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智慧型能源管理機最佳控制策略之研究

An Investigation of Optimal Control Strategy for a Smart Energy Management Device

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摘要

全球暖化議題已成為全世界所關注之焦點，許多學者也對再生能源研究領域投以高度重視，著眼於此，本研究配合政府提倡之節能減碳政策，建構一智慧型能源管理機 (Smart Energy Management Device，簡稱 SEMD)，期能在節能下滿足一般家庭之民生需求。其作法源自熱泵技術之啟發，透過 SEMD 同時提供家庭民生所需之熱能與冷能，另外也設計一熱冷能回收系統以降低能源之損失。本論文特別針對 SEMD 進行最佳化探討，希望使能源損失與運轉成本降至最低，其作法為求得 SEMD 之熱能方程式，並利用粒子族群演算法 (Particle Swarm Optimization，簡稱 PSO)求取系統之最佳控制策略及運轉成效，最後透過數值模擬獲得最佳控制策略及系統之最低生命週期成本。本研究建構的 SEMD 系統其水槽容積與系統功率之最佳設計分別為 1 千公升與 10 千瓦，而 PSO 控制策略相較於一般控制策略則可節省約 28.82%之生命週期成本。

關鍵字：生命週期成本、運轉策略、粒子族群演算法、能源管理

Abstract

The issue of global warming has become an imperative concern to the world. Many researchers attach great importance on renewable energy issues. In conjunction with Taiwan's government policy about saving energy and reducing carbon emission, a Smart Energy Management Device (SEMD) is proposed in this study. The intention of the SEMD design is to fulfill the energy demands of household appliances. Inspired from heat pump technology, the SEMD is designed not only to provide heat energy but also cold energy for household appliances. In this system, heat and cold energy recovery subsystems are constructed simultaneously to reduce the loss of energy. The focus of this study is to investigate and optimize the performance of the SEMD system in order to minimize the power consumption and achieve minimum operating costs. To this end, heat energy equations of the system are derived and Particle Swarm Optimization (PSO) is applied to find an optimal operating control strategy for the system. The minimum life cycle cost of the system can be achieved accordingly. It is found through numerical examples and demonstration, the most decent design of water storage and system capacity for the SEMD is 1000 L and 10 kW respectively. The life cycle cost after applying the control strategy based on PSO can save 28.82% in comparison with the ordinary control strategy. This research can improve the overall economic efficiency of the SEMD system and provide a reference point for manufacturers to create new solutions in the field of heat pump systems engineering.

Keywords: Life Cycle Cost, Operation Strategies, Particle Swarm Optimization, Energy Management.

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Nomenclatures

a_0	0th coefficient
a_1	1st coefficient
a_2	2nd coefficient
a_3	3rd coefficient
B_o	auxiliary heating system capacity (kW)
c_1	acceleration constant
c_2	acceleration constant
COP	coefficient of performance
COP_B	coefficient of performance of boiler
COP_C	coefficient of performance of chiller
C_P	specific heat of water (4.186 kJ/(kg•℃))
$E_{BO,on}$	boiler energy cost at peak-on period (NTD)
$E_{BO,off}$	boiler energy cost at peak-off period (NTD)
E_E	energy cost (NTD)
$E_{HP,on}$	modified heat pump energy cost at peak-on period (NTD)
$E_{HP,off}$	modified heat pump energy cost at peak-off period (NTD)
$E_{HPB,on}$	boiler energy cost at peak-on period (NTD)
$E_{HPB,off}$	boiler energy cost at peak-off period (NTD)
$E_{HPC,on}$	chiller energy cost at peak-on period (NTD)
$E_{HPC,off}$	chiller energy cost at peak-off period (NTD)
E_L	life cycle cost (NTD)
E_S	installation cost (NTD)
E_T	total energy cost of each component including water pumps, boiler, modified heat

	pump, chiller, and heat exchanger (NTD)
$E_{WP,on}$	water pump energy cost at peak-on period (NTD)
$E_{WP,off}$	water pump energy cost at peak-off period (NTD)
h	number of heat exchangers
HPC	heating or cooling capacity (kW)
HPC_B	heating capacity (kW)
HPC_C	cooling capacity (kW)
K	compressor on-off status
$Life$	system’s life
$\dot{m}_{CHE}$	cold water flow rate which is shifted to heat exchanger from storage (L/s)
$\dot{m}_{CHL}$	hot water flow rate for closed load system (L/s)
$\dot{m}_{CL}$	cold water flow rate for closed load system (L/s)
$\dot{m}_{CO}$	cold water flow rate (L/s)
$\dot{m}_F$	feed water flow rate (L/s)
$\dot{m}_{HC}$	hot water flow rate for closed loop system (L/s)
$\dot{m}_{HHE}$	hot water flow rate which is shifted to heat exchanger from storage (L/s)
$\dot{m}_{HO}$	hot water flow rate for open loop system (L/s)
$\dot{m}_{OHL}$	hot water flow rate for open load system (L/s)
M_{CT}	cold water mass (L)
M_{HT}	hot water mass (L)
M_{on}	electricity cost at peak-on period (NTD).
M_{off}	electricity cost at peak-off period (NTD).
Mt	water storage size (L)

n	number of water pumps
P	power consumption (kJ)
P_{WP}	power consumption of water pump (kJ)
Q	each system’s hot or cold energy (kJ)
Q_{BO}	auxiliary boiler energy (kJ)
Q_{CHE}	cold energy which is taken away by heat exchanger (kJ)
Q_{CO}	output cold energy from storage (kJ)
Q_{F}	input heat energy to storage from supplied water (kJ)
Q_{HC}	output heat energy from storage for closed loop system (kJ)
Q_{HHE}	heat energy which is sunk by heat exchanger (kJ)
Q_{HO}	output heat energy from storage for open loop system (kJ)
Q_{HP}	heat and cold energy of system (kJ)
$Q_{HP,B}$	heat energy of traditional system (kJ)
$Q_{HP,C}$	cold energy of traditional system (kJ)
r_1	random function in the range [0, 1]
r_2	random function in the range [0, 1]
r_3	random function in the range [0, 1]
R	water pump on and off condition
T_A	air temperature (℃)
T_C	cold water temperature (℃)
T_{CL}	cold water user load temperature (℃)
T_{CR}	cold water input temperature after heat exchanging (℃)
T_{CT}	cold water storage temperature (℃)
T_{CTR}	cold water recovery temperature (℃)
T_{CW}	city water temperature (℃)

T_F	feed water temperature (℃)
T_H	hot water temperature (℃)
T_{HCL}	cold water input temperature after heat exchanging (℃)
T_{HER}	hot water input temperature after heat exchanging (℃)
T_{HL}	hot water user load temperature (℃)
T_{HE}	hot water input temperature after heat exchanging (℃)
T_{HT}	hot water storage temperature (℃)
T_{HTR}	hot water recovery temperature (℃)
T_{HU}	default temperature of hot water user (℃)
S	searching point
V	particle’s velocity
$V_{\mathbf{g}}$	velocity based on group best
V_{gi}	the best position of all the particles found at present (gbest)
V_i	velocity of particle i
V_p	velocity based on personal best
V_{pi}	personal best position of particle i (pbest)
X_i	the position of particle i

Greek Symbols

Δt	estimation time interval (s)
η	efficiency of pump
ω	inertial weight

Subscripts

k	iteration number

$k+1$	the next iteration number
n	time interval
$n+1$	the next time interval

Chapter 1 Introduction

1.1 Background and Motivation

Nowadays, since the growing environmental concern about global warming caused by greenhouse gas emission, the development of renewable energy to reduce carbon emission has become an important issue. Meanwhile, to overcome this issue, renewable energy devices have been developed, such as wind turbine, solar cell, photovoltaic cell, and heat pump.

According to European Heat Pump Association (EHPA), by passing Renewable Energy Sources (RES) directive where aero-, hydro, and geothermal energies captured by heat pumps, has made them recognized as a unique renewable technology for heating and cooling. The reduction energy demand of heat pumps leads to much lower amounts of green house gases per se. Depending on the national power production, heat pumps can provide heating, cooling and hot water nearly emission free. However, they can make a major contribution towards climate achievements and energy challenges [1].

The first heat pump emerged in the 1940s when Robert C. Webber, an American inventor discovered the idea of pumping heat via his freezer in his home. The idea was later furthered by another individual known as Lord Kelvin, and theoretically became a scientific concept. The main objective is to move heat from one location (the 'source') at a lower temperature to another location (the 'sink' or 'heat sink') at a higher temperature using mechanical work or a high-temperature heat source [2]. The basic concept of heat pump is still using the basic refrigeration cycle. Thus, heat pump can change which coil acts as the condenser and which is the evaporator by utilizing a reversing valve. In cooler climates, it is common to have heat pumps that are designed only to provide heating.

Most of the researches concentrate on modifying components of heat pump to increase the energy performance. On contrary, decent operating strategy also plays an important role in energy saving and cost reduction. However, sponsored by National Science Council, we are complying research about “Energy saving technology research and development project for livelihood system” [3]. The main objective is to develop a device that can provide heating and cooling energy for household appliances simultaneously. Inspired from the heat pump technology, the Smart Energy Management Device (SEMD) has been introduced to overcome this problem. With this novice technology, it is hoped that the SEMD can improve traditional heat pump’s performance, reliability, efficiency, and long cycle life.

Moreover, in conjunction with Taiwan government policy about saving energy and reducing carbon emission, the main objective of this research is to establish control strategies to save energy consumption and minimize electricity usage of household appliances. Hence, green environment can be achieved. Furthermore, we implement Swarm Intelligence Technology to develop optimal control strategy. Then, by applying numerical analysis, we analyze either energy or electricity consumption of each SEMD component. This highly efficient control strategy is expected can achieve minimum energy consumption and cost.

1.2 Literature Review

In thermodynamic system, the SEMD performance is not only affected by its components but also by operating strategies. In the previous studies, most researchers focus on improving the energy performance of heat pumps and solar assisted heat pumps instead of energy management. Besides, decent operating strategy also becomes an imperative factor in saving energy.

Zhang et al. proposed numerical and experimental method to optimize the air source heat pump water heater. Air energy was absorbed at the evaporator and pumped to storage tank via a Rankine cycle. The coil pipe/condenser released condensing heat of the refrigerant to the water side. The result shows that the energy performance can be improved by choosing proper capillary tube length, filling quantity of refrigerant, condenser coil tube length and water tank capacity [4].

Lee et al. proposed a study of heat pump system which is applied for indoor swimming pool. Since water is evaporated from the pool surface, the exhausted air contains more water and specific enthalpy. In response to this indoor air, heat pump is generally used in heat recovery for indoor swimming pools. This paper utilizes particle swarm optimization to optimize the life cycle energy cost of heat pump system. The former consists of outdoor air mass flow and heat conductance of heat exchangers; the latter comprises compressor type and boiler type. In this regard, the optimized outdoor air flow and the optimized design for heating system can be deduced by using particle swarm algorithm [5].

Wang et al. investigated the performance of heat pump for high temperature water and found that the heat pump using parallel cycles with serial heating has the best energy performance when the condensing water temperature exceeds 75℃. The experimental results indicate that the average heating capacity and coefficient of performance of the High Temperature Heat Pump (HTHP) could be improved significantly in high-temperature conditions due to the parallel cycles with serial heating on the water side and the modified compressor. All the results indicate that the HTHP using parallel cycles and modified compressor with serial heating on the water side is very competitive in industrial heating applications [6].

Brenn et al. presents annual efficiencies of these systems and compares internal combustion engine and electrically driven heat pumps in terms of primary energy consumption and CO_2 emissions. Because heat pump performance depends strongly on the heating circuit's flow temperature level, the comparison is performed for air-to-water and geothermal heat pump systems. In addition, this research compared the energy performance of natural gas driven heat pumps and electrically driven heat pumps, the results showed that these two kinds of heat pumps have equal energy performance [7].

Fardoun et al. proposed a study about heat pump design and optimization tool. The operational data provided by different manufacturers for each component is used by system’s designers to specify installation and operational procedures of the system. The optimum of an individual piece of equipment results in sub-optimal system performance due to unforeseen interactions between the different system components. However, in order to optimize the performance, it is essential to identify and monitor key parameters of the system, such as power consumption and refrigeration effect [8].

Kim et al. designed a dynamic model of a water heater system driven by a heat pump to investigate transient thermal behavior of the system which was composed of a heat pump and a hot water circulation loop. From the simulation, the smaller size of the water reservoir was found to have larger transient performance degradation, and the larger size can caused additional heat loss during the hot water storage period. Therefore, the reservoir size should be optimized in a design process to minimize both the heat loss and the performance degradation [9].

Hsiao et al. used an ice storage subcooler to improve the heat pump performance. The system supplies heating and cooling demands to two greenhouses with temperature ranging 308~323 K and 273~291 K respectively and utilizes an ice storage tank to subcool the condensed refrigerant which can enhance the system coefficient of performance (COP). The ice storage tank will charge storing ice when the cooling load is less than the nominal cooling capacity. The experimental presented that the COP of a heat pump with subcooler is higher than the one without subcooler, which are 12% and 15% in charge and discharge mode, respectively [10].

Chen investigated and compared the performance of four different operating strategies which consist of simple temperature control, temperature and water amount control, optimization temperature control and optimization temperature and water amount control. In this research, Particle Swarm Optimization has been utilized to optimize the heat pump system. The results showed that the optimization temperature and water amount control has the best performance in both energy consumption and energy cost [11].

Rankin et al. presented a study about demand side management for commercial building using an inline heat pump water heater methodology. The results based on actual data from the monitored installations showed a significant peak demand reduction for each installation. The peak demand for whole hotel's building with occupancy of 220 people has been taken into account for one installation. The savings incurred by the building owner also included significant energy consumption savings due to the superior energy efficiency of the heat pump water heater. In one case study, the peak demand contribution was reduced by 86% for hot water heating and 36% for the whole building [12].

Hepbasli et al. proposed study dealt with reviewing Heat Pump Water Heater (HPWH) systems in terms of energetic and exergetic aspects. The performance evaluation has been modeled by using energy and exergy analysis methods. Moreover, a comprehensive review of studies conducted on them were classified and presented.

It is expected that this comprehensive review will be very beneficial to everyone involved or interested in the energetic and exergetic design, simulation, analysis, performance assessment and applications of various types of heat pump water heater systems [13]. Moreover, due to solar energy is a clean energy, some studies [14~16] investigated solar assisted heat pumps.

1.3 Research Structure

Following is the structure of the thesis which can be shown in figure 1.1:

Chapter 1: Introduction

The research background, literature review, and the objective of this study are introduced

Chapter 2: Smart Energy Management Device System

This chapter is describing principle and structure of Smart Energy Management Device (SEMD) system. In addition, traditional system is also described in this chapter.

Chapter 3: Optimization Method

Many kinds of optimization methods have been introduced and particle swarm optimization has been chosen as a method to optimize the cost in this research.

Chapter 4: System and Component Analysis

In this chapter, the mathematical models of each component and control strategies of SEMD have been established.

Chapter 5: Result and Discussion

Result and discussion of each case study is presented in this chapter.

Chapter 6: Conclusion

The conclusions of this research have been presented and recommendations have been made.

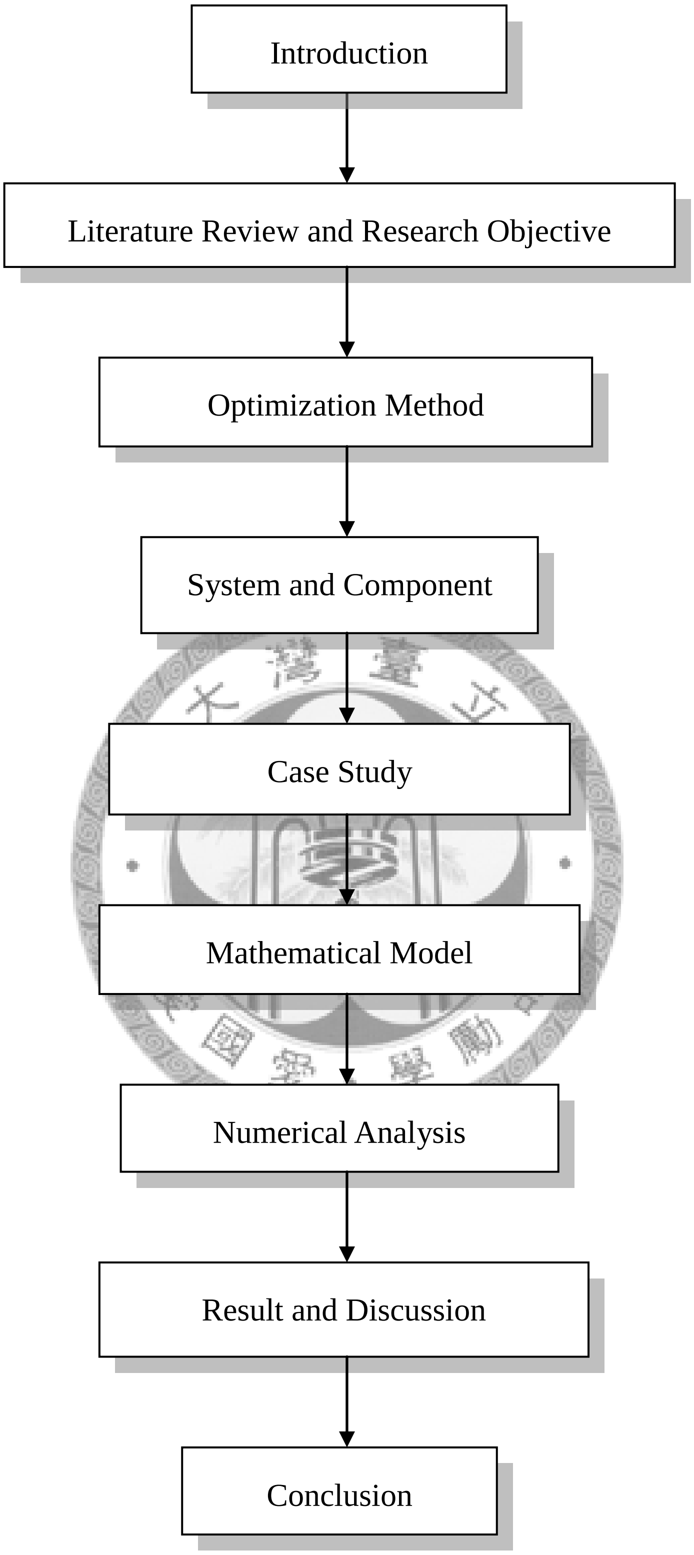


Figure 1.1 Structure of Study

Chapter 2 Smart Energy Management Device System and Traditional System

2.1 Introduction

Inspired from heat pump technology, the SEMD has been developed in order to fulfill energy demand for household in Taiwan. Heat pumps have the ability to move and absorb heat energy from one environment to another and in either direction once at a time. On the other hand, the SEMD is designed to move and absorb heat energy from one environment to another in either direction simultaneously. Although heat pump has become very common technology used in Europe, but this technology is rarely used in Taiwan. Nowadays, we are trying to implement this technology to provide both heat and cold energy to empower household appliances by modifying heat pump. Not only the components of heat pump need to be modified, but household appliances also have to be modified in conjunction with the SEMD. The electricity is applied to the SEMD to convert electrical energy into heat and cold energy to activate appliances. For appliances which are activated by heat energy include hot water for hand washing, hot water for showering, drier, shoe drier, foot bath machine, floor heating system, etc. On the contrary, for appliances which are activated by cold energy consist of air-conditioner, refrigerator, drinking fountain, cold spa, etc. In addition, the SEMD's system operation is also connected directly to computer, modem and human-machine interface. To provide a comfort and healthy environment to people who live in the house, thermal, ambient light, humidity, and CO_2 sensors are installed in order to monitor environment condition inside the house. According to American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE), the effects of increasing CO_2 level to adult's health condition can be summarized in table 2.1. The product, chip control, and sensors specifications are shown in table 2.2, 2.3, and 2.4 respectively. Moreover, power consumption, heating and cooling capacity of the SEMD can be shown in figure 2.1, 2.2 and 2.3 respectively. In order to analyze the performance of the SEMD, heating and cooling coefficient of performance (COP) have to be calculated based on the experimental data in figure 2.1, 2.2 and 2.3. The results are shown in table 2.5 and 2.6, respectively. The picture of the SEMD and sensors is shown in appendix I.

2.2 Principle of SEMD

The SEMD system is composed of a modified heat pump, hot and cold water storages, feed water pump, water circulation pumps for hot and cold water, and an auxiliary electric heater for hot water load, as shown in figure 2.4. The modified heat pump is used to heat and cool the water in hot and cold water storage respectively.

The structure of modified heat pump consists of compressor, expansion valve, hot and cold water storages and heat exchanger. The SEMD uses an intermediate fluid called a refrigerant which absorbs heat as it vaporizes and releases the heat when it condenses. Therefore, in hot water storage the heat is absorbed from inside an occupied space and rejects this heat to cold water storage to cool down the refrigerant. In SEMD, heating and cooling mode is happened at the same time while the compressor is activated.

Moreover, the working fluid, in its gaseous state, is pressurized and circulated through the system by a compressor. On the discharge side of the compressor, the present hot and highly pressurized vapor is cooled in cold water storage, called a condenser, until it condenses into a high pressure and moderate temperature liquid. The condensed refrigerant then passes through a pressure-lowering device also called a metering device such as an expansion valve, capillary tube, or possibly a work-extracting device such as a turbine. The low pressure and liquid refrigerant then leaves the expansion device and enters hot water storage which is known as evaporator, in which the fluid absorbs heat and boils. The refrigerant then returns to the compressor and the cycle is repeated.

In addition, heat exchanger is connected to hot and cold water storage in order to prevent freezing in cold water storage. While cold water load demand is higher than hot water load demand, heat exchanger is activated to decrease water temperature in hot water storage and vice versa.

The load for the SEMD divided into hot water and cold water load. Hot water load consist of open loop load and closed loop load. In open loop load, the heat energy which has been used cannot be recycled. Hence, hot water storage is also supported with feed water system in order to supply water which has been used for open loop load. In contrast, in closed loop; the heat energy which has been used can be recycled into hot water storage. In addition, an auxiliary heating boiler is installed in this system in order to keep the hot water temperature at a default load temperature. On the other hand, the system in cold water load is closed loop system. The cold energy used for household appliances can be recycled into cold water storage. The advantage of recycled process is that operating time of compressor can be minimized in association with heat and cold energy loss.

2.3 Traditional System

Traditional system consists of steam boiler which is designed to produce heat energy and chiller which is designed to produce cold energy. Heat energy from hot water storage is shifted directly to hot water load. On the other hand, cold energy which is produced in cold water storage is also transferred directly to cold water load. Alike in the SEMD system, in traditional system, both heat and cold from water storage is taken away and released to the air through heat exchanger. In order to compare with SEMD system, the specification of the system, including boiler and chiller capacity, storage size, water pump capacity, hot and cold water load, and auxiliary boiler capacity is designed exactly the same as in SEMD system. The system can be illustrated as figure 2.5.

Table 2.1 CO_2 Standard Level

Properties	Specification
Normal Outdoor Level	350 - 450
Acceptable Level	< 600
Complaints of Stiffness and Odors	600 - 1000
ASHRAE and OSHA Standards	1000
General Drowsiness	1000 - 2500
Expected Adverse Health Effects	2500 - 5000
Maximum Allowed Concentration Within 8 Hours Working Period	5000

Unit : ppm

Table 2.2 Product Specification

SEMD Component Specification		
Component	Model	Electricity consumption
Compressor	TS-185-HA(R-134a)	Cooling Capacity：30.9 kW
		Input Power：11.3 kW
Evaporator	B03-052-38-HQ	30.9 kW
Condenser	B03-052-78-H	42.2 kW
Electric Expansion Valve	AKV-15-3	-
Refrigerant	R-134a	-
Operating Condition		
Evaporator Temperature	7.2 ^{o}C	
Condenser Temperature	60 ^{o}C	
Overheating	5 K	
Overcooling	5 K	
Compressor Input Voltage and Current		
Voltage	220V-3ψ-60 Hz	
Current	35.9 A	

Table 2.3 Control Chip Design Specification

Chip Element	Specification
Execution Speed	0.375~12.56 μs
Input Points	128 points
Output Points	64 points
Temperature Module	K or J type thermo couple, resolution 0.1 ^{o}C, in compensation with cold junction temperature, digital filter and disconnecting function
Pulse Output	2 points，maximum output pulse frequency7 kHz
Programmable Device Interface Link	RS-232C，can be directly connected to the computer, human-machine interface and modem
Programs Link Interface (Optional Equipment)	RS-232C or RS-422/RS-485

Table 2.4 Sensors Specification

Properties		Specification
Carbon Dioxide (NDIR)	Range	0 to 5% (volume concentration in air)
	Accuracy	±5% of reading
Temperature	Range	-40 to +125℃
	Accuracy	±5%
Relative Humidity	Range	0 to 100%
	Accuracy	±2.5%
Illuminance	Dark Current	3 to 50 μA
	Ev = 100 lux Light Current	Typical 50 μA
Respond Time		< 2 Minutes
Product Size		90*50*32 mm
PC Software Requirements		Win 2000/XP (with .NET 2.0+ installed), Vista, Win 7

Table 2.5 Heating Coefficient of performance (COPh)

		Condenser Input Temperature (°C)				
		30	35	40	45	50
Evaporator Input Temperature (°C)	10	4.52	3.79	3.12	2.73	2.39
	11	4.64	3.93	3.25	2.88	2.55
	12	4.85	4.06	3.32	2.93	2.61
	13	5.11	4.25	3.43	3.05	2.78
	14	5.36	4.39	3.48	3.07	2.84
	15	5.42	4.42	3.55	3.18	2.97
	16	5.44	4.45	3.63	3.28	3.05
	17	5.45	4.55	3.72	3.41	3.10
	18	5.53	4.64	3.85	3.52	3.15
	19	5.60	4.75	4.02	3.61	3.28
	20	5.68	4.86	4.21	3.74	3.38

Table 2.6 Cooling Coefficient of performance (COPc)

		Condenser Input Temperature (ºC)				
		30	35	40	45	50
Evaporator Input Temperature (ºC)	10	3.16	2.76	2.13	1.89	1.61
	11	3.35	2.91	2.15	1.93	1.72
	12	3.33	2.94	2.28	2.01	1.72
	13	3.49	3.00	2.30	2.02	1.76
	14	3.69	3.06	2.35	2.04	1.90
	15	3.68	3.16	2.35	2.10	1.92
	16	3.83	3.02	2.45	2.20	1.94
	17	4.02	3.08	2.62	2.39	2.10
	18	4.04	3.25	2.61	2.40	2.15
	19	3.99	3.32	2.75	2.51	2.18
	20	4.06	3.51	2.81	2.54	2.22

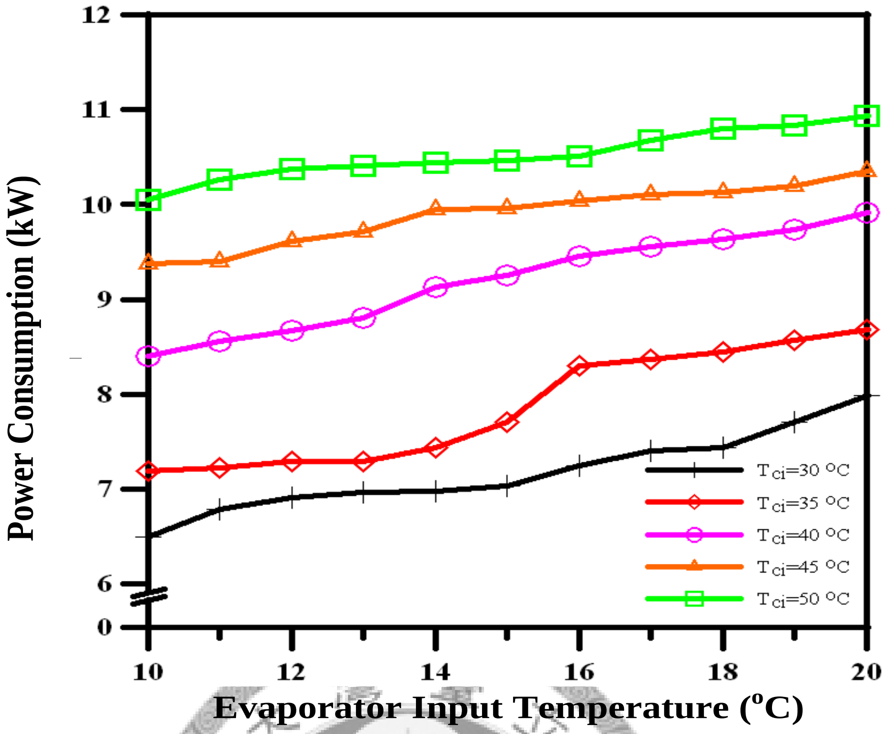


Figure 2.1 Power Consumption

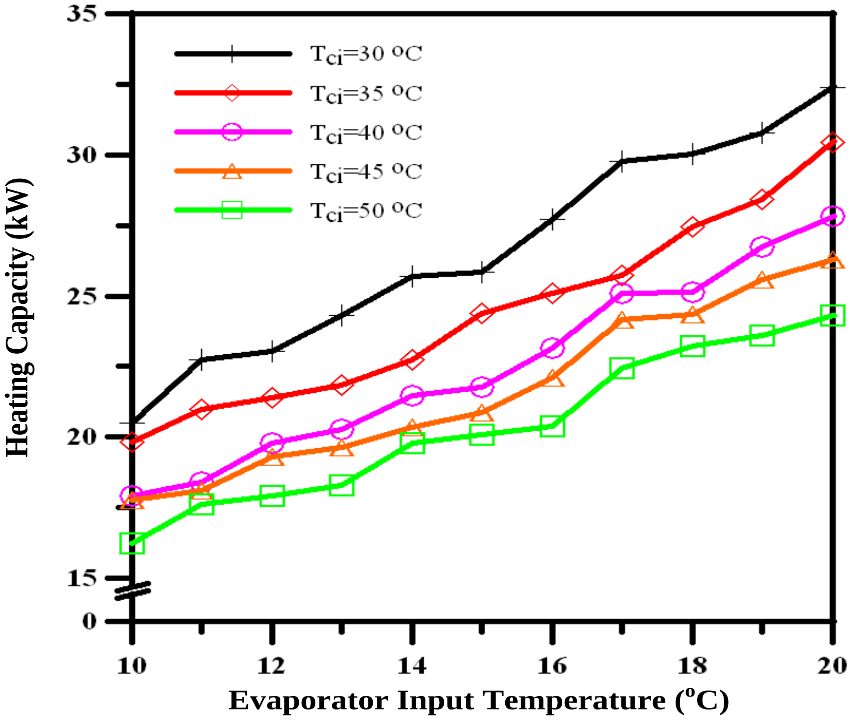


Figure 2.2 Heating Capacity

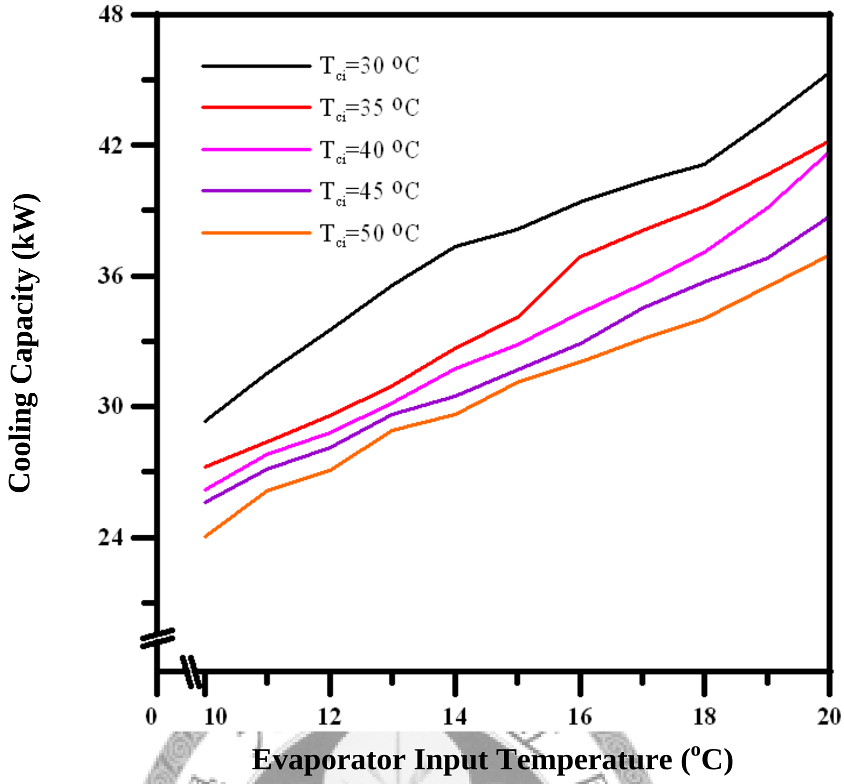


Figure 2.3 Cooling Capacity

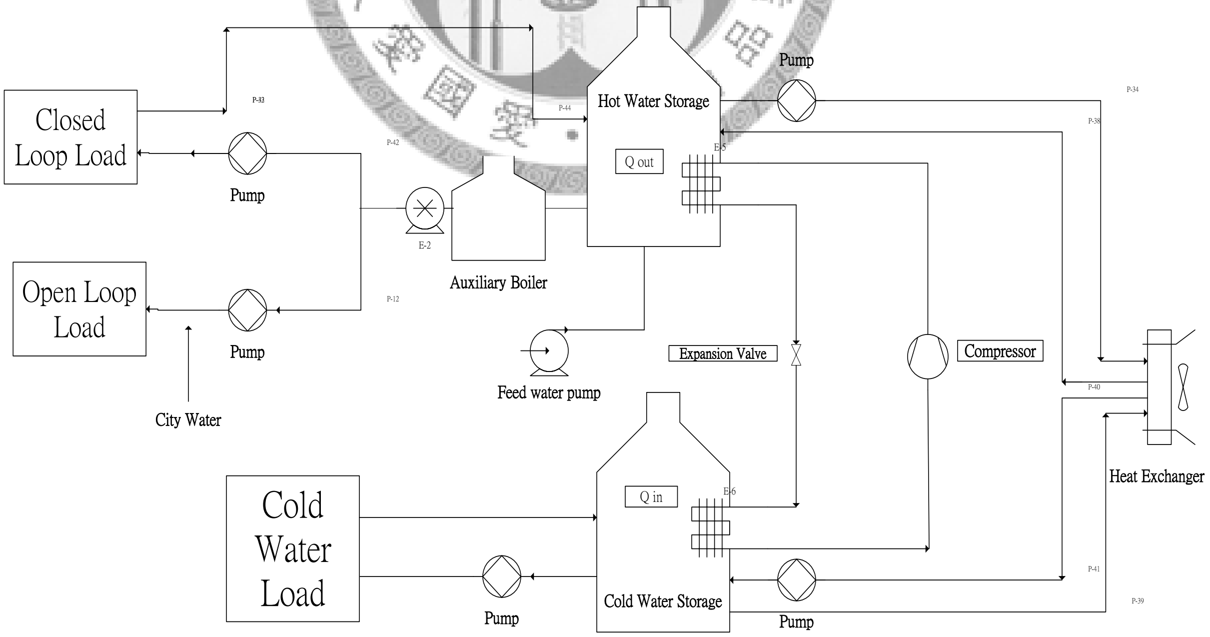


Figure 2.4 The SEMD Structure

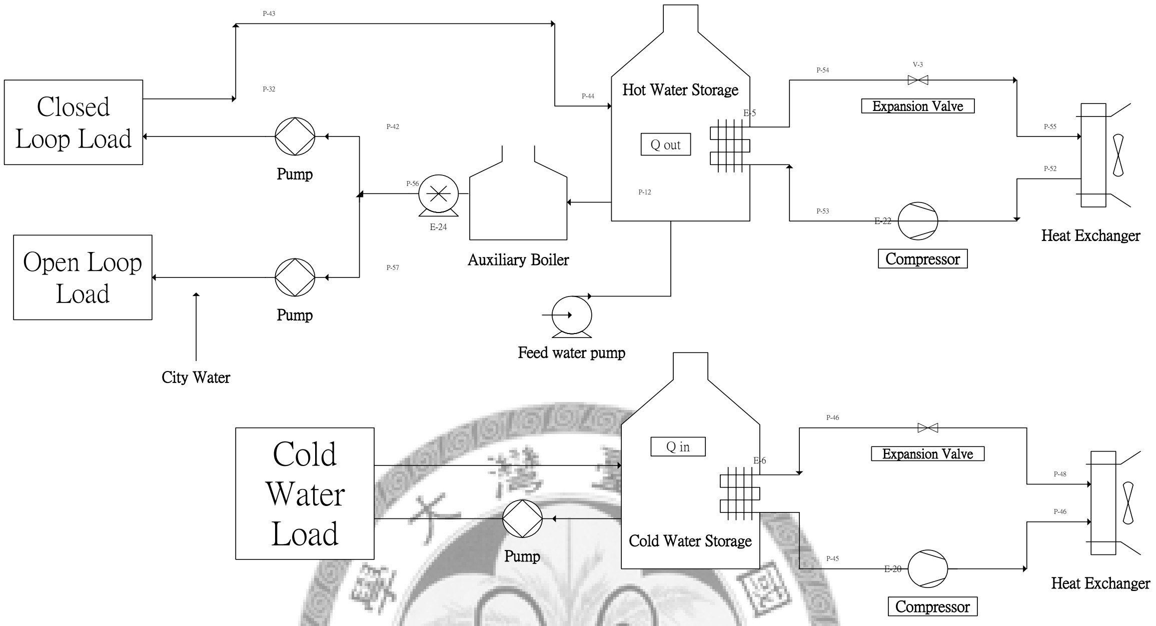


Figure 2.5 Traditional System

Chapter 3 Optimization Method

3.1 Introduction to Optimization

In 1947, Dantzig published the Simplex algorithm to propose training and logistics schedules in conjunction with the use of the program by the United States military and later became the first optimization technique, which is known as linear programming. Although much of the theory had been introduced by Kantorovich in 1939, Neumann developed the theory of the duality in the same year as Dantzig did. In 1954, Barricelli started using computer to run a simulation, but his publication was not widely noticed [17, 18]. Starting in 1957, the Australian quantitative geneticist Fraser published a series of papers on simulation of artificial selection of organisms with multiple loci controlling a measurable trait [19].

In applications, mathematical optimization is often used in engineering and economics fields to select the best element from some set of available alternatives. More generally, it means finding maximum or minimum best available values of some objective function in a given defined domain, including a variety of different types of objective functions and different types of domains.

Nowadays, there are many kinds of optimization algorithms used by researches to find an optimal solution for various issues in many fields. Choi et al. used genetic algorithm to presents the capacity control of a heat pump system using the discharge superheating of the compressor, concerns the design of a fuzzy controller for a heat pump at the outlet of a compressor and compares an optimized fuzzy controller with one that is not optimized. The result show that the optimized fuzzy controller makes undershoot and overshoot alleviated significantly in the discharge superheating, outlet temperature of secondary fluid and refrigerant mass flow rate [20]. Chebouba et al.

proposed an ant colony optimization (ACO) algorithm is proposed for operations of steady flow gas pipeline. The system is composed of compressing stations linked by pipelegs. The decisions variables are chosen to be the operating turbocompressor number and the discharge pressure for each compressing station. The objective function is the power consumed in the system by these stations. The results are compared with those obtained by employing dynamic programming method. We obtain that the ACO is an interesting way for the gas pipeline operation optimization [21].

3.2 Particle Swarm Optimization (PSO)

The particle swarm optimization (PSO) is a robust stochastic optimization technique based on the movement and intelligence of swarms which is proposed by Kennedy and Eberhart in 1995 [22, 23]. The concept was intended to graphically simulate the graceful but unpredictable choreography of bird flock. Moreover, it has been applied as a simulation of a simplified social system in which individual members of a school can profit from the discoveries and previous experiences of all the other members of the school during the search [22].

A particle swarm in PSO refers to a number of potential solutions to the optimization problem, where each potential solution is referred to as a particle position. Each particle is initialized by a random position in multi-dimensional problem space and then is “flown” through this space to locate the best position [5, 24]. A fitness function (referred to as an objective function) quantifies the optimality of a solution (that is, a partical) in a partical swarm algorithm so that the solution of each particle can be compared. Each particle keeps track of its coordinates in the solution space which are associated with the best solution (fitness) that has achieved so far by that particle. This value is called personal best. Another best value that is tracked by the

PSO is the best value obtained so far by any particle in the neighborhood of that particle. This value is called group best. The basic concept of PSO lies in accelerating each particle toward its personal best and the group best locations, with a random weighted acceleration at each time step as shown in figure 3.1

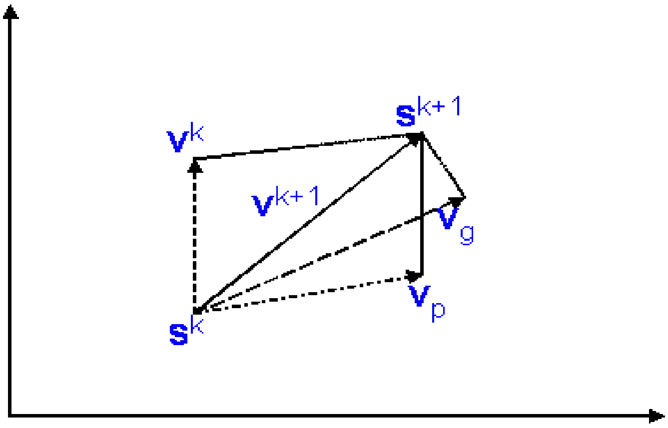


Figure 3.1 Modification Concept of a searching point by PSO

Where S^k and S^{k+1} refer to current and modified searching point; V^k and V^{k+1} are current and modified velocity; and V_p and V_g represent velocity based on personal best and group best.

The modification of the particle's position can be mathematically modeled according the following equation:

$$V_i^{k+1} = \omega \times V_i^k + c_1 \times r_1 \times (V_{p_i}^{\ k} - S_i^k) + c_2 \times r_2 \times (V_{g_i} - S_i^k) \qquad (3.1)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \qquad (3.2)$$

where V_i represents the velocity of particle i; k stands for the iteration number; ω represents inertial weight; c_1 and c_2 are acceleration constants; r_1 and r_2 are two random functions in the range [0, 1]; S_i represents the current position of particle i; V_{pi} is the personal best position of particle i (pbest); and V_{gi} is the best position of all the particles found at present (gbest).

The acceleration constants represent the weighting of the acceleration terms in which each particle moves toward personal best and group best positions. Thus, low acceleration constant values allow particles to move slowly toward target regions, while high values result in fast movement toward, or past, target regions. That the acceleration constants c_1 and c_2 equal to 2.0 in nearly every application is suggested in [25].

The inertial weight is used to control the move velocity; when the weight is too high, particles might move past the best solution. In contrast, if the weight is too small, particles might execute a limited exploration within the local regions and might be unable to move far enough to reach a better position. The weight adopted in this research is from about 1.2 to 0.9 during a run [23].

Moreover, for discrete binary problem, Kennedy and Eberhart [26] proposed a discrete binary version of the particle swarm algorithm (BPSO). In the binary version, the evolution of particle velocity is the same as PSO, but the evolution of particle position is different and in accordance with the following equation:

$$S(V_i^{k+1}) = \frac{1}{1+exp(-V_i^{k+1})} \tag{3.3}$$

$$\text{If } r_3 < S(V_i^{k+1}) \text{ then } X_i^{k+1} = 1\text{, else } X_i^{k+1} = 0 \tag{3.4}$$

where V_i represents the velocity of particle i; k stands for the iteration number; r_3 is random functions in the range [0, 1]; X_i refers to the position of particle i.

Limiting the maximum value of velocity is helpful to further exploration after the population has converged; Therefore, the maximum value of velocity is set to 4 in this study [27].

The process for implementing the BPSO is shown in figure 3.2 and described as follows:

1. Initializing a population of particles with random positions and velocities on dimensions in the problem space.
2. Evaluating each particle’s position according to the objective function.
3. Comparing particle's fitness evaluation with particle's personal best. If current value is better than personal best, then set personal best value equal to the current value and the personal best location equal to the current location.
4. Comparing fitness evaluation with the population's overall previous best. If current value is better than group best, then reset group best to the current particle's array index and value.
5. Changing the velocity and position of the particle according to the equation 3.1, 3.3 and 3.4
6. Loop to step 2 until a criterion is met, usually a sufficiently good fitness or a maximum number of iterations.

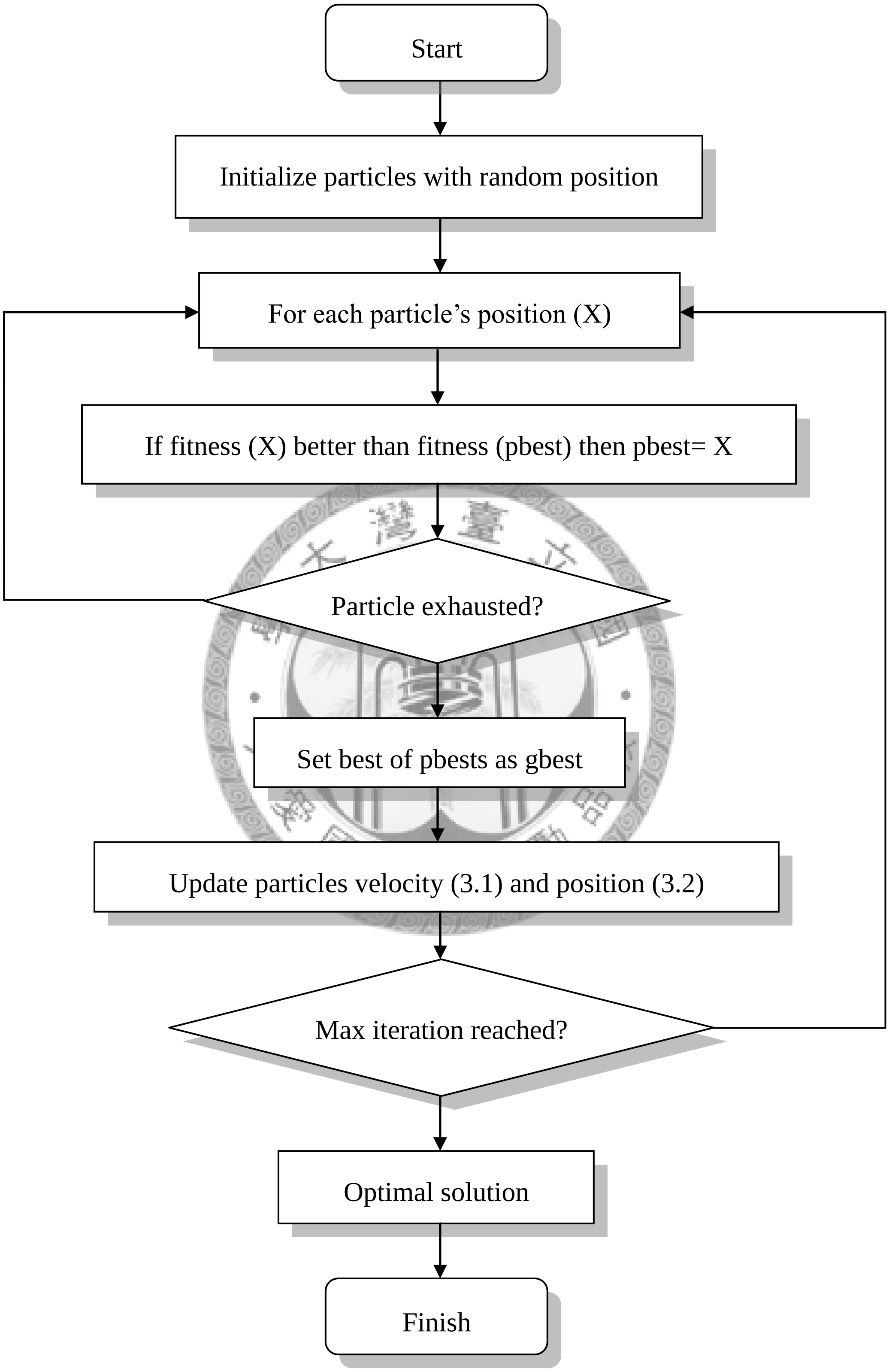


Figure 3.2 PSO Flow Chart

Chapter 4 System and Component Analysis

The components of the SEMD consist of modified heat pump, hot and cold water storages, auxiliary heating boiler, hot and cold loads and feed water pump. This research discusses an optimization strategies based on the SEMD switch on and off condition of the compressor. To simplify the system, firstly, we divide the whole system into several subsystems and determine control volume for the each subsystem, and then applying first thermodynamic law to govern energy and mass conservation equations for each control volume based on SEMD switch on and off condition. The terms and conditions of system simplification have to satisfy thermodynamic law which is shown as follows:

1. Satisfying energy and mass conservation.
2. Neglecting the change of temperature in hot and cold water storage between time intervals.
3. Neglecting heat and cold loss between storages and environment.
4. Neglecting heat and cold loss on pipes while water travels to load and heat exchanger in SEMD.
5. Neglecting kinetic and potential energy that occur on pipes.
6. Assuming that temperature for each particle of water inside storages is considered average to whole temperature of storage.
7. Assuming that increasing or decreasing temperature for each particle of water inside storage from heating or cooling process is considered average to whole temperature of storage

4.1 Heat and Cold Energy Analysis

The main objective of SEMD is to produce either heat or cold energy to water storage, respectively. At the same time, when compressor is activated, it supplies both heat and cold energy to hot and cold storage. The heat and cold energy which is supplied to the storage are related to the changes of water temperature in hot and cold storage. Heat and cold energy can be calculated as follow:

$$Q_{HP} = HPC \times \Delta t \times K \tag{4.1}$$

Q_{HP} shows heat or cold energy of system (kJ); HPC is heating or cooling capacity (kW); Δt is estimation time interval (s); K refers to compressor on-off status, 0 refers to off status and 1 refers to on status.

For traditional system, heat energy of boiler in which heating capacity is related to hot water temperature and air temperature and can be represented as follow:

$$Q_{HP,B} = HPC_B \times \Delta t \times K \tag{4.2}$$

$Q_{HP,B}$ shows heat energy of traditional system (kJ); HPC_B is heating capacity (kW); Δt is estimation time interval (s); K refers to compressor on-off status, 0 refers to off status and 1 refers to on status.

On the other hand, cold energy of chiller in which cooling capacity is related to hot water temperature and air temperature and can be calculated as follow:

$$Q_{HP,C} = HPC_C \times \Delta t \times K \tag{4.3}$$

$Q_{HP,C}$ shows cold energy of traditional system (kJ); HPC_C is cooling capacity (kW); Δt is estimation time interval (s); K refers to compressor on-off status, 0 refers to off status and 1 refers to on status.

The coefficient of performance of SEMD system for hot and cold water system are related to hot and cold water temperature and can be calculated as follows

$$COP = a_0 + a_1 T_H + a_2 T_C + a_3 T_H T_C \tag{4.4}$$

COP shows coefficient of performance; a_0 to a_3 are coefficients; T_H means hot water temperature (℃) and T_C means cold water temperature (℃).

Moreover, the coefficient of performance of boiler in traditional system is related to hot water temperature and air temperature and can be calculated as follows

$$COP_B = a_0 + a_1 T_H + a_2 T_A + a_3 T_H T_A \tag{4.5}$$

COP_B shows coefficient of performance of boiler; a_0 to a_3 are coefficients; T_H means hot water temperature (℃) and T_A means air temperature which is set to 26℃ [28].

However, the coefficient of performance of chiller in traditional system is related to cold water temperature and air temperature and can be calculated as follows

$$COP_C = a_0 + a_1 T_C + a_2 T_A + a_3 T_C T_A \tag{4.6}$$

COP_C shows coefficient of performance of chiller; a_0 to a_3 are coefficients; T_C means cold water temperature (℃) and T_A means air temperature which is set to 26℃ [28].

After calculating the coefficient of the performance (COP), we can calculate the power consumption of the system by using equation below:

$$P = Q / COP \tag{4.7}$$

P shows power consumption (kJ); Q represents each system's hot or cold energy (kJ); COP is the coefficient of performance.

To sum up, by proceeding regression, the coefficients for COP for heating part are

6.494, 0.134, -0.103, and -0.001 respectively, with R^2 equals to 0.952. For cooling part are 4.526, -0.073, 0.113, and -0.001 respectively, with R^2 equals to 0.949.

4.2 Storage Analysis

There are many sorts of materials can be selected, such as carbon steel, stainless steel, fiber reinforce plastic (FRP) and etc. Nowadays, FRP material becomes widely used since it has many advantages, for instance, rust proof, leak proof, robust structure, hygienic, structurally strong, easy to install, lightweight, easy to transport, durable, and cost effective. This kind of material will become the best choice for the system. During the operation of the SEMD, the water pressure is easily unstable especially when shifting water to load user. So, it is essential to select water storage material that can overcome this problem instead of low cost. In this section, the water storage capacity is assumed to same type and capacity for both hot and cold water storage and then the analysis of water storage will be discussed separately as follows:

1. Hot Water Storage

Firstly, hot water flow rate in relation with hot water storage temperature and load demand has to be calculated before calculating output heat energy of hot water storage. In this research, the default hot water load temperature needed is set to 50℃ and feed water temperature is set to 20℃. When storage temperature is lower than default hot water load, hot water is shifted directly to auxiliary electric boiler in order to raise the water temperature to 50℃ and then hot water from boiler is shifted to hot water appliances which need heat energy. On the other hand, when storage temperature is higher than default hot water load, by integrating thermodynamic law, the output hot water flow rate is adjusted in relation with default hot load temperature, hot recycled temperature, feed water temperature, city water temperature, and storage temperature. In this case, we divide hot water load into closed loop and open loop. For open loop system, while hot water temperature of storage is higher than default hot water load, hot water flow rate adjustment can be calculated as follow:

$$\dot{m}_{HO} = \dot{m}_{OHL} \times \frac{(T_{HL} - T_{CW})}{(T_{HT}^{n} - T_{F})} \tag{4.8}$$

$\dot{m}_{HO}$ shows hot water flow rate for open loop system (L/s); $\dot{m}_{OHL}$ is hot water flow rate for open load system (L/s); T_{HL} is hot water user load temperature (℃); T_{CW} refers to city water temperature which is set to 20℃ ; T_F means feed water temperature which is set to 20℃, and T_{HT}^{n} means hot water storage temperature at time n (℃).

However, for closed loop system, when hot water temperature of storage is higher than default hot water load, hot water flow rate adjustment is shown as follow:

$$\dot{m}_{HC} = \dot{m}_{CHL} \times \frac{(T_{HTR} - T_{HL})}{(T_{HTR} - T_{HT}^{n})} \tag{4.9}$$

$\dot{m}_{HC}$ shows hot water flow rate for closed loop system (L/s); $\dot{m}_{CHL}$ is hot water flow rate for closed load system (L/s); T_{HL} is hot water user load temperature (℃); T_{HTR} refers to hot water recovery temperature (℃); T_{HT}^{n} means hot water storage temperature at time n (℃).

Moreover, in open loop system, heat energy which is shifted through hot water to user cannot be recycled. Hence, heat pump need to heat water which is supplied to water storage before shifted to the user. The calculation of heat energy can be shown as follow:

$$Q_{HO} = \dot{m}_{HO} \times \Delta t \times C_p \times (T_{H}^{n} - T_{HU}) \tag{4.10}$$

Q_{HO} shows output heat energy from storage for open loop system (kJ); $\dot{m}_{HO}$ refers to output hot water flow rate (L/s); T_{HU} is default temperature of hot water user which is set to 50℃; Δt is estimation time interval (s); C_P refers to water specific heat (4.186 kJ/(kg•℃)); T_H^n means hot water temperature in storage at time n (℃).

In closed loop system, heat energy can be recycled after heat exchanging, so heat energy which is produced from heat pump can be minimized. In contrast, the heat energy which is used for open loop load cannot be recycled. After calculating hot water flow rate for each case study, then the output heat from storage can be calculated as follow:

$$Q_{HC} = \dot{m}_{HC} \times \Delta t \times C_p \times (T_H^n - T_{HR}^n) \tag{4.11}$$

Q_{HC} shows output heat energy from storage for closed loop system (kJ); $\dot{m}_{HO}$ refers to output hot water flow rate (L/s); T_{HR}^n is hot water input temperature after heat exchanging at time n (℃); Δt is estimation time interval (s); C_P refers to water specific heat (4.186 kJ/(kg•℃)); T_H^n means hot water temperature in storage at time n (℃).

Feeding water is needed in open loop system; the amount of water supplied to storage depends on amount of water shifts to the user. In this system, the water level in storage is assumed always in full condition. When feeding the storage, the heat energy in the storage is absorbed by the feed water and the energy can be calculated as follow:

$$Q_F = \dot{m}_F \times \Delta t \times C_p \times T_F \tag{4.12}$$

Q_F shows input heat energy to storage from supplied water (kJ); $\dot{m}_F$ refers to feed water flow rate (L/s); Δt is estimation time interval (s); C_P refers to water specific heat (4.186 kJ/(kg•℃)); T_F means feed water temperature to storage (℃).

2. Cold Water Storage

Before calculating input cold energy of cold water storage, cold water flow rate in relation with hot water storage temperature and load demand has to be calculated first. In this research, the default cold water load temperature needed is set to 5℃. In the SEMD, cold water system is a closed loop system, so the cold energy can be recycled after shifting through cold water load for heat exchanging. Due to there is no cooling device installed for cold water system, cooling process becomes the priority to the operation of SEMD instead of heating process. When storage temperature is higher than default cold water load, cold water is not going to be shifted to the appliances until the water temperature reach the expected default temperature. Conversely, when storage temperature is lower than default cold water load, adjustment has to be made to the output cold water flow rate in relation with default cold load temperature, cold recycled temperature, input water temperature from heat exchanger and storage temperature. When cold water temperature of storage is lower than default cold water load, cold water flow rate adjustment is shown as follow:

$$\dot{m}_{CO} = \dot{m}_{CL} \times \frac{(T_{CTR} - T_{CL})}{(T_{CTR} - T_{CT}^{n})} \tag{4.13}$$

$\dot{m}_{CO}$ shows cold water flow rate (L/s); $\dot{m}_{CL}$ is cold water flow rate for closed load system (L/s); T_{CL} is cold water user load temperature (℃); T_{CTR} refers to cold water recovery temperature (℃); T_{CT}^{n} means cold water storage temperature at time n (℃).

Next, after calculating cold water flow rate for each case study, then the output cold energy from storage can be calculated as follow:

$$Q_{CO} = \dot{m}_{CO} \times \Delta t \times C_p \times (T_{CR}^{n} - T_{C}^{n}) \tag{4.14}$$

Q_{CO} shows output cold energy from storage (kJ); $\dot{m}_{CO}$ refers to output cold water flow rate (L/s); Δt is estimation time interval (s); T_{CR}^{n} is cold water input temperature after heat exchanging at time n (℃)；C_P refers to water specific heat (4.186 kJ/(kg•℃)); T_C^n means cold water temperature in storage at time n (℃).

4.3 Auxiliary Heating System Analysis

The auxiliary heating system which is installed in both traditional and the SEMD system refer to boiler, which acts as an assistance to provide auxiliary heat energy to water when the water temperature increased by heat pump does not reach default load temperature. Nevertheless, hot water before shifted to user has to pass through boiler in order to assure the water temperature is approaching default temperature. When the temperature is below default temperature, boiler will be activated to supply heat energy to water. There are many kinds of boiler, such as gas, fuel oil, coal, electric, etc. in correspondence to this system, electric boiler has been chosen. When the output water from storage does not reach 50℃, boiler will be activated to increase temperature to 50 ℃ before shifting to user. The heat energy added to hot water can be represented as follow:

$$Q_{BO} = \dot{m}_{HO} \times \Delta t \times C_p \times (T_{HU} - T_H^n) \tag{4.15}$$

Q_{BO} shows supplied boiler energy (kJ); $\dot{m}_{HO}$ refers to storage's output hot water flow rate (L/s); Δt is estimation time interval (s); C_P refers to water specific heat (4.186 kJ/(kg•℃)); T_{HU} is default temperature of hot water user which is set to 50℃; T_H^n means hot water temperature in storage at time n (℃).

4.4 Heat Exchanger Analysis

For traditional system, heat exchanger is not taken into account since it has already built in either boiler or chiller. On the contrary, in the SEMD system, both hot and cold water storage are connected to heat exchanger. Water is shifted to heat exchanger in order to decrease temperature in hot water storage to prevent overheating and increase temperature in cold water storage to avoid freezing simultaneously. For hot water system, heat exchanger is activated when storage temperature is higher than 57℃ in order to prevent overheating of water in storage. The heat energy taken from water can be calculated as follow:

$$Q_{HHE} = \dot{m}_{HHE} \times \Delta t \times C_p \times (T_{HER}^n - T_H^n) \tag{4.16}$$

Q_{HHE} shows heat energy which is sunk by heat exchanger (kJ); $\dot{m}_{HHE}$ refers to hot water flow rate which is shifted to heat exchanger from storage (L/s); Δt is estimation time interval (s); C_P refers to water specific heat (4.186 kJ/(kg•℃)); T_{HER}^n is hot water input temperature after heat exchanging at time n (℃); T_H^n means hot water temperature in storage at time *n* (℃).

On the other hand, for cold water system, heat exchanger is activated when storage temperature is lower than 4℃ in order to prevent freezing on storage which can cause malfunctioning of the machine. The heat energy supply to increase water temperature can be calculated as follow:

$$Q_{CHE} = \dot{m}_{CHE} \times \Delta t \times C_p \times (T_{HCR}^n - T_C^n) \tag{4.17}$$

Q_{CHE} shows cold energy which is taken away by heat exchanger (kJ); $\dot{m}_{CHE}$ refers to cold water flow rate which is shifted to heat exchanger from storage (L/s); Δt is estimation time interval (s); C_P refers to water specific heat (4.186 kJ/(kg•℃)); T_{HCR}^n is cold water input temperature after heat exchanging at time n (℃); T_C^n means cold water temperature in storage at time n (℃).

4.5 Water Pump Analysis

In traditional system, there are four water pumps which are used to shift water either from hot or cold water storage to load before proceeding heat exchanging and it will be activated when hot and cold water load exist. The last water pump is used to feed water for hot water storage. On the other hand, there are six water pumps will be analyzed in the SEMD system. Two water pumps are used to shift water either from hot or cold water storage to load before proceeding heat exchanging and it will be activated when hot and cold water load exist. The other two water pumps are used to shift the water from both hot and cold water storage to heat exchanger and it will be activated when overheating or overcooling occurs. The last water pump is used to feed water for hot water storage. Water pump power consumption can be calculated as follow:

$$P_{WP} = WPC / \eta \times \Delta t \times R \tag{4.18}$$

P_{WP} shows power consumption of water pump (kJ); η refers efficiency of pump which is 0.8; Δt is estimation time interval (s); R refers water pump on and off condition.

4.6 Load Analysis

To save energy usage, the household appliances have been modified in conjunction with the circulation of water. The design of appliances focuses on using either hot or cold water for heat exchanging to fulfill both heat and cold energy demand in household. Thus, water paths are designed to open and closed loop systems for hot water and closed loop system for cold water. In closed loop system, water from storage is shifted to load for heat exchanging. After heat exchanging, water is shifted back to storage for heating or cooling process. Conversely, in open loop system, once water is shifted to load, the water cannot be shifted back to storage. Hot water appliances include hot water shower, drier, shoe drier, foot bath machine, floor heating system, etc. On the contrary, cold water appliances consist of air-conditioner, refrigerator, drinking fountain, cold spa, etc. in brief, either hot or cold water load can be shown in appendix I. In association with load consumption of Taiwan's household, the user load for hot, cold water system, and load distribution can be illustrated in table 4.3 to 4.5 and figure 4.4 and 4.5. In order to compare life cycle cost of the SEMD with traditional system, both hot and cold water load remain the same in the calculation.

4.7 Mathematical Model

Mathematical model is established in order to minimize the electricity consumption of the SEMD. By implementing particle swarm optimization (PSO) which is introduced in chapter 2, it is expected that the operation time of the SEMD can be optimized in order to achieve minimum electricity consumption of the SEMD. Meanwhile, the components which are considered will consume electricity in this system consist of hot and cold water pump, compressor, heat exchanger, and boiler. In this case, life cycle cost is set as an objective function; operation time of the SEMD as control parameter. As a result, minimum life cycle cost control strategy based on the SEMD operation time of each time interval can be modeled by using numerical analysis corresponding to each user load, storage, auxiliary heating system, and electricity rate. It is expected that optimum control strategy can be found in order to achieve economy efficiency in terms of Taiwan government policy about saving energy and reducing carbon emission.

4.7.1 System Setting

The main components of SEMD system consist of scroll compressor, plate heat exchanger, and electrical expansion valve. The design temperature of heat pump operation for evaporator and condenser are 7.2℃ and 60℃ respectively. When cooling capacity is 30.9 kW, energy consumption for compressor is 11.3 kW. In addition, water pump and heat exchanger capacity which is used in this system are 0.5 Hp.

For the operation of SEMD, cold water temperature will be taken as the first priority since auxiliary boiler is installed in the system to increase hot water temperature whenever needed. When cold water temperature is above 8℃, the SEMD will be activated to decrease temperature until 5℃. On contrary, when cold water temperature is under 4℃, heat exchanger will be activated to increase water temperature in order to overcome overcooling. However, the range of cold water temperature is 5℃ and 8℃. On the other hand, when hot water temperature is below 50℃, SEMD will be activated to increase temperature until 55℃. Conversely, when the hot water temperature reaches 57℃, heat exchanger will be activated to decrease water temperature to overcome overheating. Besides, the range of hot water temperature will be adjusted between 50℃ to 55℃. Moreover, to overcome lack of heat energy, auxiliary heating boiler is installed to assist the SEMD to ensure hot water temperature which is shifted to user reaches 50℃.

According to Taiwan power Company as shown in table 4.1, the average electricity rate for summer and non-summer in a year of electricity rate for peak-on and off time are 2.7 NTD/kWh and 1.48 NTD/kWh respectively. The time period for peak on is from 07:30 am until 10:30 pm, conversely, time period for peak off is from 10:30 pm until 07:30 am [29]. However, feed water flow rate and temperature are 0.15 L/s and 20℃ respectively. In this case study, the compressor switch on and off condition is determined based on load consuming time interval which is modeled for 24 hours; the system's life is assumed to 5 years. Moreover, setting parameters above will be shown significantly in table 4.2.

The user load for hot and cold water system is assumed to 24 hours. For hot water system, load is divided into open loop system and open and closed loop system which can be shown in table 4.3 and table 4.4 respectively. On the contrary, for cold water system, the load can be shown in table 4.5. Meanwhile, the load distribution can be shown in figure 4.4 and 4.5

Furthermore, in PSO parameter setting, initial particle is set to 10 particles randomly and iterations is done for 300 times with range of weighting factor between 0.9 and 1.2; learning factor is 2; velocity boundary range between -4 to 4. The setting parameter can be shown significantly in table 4.9.

4.7.2 System Analysis

As mentioned in section 4.1 to 4.5 about the SEMD and traditional system component's analysis. In fact, to analyze the storage's heat circulation, the energy conservation equations of hot and cold water storage have to be derived. Besides, since there is open loop load for hot water system, either heat or water circulation in hot water storage has to be balanced. Therefore, we need to derive mass conservation equation for water circulation of hot water storage instead of energy conservation equations.

However, by combining equation 4.1, 4.2, 4.10, 4.11, 4.12, and 4.16, we can derive energy conservation and mass conservation equation of hot water storage for the SEMD system and traditional system, which can be expressed respectively as follows:

$$M_{HT}^{n+1} \times T_{HT}^{n+1} \times C_p - M_{HT}^{n} \times T_{HT}^{n} \times C_p = Q_{HP} - Q_F - Q_{HO} - Q_{HC} - Q_{HHE} \tag{4.19}$$

$$M_{HT}^{n+1} \times T_{HT}^{n+1} \times C_p - M_{HT}^{n} \times T_{HT}^{n} \times C_p = Q_{HP,B} - Q_F - Q_{HO} - Q_{HC} \tag{4.20}$$

For mass conservation equation of the SEMD and traditional system can be represented respectively as follows:

$$M_{HT}^{n+1} = M_{HT}^{n} + \dot{m}_{HHE} \times \Delta t + \dot{m}_F \times \Delta t - \dot{m}_{HC} \times \Delta t \tag{4.21}$$

$$M_{HT}^{n+1} = M_{HT}^{n} + \dot{m}_F \times \Delta t - \dot{m}_{HC} \times \Delta t \tag{4.22}$$

M_{HT}^{n+1} shows hot water mass at time $n+1$ (L); M_{HT}^{n} refers to hot water mass at time n (L); T_{HT}^{n+1} shows hot water temperature at time $n+1$ (℃); T_{HT}^{n} expresses hot water temperature at time n (℃); C_P refers to water specific heat (4.186 kJ/(kg•℃)); Q_{HP} is heat energy from heat pump for the SEMD (kJ); $Q_{HP,B}$ is heat energy from steam boiler in traditional system (kJ); Q_F shows input heat energy to storage from supplied water (kJ); Q_{HO} refers to output heat energy from storage for open loop system (kJ); Q_{HC} means output heat energy from storage for closed loop system (kJ); Q_{HHE} expresses heat energy which is sunk by heat exchanger (kJ); $\dot{m}_{HHE}$ refers to hot water flow rate which is shifted to heat exchanger from storage (L/s)

Moreover, by combining equation 4.1, 4.3, 4.14, and 4.17, we can derive energy conservation and mass conservation equation of cold water storage for the SEMD system and traditional system, which can be expressed respectively as follows:

$$M_{CT}^{n} \times T_{CT}^{n+1} \times C_p - M_{CT}^{n} \times T_{CT}^{n} \times C_p = Q_{CHE} + Q_{CO} - Q_{HP} \tag{4.23}$$

$$M_{CT}^{n} \times T_{CT}^{n+1} \times C_p - M_{CT}^{n} \times T_{CT}^{n} \times C_p = Q_{CO} - Q_{HP,C} \tag{4.24}$$

M_{CT}^{n+1} shows cold water mass at time $n+1$ (L); M_{CT}^{n} refers to cold water mass at time n (L); T_{CT}^{n+1} shows cold water temperature at time $n+1$ (℃); T_{CT}^{n} expresses cold water temperature at time n (℃); C_P refers to water specific heat (4.186 kJ/(kg•℃)); Q_{HP} is heat energy from heat pump for the SEMD (kJ); $Q_{HP,C}$ is heat energy from chiller in traditional system (kJ); Q_{CO} refers to output heat energy from cold water storage (kJ); Q_{CHE} expresses cold energy which is absorbed by heat exchanger (kJ);

Furthermore, in order to simulate energy change in hot and cold water storage in 24 hours, we need to calculate either hot or cold water temperature at next time interval which can be found from energy conservation equations mentioned above. Meanwhile, since water level in cold water storage will not decrease, it is not imperative to derive mass conservation equation on cold water system.

4.8 The SEMD Optimization

To reach the minimum cost of the SEMD operation is not only depends on design optimization but also control strategy optimization. In this research, both design and control strategy optimization is analyzed. In design optimization, the water storage and system’s heating and cooling capacity optimization have been taken into consideration. On the other hand, in control strategy optimization, we adopted Visual Basic 6.0 to manipulate data in numerical calculation. In this analysis, we analyze traditional control strategy based on temperature as control parameter to simulate operation of the SEMD. For advanced analysis, Particle Swarm Optimization method analysis is integrated to reach optimal control strategy to minimize cost. In addition, traditional system is also analyzed in this section in order to compare the cost with the SEMD system. The operation time for both systems is 24 hours, in which switch on and off decision time interval for both systems is 6 minutes with 5 years of life cycle. In other words, there are three case studies presented in this section.

4.8.1 Case Study 1

Due to water storage, heating and cooling capacity hold an important part in saving energy, the design optimization of the system has been proposed in this research. The larger the storage, the bigger heating or cooling capacity has to be selected to increase or decrease the temperature in water storage, and vice versa. To simplify the calculation, hot and cold water storage, heating and cooling capacity are assumed to same size. In this term, the hot water storage temperature is also affected by supply water to storage, in which it depends on the amount of water that is shifted to hot water open loop load. The analysis is shown in figure 4.1 and described in more detail as follows:

1. Initializing system parameters, open loop hot water, and closed loop cold water load settings.
2. Proceeding trial and error calculation for both water storage capacity and heating or cooling capacity to determine the most decent combination.
3. According to time interval chosen, determining system switch on and off status based on water temperature in both storages.
4. Calculating heat and cold energy and water temperature for both hot and cold water storage for the next time interval.
5. According to hot and cold water temperature, determining activation of auxiliary boiler in each time intervals.
6. Calculating heat energy added by auxiliary boiler.
7. According to hot and cold water temperature, for the SEMD system, activation of heat exchanger is determined in each time intervals.

8. Calculating heat energy sunk and cold energy taken away by heat exchanger to prevent overheating and overcooling.
9. Calculating all loads for each time intervals in 24 hours. If the calculation has not finished, loop to step 2, but if the calculation has finished, continue to step 10.
10. Using heat and cold energy which are calculated above to calculate life cycle cost and get minimum life cycle cost. If the minimum life cycle cost has not been reached, loop to step 2, but if the minimum life cycle cost has not been reached, continue to step 11.
11. Calculating and representing results.

4.8.2 Case Study 2

After calculating the most decent water storage, heating, and cooling capacity, in this case study, traditional control strategy based on water storage temperature as control parameter and life cycle cost as objective function is proposed to determine minimum life cycle cost. However, the operation of the compressor is subjected to water storage temperature. When hot water storage temperature reaches maximum default temperature, heating process will be stopped, on the other hand, when cold water storage temperature reaches minimum default temperature, cooling process will be stopped, and vice versa. Due to heating and cooling process are preceded simultaneously, overheating or overcooling may occur during the SEMD operation. Thus, heat exchanger is installed to prevent overheating or overcooling. In addition, traditional control strategy is also applied to traditional system in order to provide life cycle cost comparison to the SEMD. In traditional system, there is no overheating or overcooling problem since the design of boiler and chiller are independent. The analysis is shown in figure 4.2 and described in more detail as follows:

1. Initializing system parameters, open and closed loop hot water, and closed loop cold water load settings
2. According to time interval chosen, determining system switch on and off status based on water temperature in both storages.
3. Calculating heat and cold energy and water temperature for both hot and cold water storage for the next time interval.
4. According to hot and cold water temperature, determining activation of auxiliary boiler in each time intervals.
5. Calculating heat energy added by auxiliary boiler.
6. According to hot and cold water temperature, for the SEMD system, activation of heat exchanger is determined in each time intervals.
7. Calculating heat energy sunk and cold energy taken away by heat exchanger to prevent overheating and overcooling.
8. Calculating for all loads for each time intervals in 24 hours. If the calculation has not finished, loop to step 2, but, if the calculation has finished, continue to step 9.
9. Using heat and cold energy which are calculated above to calculate life cycle cost
10. Calculating and representing results.

4.8.3 Case Study 3

In previous case studies, design optimization and traditional control strategy have been analyzed. To reach an optimal control strategy and life cycle cost, Particle Swarm Optimization (PSO) method has been integrated to analyze the most decent control strategy of the system. By setting life cycle cost as objective function, and the SEMD compressor switch on and off status as control parameter, it is hoped that optimal control strategy in every specified time intervals can be found and minimum life cycle cost can be achieved. In this term, there are many probabilities of control strategies will occur, by applying PSO, the most decent control strategy can be simulated. Based on this strategy, minimal life cycle cost can be calculated. The analysis is shown in figure 4.3 and described in more detail as follows:

1. Initializing system parameters, open and closed loop hot water, closed loop cold water load settings, and PSO parameter settings.
2. Initializing particles with random positions and velocities on dimensions in the problem space.
3. Evaluate each particle’s position according to the objective function which is life cycle cost.
4. Comparing particle’s fitness evaluation with particle's personal best. If current value is better than personal best, then set personal best value equal to the current value and the personal best location equal to the current location.
5. Comparing fitness evaluation with particle’s overall previous best. If current value is better than group best, then reset group best to the current particle's array index and value.
6. Changing the velocity and position of the particle
7. Loop to step 3 until a sufficiently good fitness or a maximum number of iterations is approached.
8. Calculating optimal solution.

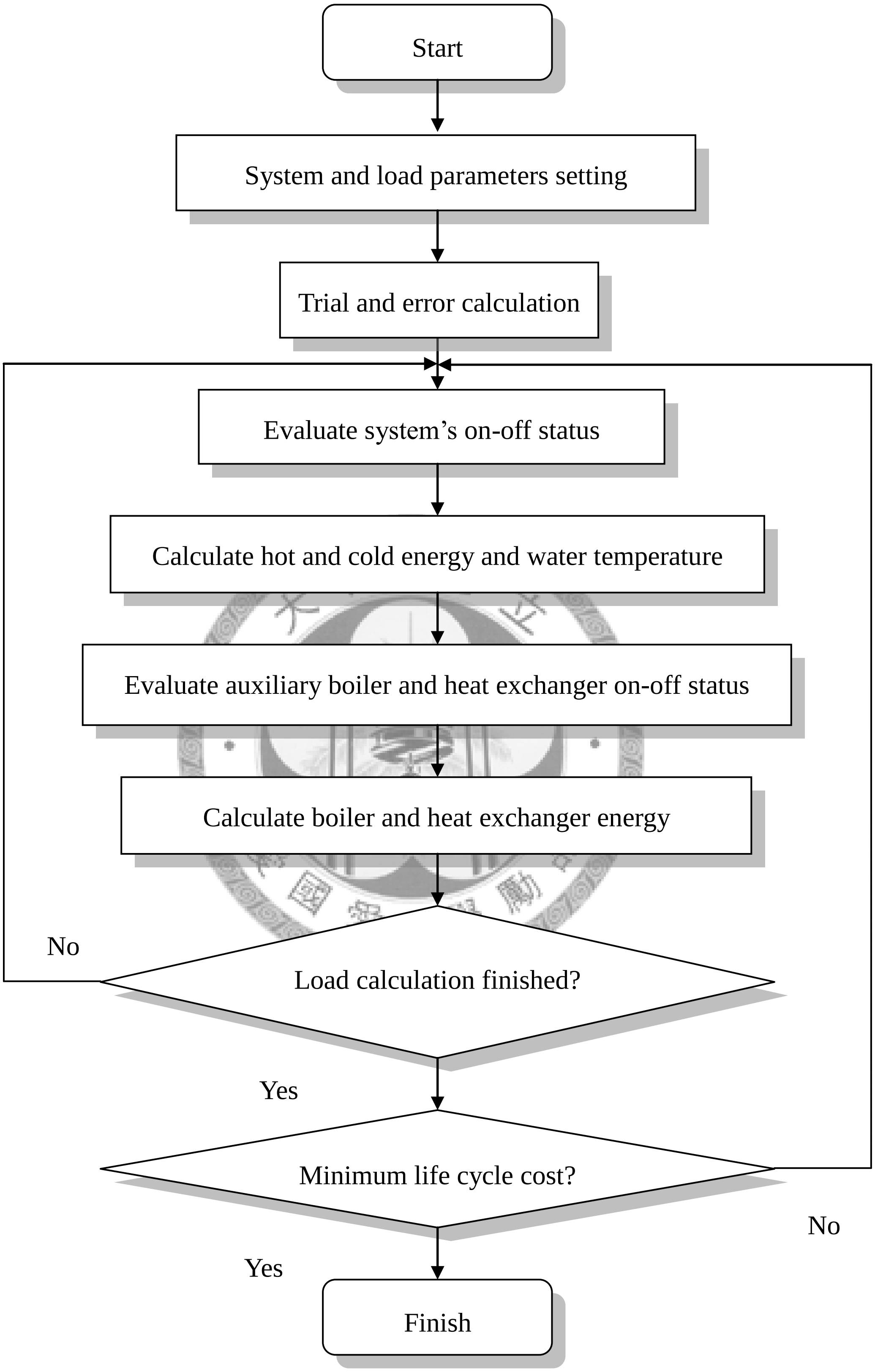


Figure 4.1 Flow Chart Analysis of Case Study 1

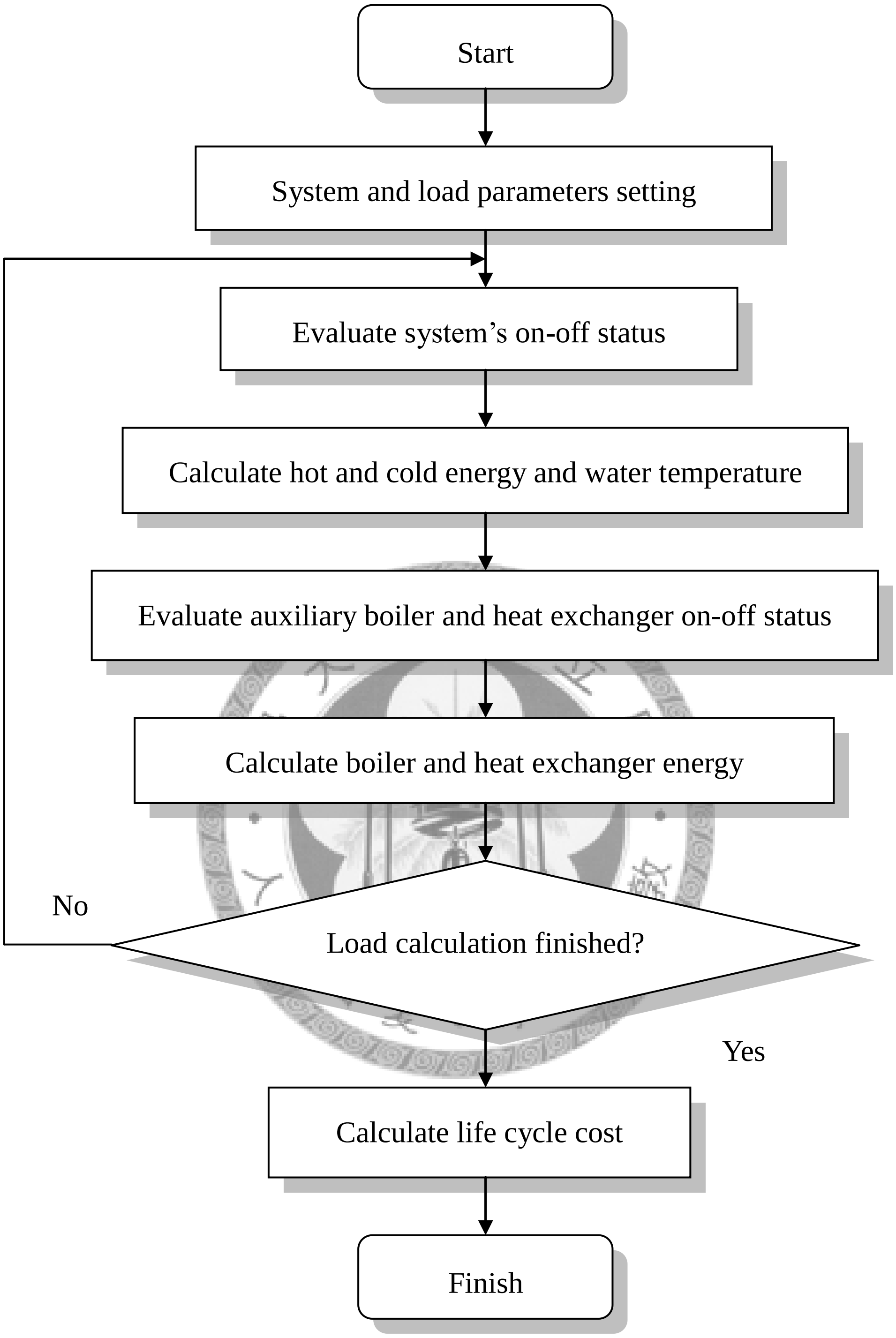


Figure 4.2 Flow Chart Analysis of Case Study 2

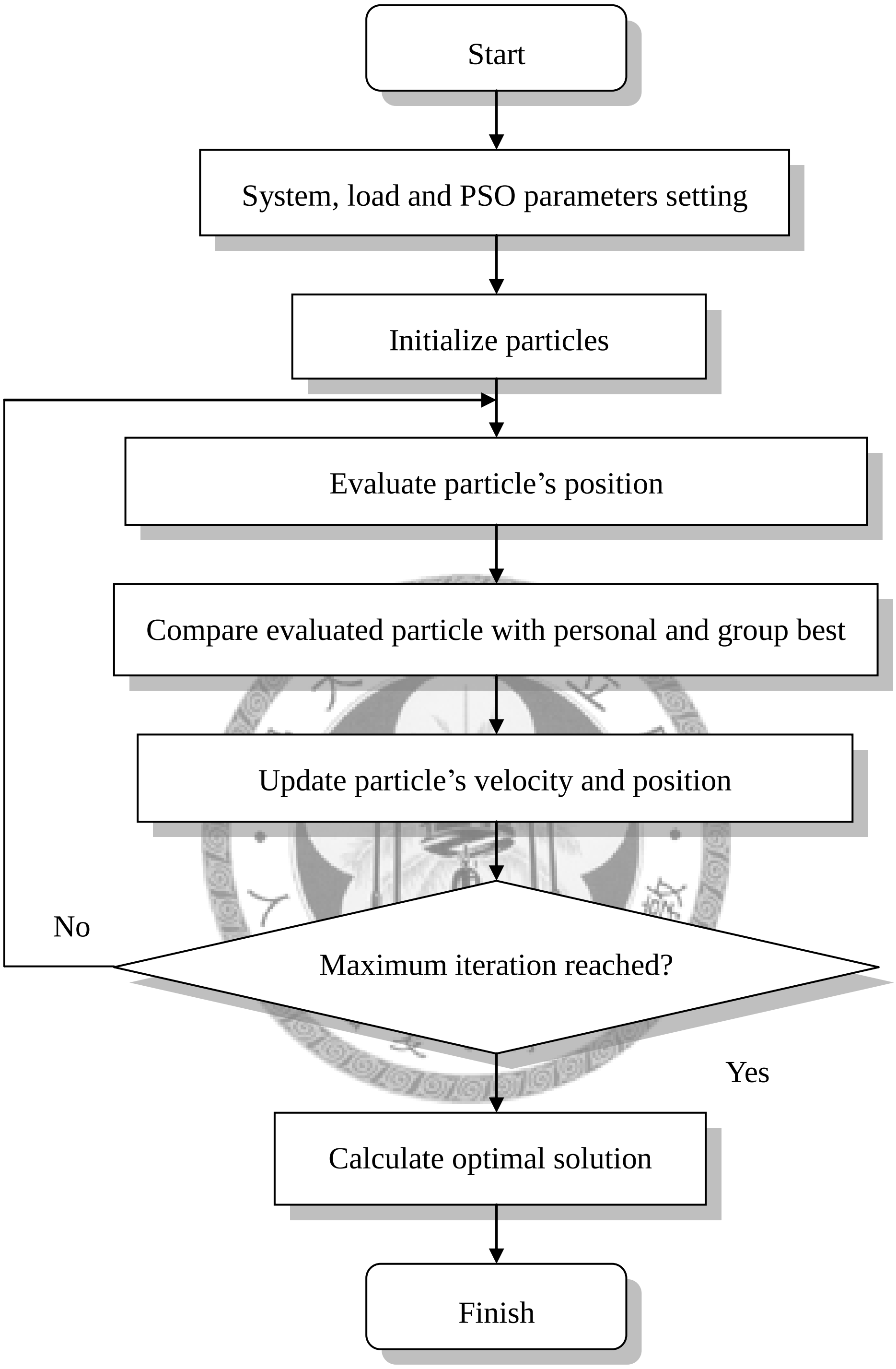


Figure 4.3 Flow Chart Analysis of Case Study 3

4.9 Life Cycle Cost

The main objective of this research is to calculate life cycle cost based on operation cost and installation cost. In general, operation costs include energy cost, maintenance cost, and human resource cost. The parameter costs mentioned in operation cost are not related to optimization; hence, by neglecting discount rate, objective function can be set to life cycle of energy cost and setup cost as shown in equation (4.9).

$$E_L = E_E + E_S \tag{4.25}$$

E_L shows life cycle cost (NTD); E_E refers to energy cost (NTD); E_S is setup cost (NTD).

4.9.1 Calculation of Energy Cost

The energy cost calculation during operation of system can be divided into peak-on and peak-off energy cost. The energy costs for both systems consist of water pumps, auxiliary boiler, modified heat pump, boiler, and chiller which can be calculated as follows:

1. Water pump energy cost at peak-on period

$$E_{WP,on} = P_{WP} \times M_{on} \tag{4.26}$$

$E_{WP,on}$ shows water pump energy cost at peak-on period (NTD); P_{WP} refers to water pump power consumption (kW); M_{on} is electricity cost at peak-on period (NTD).

2. Water pump energy cost at peak-off period

$$E_{WP,off} = P_{WP} \times M_{off} \tag{4.27}$$

$E_{WP,off}$ shows water pump energy cost at peak-off period (NTD); P_{WP} refers to water pump power consumption (kW); M_{off} is electricity cost at peak-off period (NTD).

3. Boiler energy cost at peak-on period

$$E_{BO,on} = Q_{BO} / \eta \times M_{on} \tag{4.28}$$

$E_{BO,on}$ shows boiler energy cost at peak-on period (NTD); Q_{BO} refers to boiler energy consumption (kJ); η is efficiency of boiler which is 0.8; M_{on} is electricity cost at peak-on period (NTD).

4. Boiler energy cost at peak-off period

$$E_{BO,off} = Q_{BO} / \eta \times M_{off} \tag{4.29}$$

$E_{BO,off}$ shows boiler energy cost at peak-off period (NTD); Q_{BO} refers to boiler energy consumption (kJ); η is efficiency of boiler which is 0.8; M_{off} is electricity cost at peak-off period (NTD).

5. Modified heat pump energy cost at peak-on period

$$E_{HP,on} = Q_{HP} / COP \times M_{on} \tag{4.30}$$

$E_{HP,on}$ shows modified heat pump energy cost at peak-on period (NTD); Q_{HP} refers to modified hot and cold energy consumption (kJ); COP is coefficient of performance; M_{on} is electricity cost at peak-on period (NTD).

6. Modified heat pump energy at peak-off period

$$E_{HP,off} = Q_{HP} / COP \times M_{off} \tag{4.31}$$

$E_{HP,off}$ shows modified heat pump energy cost at peak-off period (NTD); Q_{HP} refers to modified hot and cold energy consumption (kJ); COP is coefficient of performance; M_{off} is electricity cost at peak-off period (NTD).

7. Boiler energy cost at peak-on period for traditional system

$$E_{HPB,on} = Q_{HP,B} / COP \times M_{on} \tag{4.32}$$

$E_{HPB,on}$ shows boiler energy cost at peak-on period (NTD); $Q_{HP,B}$ refers to boiler energy consumption (kJ); COP is coefficient of performance; M_{on} is electricity cost at peak-on period (NTD).

8. Boiler energy at peak-off period for traditional system

$$E_{HPB,off} = Q_{HP,B} / COP \times M_{off} \tag{4.33}$$

$E_{HPB,off}$ shows boiler energy cost at peak-off period (NTD); $Q_{HP,B}$ refers to boiler energy consumption (kJ); COP is coefficient of performance; M_{off} is electricity cost at peak-off period (NTD).

9. Chiller energy cost at peak-on period for traditional system

$$E_{HPC,on} = Q_{HP,C} / COP \times M_{on} \tag{4.34}$$

$E_{HPC,on}$ shows chiller energy cost at peak-on period (NTD); Q_{HPC} refers to chiller energy consumption (kJ); COP is coefficient of performance; M_{on} is electricity cost at peak-on period (NTD).

10. Chiller energy at peak-off period for traditional system

$$E_{HPC,off} = Q_{HP,C} / COP \times M_{off} \tag{4.35}$$

$E_{HPC,off}$ shows chiller energy cost at peak-off period (NTD); $Q_{HP,C}$ refers to chiller energy consumption (kJ); COP is coefficient of performance; M_{off} is electricity cost at peak-off period (NTD).

Furthermore, by combining energy cost of water pumps, boiler, modified heat pump, boiler, and chiller which is shown in equation 4.26 to 4.35, energy cost during system operation for five years can be calculated as follow:

$$E_E = Life \times 365 \times E_T \tag{4.36}$$

E_E shows system energy cost (NTD); *Life* refers to system's life for 5 years; E_T is total energy cost of each component including water pumps, boiler, modified heat pump, boiler, and chiller (NTD).

4.9.2 Calculation of Installation Cost

Not only energy cost, but installation cost also holds an important part in calculating life cycle cost. In calculating the installation cost, heat and cold energy, storage size, boiler's capacity, water pump and heat exchange will be taken into account. In this research, the reference of the average setup cost for the SEMD is based on manufacturers in Taiwan which is shown in table 4.10. The calculation of device cost can be shown as follow [11, 30, 31]:

$$E_S = HPC \times 4500 + Mt \times 10 + Bo \times 500 + n \times 1531 + h \times 45490 \tag{4.37}$$

E_S shows SEMD setup cost (NTD); *HPC* refers to modified heat pump capacity which is set to 20 kW; *Mt* is water storage size (L); *Bo* is auxiliary heating system capacity (kW); *n* is number of water pumps; *h* is number of heat exchangers.

Table 4.1 Taipower Company Electricity Cost [29]

Categories			Summer Period (June 1st until September 30th)	Non-summer Period
Week	Period	Time		
Monday to Friday	Peak-on	07.30-22:30	3.22	3.13
	Peak-off	22:30-07:30	1.52	1.42
Saturday	Peak-on	07:30-22:30	2.26	2.16
	Peak-off	22:30-07:30	1.52	1.42
Sunday	All Day		1.52	1.42

Unit: Electricity Cost (NTD/kWh)

Table 4.2 SEMD System Parameter Setting

Parameter	Specification
Storage Capacity	1000 L
Boiler Switch-on Temperature	Below 50℃
Hot Water Storage Temperature Range	50~55℃
Cold Water Storage Temperature Range	5~7℃
Outside Air Temperature	26℃
Initial Hot Water Storage Temperature	55℃
Initial Cold Water Storage Temperature	5℃
Heat Exchanger Capacity	0.5 hp
Water Pump Capacity	0.5 hp
Specific Heat for Water	4.186 kJ/(kg•℃)
Peak-on Electricity Cost	2.74 NTD/kWh
Peak-off Electricity Cost	1.52 NTD/kWh
Peak-on Time Period	07:30-22:30
Peak-off Time Period	22:30-07:30
Feed Water Temperature	20℃
Feed Water Flow Rate	0.15 L/s
SEMD Switched On-Off Time Interval	Every 6 minutes
Hot Water Load Demand Temperature	50℃
Cold Water Load Demand Temperature	6℃
SEMD Life	5 Years

Table 4.3 Hot Water System Load for Open Loop

Time Interval	Load	Time Interval	Load
00:30-01:30	0.000	12:30-13:30	0.060
01:30-02:30	0.000	13:30-14:30	0.060
02:30-03:30	0.000	14:30-15:30	0.000
03:30-04:30	0.000	15:30-16:30	0.000
04:30-05:30	0.000	16:30-17:30	0.000
05:30-06:30	0.000	17:30-18:30	0.000
06:30-07:30	0.000	18:30-19:30	0.000
07:30-08:30	0.095	19:30-20:30	0.000
08:30-09:30	0.097	20:30-21:30	0.085
09:30-10:30	0.000	21:30-22:30	0.083
10:30-11:30	0.000	22:30-23:30	0.000
11:30-12:30	0.000	23:30-00:30	0.000

Unit: Load (L/s)

Table 4.4 Hot Water System Load for Closed Loop

Time Interval	Load	Time Interval	Load
00:30-01:30	0.012	12:30-13:30	0.025
01:30-02:30	0.012	13:30-14:30	0.023
02:30-03:30	0.012	14:30-15:30	0.081
03:30-04:30	0.012	15:30-16:30	0.000
04:30-05:30	0.012	16:30-17:30	0.012
05:30-06:30	0.035	17:30-18:30	0.000
06:30-07:30	0.035	18:30-19:30	0.037
07:30-08:30	0.000	19:30-20:30	0.012
08:30-09:30	0.000	20:30-21:30	0.000
09:30-10:30	0.000	21:30-22:30	0.000
10:30-11:30	0.000	22:30-23:30	0.083
11:30-12:30	0.012	23:30-00:30	0.035

Unit: Load (L/s)

Table 4.5 Cold Water System Load

Time Interval	Load	Time Interval	Load
00:30-01:30	0.016	12:30-13:30	0.072
01:30-02:30	0.016	13:30-14:30	0.072
02:30-03:30	0.016	14:30-15:30	0.008
03:30-04:30	0.016	15:30-16:30	0.008
04:30-05:30	0.016	16:30-17:30	0.016
05:30-06:30	0.006	17:30-18:30	0.016
06:30-07:30	0.006	18:30-19:30	0.016
07:30-08:30	0.092	19:30-20:30	0.016
08:30-09:30	0.092	20:30-21:30	0.092
09:30-10:30	0.008	21:30-22:30	0.082
10:30-11:30	0.002	22:30-23:30	0.018
11:30-12:30	0.002	23:30-00:30	0.019

Unit: Load (L/s)

Table 4.6 Particle Swarm Optimization (PSO) Parameter Setting

Parameter	Specification
Number of Particles	10
Number of Iterations	300
Weighting Factor	0.9 to 1.2
Learning Factor	2
Velocity Boundary	-4 to 4

Table 4.7 Setup Cost of SEMD System [11, 30, 31]

Component	Device Cost Rate
Modified Heat Pump	4500 NTD/kW
Water Storage	10 NTD/L
Boiler	500 NTD/kW
Water Pump	1531 NTD/Unit
Heat Exchanger	45490 NTD/Unit

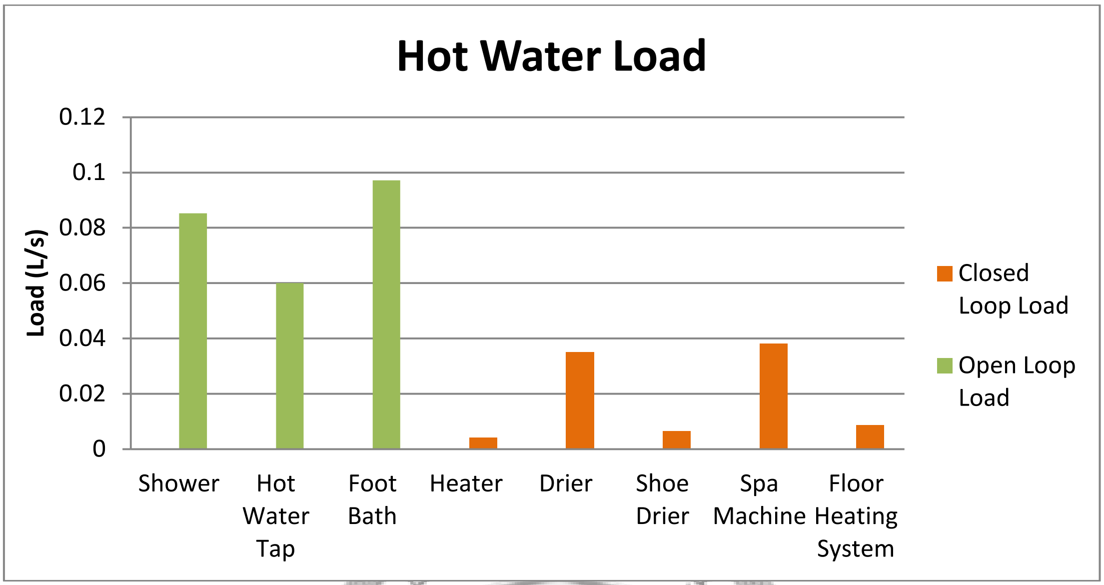


Figure 4.4 Hot Water Load

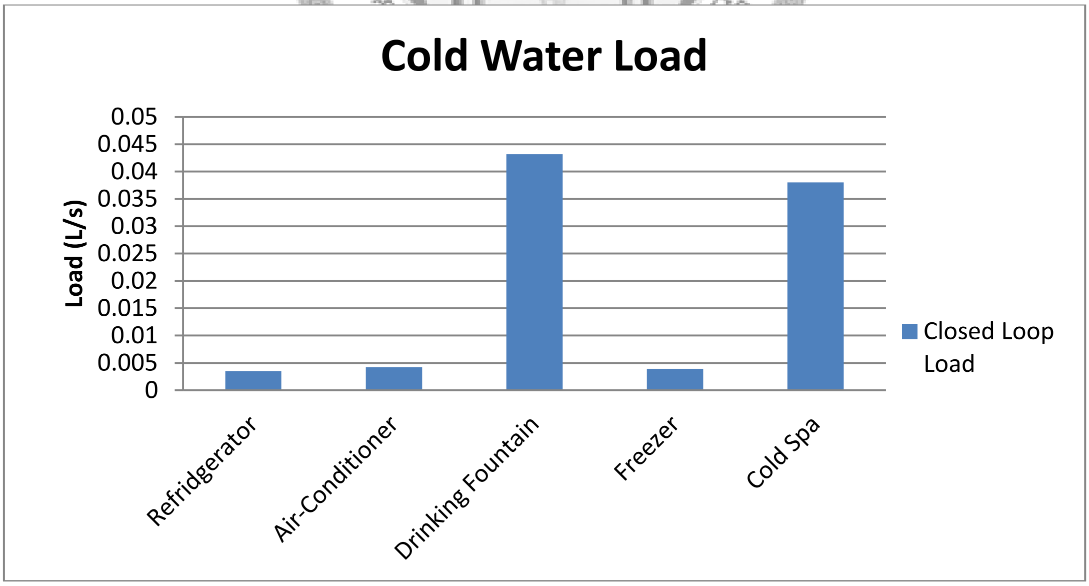


Figure 4.5 Cold Water Load

Chapter 5 Result and Discussion

The main focus of this research is to approach minimum life cycle cost of the SEMD system. Therefore, optimization in either water storage or system's capacity is approached. Meanwhile, in energy management's point of view, traditional control strategy has been applied to simulate the energy consumption in a day. Furthermore, to improve energy management, PSO optimization method is implemented to gain the most decent control strategy. Nevertheless, to compare the performance of the SEMD with traditional system, life cycle cost for traditional system will also be calculated. Moreover, the results are presented as follows:

5.1 Case Study 1

To optimize the design of the system, there are many parts which can be considered. The capacity selection of water pump, water storage, boiler, chiller and compressor is very important instead of optimizing the product design. Due to compressor and water storage hold an important part to whole system. Thus, the analysis in this case study focuses on design of the system which is concentrating on optimizing water storage and compressor's heating or cooling capacity. Due to the design optimization has a strong relation to load; the appropriate selection of capacity should be made. However, to simplify the calculation, hot and cold water storage remains the same. By using trial and error method, the comparison of system and water storage capacity can be shown in figure 5.1 to 5.8.

However, to compare design of the SEMD with traditional system, the design of traditional system under the same load and water storage have been simulated. Despite the chiller has standard capacity, in traditional system, the chiller's cooling capacity has been set to 7 kW. Meanwhile, the boiler capacity is simulated in this case study under the same capacity of water storage as calculated in the SEMD above and the result is illustrated in figure 5.9.

To sum up, after comparing life cycle cost under simulation of various water storage and system capacity, it is found that the most decent design of water storage and system capacity for the SEMD is 1000 L and 10 kW respectively. On the other hand, the most decent design of boiler capacity under 7 kW and 1000 L of chiller and water storage capacity respectively is 9 kW.

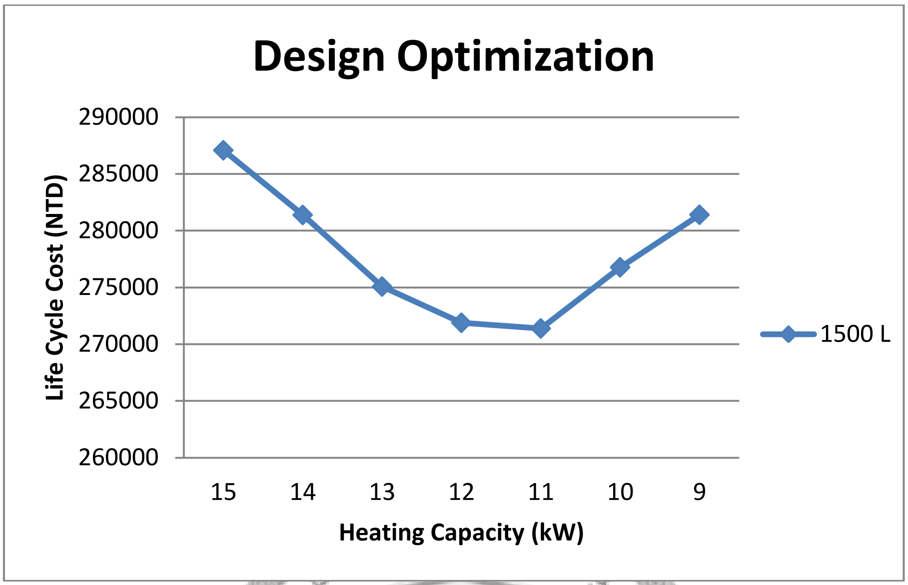


Figure 5.1 Design Optimization of the SEMD under 1500 L

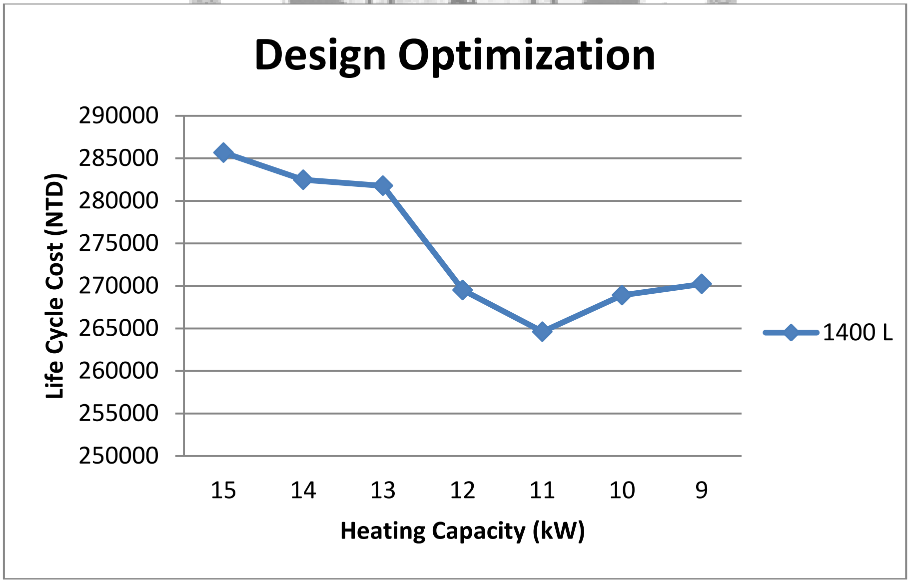


Figure 5.2 Design Optimization of the SEMD under 1400 L

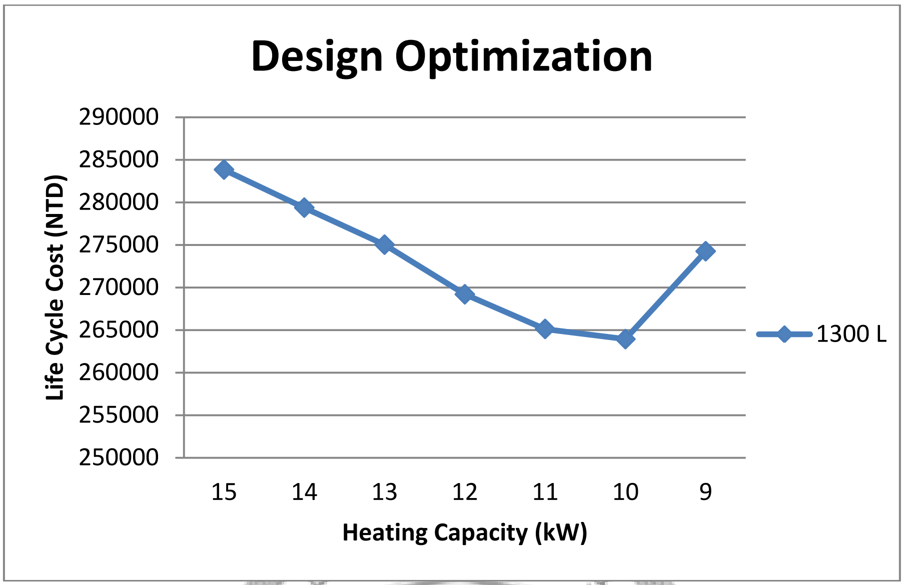


Figure 5.3 Design Optimization of the SEMD under 1300 L

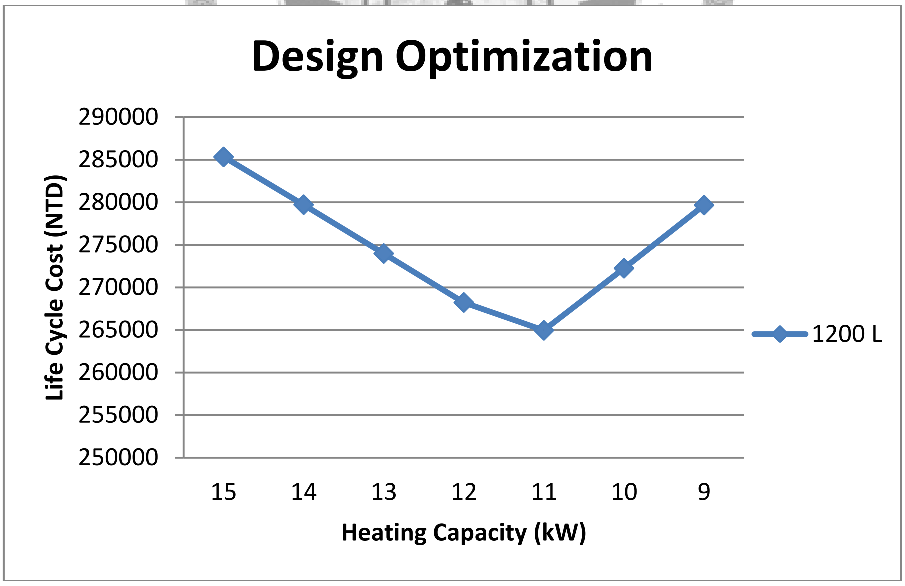


Figure 5.4 Design Optimization of the SEMD under 1200 L

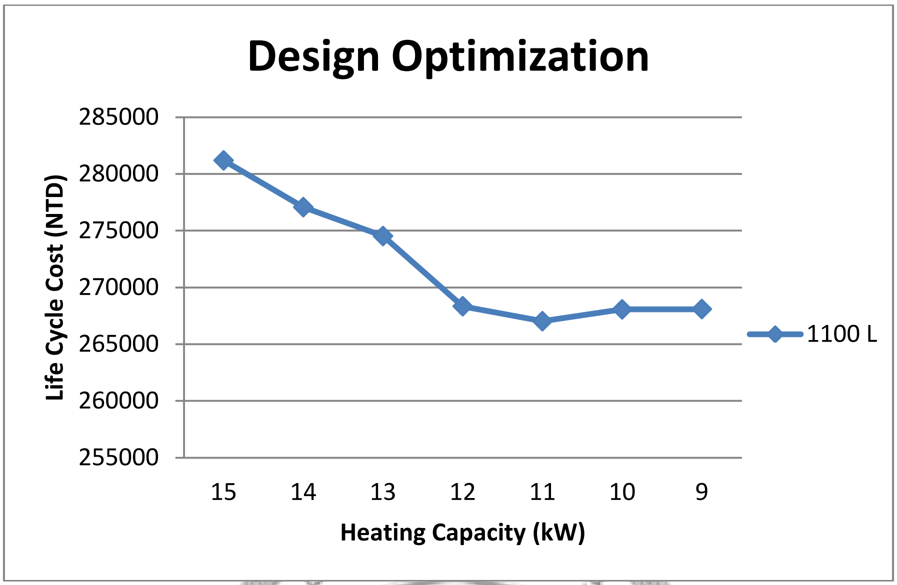


Figure 5.5 Design Optimization of the SEMD under 1100 L

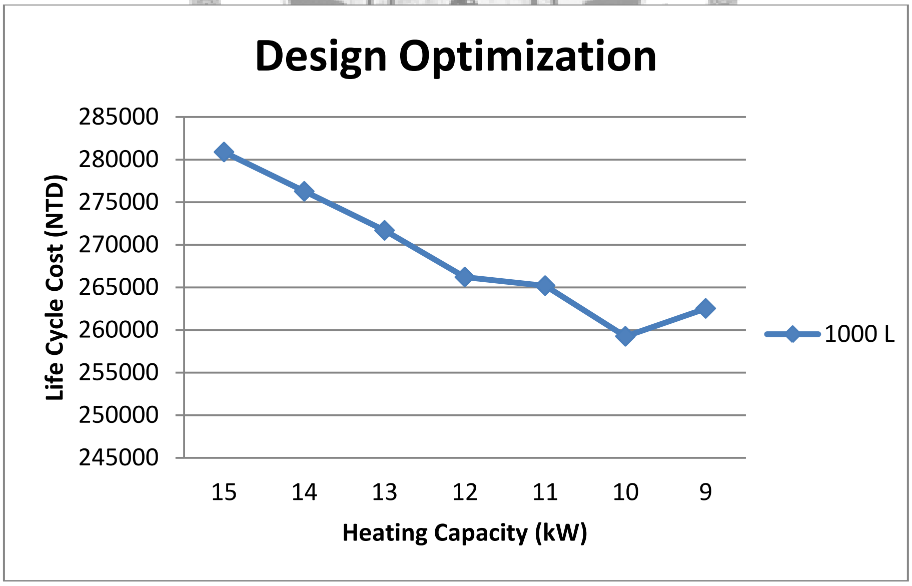


Figure 5.6 Design Optimization of the SEMD under 1000 L

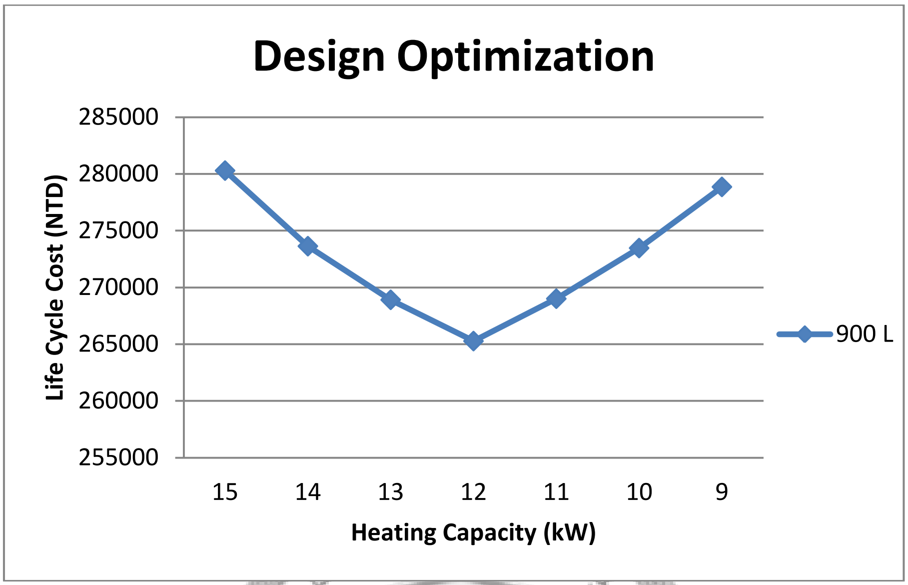


Figure 5.7 Design Optimization of the SEMD under 900 L

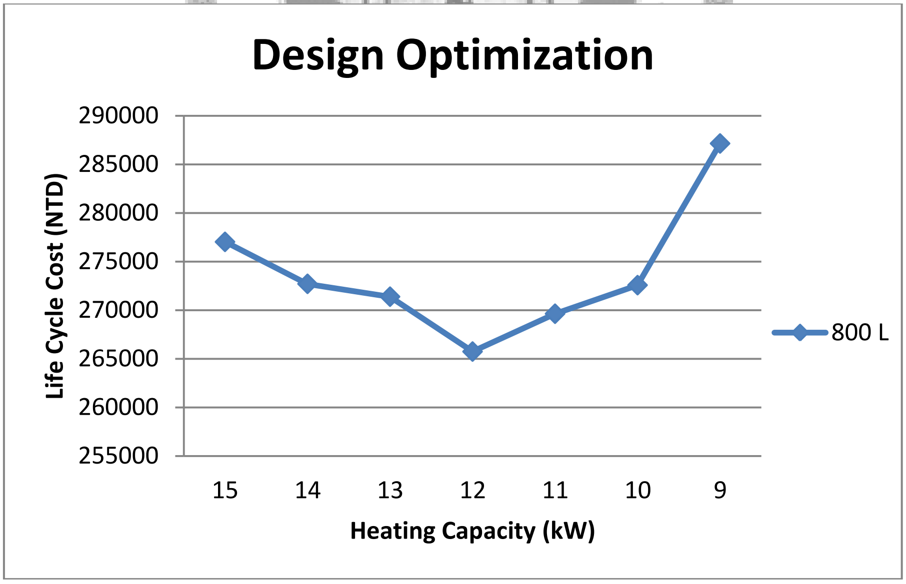


Figure 5.8 Design Optimization of the SEMD under 800 L

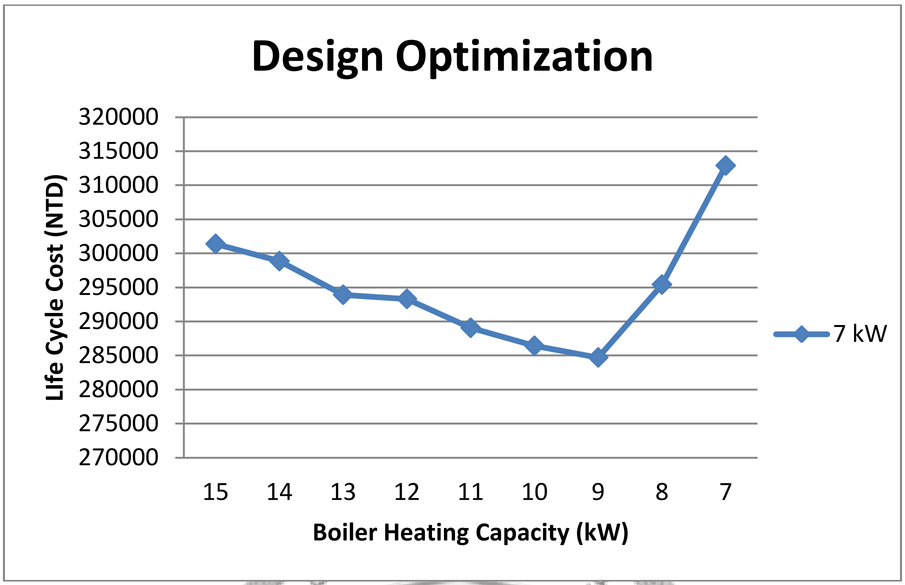


Figure 5.9 Design Optimization of Traditional System under 1000 L and 7 kW

5.2 Case Study 2

In previous case study, the design optimization has been simulated. Furthermore, the analysis in this case study focuses on simulating control strategy to manage energy consumption. Through traditional control method, this case study is simulating system operation in a day based on the result mentioned in case study 1. The objective is to calculate the life cycle cost of the SEMD for five years. In traditional control strategy, the compressor operation is based on the range of default water temperature. When water temperature reaches maximum default temperature in hot water storage, the compressor will be terminated, and vice versa. On the other hand, in cold water storage, compressor will be terminated when water temperature once reaches minimum default temperature, and vice versa. In this case, cold water system is taken as the first priority of compressor operation, since the load in cold water system is smaller than hot water system. The life cycle cost calculation can be illustrated in table 5.1. Moreover the simulation of compressor on-off status, hot and cold storage temperature are illustrated in figure 5.10 to 5.12 respectively.

However, to compare life cycle cost of the SEMD with traditional system, we also analyze traditional system under the same setting condition. The result is illustrated in table 5.2. Furthermore, the simulation of compressor on-off status, hot and cold storage temperature are illustrated in figure 5.13 to 5.15 respectively.

In brief, from economic point of view, life cycle cost of the SEMD and traditional system for five years are 259237 NTD and 284708 NTD respectively. On the other hand, total energy consumption of the SEMD and traditional system per day are 80994.97 kJ and 43985.37 kJ respectively. In short, the SEMD can save 8.95% of life cycle cost. Meanwhile, the SEMD consumes 45.69% more energy than traditional system since heating and cooling system of the SEMD system is not independent. The unbalanced load between hot and cold water load causes the cold energy provided by the SEMD is not intensively consumed and some of them are wasted. In a word, the SEMD is more suitable to use under a balanced load. The bigger the cold water load, the smaller energy wasted.

Table 5.1 Traditional Control Strategy Analytical Result for the SEMD

Properties	Unit	Specification
Auxiliary Boiler Energy Consumption	kJ/day	9346.50
Water Pump Energy Consumption	kJ/day	19271.25
Compressor Energy Consumption	kJ/day	47337.22
Heat Exchanger Energy Consumption	kJ/day	5040.00
Total Energy Consumption	kJ/day	80994.97
Auxiliary Boiler Electricity Cost	NTD/day	5.48
Water Pump Electricity Cost	NTD/day	42.80
Compressor Electricity Cost	NTD/day	30.60
Heat Exchanger Electricity Cost	NTD/day	3.25
Total Energy Cost	NTD/day	82.13
Installation Cost	NTD	109355.23
Life Cycle Cost	NTD	259237.00

Table 5.2 Traditional Control Strategy Analytical Result for Traditional System

Properties	Unit	Specification
Auxiliary Boiler Energy Consumption	kJ/day	836.15
Water Pump Energy Consumption	kJ/day	18596.25
Compressor Energy Consumption	kJ/day	24552.98
Total Energy Consumption	kJ/day	43985.37
Auxiliary Boiler Electricity Cost	NTD/day	0.61
Water Pump Electricity Cost	NTD/day	39.31
Compressor Electricity Cost	NTD/day	17.81
Total Energy Cost	NTD/day	57.73
Installation Cost	NTD	179350.75
Life Cycle Cost	NTD	284708.00

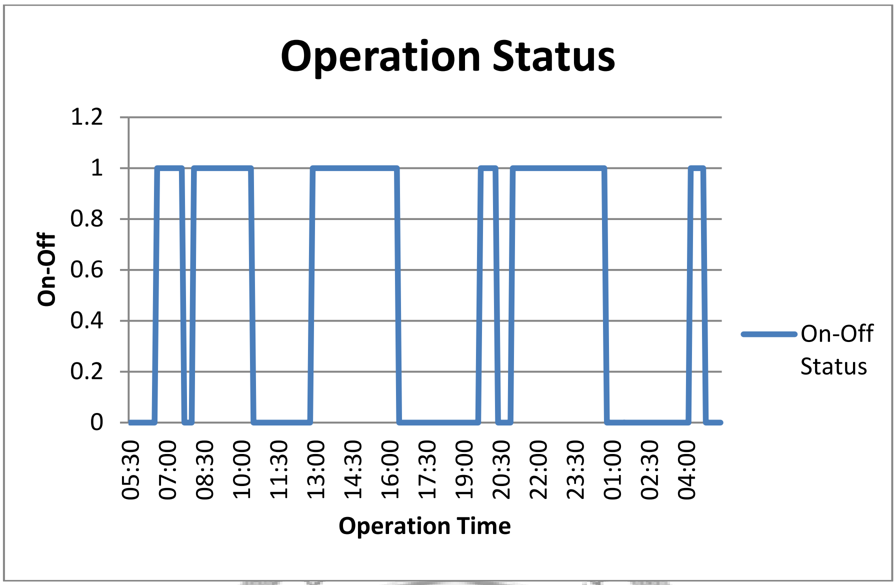


Figure 5.10 Operation Status of the SEMD

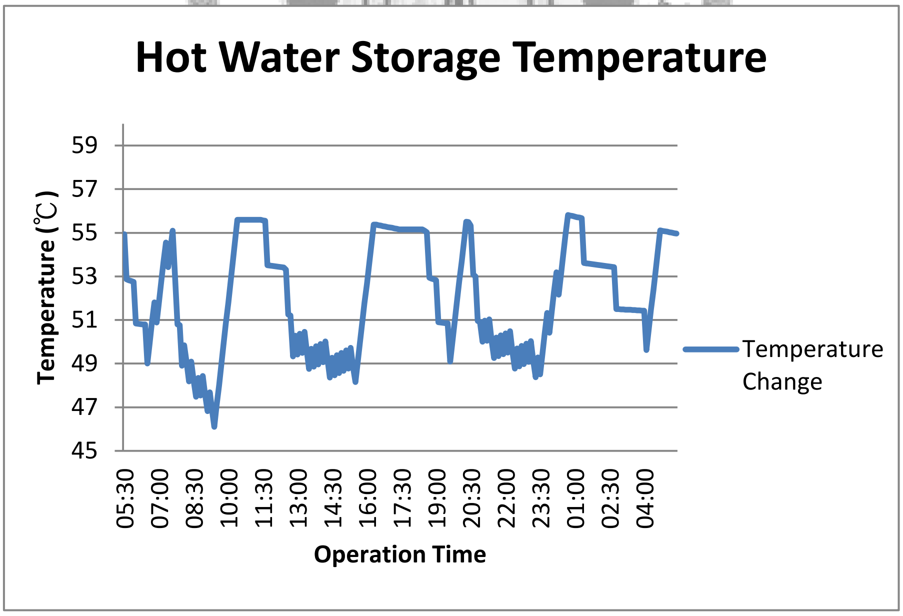


Figure 5.11 Hot Water Temperature Simulation of the SEMD

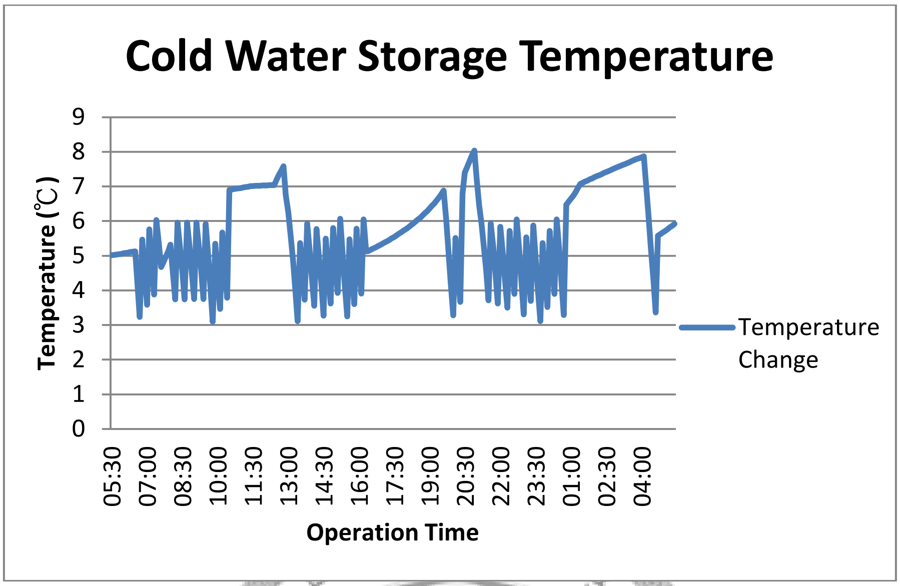


Figure 5.12 Cold Water Temperature Simulation of the SEMD

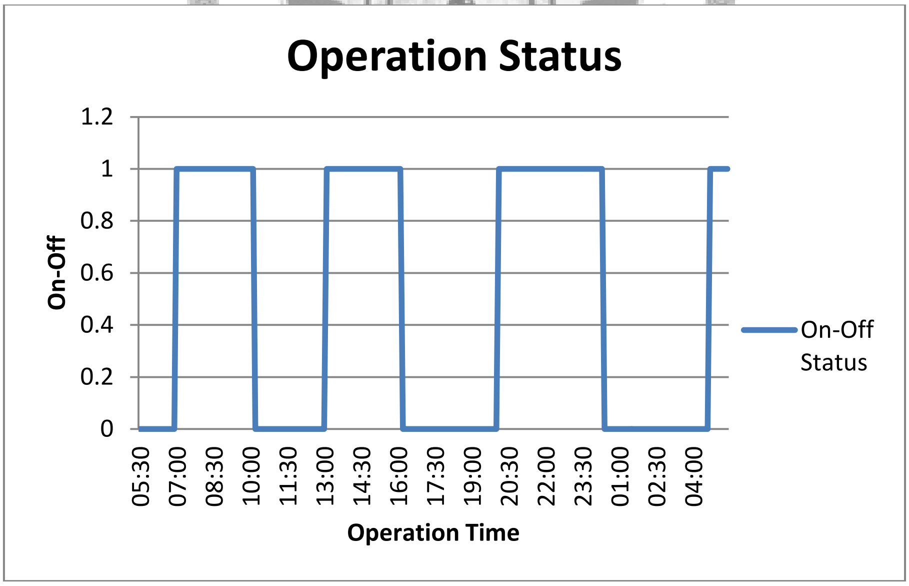


Figure 5.13 Operation Status of Traditional System

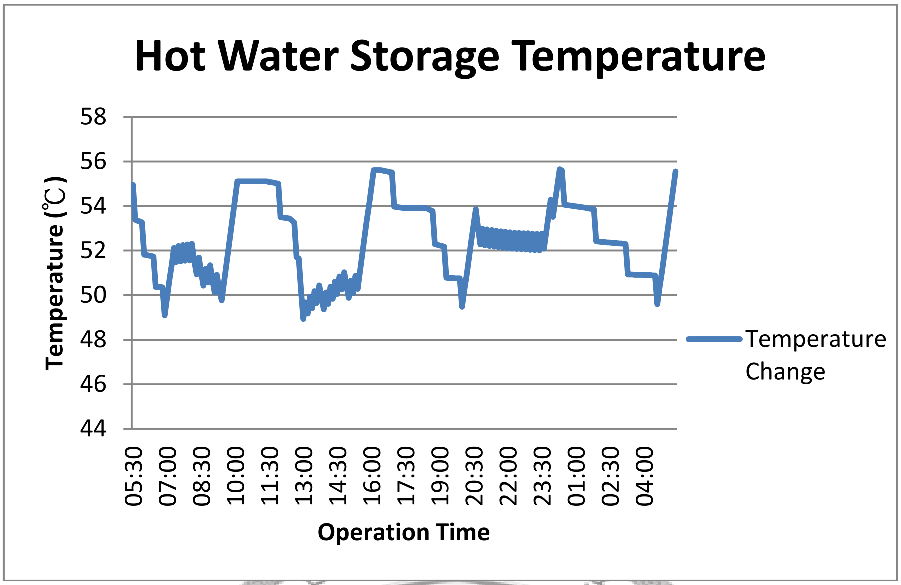


Figure 5.14 Hot Water Temperature Simulation of Traditional System

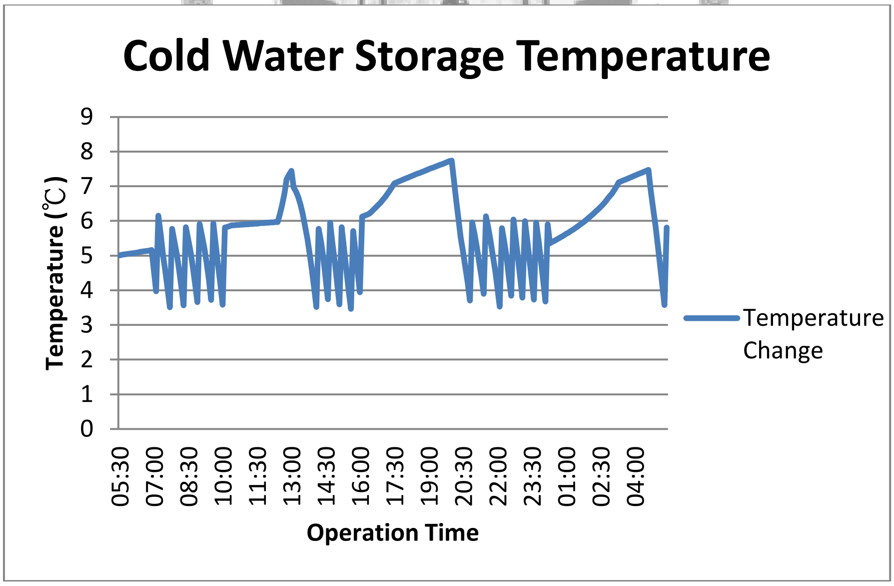


Figure 5.15 Cold Water Temperature Simulation of Traditional System

5.3 Case Study 3

However, to save more energy cost and consumption of the SEMD, this case study concentrates on managing the energy usage by improving the control strategy. PSO optimization method is integrated into the simulation with 6 minutes on-off time interval to find the most decent control strategy in order to approach minimum life cycle cost, in which the result is shown in table 5.3. Furthermore, to improve the accuracy of PSO, the simulation has been executed 50 times, in which the standard deviation and mean value can be shown in table 5.4. Nevertheless, the simulation of convergence status, compressor on-off status, hot and cold storage temperature are illustrated in figure 5.16 to 5.19 respectively.

From the energy management and control strategy views, it is found that the less compressor on-off time interval, the better accuracy can be obtained. However, to extend the system's lifespan, it is imperative that reliability and maintainability of the components be considered. Technically, to start and stop compressor frequently will bring in rush current impact and huge energy expenditure. Hence, to avoid frequent rush current impact to compressor and extends compressor's lifespan, the optimized control strategy with 15 minutes on-off time interval has been simulated. The result can be illustrated in table 5.5. In addition, to improve the accuracy of PSO, the simulation has been executed 50 times, in which the standard deviation and mean value can be shown in table 5.6. Nonetheless, the simulation of convergence status, compressor on-off status, hot and cold storage temperature are illustrated in figure 5.20 to 5.23 respectively.

In a word, life cycle costs calculation of the SEMD by using either traditional or PSO control strategy are 259237 NTD and 184521 NTD respectively. Moreover, the energy consumption of the SEMD simulated by both traditional and PSO control strategy are 80994.97 kJ and 22854.08 kJ respectively. Meanwhile, by using PSO as optimization method, the SEMD can save 28.82% of life cycle cost and 71.78% of energy consumption. However, due to technical consideration, optimized control strategy for the SEMD with 15 minute on-off time interval has also been proposed. The result is found that the life cycle cost approach 194859 NTD with 25809.89 kJ of energy consumption. Nevertheless, from the result mentioned above, optimized control strategy for the SEMD with 15 minute on-off time interval can save 24.83% and 68.13% of energy consumption in comparison with traditional system.

Table 5.3 PSO Control Strategy Analytical Result under 6 Minute Time Interval

Properties	Unit	Specification
Auxiliary Boiler Energy Consumption	kJ/day	0.00
Water Pump Energy Consumption	kJ/day	16621.88
Compressor Energy Consumption	kJ/day	5602.20
Heat Exchanger Energy Consumption	kJ/day	630.00
Total Energy Consumption	kJ/day	22854.08
Auxiliary Boiler Electricity Cost	NTD/day	0.00
Water Pump Electricity Cost	NTD/day	31.66
Compressor Electricity Cost	NTD/day	3.51
Heat Exchanger Electricity Cost	NTD/day	0.35
Total Energy Cost	NTD/day	35.51
Installation Cost	NTD	119715.25
Life Cycle Cost	NTD	184521.00

Table 5.4 PSO Statistical Analysis under 6 Minute Time Interval

Maximum Value (NTD)	Minimum Value (NTD)	Standard Deviation	Mean Value (NTD)
184756.90	184521.00	87.48	184752.00

Table 5.5 PSO Control Strategy Analytical Result under 15 Minute Time Interval

Properties	Unit	Specification
Auxiliary Boiler Energy Consumption	kJ/day	0.00
Water Pump Energy Consumption	kJ/day	17752.50
Compressor Energy Consumption	kJ/day	7269.89
Heat Exchanger Energy Consumption	kJ/day	787.50
Total Energy Consumption	kJ/day	25809.89
Auxiliary Boiler Electricity Cost	NTD/day	0.00
Water Pump Electricity Cost	NTD/day	37.08
Compressor Electricity Cost	NTD/day	3.66
Heat Exchanger Electricity Cost	NTD/day	0.43
Total Energy Cost	NTD/day	41.18
Installation Cost	NTD	120457.83
Life Cycle Cost	NTD	194859.00

Table 5.6 PSO Statistical Analysis under 15 Minute Time Interval

Maximum Value (NTD)	Minimum Value (NTD)	Standard Deviation	Mean Value (NTD)
195511.70	194859.00	147.03	194867.60

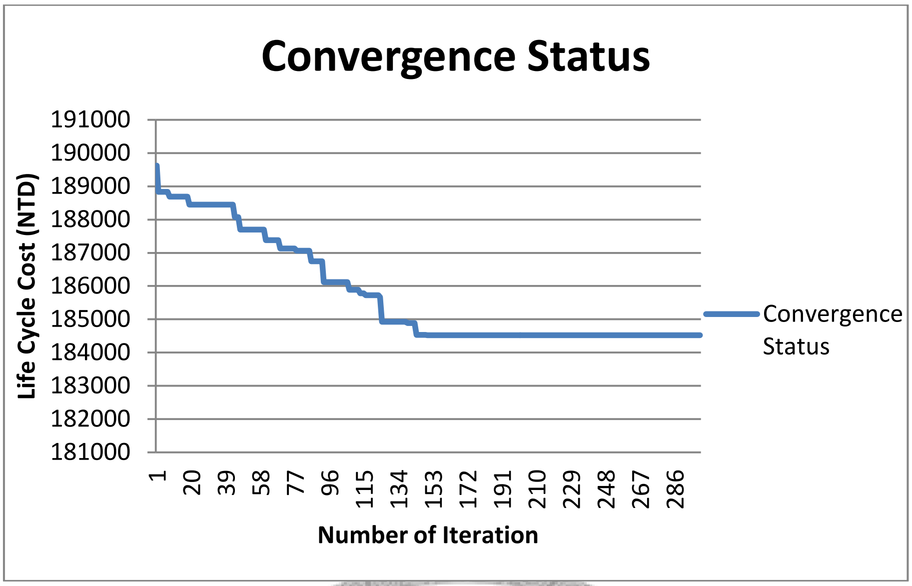


Figure 5.16 Convergence Status under 6 Minute Time Interval

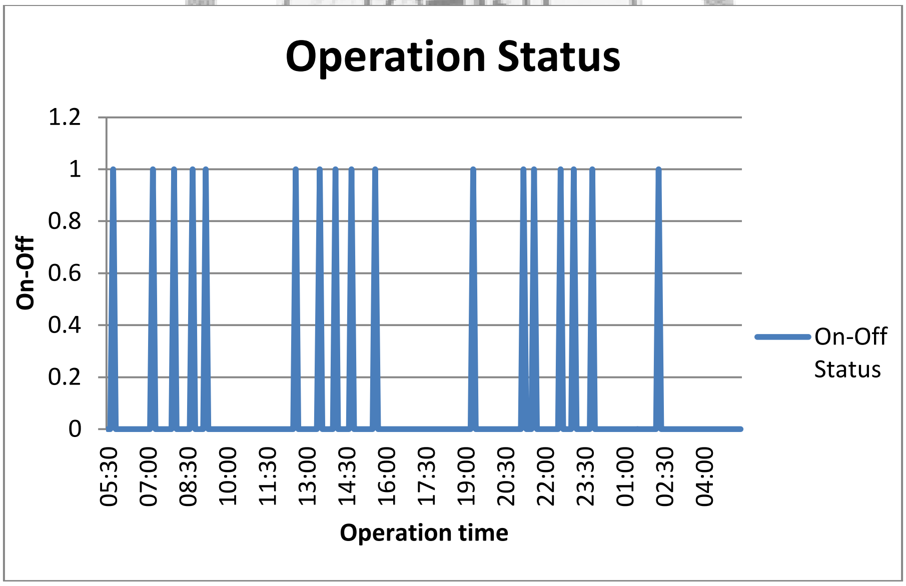


Figure 5.17 Optimized Operation Status under 6 Minute Time Interval

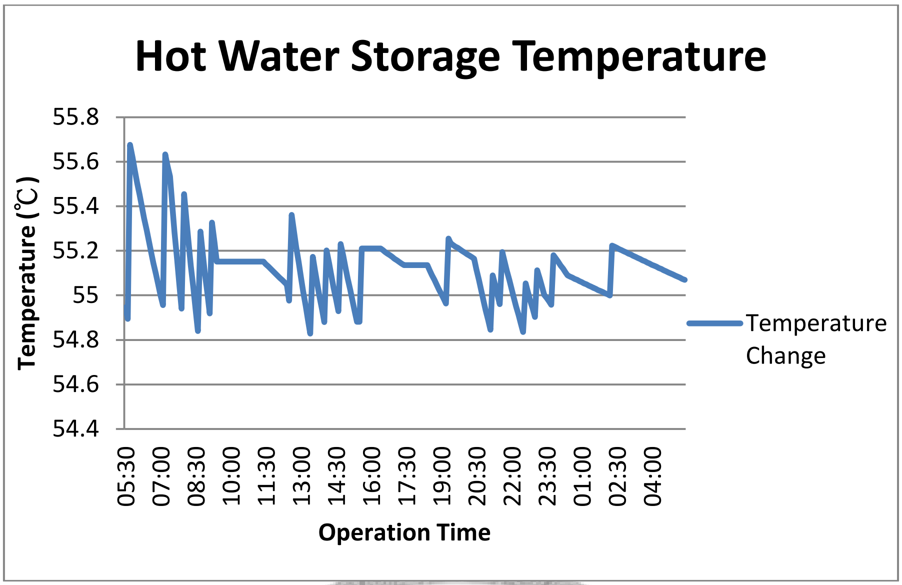


Figure 5.18 Optimized Hot Water Temperature under 6 Minute Time Interval

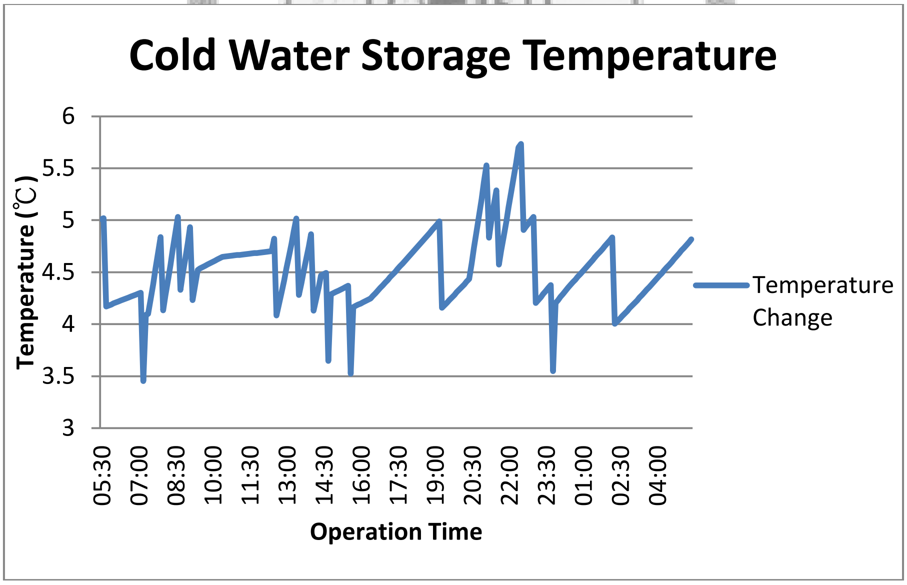


Figure 5.19 Optimized Cold Water Temperature under 6 Minute Time Interval

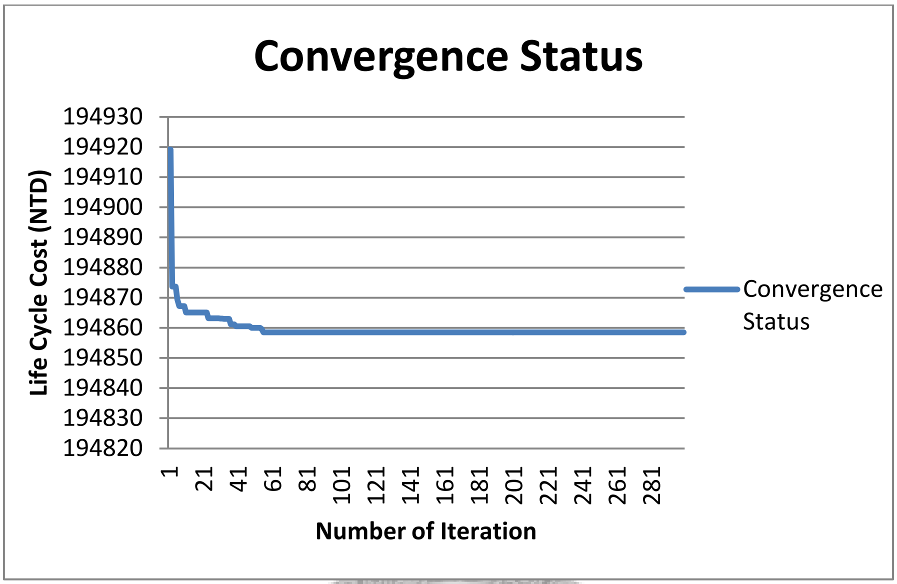


Figure 5.20 Convergence Status under 15 Minute Time Interval

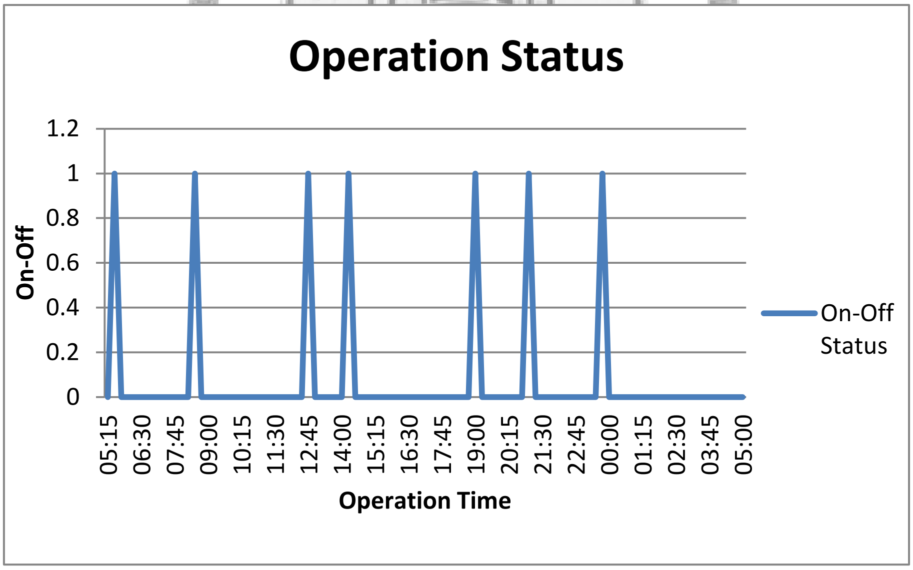


Figure 5.21 Optimized Operation Status under 15 Minute Time Interval

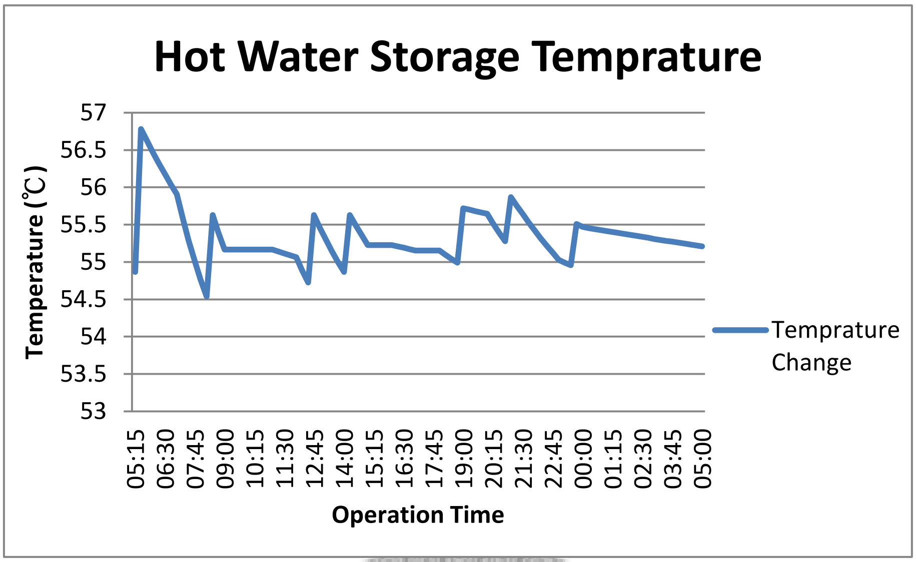


Figure 5.22 Optimized Hot Water Temperature under 15 Minute Time Interval

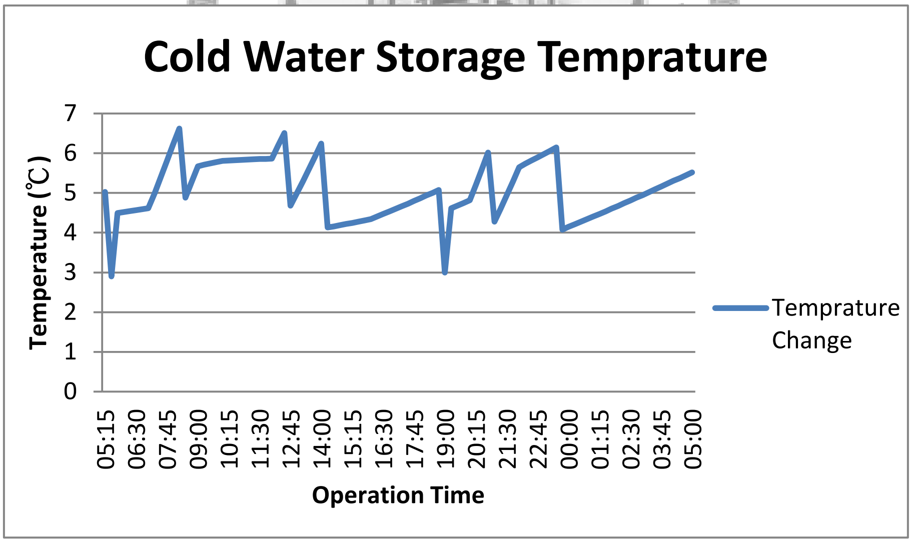


Figure 5.23 Optimized Cold Water Temperature under 15 Minute Time Interval

Chapter 6 Conclusion

6.1 Conclusion

In this research, we integrate Particle Swarm Optimization method to optimize control strategy in order to minimize life cycle cost. However, to compare the result, traditional control strategy is also analyzed in either traditional system or the SEMD system. This research is divided into three case studies which include design and control strategy optimization. From the design optimization analysis, it is found that the decent design of water storage and system capacity of SEMD is 1000 L and 10 kW respectively. To compare the SEMD with the traditional system, the chiller and water storage capacity is set to 7 kW and 1000 L. After preceding the analysis, it is found that the decent design of boiler capacity is 9 kW. However, by applying traditional control strategy, the result indicates that the SEMD could reduce 8.95% of life cycle cost in comparison with traditional system. Conversely, the SEMD consumes 45.69% more energy than traditional system which is caused by unbalanced load between hot and cold water load. Moreover, the SEMD is more appropriate to use under a balanced load.

Despite the result mentioned above, we made another improvement in optimizing control strategy to reduce more energy and cost. By implementing PSO method, we found the most decent control strategy for the SEMD operation. Hence, the result indicates that the SEMD could reduce 28.82% of life cycle cost and 71.78% of energy consumption in correspondence with traditional control strategy respectively. However, due to technical consideration, optimized control strategy for the SEMD with 15 minute on-off time interval has also been proposed, in which the result indicates that this control strategy can save 24.83% and 68.13% of energy consumption in comparison with traditional system.

To sum up, from the result shown above, we can conclude that the performance of the SEMD can be improved not only by optimizing the product design but also its control strategy. Nevertheless, in terms of Taiwan government policy about energy saving and carbon reduction, the design of the SEMD has successfully decreased household’s energy consumption in Taiwan. Furthermore, the SEMD has shown a remarkable performance in reducing electricity cost and energy consumption in comparison with traditional system.

6.2 Recommendations

The present article proposed the ideas of thermodynamic analysis for the SEMD. Basically, the research already covers major part of the contents in the study of heat pump, but several goals still need to be achieved. Firstly, this research focuses on numerical analysis based on hypothetical data assumption. An experimental data is needed to verify the result of this research. Secondly, the main electricity source that supports the SEMD operation is provided by Taiwan Power Company (Taipower). However, we can replace the main electricity source with renewable energy in order to save energy and reduce carbon emission. Many ideas about combining renewable energy source with household appliances in conjunction with the SEMD are still under investigation, some of them can be shown in appendix I. Thirdly, in this research, the time interval of the SEMD operation remains constant. To make it more efficient, we can optimize operation time of the system operation. Fourthly, life cycle cost which is considered in this analysis includes installation and energy cost. To increase the accuracy of cost calculation, we can consider other factors, for instance, maintenance cost, transportation cost, disassembly cost, etc.

References

[1] European Heat Pump Association.
http://www.ehpa.org/fileadmin/red/downloads/EHPA_action_plan.pdf

[2] Zogg M., "History of Heat Pumps", Final Report, CH-3414, Swiss Federal Office of Energy Process and Energy Engineering, 2008.

[3] National Science Council.
www.nsc.gov.tw/eng/public/Attachment/951810173271.doc

[4] Zhang J., Wang R.Z., Wu J.Y., "System Optimization and Experimental Research on Air Source Heat Pump Water Heater", Applied Thermal Engineering, Vol. 27, pp. 1029–1035, 2007.

[5] Lee W.S., Kung C.K., "Optimization of Heat Pump System in Indoor Swimming Pool Using Particle Swarm Algorithm", Applied Thermal Engineering, Vol. 28, pp. 1647–1653, 2008.

[6] Wang K., Cao F., Wang S., Xing Z., "Investigation of the Performance of a High-temperature Heat Pump Using Parallel Cycles with Serial Heating on the Water Side", International Journal of Refrigeration, Vol. 33, pp. 1142–1151, 2010.

[7] Brenn J., Soltic P., Bach Ch., "Comparison of Natural Gas Driven Heat Pumps and Electrically Driven Heat Pumps with Conventional Systems for Building Heating Purposes", Energy and Buildings, Vol. 42, pp. 904–908, 2010.

[8] Fardoun F., Hajjar M., Fardoun H., "Heat Pump Designing and Optimization Tool", Advances in Computational Tools for Engineering Application, 2009, ACTEA, '09, International Conference on July 15-17, 2009.

[9] Kim M., Kim M.S., Chung J.D., "Transient Thermal Behavior of a Water Heater

System Driven by a Heat Pump", International Journal of Refrigeration, Vol. 27, pp. 415–21, 2004.

[10] Hsiao M.J., Kuo Y.F., Shen C.C., Cheng C.H., Chen S.L., "Performance Enhancement of a Heat Pump System with Ice Storage Subcooler", International Journal of Refrigeration, Vol. 33, pp. 251–258, 2010.

[11] Chen X.S., "Optimal Control Strategy of Heat Pump Water Heating System Using Particle Swarm Optimization", Master Thesis, 2010.

[12] Rankin R., Rousseau P.G., Eldik M.V., "Demand Side Management for Commercial Buildings Using an Inline Heat Pump Water Heating Methodology", Energy Conversion and Management, Vol. 45, pp. 1553–1563, 2004.

[13] Hepbasli A., Kalinci Y., "A Review of Heat Pump Water Heating Systems", Renewable and Sustainable Energy Reviews, Vol. 13, Iss. 6-7, pp. 1211-1229, 2008.

[14] Xu G., Zhang X., Deng S., "A Simulation Study on the Operating Performance of a Solar–air Source Heat Pump Water Heater", Applied Thermal Engineering, Vol. 26, pp. 1257–1265, 2006.

[15] Li Y.W., Wang R.Z., Wu J.Y., Xu Y.X., "Experimental Performance Analysis and Optimization of a Direct Expansion Solar-assisted Heat Pump Water Heater", Energy, Vol. 32, pp. 1361–1374, 2007.

[16] Huang B.J., Lee J.P., Chyng J.P., "Heat-pipe Enhanced Solar-assisted Heat Pump Water Heater", Solar Energy, Vol. 78, pp. 375–381, 2005.

[17] Barricelli, Nils A., "Esempi Numerici di Processi di Evoluzione", Methodos, pp. 45–68, 1954.

[18] Barricelli, Nils A., "Symbiogenetic Evolution Processes Realized by Artificial Methods", Methodos, pp. 143–182, 1957.

[19] Schwefel, H.-P., “Numerische Optimierung von Computer-Modellen”, PhD Thesis, 1974.

[20] Choi J.W., Lee G., Kim M.S., “Capacity Control of a Heat Pump System Applying a Fuzzy Control Method”, Applied Thermal Engineering, Vol. 30, pp. 1-8, 2011.

[21] Chebouba A., Yalaoui F., Smati A., Amodeo L., Younsi K., Tairi A., ” Optimization of Natural Gas Pipeline Transportation Using Ant Colony Optimization”, Computers and Operations Research, Vol. 36, Iss. 6, pp. 1916-1923, 2009.

[22] Kennedy J., Eberhart R., “Particle Swarm Optimization, Proceedings of the IEEE International Joint Conference on Neural Networks”, Vol. 4, pp. 1942–1948, 1995.

[23] Shi Y., Eberhart R., “A Modified Particle Swarm Optimizer”, Proc. of IEEE International Conference on Evolutionary Computation, Anchorage, pp. 69-73, 1998.

[24] Lee W.S., Chen Y.T., Wu T.H., “Optimization for Ice-storage Air-conditioning System Using Particle Swarm Algorithm”, Applied Energy, Vol. 86, pp. 1589–1595, 2009.

[25] Eberhart R.C., Shi Y., “Particle Swarm Optimization: Developments, Applications and Resources”, Proc. of IEEE International Conference on Evolutionary Computation, vol. 1, pp. 81-86, 2001

[26] Kennedy J., Eberhart R.C., “A Discrete Binary Version of the Particle Swarm Algorithm”, Proc. of the IEEE International Conference on Systems, Man, and Cybernetics, pp. 4104–4108, 1997.

[27] Franken N., Engelbrecht A.P., “Investigating Binary PSO Parameter Influence on

the Knights Cover Problem", IEEE Congress on Evolutionary Computation, Vol. 1, pp. 282- 289, 2005.

[28] Taiwan Weather Temperature.
http://www.world-temperature.com/country_weather/taiwan/775

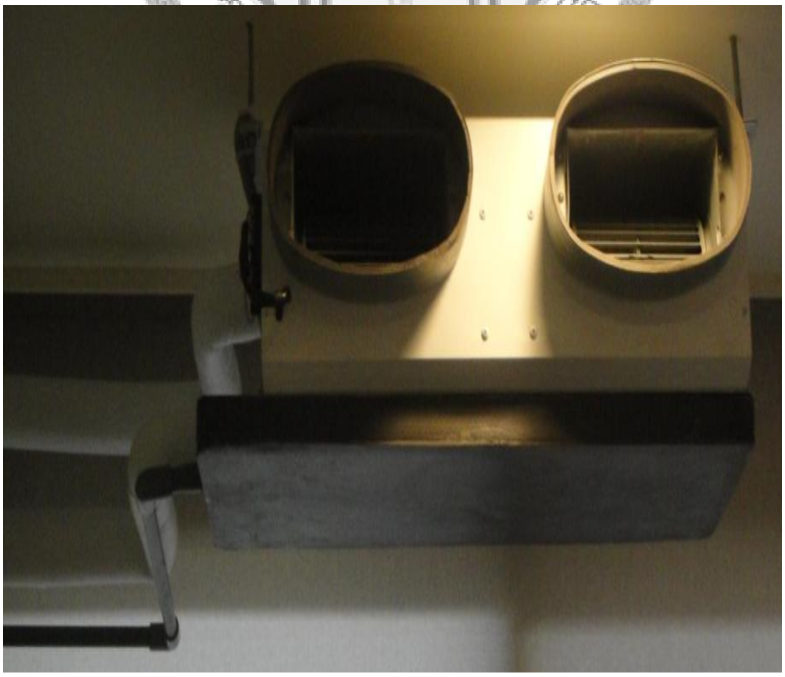
[29] Taiwan Power Company.
http://www.taipower.com.tw/TaipowerWeb/upload/files/11/main_3_6_3.pdf

[30] Hai Tai Pump Industry Co., Ltd.
http://www.haitaipump.com/proshow.asp?pid=63

[31] 杭州風行機電設備有限公司
http://www.hbsb-z.com/zt459781/zh-tw/default.html

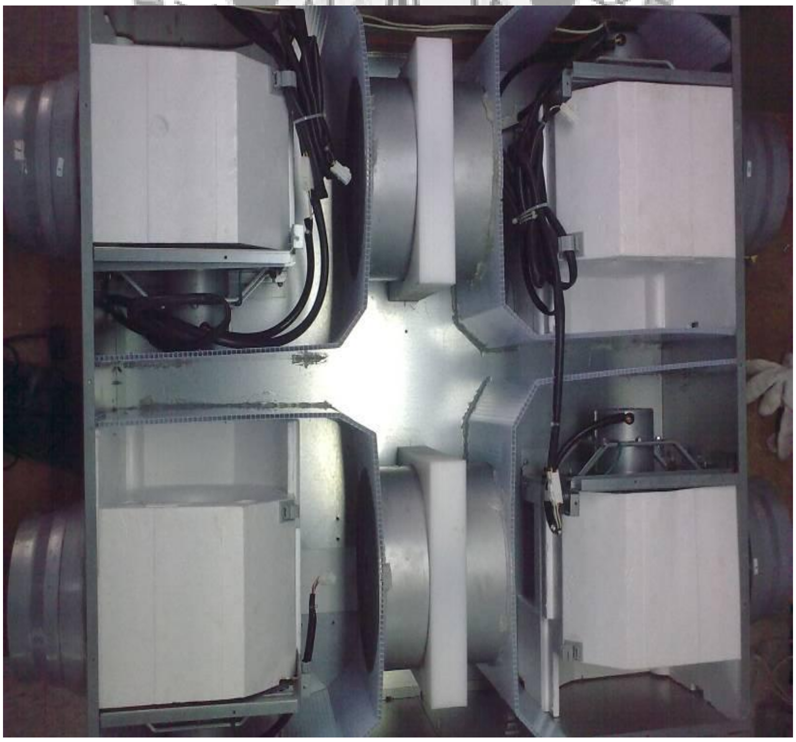
Appendix I

The SEMD System



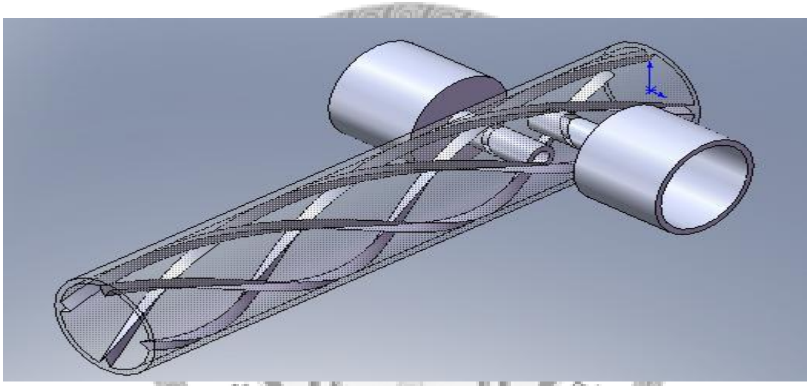
Modified Air-conditioner for the SEMD

Floor Heating System

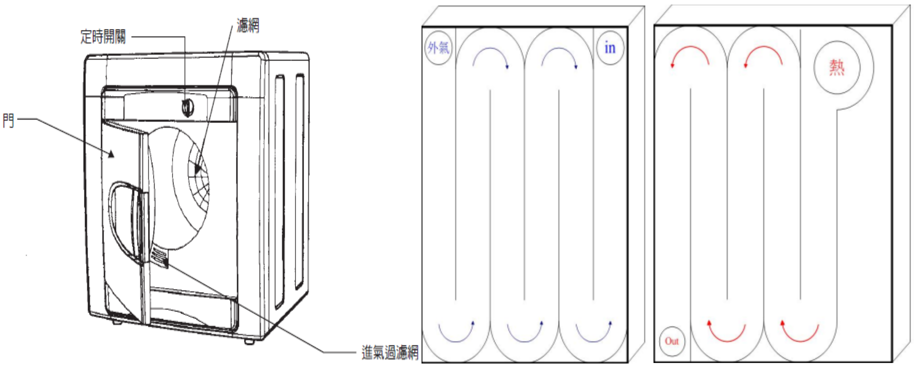


Heat Exchanger for the SEMD

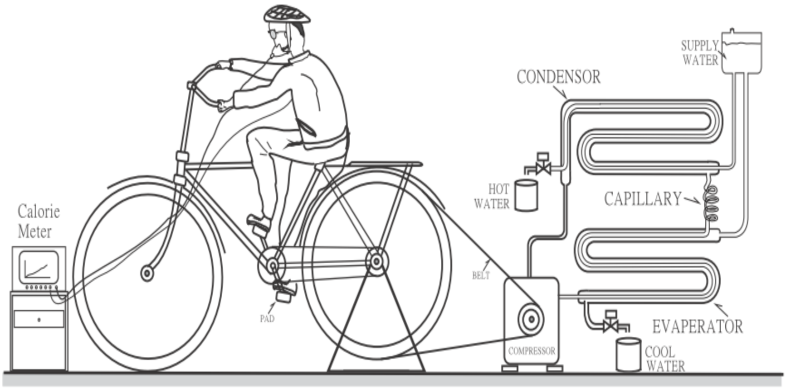
Solar-powered Refrigerator



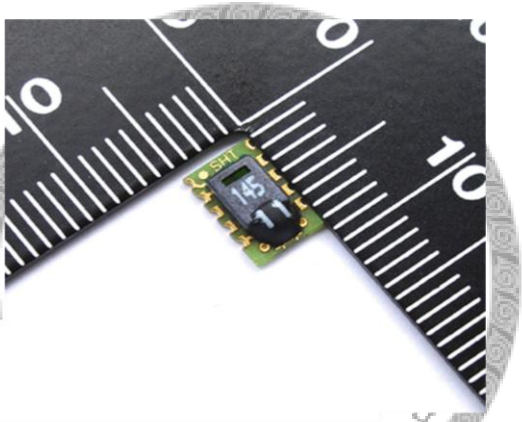
Micro Bubble Shower Head



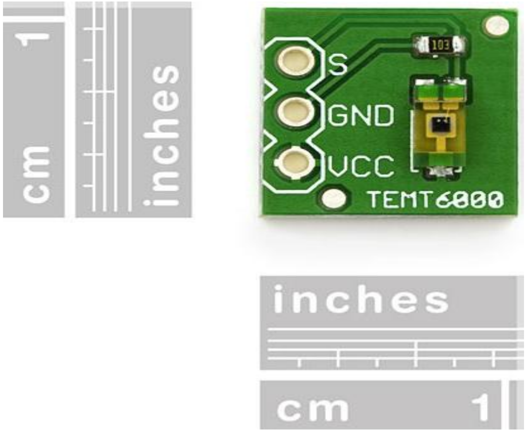
Modified Drier for the SEMD



Pedal-powered Power Generators

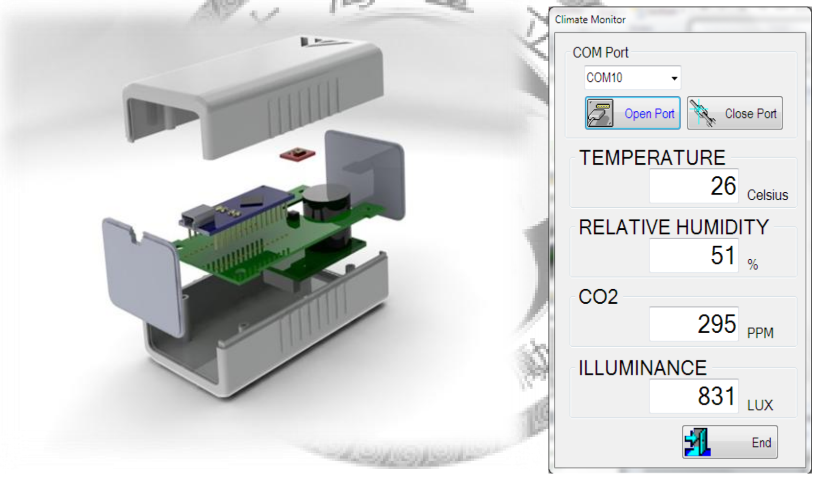


SHT11 RH and Temperature sensor



TEMT6000 Ambient Light Sensor

C20 CO$_2$ Sensor



COM Port
COM10

TEMPERATURE
26 Celsius

RELATIVE HUMIDITY
51 %

CO2
295 PPM

ILLUMINANCE
831 LUX

Taroko Wireless Sensor