CHAPTER III

RESEARCH METHODOLOGY

The Optimal Concept

The performance of YAZAKI chiller: 35kW-Standard Cooling Capacity that was work for solar absorption cooling system in testing building at School of Renewable Energy and Technology, SERT, was known as the Coefficient of Performance (COP) which was the ratio of energy demand and energy supply, is not as good as expected, COP=0.70. The COP not only indicated the performance of chiller in the cooling system, but also indicated the ability of energy balancing. To find the method for increasing the efficiency by mean of optimization was importance and as shown in Figure 16.

First of all, the measurement data had been recorded in every minute during 2006 to 2007 years by VEE Pro-Cooling K641-W6G software. Then the principle equations were used to evaluate the experiment and Least Square Method was used to find out the relationship between X and Y by mean of system's equation and validated by Relative Error obtained being less than 15% (in the worst case) that generating the developed equation. While the optimal equation was appearing when the water flow rate via the main components was adjusted and the optimization equations were writing in form of SIMULINK, MATLAB. The economic equation was purpose to study of how the variation both of the coefficient of performance (COP) was 0.2 - 0.7 and the solar fraction ($SOLF_{the}$) was 0.5 – 1. They come from the technical equation that were generated the optimal output of SLCCA by means of the lowest total cost of a system throughout its life time. In addition, the shorten time for pay back period (PB), and the highest rate of return (IRR), net present value (NPV), computation of B/C for a single investment throughout its life time was appeared when the maximum COP was produced.

1. The Technical Equation

1.1 The Measurement Data

All measurement quantities were converted into electric signals and elaborated through a data acquisition system from the system. These data carried out the real time parameters as shown in Table 2.

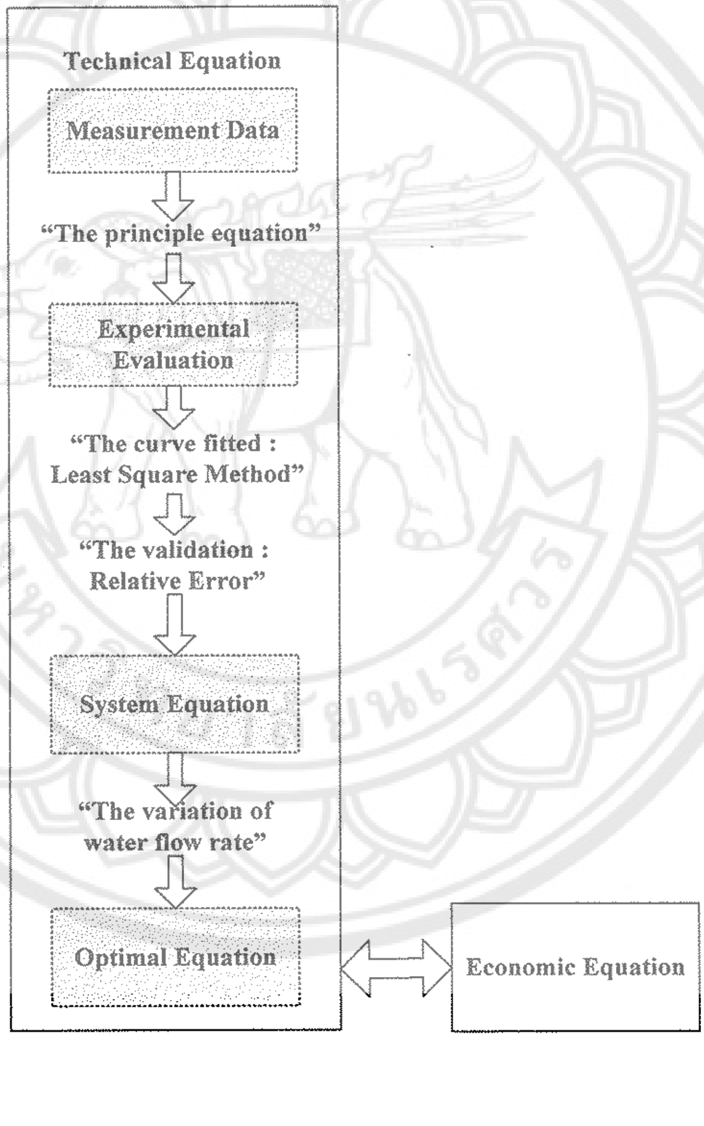

Figure 16 Flow chart of research methodology, optimal concept

Table 2 Parameters acquired by the system in real time

Acquired data	Description
The global and tilted radiation that strike on the horizontal and collector plane ; G and G_β	Pyranometers; Kipp and Zonen model CM 3
The inlet and outlet temperature in main flow circuits ; $T_1 - T_9$	Analogue thermometers; RTD PT100 Sensor
The room temperature ; $RT_1 - RT_7$	Compact Room Air; MincoS448PDYK4K1
The inlet and outlet pressure in main flow circuits ; $P_1 - P_4$	Pressure seneor; Keller Series 21
The water flow rates transducers on the main circuits ; $F_1 - F_4$	Flow meters; Woltman Meter WP- MFD 222

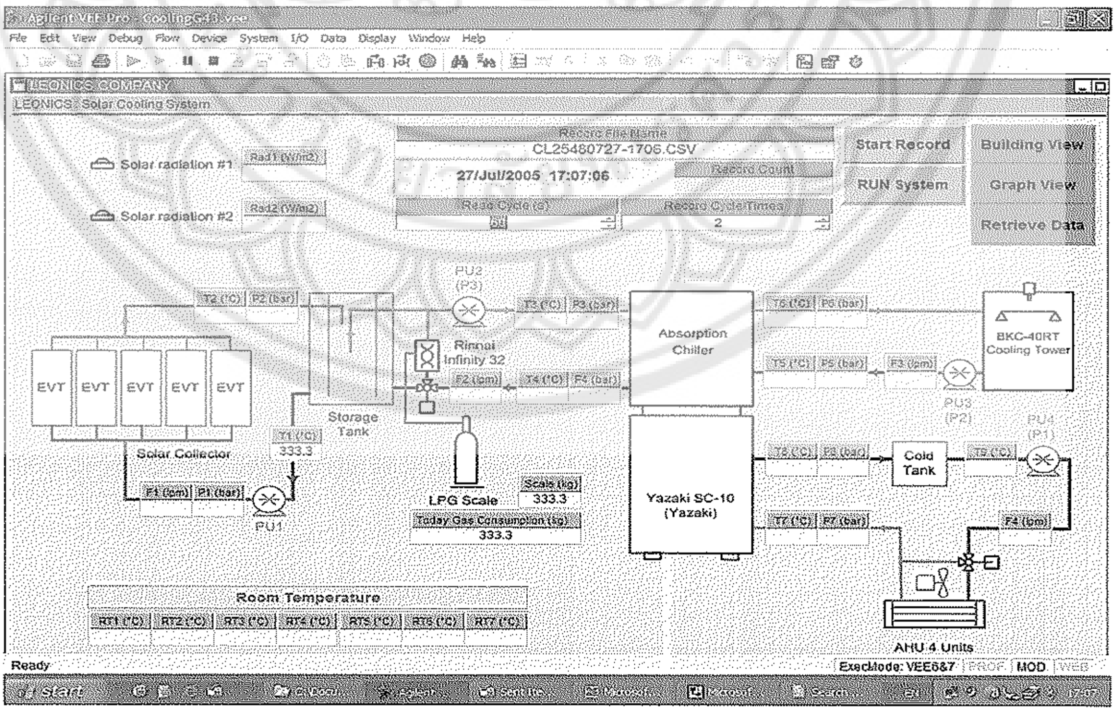

Figure 17 Measurement points of the solar absorption cooling at SERT

Where T_1 = Return water temperature to collectors, (°C)

T_2 = Heated water temperature from collectors, (°C)

T_3 = Supplying hot water inlet temperature to chiller, (°C)

T_4 = Supplying hot water outlet temperature from chiller, (°C)

T_5 = Cooling water inlet temperature to chiller, (°C)

T_6 = Cooling water outlet temperature from chiller, (°C)

T_7 = Refrigerated water inlet temperature to chiller, (°C)

T_8 = Refrigerated water outlet temperature from chiller, (°C)

T_9 = Refrigerated water outlet temperature from cold tank, (°C)

T_{TT} = Hot water temperature inside hot storage tank, (°C)

RT = Room temperature, (°C)

F_1 = Water flow rate via Collectors, (lpm)

F_2 = Supplying hot water flow rate, (lpm)

F_3 = Cooling water flow rate, (lpm)

F_4 = Refrigerated water flow rate, (lpm)

G_β = Irradiation on the tilted plane, ($W.m^{-2}$)

G = Irradiation on the Horizontal, ($W.m^{-2}$)

1.2 The Principle Equation

By mean of the first and the second law of thermodynamics, the heat balance could be established (Garp and Prakash., 1990, unpaged).

$$\dot{Q}_{ab} + \dot{Q}_{cond} = \dot{Q}_{gen} + \dot{Q}_{evap} \quad (3\text{-}1)$$

$$\dot{Q}_{ab} + \dot{Q}_{cond} = \dot{Q}_{rej} \quad (3\text{-}2)$$

$$\dot{Q}_{gen} = \dot{Q}_{storage} + \dot{Q}_{auxiliary} \quad (3\text{-}3)$$

In this case

$$\dot{Q}_{auxiliary} = 0.80 * \text{LPG energy consumption} \quad (3\text{-}4)$$

$$\dot{Q}_{storage} = \eta_{storage} \cdot \dot{Q}_{collector} \quad (3\text{-}5)$$

The thermal energy quality as measurement by the temperature of the material entering, leaving and stored (Dinçer and Rosen, 2002, unpaged).

Storage Efficiency $\eta_{storage} = \frac{output}{input} = \frac{\Delta T_{TT1-TT3}}{\Delta T_{2-1}}$ (3-6)

Duffie and Beckman , 1999 were expressing the useful gain of solar collector as

$$\dot{Q}_{collector} = \eta . A . G_{\beta} \quad (3\text{-}7)$$

$$\eta = \eta_0 - a_1 T_m^* - a_2 G_{\beta} T_m^* \quad (3\text{-}8)$$

$$T_m^* = \left(\frac{T_m - RT}{G_{\beta}} \right) \quad (3\text{-}9)$$

$$T_m = \left(\frac{T_2 + T_1}{2} \right) \quad (3\text{-}10)$$

In this case $\eta_0 = 0.717$, $a_1 = 1.52$ W.m^{-2}.K^{-1} and $a_2 = 0.0085$ W.m^{-2}.K^{-1} (Swiss Testing, 2004, unpaged). The sensible heat equation via the main circuits could be explained as

Collector circuit $\dot{Q}_1 = \dot{m}_1 C_P \Delta T_{2-1}$ (3-11)

Generator circuit $\dot{Q}_{gen} = \dot{m}_2 C_P \Delta T_{3-4}$ (3-12)

Evaporator circuit $\dot{Q}_{evap} = \dot{m}_4 C_P \Delta T_{7-8}$ (3-13)

Usage circuit $\dot{Q}_{usage} = \dot{m}_4 C_P \Delta T_{7-9}$ (3-14)

Condenser/Absorber circuit $\dot{Q}_{rej} = \dot{m}_3 C_p \Delta T_{6-5}$ (3-15)

In this case $\dot{m}_1 = 0.95$, $\dot{m}_2 = 2.25$, $\dot{m}_3 = 5.25$, and $\dot{m}_4 = 1.92$ kg.s^{-1}

For the heat losses could be avoided and kept at a minimum by insulation all parts of system's junctions and pipe.

$$\dot{Q}_{loss} = \dot{Q}_{in} - \dot{Q}_{out} \quad (3\text{-}16)$$

The thermal performance of refrigeration units expressed in terms of the "Coefficient of Performance, COP". The COP of the absorption system was define as the heat load in the evaporator per unit of heat load in the generator and could be written (Liess, et al., 2000, unpaged).

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{gen}} \tag{3-17}$$

The fraction of the solar energy met by the total energy input could be expressed as(Liess, et al., 2000, unpaged).

$$SOLF_{the} = \frac{\dot{Q}_{storage}}{\dot{Q}_{storage} + \dot{Q}_{auxiliary}} \tag{3-18}$$

1.3 The Curve Fitting

Data was often given for discrete values along a continuum. However, you may require estimates at point between the discrete values. One way was use to compute values of the function at a number of discrete values along the range of interest was known as "curve fitting" (Chapre and Canale, 2002, unpaged).

1.4 The Validation: Relative Error Equation

Considering the lowest relative error value was better driven the system's equation to be the development equation, was written as (Ketjoy, 1999, unpaged). In this case, the relative error obtained being less than 15% (in the worst case).

$$Error(\%) = \left(\frac{Measure - Calculate}{Measure}\right) x100 \tag{3-19}$$

1.5 The Optimization Process

Optimization was the process of finding the conditions that gave maximum or minimum values of a function (Stoecker, 1989, unpaged).

1.5.1 Mathematical Representation

The elements of the mathematical statement of optimization included specification of the function and the constraints. Let Y represent the function that was to be optimized, called the objective function; y was a function of $X_1, X_2, \ldots, X_n$, which were called the independent variables. The objective function, then, was

$$Y = Y(X_1, X_2, \ldots, X_n) \rightarrow Optimization \tag{3-20}$$

1.5.2 The Technical Optimal Equation

The basic assumption of this work needed the optimal COP in the range of 0.35 – 0.65 when the cooling system was operated during 09:00 – 17:00 by adjusting water flow rate, $\dot{m}$, via the main components by means of balancing cooling load and cooling supply through the chiller. As the Eqs. (3-17), the objective function was written as

$$COP = Y(\dot{Q}_{evap}, \dot{Q}_{gen}) \approx 0.35 - 0.65 \quad (3\text{-}21)$$

The Eqs. (3-12) and (3-13) were written inform of sensible heat; therefore, the objective function could be rewritten as

$$COP = Y(\dot{m}_{evap}, \Delta T_{evap}, \dot{m}_{gen}, \Delta T_{gen}) \approx 0.35 - 0.65 \quad (3\text{-}22)$$

The validation of the system's equation base on the thermodynamic could divided into two groups and three characters base on the auxiliary energy consumption and the season change in Thailand, winter, summer and rainy season. The period of winter, summer and rainy season are September – February, February – May and May – September, respectively, (Maneewan and Zeghmati, 2004, unpaged). The basic assumption of this work could be avoided the heat losses and kept at a minimum by insulation all parts of system's junctions and pipe and no flow drop of water flow rate because of pump working for generating the optimal mathematic equation. The objective of this mathematic was the always maximum COP that produced by adjusting water flow rate via the main components to balance cooling load and cooling supply of chiller. The optimal equation was the characteristic mathematic function of cooling system that install at SERT, Thailand as shown in Figure 18. The mathematic model in each component came from either the principle equation or curve fitting. The energy supply components were solar collector, hot water storage tank and generator. The energy demand component was come from the cooling load, $\dot{Q}_{load}$, inside the building.

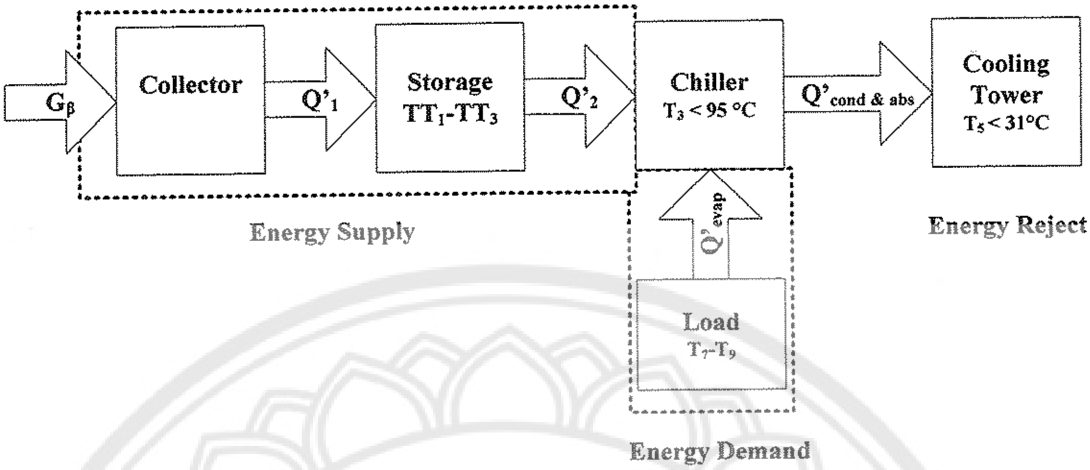

Figure 18 The flow chart of energy demand – supply of cooling system

Table 3 The beginning temperature and constant value used for simulation

Average Value	T_1 (°C)	T_6 (°C)	T_7 (°C)	$TT_1 - TT_3$ (°C)	$T_2 - TT_1$ (°C)	T_7-T_9 (°C)
Winter	50	30	20	-1.99	0.03	0.39
Summer	60	30	27	-2.50	0.5	1.55
Rainy season	70	33	27	-5.58	-6.25	1.81

The data in Table 3 were come from the experimental data that average and used as a beginning value of T and ΔT for simulation when the $\dot{m}$ and $\dot{Q}$ was used for this situation. The model was consisting of three parts, energy supply, demand and reject. First, the water had been passed the supply part for rise up temperature of itself that consisted of solar collector and hot water storage tank. Then went through the generator while the energy demand was the heat load inside the building carried by the chilled water. Finally, all usage heat in this process should be rejected by working of the cooling tower.

For the equation via the solar collector, the input was come from the tilt solar irradiation, G_β (Wm^{-2}). In Eqs. (3-7) this mathematic model would be written as

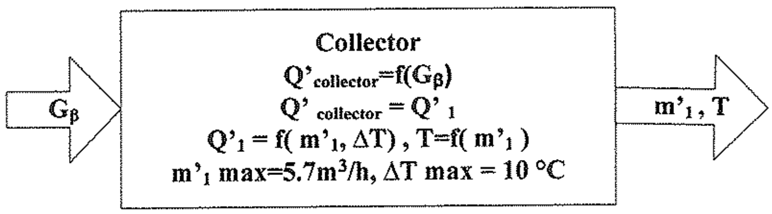

Figure 19 The flow chart of solar collector's mathematic model

In Figure 19, the input of the model was G_β that generate the $\dot{Q}_{collector}$. The mathematic of this relation was come from curve fitting method with the maximum of $\dot{m}_1$ and ΔT that limited by performance of pump and solar collector, respectively. Due to the first of basic assumption, the $\dot{Q}_{collector} = \dot{Q}_1$ for generating the maximum energy supply while the output of this model was $\dot{m}_1$ and T for generating the optimal water flow rate and temperature from the collector through the hot water storage tank. The mathematic model would be written in Figure 20, the input of this model was come from the collector, $\dot{Q}_1$, the first of basic assumption was $\dot{Q}_{stroage} = \dot{Q}_2$ for generating the maximum energy supply There were two energy supplies for the storage tank, tilt solar irradiation and the auxiliary heat , the equation would be written as.

$$\dot{Q}_{stroage} = \dot{Q}_{collector} + \dot{Q}_{auxiliary} \quad (3\text{-}23)$$

$$\dot{Q}_{stroage} = \eta_{storage} \cdot \dot{Q}_1 \quad (3\text{-}24)$$

Where
$$\eta_{stroage} = f(G_\beta) \quad (3\text{-}25)$$

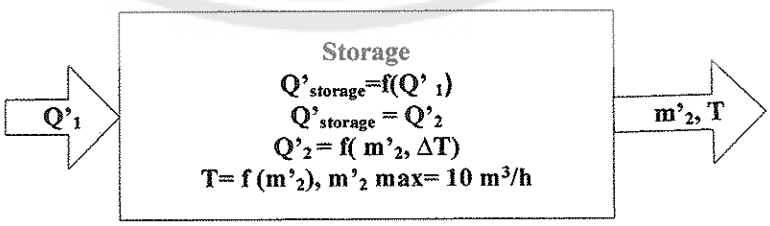

Figure 20 The flow chart of hot water storage tank's mathematic model

The Eqs. 3-29 was the mathematic of this relation was come from curve fitting method.

The output of this model was $\dot{m}_2$ and T for generating the optimal water flow rate and temperature from the hot water storage tank through the generator. The mathematic model would be written equation was written as.

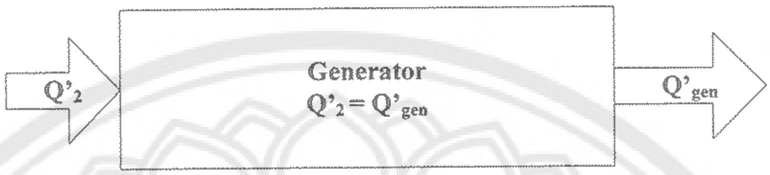

Figure 21 The flow chart of generator's mathematic model

In Figure 21, due to the first of basic assumption, the $\dot{Q}_2 = \dot{Q}_{gen}$ for generating the maximum energy supply through the generator was written as

$$\dot{Q}_{gen} = f(\dot{m}_2, \Delta T_{3-4}) \qquad (3\text{-}26)$$

To balance the energy demand of chiller, the mathematic model of energy demand or cooling load was written as

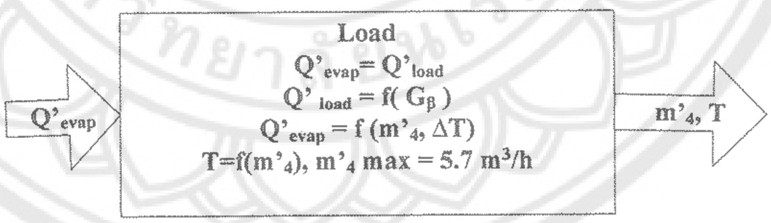

Figure 22 The flow chart of evaporator's mathematic model

In Figure 22, the input of the model was $\dot{Q}_{evap}$, the mathematic relationship was come from curve fitting method. Due to the first of basic assumption, the $\dot{Q}_{evap} = \dot{Q}_{load}$ for receiving the maximum energy demand while the output of this model was $\dot{m}_4$ and T for generating the optimal water flow rate and temperature from the evaporator through the building.

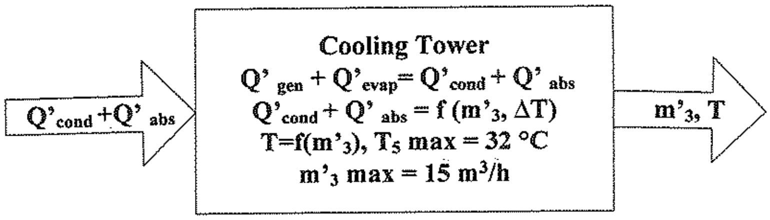

Figure 23 The flow chart of cooling tower's mathematic model

All energies input would be rejected by working of cooling tower that limited the cooling water inlet temperature by the specific of chiller. The capacitance of heat rejected of cooling tower for this system was higher than the maximum energy input so that all input through the chiller would be rejected. Due to the first of basic assumption, the $\dot{Q}_{gen} + \dot{Q}_{evap} = \dot{Q}_{cond} + \dot{Q}_{abs}$ for generating the maximum energy rejection while the output of this model was $\dot{m}_3$ and T generate the optimal water flow rate and temperature from the cooling tower through the chiller. The mathematic model would be written in Figure 23. From the heat balance Eqs. 3-1, in Figure 24 could explain the energy balance through the working of chiller as

$$\text{(Collector+Storage) +Evaporator = Condenser + Absorber} \qquad (3\text{-}27)$$

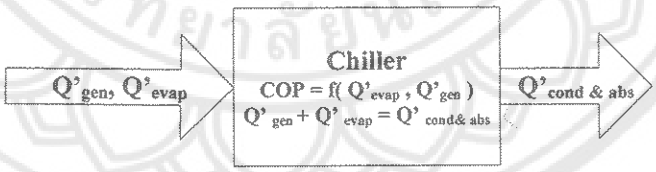

Figure 24 The energy demand-supply balance diagram through the working of chiller's mathematic model

When rewrite it in term of the water flow rate that shown in Figure 25, the mass balance equation through the working of chiller was

$$(\dot{m}_1 \Delta T_{1-2} + \dot{m}_2 \Delta T_{3-4}) + \dot{m}_4 \Delta T_{7-8} = \dot{m}_3 \Delta T_{6-5} \qquad (3\text{-}28)$$

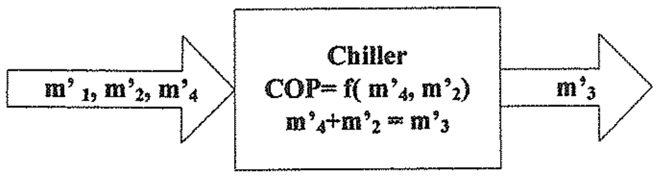

Figure 25 The mass balance diagram through the working of chiller's mathematic model

The ΔT was controlled when adjusted the $\dot{m}$ via the main components with the temperature of hot water supply through the generator not exceed 95 °C. The flow chart of mathematic model used for perdition the optimal water flow rate that was generating the always maximum COP as shown in Figure 26.

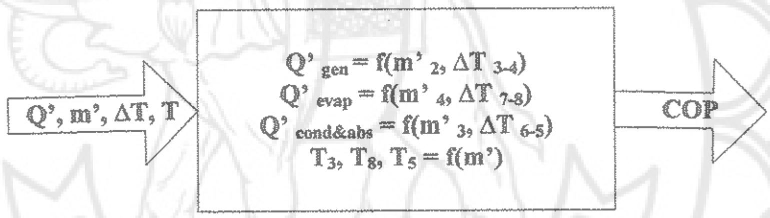

Figure 26 The technical optimal equation flow chart

While the output of the model was the water flow rate via the main components, $\dot{m}_1, \dot{m}_2, \dot{m}_3, \dot{m}_4$ which was generated the optimal COP base on the balancing demand and supply energy of chiller. The input of the technical optimal modeling was $\dot{Q}$ and $\dot{m}$ through the main components, generator, evaporator, condenser and absorber that generating ΔT and T of water. The optimal $\dot{m}$ not only controlled the ΔT via the main components but also generated the optimal temperature of heat medium inlet and the chilled water outlet temperature.

2. The Economic Equation

The optimal economic equation was the characteristic mathematic function of cooling system that install at SERT. The input was the total cost of a system, LCCA, the solar fraction, $SOLF_{the}$, and the Coefficient of Performance, COP while the output was the (SLCCA), the payback period (PB), the rate of return

(IRR), net present value (NPV), computation of B/C for a single investment throughout its life time. The optimal condition was the lowest total cost , the shortest time for pay back period and the highest IRR, B/C, NPV of a system throughout its life time was appearing when the maximum actual COP was produced.

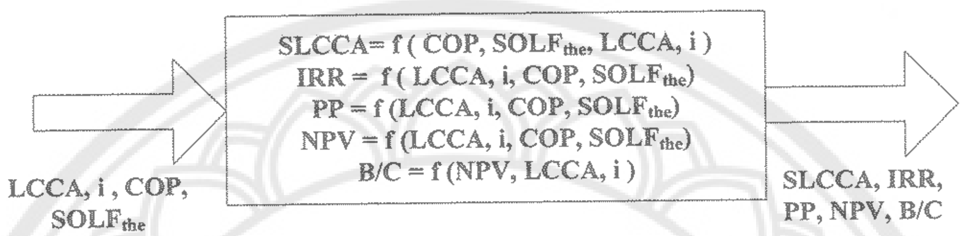

Figure 27 The economic optimal equation flow chart

The Optimization Equation

This equation was optimizing both the technically and economically of LiBr – H_2O solar absorption cooling system in Thailand. The input of technical equations were $\dot{Q}$, $\dot{m}$, ΔT and T which were generated the maximum COP while the input of the economic equation not only was LCCA, i and n but also the output of technical model, COP and SOLF $_{the}$. The hypothesis of this work was that the COP should be range 0.35 - 0.65 and the solar fraction ($SOLF_{the}$) was 0.5 – 1 for generating the minimum of cost per cooling unit that produced by the working of chiller, the maximum rate of return (IRR), Net Present Value (NPV), Benefit-Cost Ratio (B/C) and the shortest time for Payback Period (PB).

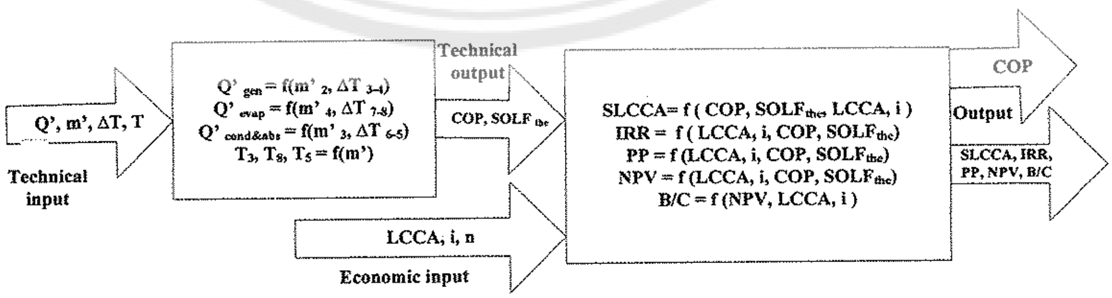

Figure 28 The optimization equation's flow chart