District Cooling Plant : Refrigeration Plant Simulation

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ABSTRACT

At present the energy cost is one of the most important factors on the manufacturing, managing, maintenance, and etc. Energy saving is being received more and more attention. This is resulted in new invention and technology to utilize energy in the more efficient way. Moreover many new concepts on energy management are being implemented with the aim to reduce energy cost.

The district cooling plant is one of many concepts involved in energy management on the air conditioning system in the buildings. The concept is to centralize the air conditioning system in the mega area into one plant. This paper presents the way to simulate the refrigeration plant by using the black box equipment model. Performance data of many equipment are collected such as chillers, pumps, and cooling towers. Data are collected at various working conditions. Thirteen configurations of chiller plant with eleven cooling load profiles are used to compare the performance of each configuration in order to provide some guidance for selecting the best suitable plant.

Computer program is developed and used to analyze the performance of the plant on various equipment configurations and cooling load profiles. The cooling load profile is characterized by using the load factor parameter. The preliminary result shows a high potential for using the program to determine the best plant configuration for the specific load profile.

1. Introduction

At present most of the cooling equipment in the air conditioning system consume energy inefficiently. This comes from several causes such as an inappropriate design, the lack of good maintenance and operation etc. For the design part, it is the result from the lack of appropriate system analysis which resulted in large energy consumption for the system, especially when it is operated at part load.

From air conditioning system comparison, it is found that we can divide the system into two configurations which are the local air conditioning system and the central air conditioning system. The study showed that 90% of total cooling capacity in the developing countries are provided by the local air conditioning system, which are the window type and split type air conditioning system. This is because its low investment cost, convenient installation, efficient heat loss control in some part of the building and no special expertise requirement in design, installation and maintenance. However, for large buildings or group of building that cover gigantic cooling spaces, this local air conditioning system is not appropriate in term of energy saving and total operating cost. Therefore in many countries, the central air conditioning system in which chillers play an important role is widely used.

After the designing engineer completes his/her total cooling load calculation and water distribution design. He/she then has to decide and select the size and number of equipment used in the cooling system. It is found that the chiller is the main equipment that has large influent in the investment and operating cost. Concept on sizing and determining the number of chiller is varied according to the cooling load profile in which at present there is no solid methodology that can support such a concept.

The objective of this research is, therefore, to set up some guidance for sizing and determining the number of chiller for the central air conditioning system by including also the water pump and the cooling tower into consideration. Several working conditions of each equipment have been studied in order to gather data for creating the mathematical simulation. Several cooling load profiles have been compared with several chiller configurations. Economics analysis has been included into consideration by concentrate mainly on the first cost and operating cost. The operating cost is varied directly to the function of the building and also related to the working percentage of chiller when compared with full load condition. This comparison procedure involves several complicated calculations and very time consuming. Therefore a computer program is being developed in order to facilitate the calculation, provide more exact data and ease the analysis. The virtual basic programming language is used to develop such a program due to its capability to provide convenient user interface. The program is run on the windows platform, which provide more user friendly.

2. Theory

It is found that the procedure for selecting cooling equipment in the central air conditioning system, in order to confine with the cooling load profile, is not appropriate and is difficult. This is because we have to consider also the detail of part load operation condition of the equipment. This makes the calculation to be even more complicated. Therefore in order to develop the cooling equipment selection program; database for each equipment is necessary. The equipment to be considered here are water-cooled centrifugal chiller, water pump and cooling tower which are the main equipment that have a direct impact on energy consumption. The black box equipment models are set up based on those data. The equations derived from those models are tested by statistical procedure in order to illustrate the reliability of those black box equipment models. The understanding on economic concept that has a direct impact on design and selection is also necessary.

2.1 Chiller

Since chillers have several kW/ton values at one specific capacity. Therefore in this study, the standard energy consumption in term of kW/ton for new building provided by the Department of Energy Development and Promotion is used. The working condition of chiller is referred to the standard design condition set up by the Air Conditioning and Refrigerating Institute (ARI) as follow;

Table 1: Standard kW/ton for Water-cooled Chiller

Chiller	kW/ton for New Building
a. Centrifugal Chiller	
- Capacity not more than 250 ton	0.75
- Capacity from 250 ton up to 500 ton	0.70
- Capacity more than 500 ton	0.67

Refer to the working condition in Thailand as follow;

- Voltage/Frequency/Phase = 380 / 50 / 3
- Supply chilled water temperature = 45°F (7.22°C)
- Return chilled water temperature = 55°F (12.78°C)
- Supply condensing water temperature = 100°F (37.78°C)
- Return condensing water temperature = 90°F (32.22°C)

Refer to the working condition of the chiller according to ARI 550/590-98

- Chilled water flow rate = 2.4 gpm/ton (0.043 L/s per kW)
- Condensing water flow rate = 3.0 gpm/ton (0.054 L/s per kW)
- Fouling factor for the cooler = 0.0001 $h*ft^2°F/Btu$ (0.000018 $m^2*°C/W$)
- Fouling factor for the condenser = 0.00025 $h*ft^2*°F/Btu$ (0.000044 $m^2*°C/W$)

According to the data collected from 112 chiller units (sizing started from 170 to 1300 ton) the black box models for chiller at each working condition can be set up as follow;

$$PLR = \frac{Q_e}{Q_{enom}} * 100 \quad \text{... (1)}$$

$$\frac{P}{P_{nom}} * 100 = a_0 + a_1 PLR + a_2 PLR^2 + a_3 PLR^3 \quad \text{... (2)}$$

$$P_{nom} = b_0 + b_1 T_{c2} + b_2 T_{c2}^2 + b_3 T_{c2}^3 \quad \text{... (3)}$$

When $a_0 \; a_1 \; a_2 \; a_3$: constant

$b_0 \; b_1 \; b_2 \; b_3$: constant

P (kW) : energy used for chiller at any working condition

P_{nom} (kW) : energy used for chiller at full load

PLR (%) : percentage of working load on chiller

Q_e (Ton) : cooling capacity generated from chiller

Q_{enom} (Ton) : cooling load capacity generated from chiller at full load

T_{c2} (°F) : supply condensing water temperature

By using statistical analysis, the accuracy of the equations shown above is as follow;

Table 2: Statistical value for analyzing the black box models of the chiller

Statistical Value	Equation (2)	equation (3)
Mean value of Adjusted R^2	1.000	0.990
Approximate value of Adjusted R^2 at 0.05 significant level	1.000	0.991

2.2 Water pump

Total of 202 horizontal split case centrifugal pump with 2 constant speeds, ie.1500 and 3000 rpm, are considered. The black box models for water pump can be set up as follow;

$$H = a_0 + a_1 Q + a_2 Q^2 \quad \text{... (4)}$$

$$P_{pump} = b_0 + b_1 Q \quad \text{... (5)}$$

When a_0 a_1 a_2 : constant

b_0 b_1 : constant

H (ft) : water pump head

P_{pump} (kW) : energy used for the water pump motor

Q (gpm) : water flow rate

The statistical analysis shows that the accuracy of the equations shown above is as follow;

Table 3: Statistical value for analyzing the black box models of the water pump

Statistical value	equation (4)	Equation (5)
Mean value of Adjusted R^2	0.996	0.978
Approximate value of Adjusted R^2 at 0.05 significant level	0.983-1.000	0.964-0.991

2.3 Cooling Tower

Counter flow type cooling tower is used in this study due to its popularity usage in Thailand. The size of cooling tower to be considered is ranged from 100 ton to 1500 ton. Each cooling tower is equipped with constant speed fan. The black box model for the cooling tower used in this study is received from Natee (7) and is as follow;

$$t_2 = a_0 + a_1 WBT + a_2 \ln W_m + a_3 (WBT)(\ln W_m) + a_4 \ln R + a_5 (WBT)(\ln R) + a_6 (\ln W_m)(\ln R) + a_7 (WBT)(\ln W_m)(\ln R) \quad \ldots (6)$$

When $a_0\ a_1\ a_2\ a_3\ a_4\ a_5\ a_6\ a_7$: constant

R (°F) : temperature difference of condensing water in and out from the cooling tower

t_2 (°F) : condensing water temperature from the cooling tower

WBT (°F) : wet bulb ambient temperature

W_m (gpm) : condensing water flow rate

The statistical analysis shows that the accuracy of the equation shown above is as follow;

Table 4: Statistical value for analyzing the black box model of the cooling tower

Statistical Value	Equation (6)
Mean value of Adjusted R^2	0.951
Approximate value of Adjusted R^2 at 0.05 significant level	0.896-1.000

Equation (6) shows that the wet bulb ambient temperature plays an important role in the equation above. Therefore the weather data is needed. In this study the weather data for the year 1998 is used. The wet bulb temperature data is collected every hour for every day of that year. The data is collected for the city of Bangkok only. The average value for each hour is used in the program for calculation

3. Sample Analysis

The refrigeration plant configuration as an example for analysis is shown in figure 1. The equipment in the power station can be seen within the control volume. The plant operation is explained as follow; when the cooling load changes, the chiller must be at least operated in such a way that it can handle such a load. All return chilled water flows back to the pipe header before flowing to the chillers. This gives an equal chilled water temperature to each chiller. This temperature is used to determine the working percentage of chillers at difference working conditions. In other word, if there are any chillers being operated at the same time, the average load is imposed on each of those chillers at the same part load ratio. The operation mode for chilled water pumps, condensing water pumps, and cooling towers will be a one to one operation mode according to the chillers' operation.

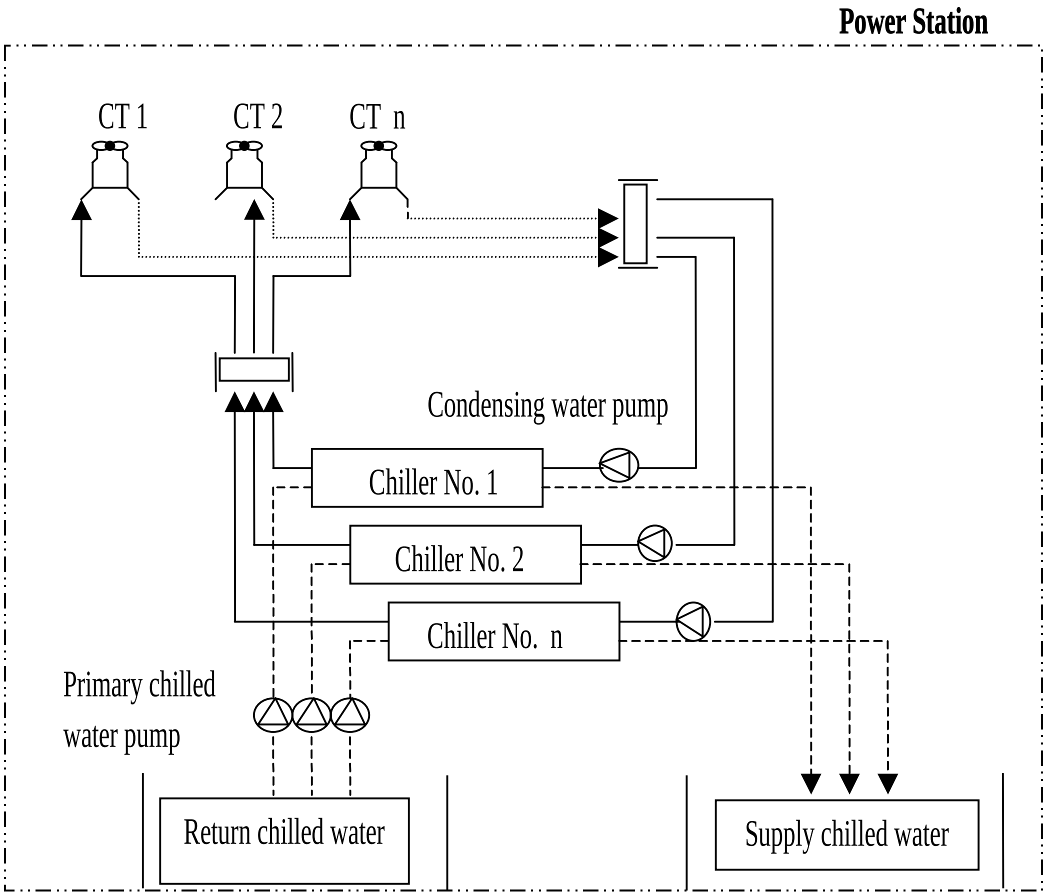

Figure 1 Power Station for refrigeration plant

The cooling equipment selection program that developed is used to analyze this plant configuration with the maximum cooling load equal to 1000 refrigeration ton as a case study. Eleven load profiles as shown in figure 2-12 are used for the study. Each load profile is designated by a factor called load factor which is defined as a ratio of the mean cooling load compared with the peak or maximum cooling load. This load factor is used as a cooling load representative for equipment selection.

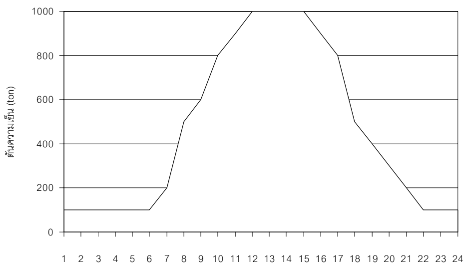

Figure 2 Load factor = 0.458

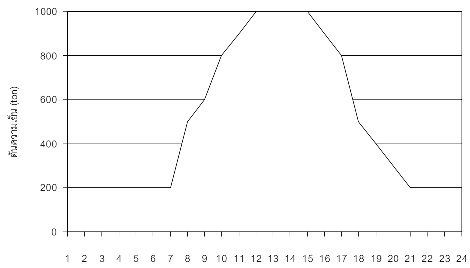

Figure 3 Load factor = 0.496

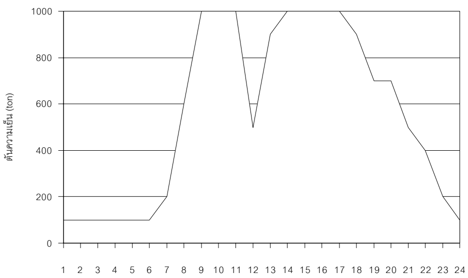

Figure 4 Load factor = 0.554

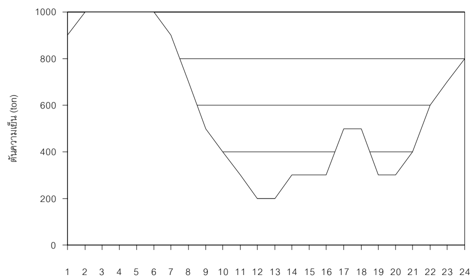

Figure 5 Load factor = 0.588

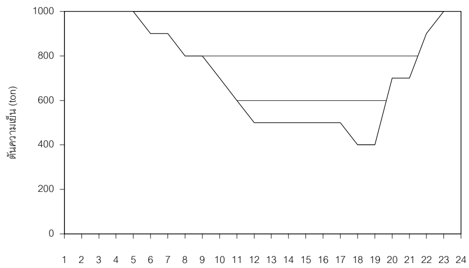

Figure 6 Load factor = 0.692

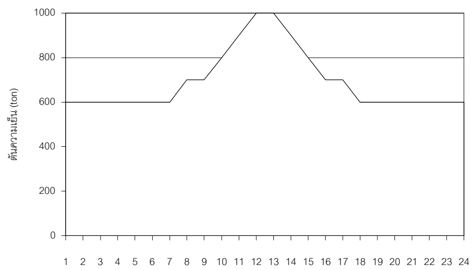

Figure 7 Load factor = 0.742

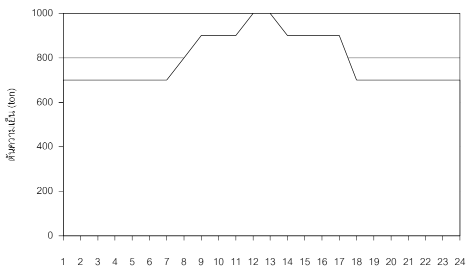

Figure 8 Load factor = 0.788

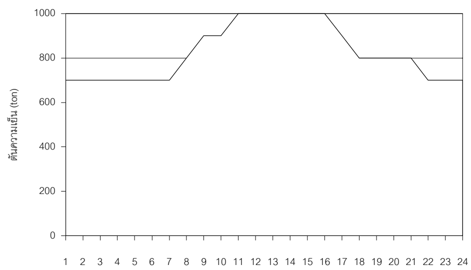

Figure 9 Load factor = 0.821

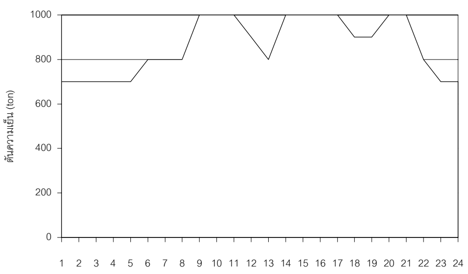

Figure 10 Load factor = 0.858

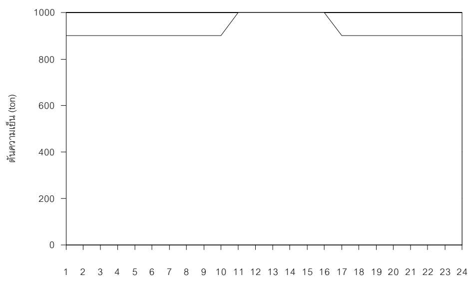

Figure 11 Load factor = 0.925

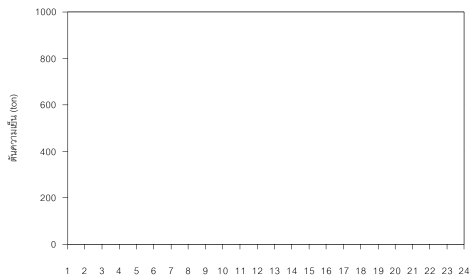

Figure 12 Load factor = 1.000

At each cooling load, the condensing water head is set to be equal to 38.21 ft. The plant is set to operate 7 days a week. The electrical cost is calculated according to the TOD or Time of Day rate at 69 kV. The primary chilled water head is set at 218.7 ft. except for the load factor equals to 0.554 and 0.742 in which the water head is set at 156.82 ft and 98.75 ft, respectively.

The cooling equipment selection program is used to test in total of 13 configurations for number and size of chillers. All eleven cooling load profiles are applied to each configuration to find the preliminary guidance for the selection of the optimum plant configuration at any cooling load profile. The thirteen configurations being tested consist of one one-chiller configuration, four two-chiller configurations, four three-chiller configurations, three four-chiller configurations, and one five-chiller configuration. However due to the large variation of the chiller data, the statistical consideration is applied in order to find the preliminary guideline in selection of the size and number of chiller for all 13 configurations at three difference kW/ton values. These three kW/ton values are as follow; the available minimum kW/ton, the maximum kW/ton according to table 1 for new building, and the kW/ton in between these two values. Therefore the calculation must be done 39 times for each cooling load profile in order to complete for 13 configurations. The results from the calculation are then averaged. The averaged value is used as a representative value for the specific configuration.

Table 5: Refrigeration plant configuration

Configuration No.	No. of Unit	Chiller's size (ton)
1	1	1000
2	2	600 / 400
3	2	800 / 200
4	2	500 / 500
5	2	700 / 300
6	3	400 / 400 / 200
7	3	400 / 300 / 300
8	3	600 / 200 / 200
9	3	500 / 300 / 200
10	4	250 / 250 / 250 / 250
11	4	400 / 200 / 200 / 200
12	4	300 / 300 / 200 / 200
13	5	200 / 200 / 200 / 200

The net present value for all equipment used in the refrigeration plant is used as an economic analysis tool. The parameters used for economic analysis are as follow;

Lifetime of project (year)	:	10
Energy inflation rate (%)	:	4.5
Discount rate (%)	:	10
Tax (%)	:	30
Percentage of loan compared with the total investment cost (%)	:	60
Pay back period(year)	:	5
Interest rate (%)	:	8

4. Result

The results from the analysis can be summarized as follow;

For engineering point of view:

1. At load factor equals to 0.458-0.588, the selection of more than one chiller receives more benefit in term of energy saving for the chiller.
2. From 1, it is found that if two or three chillers are selected and one of those selected chillers has more capacity or at least equal capacity to the rest then it will gain more benefit in term of energy saving for the chiller.

3. If one decides to use four chillers then the selection for equal size of chiller is the best.
4. The conclusion from 2 and 3 is also true at the high load factor between 0.692-1.000
5. At load factor between 0.692-1.000, the selection of one chiller achieves more energy saving for the chiller than the selection of several chillers.
6. When considering the total energy consumption for the whole refrigeration plant at difference load factors, it is found that at load factor between 0.925-1.000, the selection of one chiller still achieves more benefit in term of total energy consumption. At load factor between 0.458-1.000, the selection of two or three chillers in which one chiller has a larger capacity than the rest gains more advantage in term of total energy consumption as well.
7. In case of four chillers are selected, if one chiller has a larger capacity than the rest, then the total energy consumption is much better than selecting four chillers with equal size.
8. From 5 and 6, it is found that energy consumption in water pump plays also an important role as well as chiller when considering the total energy consumption for the refrigeration plant. While the energy consumption for the cooling tower plays virtually no significant effect to the total energy consumption when compare with those two.

For economic point of view:

1. At load factor between 0.788-1.000, the selection of one chiller provides the maximum net present value.
2. At load factor between 0.458-0.692, the selection of two chillers provides better net present value than the selection of one chiller.
3. At load factor between 0.458-0.588, the selection of three chillers provides better net present value than the selection of one chiller.
4. At load factor between 0.458-1.000 the selection of four or five chillers provide lower net present value than the selection of one or two or three chillers.
5. From conclusion in 1, 2, 3, and 4, it shows that at the maximum cooling load equals to 1000 ton, the maximum number of chiller should not be greater than three units when considering the net present value.
6. For the selection of two chillers, it is found that at load factor between 0.458-0.858 the selection of chiller in which one has a larger capacity than the other provides higher net present value than the selection of two chillers with equal size except at the load factor equal to 0.588.
7. At high load factor 0.925-1.000, there is no difference in the net present value for the selection of two chillers with difference sizes.
8. In case of selecting three or four chillers, the selection of one chiller that has a larger capacity than the rest provides higher net present value than the other types.

However, the conclusion shown above is based on the maximum cooling load of 1000 ton only. Therefore this conclusion must receive further investigation depend on the available larger size chiller’s data. Nevertheless the analysis illustrated can be adjusted when one would like to study a much larger size of refrigeration plant such as a district cooling plant.

5. Conclusion

Using the developed cooling equipment selection program enables the designing engineer to analyze several configurations of the refrigeration plant for the specified cooling load profile. This provides the guideline for making a decision to select an optimum refrigeration plant configuration both for engineering point of view through the characteristic of cooling load profile and for economic point of view through the net present value analysis. This approach provides more benefit to the designing engineer as well as to the project owner since the conventional way is to select the equal size of chillers for the sake of easy maintenance and operation or just concentrate only on the energy consumption of the chiller without considering the total energy consumption and cost. These energy consumption and cost definitely gain more and more important role when the project is getting larger and larger, especially when one mentions about the district cooling plant.

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