CHAPTER III

METHODOLOGY

Description of absorption system

Compared to an ordinary cooling cycle the basic idea of an absorption system is to avoid compression work. This is done by using a suitable working pair. The working pair consists of a refrigerant and a solution that can absorb the refrigerant. In this study, LiBr - H_2O is used, water is the refrigerant. The system is shown schematically in Figure 4.

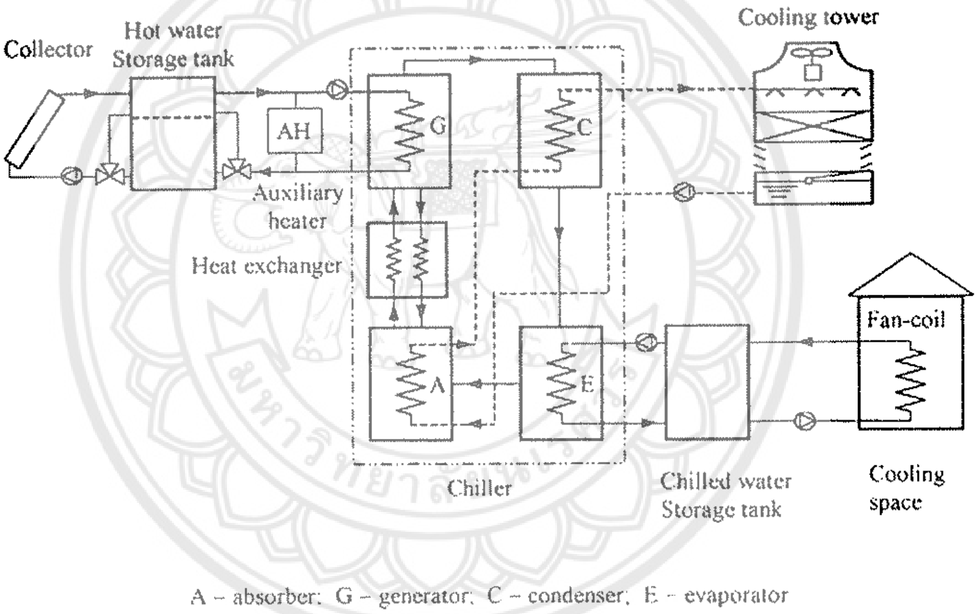


Figure 4 Schematic diagram of the solar-powered air conditioning system.

It shows the schematic diagram of a solar absorption air conditioning system. To begin with, the solar energy is gained through the collector and is accumulated in the storage tank. Then, the hot-water in the storage tank is supplied to the generator to boil off water vapor from a solution of lithium bromide and water. The water vapor is cooled in the condenser and then passed to the evaporator, where it again gets evaporated at low pressure, thereby providing cooling to the space to be cooled. Meanwhile, the strong solution leaving the generator for the absorber passes through a heat exchanger in order to preheat the weak solution entering the generator. In the absorber, the strong solution absorbs the water vapor leaving the evaporator. Cooling water from the cooling tower removes the heat of mixing and condensation. Since the temperature of the absorber has a higher influence on the efficiency of the system than the condensing temperature, the heat rejection (cooling water) fluid is allowed to flow through the absorber first and then the condenser. An auxiliary energy source is provided so that hot-water is supplied to the generator when solar energy is not sufficient to heat the water to the required temperature level needed by the generator. The hot-water storage tank is partitioned to serve as two separate tanks. In the morning, the collector system is connected to the upper part of the tank, whereas in the afternoon, the whole tank would be used to provide heat energy to the chiller.

Components of the solar absorption cooling system

Generator: When the heat medium inlet temperature exceeds the evaporating temperature of the refrigerant, the solution pump forces dilute lithium bromide solution into the generator. The solution boils vigorously under a vacuum and droplets of concentrated solution are carried with refrigerant vapor to the primary separator. After separation, refrigerant vapor flows to the condenser and concentrated solution is precooled in the heat exchanger before flowing to the absorber.

Condenser: In the condenser, refrigerant vapor is condensed on the surface of the cooling coil and latent heat, removed by the cooling water, is rejected to a cooling tower. Refrigerant liquid accumulates in the condenser and then passes through an throttling valve into the evaporator.

Evaporator: In the evaporator, the refrigerant liquid is exposed to a substantially deeper vacuum than in the condenser due to the influence of the absorber. As refrigerant liquid flows over the surface of the evaporator coil it boils and removes heat, equivalent to the latent heat of the refrigerant, from the chilled water circuit. The recirculation chilled water is cooled and the refrigerant vapor is attracted to the absorber.

Absorber: A deep vacuum in the absorber is maintained by the affinity of the concentrated solution from the generator with the refrigerant vapor formed in the evaporator. The refrigerant vapor is absorbed by the concentrated lithium bromide solution flowing across the surface of the absorber coil. Heat of condensation and dilution are removed by the cooling water and rejected to a cooling tower. The resulting dilute solution is preheated in a heat exchanger before returning to the generator where the cycle is repeated.

Auxiliary heating: The manner in which auxiliary heat is supplied affects the overall performance and cost of the system. Auxiliary heat may be used to boost the temperature of the hot-water from the storage tank if the temperature of the solar driven heat does not meet the heating or cooling requirements. The auxiliary heat may also be used to meet the full load whenever the storage temperature is too low to be useful. In the actual system, the auxiliary heater may be in parallel connection between the chiller and the hot-water storage tank because the chiller has the best performance at higher temperatures. The series connection is not preferred since the temperature of the returned water from the chiller to the storage tank may be higher than the storage tank temperature itself, which raises the storage temperature and results in lower system efficiency.

Wet cooling towers: is essentially a semi-enclosed evaporative cooler. Air is drawn into the tower from bottom and leaves through the top. Warm water from the condenser is pumped to the top of tower and is sprayed into this air-stream. The purpose of spraying is to expose a larger surface of water to the air. As the water droplets fall under the influence of gravity, a small fraction of water evaporates and cools the remaining water. The cooled water collects at the bottom of the tower and is pumped back to the chiller to pick up additional waste heat.

Thermodynamic analysis

For the thermodynamic analysis of the absorption system the principles of mass conservation, first and second laws of thermodynamics are applied to each component of the system. Each component can be treated as a control volume with inlet and outlet streams, heat transfer and work interactions. The principle of the system is shown schematically in Figure 5.

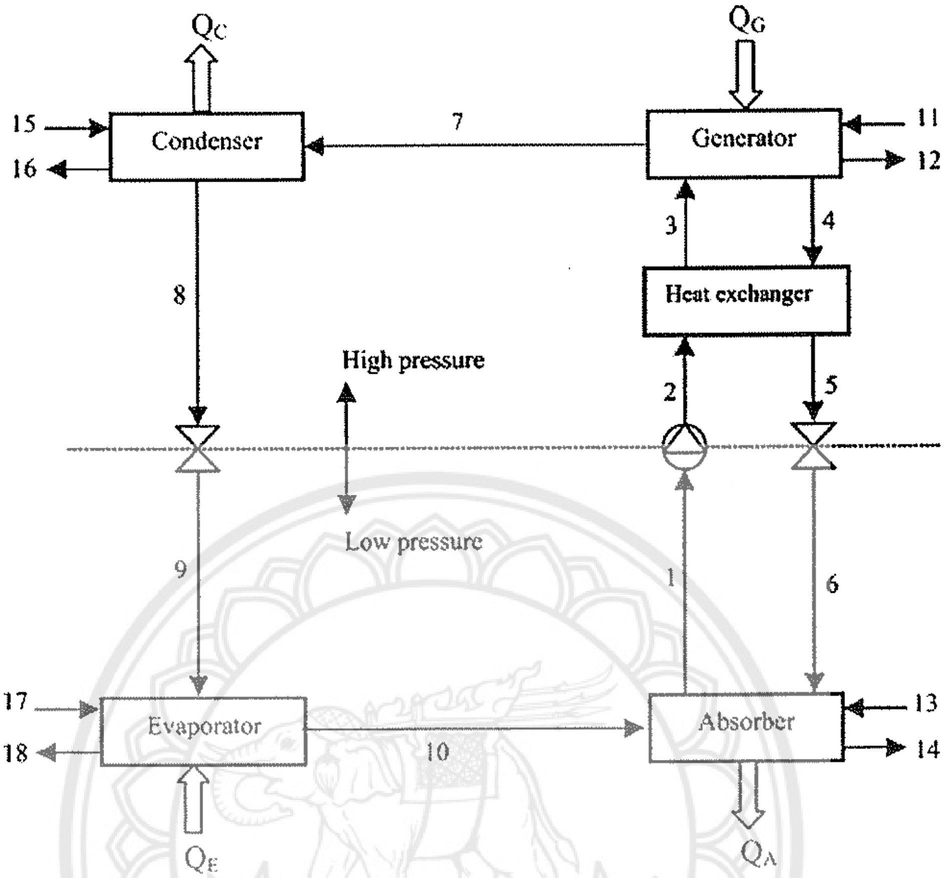


Figure 5 Schematic of a single effect LiBr–water absorption system.

As shown in Fig5, when the refrigerant vapor is coming from the evaporator (10) it is absorbed in the solution (1). This solution is pumped to higher pressure (1–2), where the refrigerant is boiled out of the solution by the addition of heat (3–7). Subsequently, the refrigerant goes to the condenser (7–8) like in an ordinary cooling cycle. Finally, the solution with less refrigerant returns back to the absorber (6).

The governing equations of mass and type of material conservation for a steady state and steady flow system are:

$$\sum \dot{m}_i - \sum \dot{m}_o = 0 \tag{3-1}$$

$$\sum (\dot{m}x)_i - \sum (\dot{m}x)_o = 0 \tag{3-2}$$

Where m is the mass flow rate and x is mass concentration of LiBr in the solution. The first law of thermodynamics yields the energy balance of each component of the absorption system as follows:

$$\sum(\dot{m}h)_i - \sum(\dot{m}h)_o + [\sum Q_i - \sum Q_0] + W = 0 \quad \text{Or:} \tag{3-3}$$

$$Q_O = Q_A + Q_C = Q_G + Q_E \tag{3-4}$$

Where:

Q_G = heat supplied to the generator, (kW)

Q_E = heat attracted to the system at the evaporator by the medium, (kW)

Q_A = heat rejected by the absorber, (kW)

Q_C = heat rejected by the condenser, (kW)

Q_O = total heat rejected to the environment, (kW)

$\dot{m}$ = the mass flow rate at each corresponding state point, (kg/s)

h = the enthalpy of working fluid at each corresponding state point, (kJ/kg)

The energy required for the pumps and funs is very small and can be neglected.

The mass, material and energy balance equations on the different components

Generator: $\dot{m}_3 = \dot{m}_4 + \dot{m}_7$ mass balance

$\dot{m}_3 x_3 = \dot{m}_4 x_4 + \dot{m}_7 x_7$ material balance

$Q_G = \dot{m}_7 h_7 + \dot{m}_4 h_4 - \dot{m}_3 h_3$ energy balance

Absorber: $\dot{m}_1 = \dot{m}_{10} + \dot{m}_6$

$\dot{m}_1 x_1 = \dot{m}_{10} x_{10} + \dot{m}_6 x_6$

$Q_A = \dot{m}_6 h_6 + \dot{m}_{10} h_{10} - \dot{m}_1 h_1$

Condenser:

$$\dot{m}_8 = \dot{m}_7$$

$$\dot{m}_8 x_8 = \dot{m}_7 x_7$$

$$Q_C = \dot{m}_8 h_8 - \dot{m}_7 h_7$$

Evaporator:

$$\dot{m}_{10} = \dot{m}_9$$

$$\dot{m}_{10} x_{10} = \dot{m}_9 x_9$$

$$Q_E = \dot{m}_{10} h_{10} - \dot{m}_9 h_9$$

Heat exchange:

$$\dot{m}_4 = \dot{m}_5$$

$$\dot{m}_2 = \dot{m}_3$$

$$\dot{m}_4 x_4 = \dot{m}_5 x_5$$

$$\dot{m}_2 x_2 = m3x_3$$

$$\dot{m}_2 h_2 + \dot{m}_4 h_4 = \dot{m}_3 h_3 + \dot{m}_5 h_5$$

Where:

h = enthalpy, (kJ/kg)

X = concentration in kg of lithium bromide per kg of solution

$\dot{m}$ = the mass flow rate in kg of solution per unit time, (kg/s)

It is seen from the fig 5. that $h_7 = h_r$ (enthalpy of refrigerant), $\dot{m}_7 = \dot{m}_r$ (flow rate of refrigerant), $x_3 = x_r$ (concentration of lithium bromide in refrigerant), $x_4 = x_{ab}$ (concentration of lithium bromide in absorbent).

The cooling COP of the absorption system is defined as the heat load in the evaporator per unit of heat load in the generator and can be written as [5]

$$COP_{cooling} = \frac{Q_E}{Q_G} = \frac{\dot{m}_{10}\, h_{10} - \dot{m}_9\, h_9}{\dot{m}_4\, h_4 + \dot{m}_7\, h_7 - \dot{m}_3\, h_3} = \frac{\dot{m}_{17}(h_{17} - h_{18})}{\dot{m}_{11}(h_{11} - h_{12})} \tag{3-5}$$

In the practical system the cooling COP was yielded from energy balances in each component as:

$$Q_E = \dot{m}_{17}\, C_p \left(T_{17} - T_{18}\right) \tag{3-6}$$

$$Q_G = \dot{m}_{18}\, C_p \left(T_{17} - T_{18}\right) \tag{3-7}$$

$$COP_{cooling} = \frac{Q_E}{Q_G} = \frac{\dot{m}_{17}\, C_p (T_{17} - T_{18})}{\dot{m}_{11}\, C_p (T_{11} - T_{12})} \tag{3-8}$$

Where:

C_p = the specific heat of waterunder constant pressure, 4.18 (kJ/kg·K).

Explanation of the solar absorption cooling system at SERT (SACS)

This study was based on a practical solar absorption cooling system which was installed at School of Renewable Energy Technology (SERT) Naresuan University.

Main components of the SACS at SERT

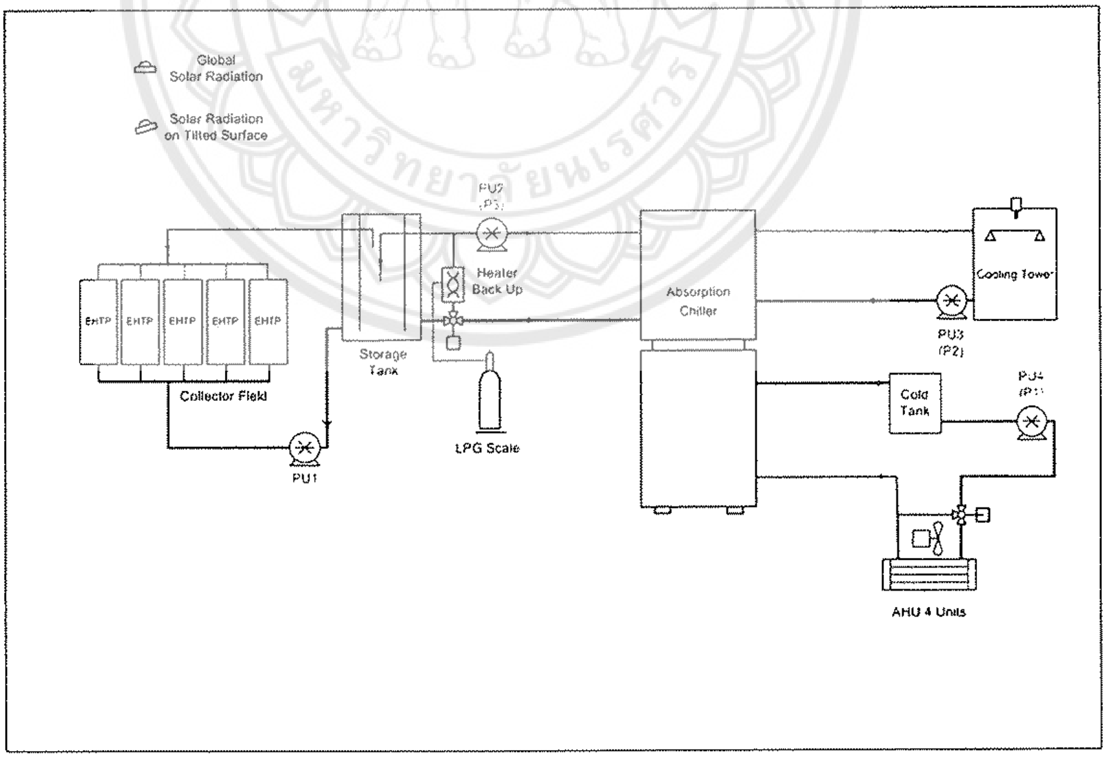
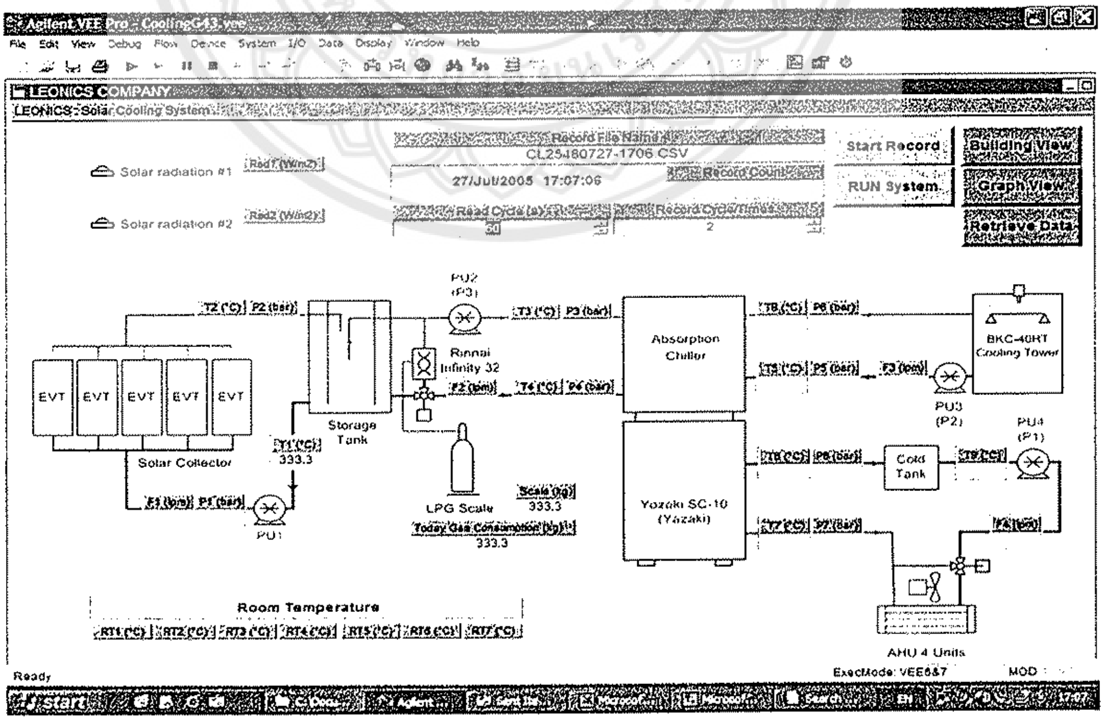


Figure 6 Components of the SACS at SERT

1. Evacuated Heat Pipe Collectors of Apricus Manifold AP-30, 72 m^2;
2. Heater Backup, Rinnai model Infinity 32;
3. Hot water storage tank, 500 Liters;
4. Yazaki WFC SC-10 Chiller,cooling capacity 35 kW
5. BKC-40RT Cooling Tower, capacity 40 ton
6. AIRCON WQW-32V Fun coil 4 units, each unit 5.6 kW
7. Pump unit:
   - GRUNDFOS PU1, 1.1 kW Type: CR10-3 A-FGJ-A-E-HQQE
   - GRUNDFOS PU2, 0.75 kW Type: CR10-5 A-FGJ-A-E-HQQE
   - GRUNDFOS PU3, 3 kW Type: MOT100LA 2-28FT130-D2
   - GRUNDFOS PU4, 0.55kW Type: CR10-4 A-FGJ-A-E-HQQE

Measurements

The measured data corresponds to inputs, outputs and meteorological data of the SACS such as Temperature, Electrical Power, LPG Weight and inclined global irradiance. The Agilent's data recorder collected every 20 seconds in mean time. The measuring points are shown in figure 7.



Record File Name: CL25480727-1706.CSV

27/Jul/2005 17:07:06

Read Cycle (s): 30

Record Cycle/Times: 2

Figure 7 Measurement points of the SACS at SERT

T_1 = Return water temperature to collectors, (^{o}C) (RTD PT100 Sensor)

T_2 = Heated water temperature from collectors, (^{o}C) (RTD PT100 Sensor)

T_3 = Supplying hot water inlet temperature to chiller, (^{o}C) (RTD PT100 Sensor)

T_4 = Supplying hot water outlet temperature from chiller, (^{o}C) (RTD PT100 Sensor)

T_5 = Cooling water inlet temperature to chiller, (^{o}C) (RTD PT100 Sensor)

T_6 = Cooling water outlet temperature from chiller, (^{o}C) (RTD PT100 Sensor)

T_7 = Refrigerated water inlet temperature to chiller, (^{o}C) (RTD PT100 Sensor)

T_8 = Refrigerated water outlet temperature from chiller, (^{o}C) (RTD PT100 Sensor)

T_9 = Refrigerated water outlet temperature from cold tank, (^{o}C) (RTD PT100 Sensor)

$\dot{F}_1$ = Water flow rate via Collectors, (kg/s)

$\dot{F}_2$ = Supplying hot water flow rate, (kg/s)

$\dot{F}_3$ = Cooling water flow rate, (kg/s)

$\dot{F}_4$ = Refrigerated water flow rate, (kg/s)

G_t = Irradiation on the tilted plane, (W/m^2) (Kipp and Zonen model CM 3)

G_h = Irradiation on the Horizontal, (W/m^2) (Kipp and Zonen model CM 3)

Calibration

In practical measuring, some errors was observed on scales of temperature. Therefore a calibration on temperature sensors was performed. The calibrating equations on the numeric value of temperatures were yielded as following:

$$T_1 = 1.0116xT_{1.sensor} + 0.1694$$

$$T_2 = 1.0182xT_{2.sensor} + 0.9738$$

$$T_3 = 0.9915xT_{3.sensor} + 4.2156$$

$$T_4 = 1.0433xT_{4.sensor} - 0.0099$$

$$T_7 = 1.0116xT_{7.sensor} - 0.1176$$

$$T_8 = 1.0077xT_{8.sensor} + 1.1867$$

$$T_9 = 1.0403xT_{9.sensor} - 2.7001$$

Calculation of the SACS performances

Calculation of energy on each part

$$Q_{gen} = \dot{F}_2\ C_p\ (T_3 - T_4) \qquad (3\text{-}9)$$

$$Q_{ev} = \dot{F}_4\ C_p\ (T_7 - T_8) \qquad (3\text{-}10)$$

$$Q_{abs} + Q_{con} = Q_{cooling} = \dot{F}_3\ C_p\ (T_6 - T_5) \qquad (3\text{-}11)$$

Where

Q_g = heat supply to Generator (kW)

Q_e = cooling load taken in by Evaporator (kW)

Q_a = heat rejected by Absorber to cooling tower (kW)

Q_c = heat rejected by Condenser to cooling tower (kW)

$Q_{cooling}$ = heat rejected by Cooling Tower to surrounding (kW)

C_p = specific heat of water, 4.18 (KJ / Kg.K)

Calculation of performances

The COP (coefficient of performance) of the chiller is given by:

$$COP = Q_e / Q_g \qquad (3\text{-}12)$$

The efficiency of collector is given by:

$$\eta_{collector} = \frac{F_1 \times C_p \times (T_2 - T_1)}{A_c \times I_t} \qquad (3\text{-}13)$$

Where:

A_c is the area of collectors, (m^2)

The whole efficient of performance (SCOP) of the SACS was yielded as:

$$SCOP = \eta_{collector} \times COP \qquad (3\text{-}14)$$

Economic section

Time value of money (discounting)

Projects in energy applications for a long time. 25-30 years is a normal useful life. Therefore, the time value of money (discounting) and the choice of a proper discount rate, is highly important.

Present valuing (discounting) is central to the economic evaluation process. Since most of the project costs, as well as benefits, occur in the future, it is essential that these should be discounted to their present value to enable proper evaluation. Present valuing will be carried out through discounting future period's financial outlay (F_t). the discount factor is a function of the discount rate (r).

$$\text{Discount factor } (a_t) = 1/(1+r)^t \qquad (3\text{-}15)$$

$$\text{Present value (PV)} = F_t \times a_t = F_t \times [1/(1+r)^t] \qquad (3\text{-}16)$$

Internal Rate of Return (IRR): is defined as the discount rate at which the after-tax NPV is zero. The calculated IRR is examined to determine if it exceeds a minimally acceptable return, often called the hurdle rate.

$$IRR = r_1 + \frac{PV(r_2 - r_1)}{PV + |NV|} \qquad (3\text{-}17)$$

Where:

PV = positive value of NPV for lower discount rate r_1 (Baht)

NV = negative value of NPV for higher discount rate r_2 (Baht)

Project financial costs

There are three main kinds of costs.

Investment cost: The items included initial costs; replacement costs and residual values.

Operating costs: operating costs are a combination of a fixed and variable costs. Fixed costs include salaries, cost of management and part of the maintenance costs. Variable costs will depend upon the level of production and include items like energy, water, and part of the maintenance costs.

Working capital: refers to the physical stock needed to allow continuous production.

Economic evaluation

The primary figures of merit are:

Net Present Value(NPV): is the sum of all year discounted after-tax flows. It is a valuable indicator because it recognizes the time of money. Projects whose returns show positive NPV are attractive.

$$NPV = \sum_{t=0}^{n} \frac{NCF}{(1+r)^{t}} - I \qquad (3\text{-}18)$$

Where:

NCF = net cash flows connected with current exploitation (without investment expenses), in years of analysis period, (year)

t, = discounting period, (year)

r = discount rate, (%)

I = investment costs, when the whole investment expenses are concentrated in year t = 0, (Baht)

Cost of Energy (COE): To calculate a levelizing cost of energy.

Levelzing Cost: is a method for expressing costs or revenues that occur once or in irregular intervals as equivalent equal payments at regular intervals. To illustrate this suppose one wants loan of present value PV is to be repaid in equal annual payments over N years.

Payback Period: compares revenues with costs and determines the length of time required to recoup the initial investment.

Payback period = Total NPV / Energy saving cost per year (3-19)

The Payback period is defined as the time after initial investment until accumulated net revenues equal the investment. i.e. the length of time required to get the investment capital back. The method is used as an approximate measure of the rate at which cash flow is generated early in the project life. It is utilized for small investments, like improvements and energy efficiency measures.

So, in this study, using the payback period method to analyze the specified system is more appropriate than other methods. And also 'Yield of cooling load' would be calculated. 'Yield of cooling load' presents that per unit cost can generate how many cooling load.

Yield of cooling load = Total cooling load / Total NPV (kWh/Baht) (3-20)

The benefit comes from energy saving per year.

Energy saving / year
= Cooling capacity x run hours daily x run days monthly x 12 months (3-21)
Energy saving cost
= Energy saving × unit price (3-22)