanks

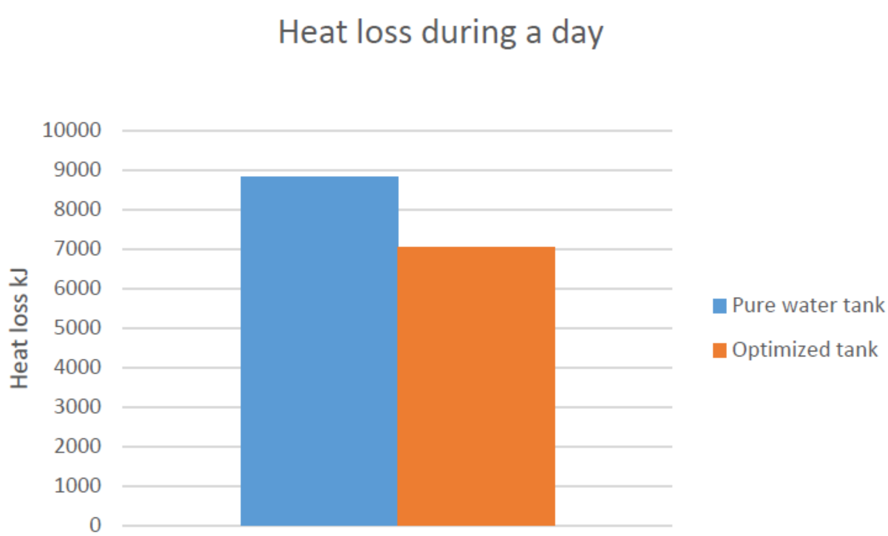

Figure C-6. Total amount of heat loss from the tanks