OPTIMIZATION OF HEATING, VENTILATION, AND AIR-CONDITIONING (HVAC) CHILLED WATER PLANT SYSTEMS.

by

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ABSTRACT

OPTIMIZATION OF HEATING, VENTILATION, AND AIR-CONDITIONING (HVAC) CHILLED WATER PLANT SYSTEMS.

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Heating, Ventilation, and Air-conditioning accounts for about 60% of the total energy consumed in commercial facilities including office buildings, hospitals, retail stores, warehouses, campuses, manufacturing facilities, medical facilities, etc. As the cost of electricity and energy continue to rise, building owners and facility managers continue to witness a rise in the Total Cost of Ownership.

Chilled water plant system is the largest consumer of energy in HVAC system consuming 75% of the total energy used in HVAC according to the Department of Energy. Operating chilled water plant systems at the recommended AHRI Standard 550/590 for performance rating of water chilling and heat pumps temperature set-points seldom results in optimized operation and cost savings, since factors such as operation schedules, site-specific conditions such as prevailing ambient conditions, part load operations, keep on changing. The aim of this project was to design an optimized heating, ventilation, and air-conditioning chilled water system for a 100,000 square feet facility complex in Houston, Texas.

By selecting a chilled water distribution system; chilled water temperatures, flow rate, and sizes; condenser water distribution system, condenser water temperatures, flow rate, and pipe sizes; cooling tower approach temperatures; and piping system optimization, a saving of 25% on the annual energy costs at peak load operations of the complex facility was obtained.

This analysis also showed that as the chilled water supply temperature is set upwards, the pump energy increases but the chiller energy and the cooling tower energy decreases resulting in a positive net system gain.

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GLOSSARY

Variables:

APPROACH: Design tower leaving water temperature minus WB

CHWFR: Chilled water flow ratio, actual flow divided by total plant design flow

CHWST: Chilled water supply temperature

CWFR: Condenser water ratio, actual condenser flow divided with plant design flow

CWRT: Condenser return water temperature (leaving condenser water temperature)

CDD65: Cooling degree day base 65^{o}F

DP: Differential pressure, feet of water degree-days base 55

Variables:

KW/TON: Chiller efficiency at AHRI conditions

GPM/HP: Tower efficiency per Ashrae 90.1

IPLV: Integrated Part Load Value per AHRI 550/590

NPLV: None-standard part Load value per AHRI 550/590

RANGE: Design tower entering temperature minus leaving water temperature

PLR: Plant Load ratio

TOPP: Theoretical optimum plant performance

WB: Wet-bulb temperature at 1% design conditions

WBDD55: Wet-bulb cooling degree-days base 55

LIST OF ILLUSTRATIONS

CHAPTER 1

INTRODUCTION

Energy use for heating and air-conditioning account for more than 25% of the primary energy consumed in commercial, industrial, and institutional complexes in the U.S. [1]. In most of these facilities, the central cooling and heating plants generate cooling and/or heating in one location for distribution to multiple locations within the facility where there is need for cooling or heating.

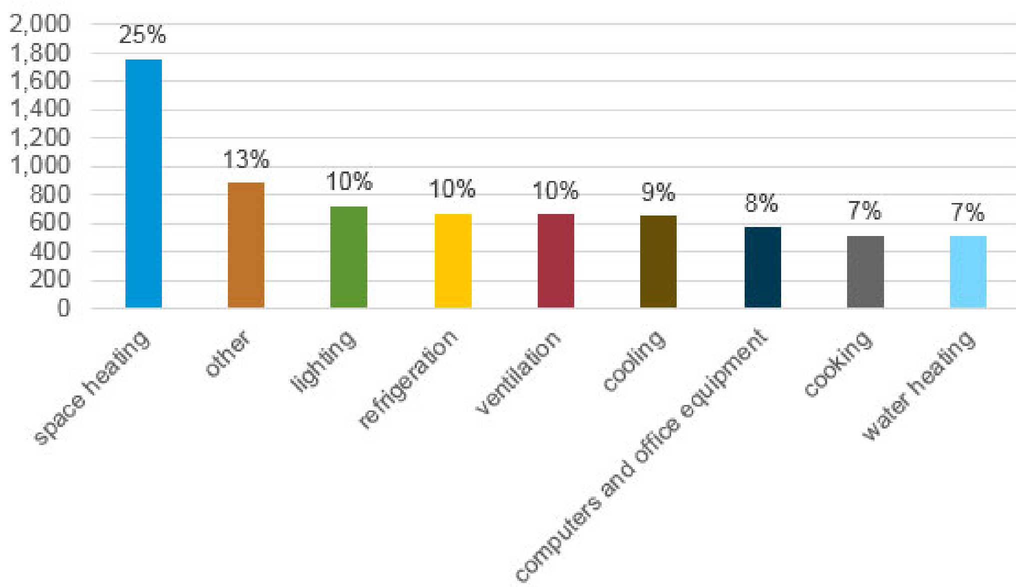


Figure 1-1 Energy use in U.S. commercial buildings [1]

Centralized systems are characterized by large chilling and/or heating equipment located in one facility or multiple smaller installations interconnected to operate as one. Though significant efforts have been made in the past 20 years to reduce the energy use of chillers and compressors, improving their efficiency from a COP of 4.24 to 5.67

(from 0.83 KW/ton to 0.62 KW/ton) [2]; chilled water systems remain one of the major energy consumers in heating, ventilation, and air-conditioning (HVAC) applications. There is therefore motivation for optimizing the design of chilled water plants to minimize first costs and operating costs (energy costs) over the plant's life cycle.

Chilled water plants have many characteristics that make each plant unique so that generalized sequence of control maximize plant efficiency are not readily determined [3]. Factors and variables that affects chilled water plant performance include:

- The full-load and part-load efficiency of each piece of the equipment in the plant (e.g. chillers, cooling towers, pumps)
- The number of each equipment and how they are staged;
- The design of the distribution system (e.g. variable flow versus constant flow, primary only versus primary-secondary);
- Weather
- Load profile.
- The control sequence such as chilled water temperature resets and differential pressure resets; and
- The pipe and valve sizing.

With so many variables, no single control sequence will maximize the plant efficiency [3].

1.1 Scope of Work

1.1.1 Objectives

The objective of this thesis is to design an optimized chilled water cooling plant for a 100,000 square feet Industrial facility complex located in Houston by analyzing the following options:

- Chilled water temperature resets and Condenser water resets
- Chiller sequencing and Variable chilled water pumping
- Energy storage systems.

1.1.2 Layout

This thesis is organized into five subsequent chapters. A review of the vapor compression cycle and the primary system components that make up the chilled water plant and energy efficient distribution system is presented in chapter 2. Chapter 3 provides information about optimization design, load analysis and estimation, optimization procedure and strategies, and plant optimized modeling.

In chapter 4 optimization results and discussions is provided, followed by conclusion in chapter 5.

CHAPTER 2

LITERATURE REVIEW

This section contains a review of the vapor compression cycle and the primary system components that make up the chilled water plant system.

2.1 Vapor compression cycle

Refrigeration cycles are used to transfer energy from a region of lower temperature to a region of higher temperature.

The most commonly used refrigeration cycle in HVAC applications is the vapor compression cycle [x]; though other equipment exist that work on absorption refrigeration cycle. The vapor-compression refrigeration cycle has four components namely the evaporator, compressor, condenser, and expansion valve as shown in figure 2-1.

In a vapor compression refrigeration cycle, the refrigerant in gaseous state enters the compressor at low temperature and pressure. It is then compressed by the compressor to the condenser temperature and pressure. Since this process requires work, an electric motor may be used. The compressors used can either be scroll, reciprocating, centrifugal, or screw type.

The hot refrigerant gas at high pressure is then passed through the condenser, where it cools down as heat is reject to either to the atmosphere in the case of air-cooled condensers, or water in case of water-cooled condensers. Heat rejection at the condenser coil takes place at constant pressure.

The high pressure, low temperature saturated refrigerant gas is then passed through a throttling or expansion valve where it expands and release pressure. At the end of the throttling cycle, the liquid refrigerant is then passed through the evaporator where it evaporates into gas as it absorbs the heat from the conditioned space of load and the cycle begins again.

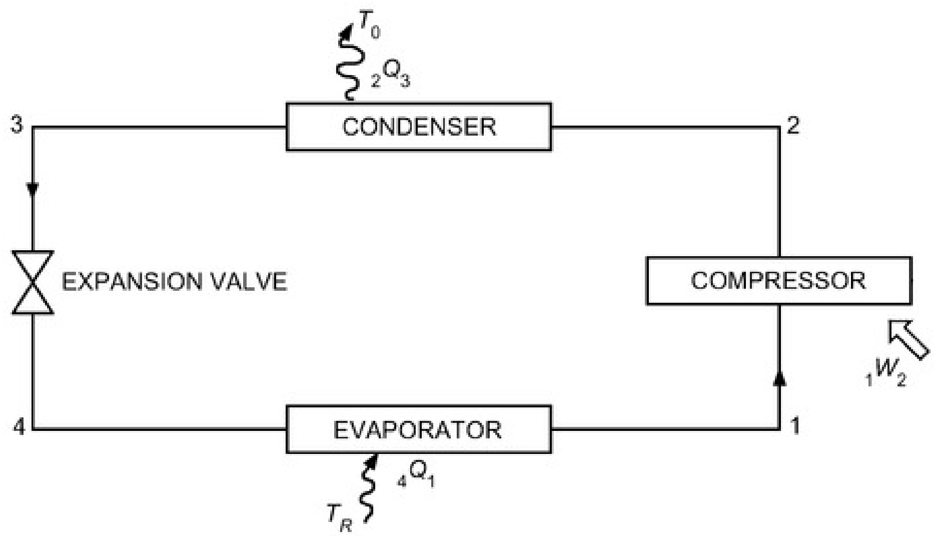


Figure 2-1 Single Stage Vapor Compression Refrigeration Cycle.

The performance of a refrigeration cycle is usually described by a **Coefficient of Performance (COP)**, defined as the amount of heat removed divided by the required energy input to the operating cycle:

$$\mathrm{COP} \equiv \frac{Q_{evaporator}}{W_{net\ input}} = \frac{h1 - h4}{h2 - h1}$$

Where h1, h2, and h4 are the enthalpy at points 1, 2, and 4 in the P-H, T-S diagram in figure 2-2. The higher the COP, the more efficient the refrigeration cycle.

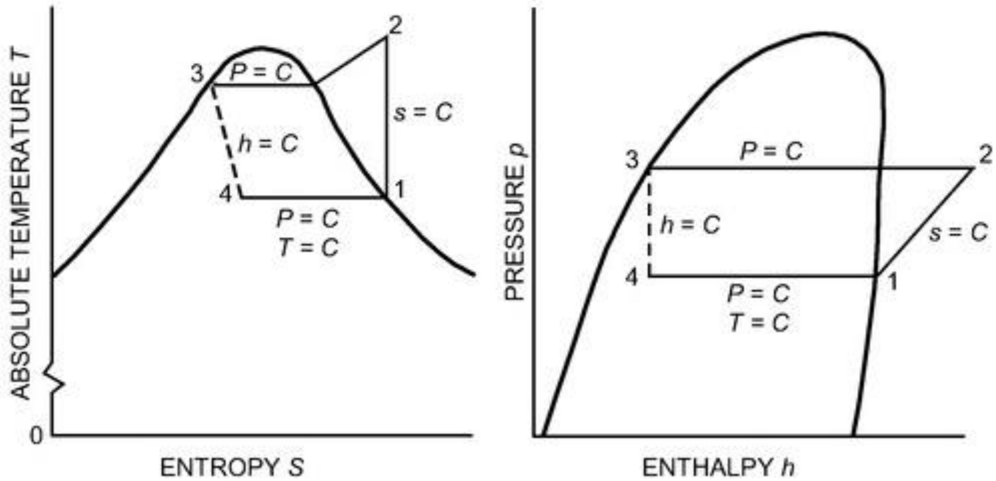


Figure 2-2 T-S and P-H diagram of Vapor Compression Cycle

2.2 <u>Primary components of Chilled Water Plant.</u>

In HVAC or process applications, the purpose of a chilled water plant is to produce cold chilled water which is then distributed via pipes, pumps, and valves to the loads, where a heat exchanger-for example, in a cooling coils in the AHUs-transfer heat from the hot air to the chilled water, which is then returned to the chiller. The primary components of chilled water plant include a chiller, cooling tower, chilled water and condenser pumps, water distribution system including pipes and valves, and the load that the load components such as cooling coils and/or air handling units.

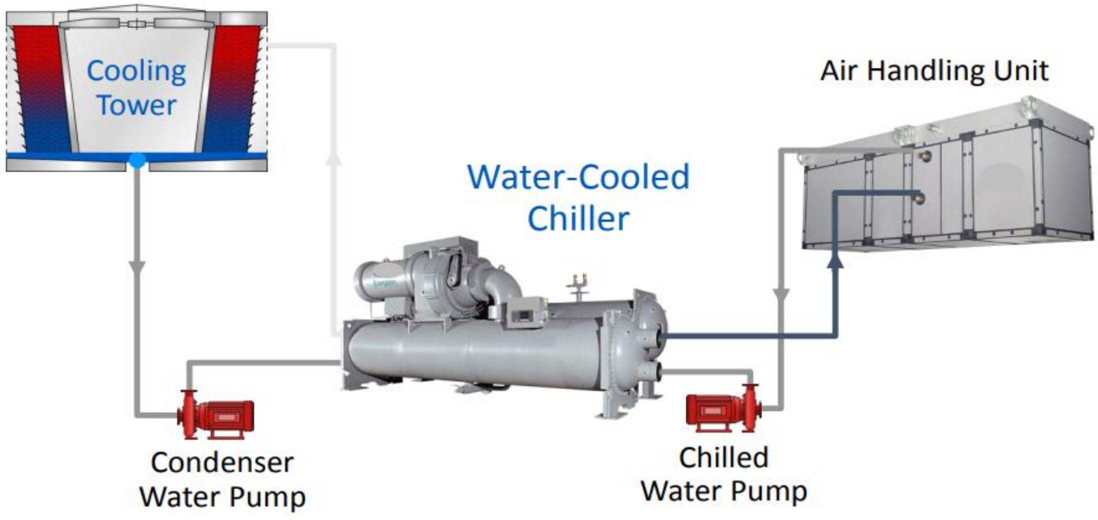


Figure 2-3 Chilled Water Plant system and components [12]

2.2.1 Chiller

The basic components of a vapor-compression chiller include one or more compressors, liquid cooler (evaporator), condenser, compressor drive(s), liquid-refrigerant expansion valve, and control devices.

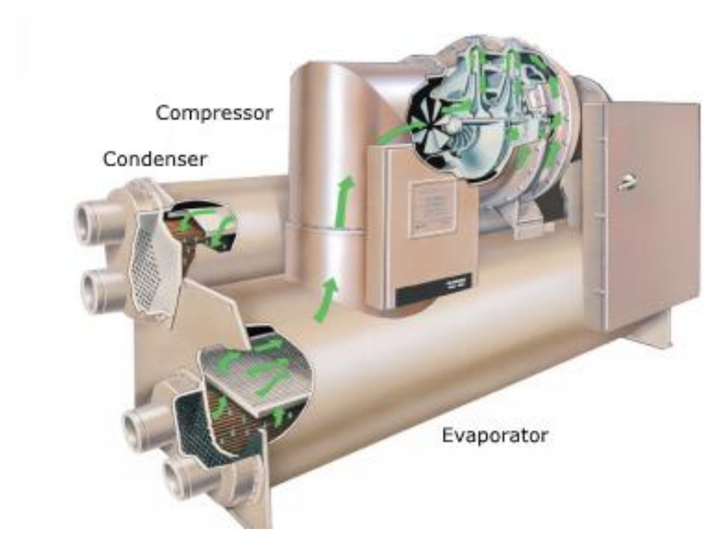
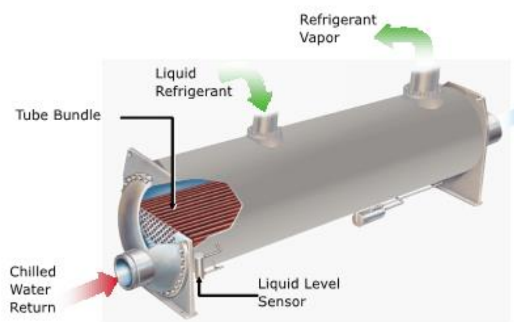


Figure 2-4 Typical Vapor-compression chiller.

The chiller evaporator section of a water-cooled chiller is a shell-and-tube, refrigerant-to-water heat exchanger. The evaporator can either be a flooded shell-and-tube type (Figure 1-3) where cool liquid refrigerants floods tube bundles through which chilled water is flowing; of direct expansion type (Figure 1-4) where the warm water fills the shell while the refrigerant flows through the tubes.



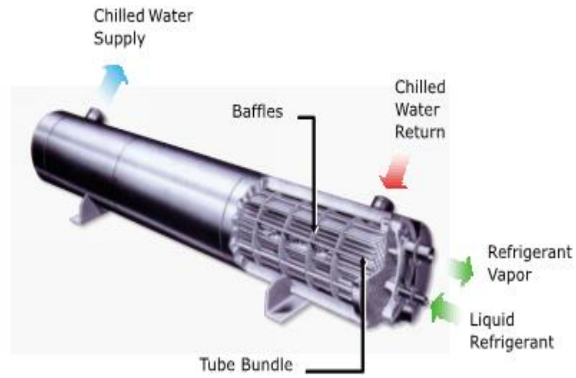


Figure 2-5 Flooded Evaporator

Figure 2-6 Direct-expansion Evaporator

The chiller condenser, which is a heat sink where heat is dissipated from the hot refrigerant gas can either be water-to-liquid heat exchanger in water cooled chillers or liquid-to-gas heat exchanger in air cooled chillers.

The compressor is the largest energy consuming component of the chiller. The type of compressor used in any chiller is determined by the chiller application and chiller load. Figure 2- [3] shows the liquid chiller availability range based on compressor type.

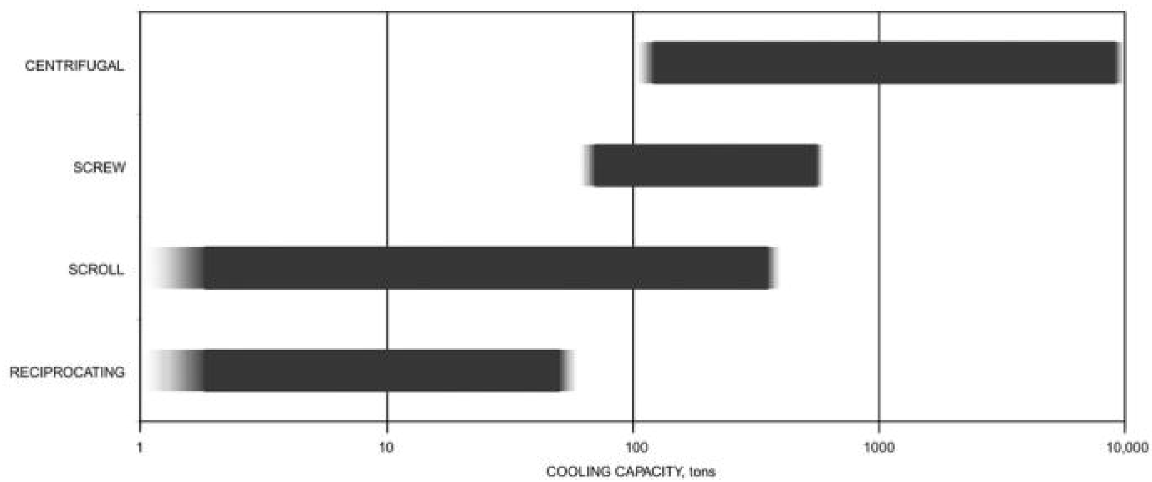


Figure 2- 7 Approximate Liquid Chiller Availability based on compressor type

2.2.1 <u>Cooling Tower</u>

Cooling tower cools water by a combination of heat and mass transfer. Water to be cooled is distributed in the tower by spray nozzles, splash bars, or film-type fill, which exposes a very area to the atmospheric air. The temperature of water and air as it passes through the tower and the psychometric process is shown in figure 2-1.

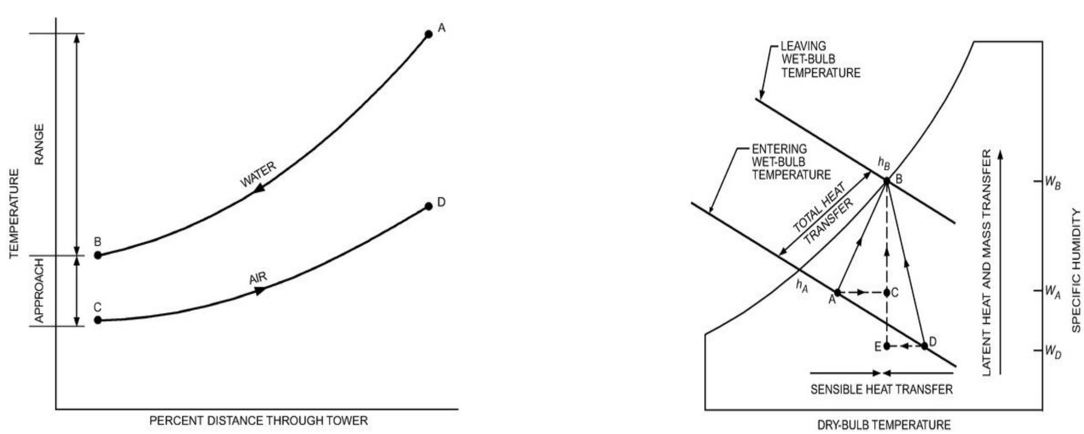


Figure 2-8 Temperature and Psychometric of air through cooling tower.

The difference between the leaving water temperature and the entering air wet-bulb temperature is called the **Approach** and the difference between leaving and entering water temperature is called the **Range**. The thermal performance of the cooling tower depends mainly on the entering air wet-bulb temperature.

- Approach = Leaving water temperature – Air wet-bulb temperature
- Range = Entering air water temperature – Leaving water temperature

2.3 Fluid Distribution System

Water distribution system is composed of pipping connecting the cooling tower and the load to the chiller; control valves that regulate fluid flow within the pipping system; and pumps that circulate both condenser water and chilled water. Generally, the pump is sized to overcome the static pressure within the system, pressure differentials across the valves, and friction loses along the pipe and at the coils [x]. The two common type of design system flow used for optimized design of chilled water systems are primary variable flow and primary/secondary variable flow. In primary variable flow, water flow rate through the system is varied either by a variable-frequency drive (VFD) or control valves while maintaining the minimum required pressure at the hydraulic most remote point. A typical fluid distribution system is shown in figure 2-2.

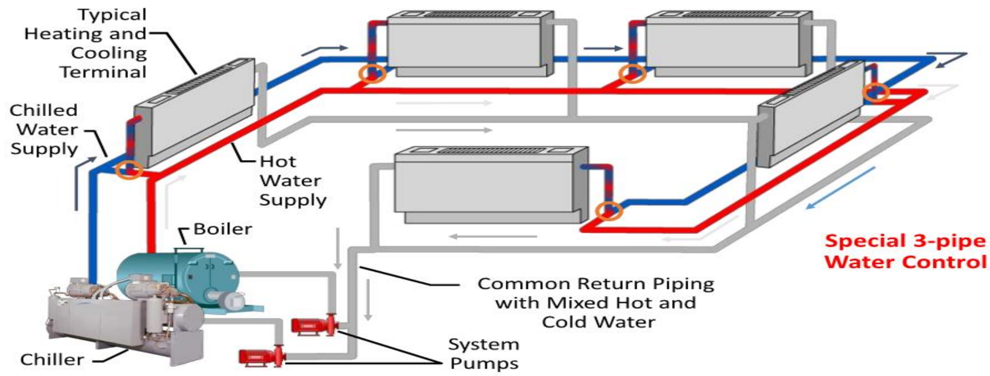


Figure 2-9 Typical Chilled water plant distribution system [9]

In the primary/secondary flow, the chiller is decoupled from the fluid distribution system. A variable-flow secondary piping system is used to distribute chilled water. The efficiency of the distribution system is affected by the designed flowrate, the pipe diameter, pipe lengths and pump heads.

CHAPTER 3

3.0 OPTIMIZING DESIGN

Chilled water plant peak loads and annual cooling load profiles, and how these loads vary with time are important parameters in the design of any cooling system because they affect the equipment capacity. The design loads determine the overall installed plant capacity including chillers, pumps, piping, valves, and towers. The cooling load is required to design the plant to stage efficiently.

This chapter covers plant load analysis and calculation procedure, chiller and tower modelling strategies for optimized design, and finally an optimized design scheme for this facility will be presented.

3.1 Load Analysis and Calculations

A cooling load profile is a time series of cooling plant loads and correlated weather data. Cooling load facilitate effective evaluation of competing design options as it determines plant configuration [2]. The factors that affect plant loads include:

- Weather conditions
- Building use: equipment within the building that generate heat
- Building occupancy
- Infiltration and moisture migration heat loads
- Fenestration heat gain

Because of the uncertainty inherent in the above factors that affect the facility load profile, there is always the risk to undersize or oversize a cooling plant, results of which has a direct effect on the overall costs of facility operation.

Currently, the two methods used to calculate heat loads are the energy balance method and the radiant time series method [2].

3.2 Optimization procedure

After the facility load profile is established, an ideal solution would be to optimize all plant components simultaneously, but this is not usually practical [4]. The near optimum plant design can be achieved by the following process [5]:

- Selecting chilled water distribution system.
- Selecting chilled water temperatures, flowrates, and primary pipe sizes.
- Select tower speed control options, efficiency, condenser water. temperature ranges and approach temperatures.
- Select chillers and pumps
- Finalize piping system design
- Develop and optimize control sequence.

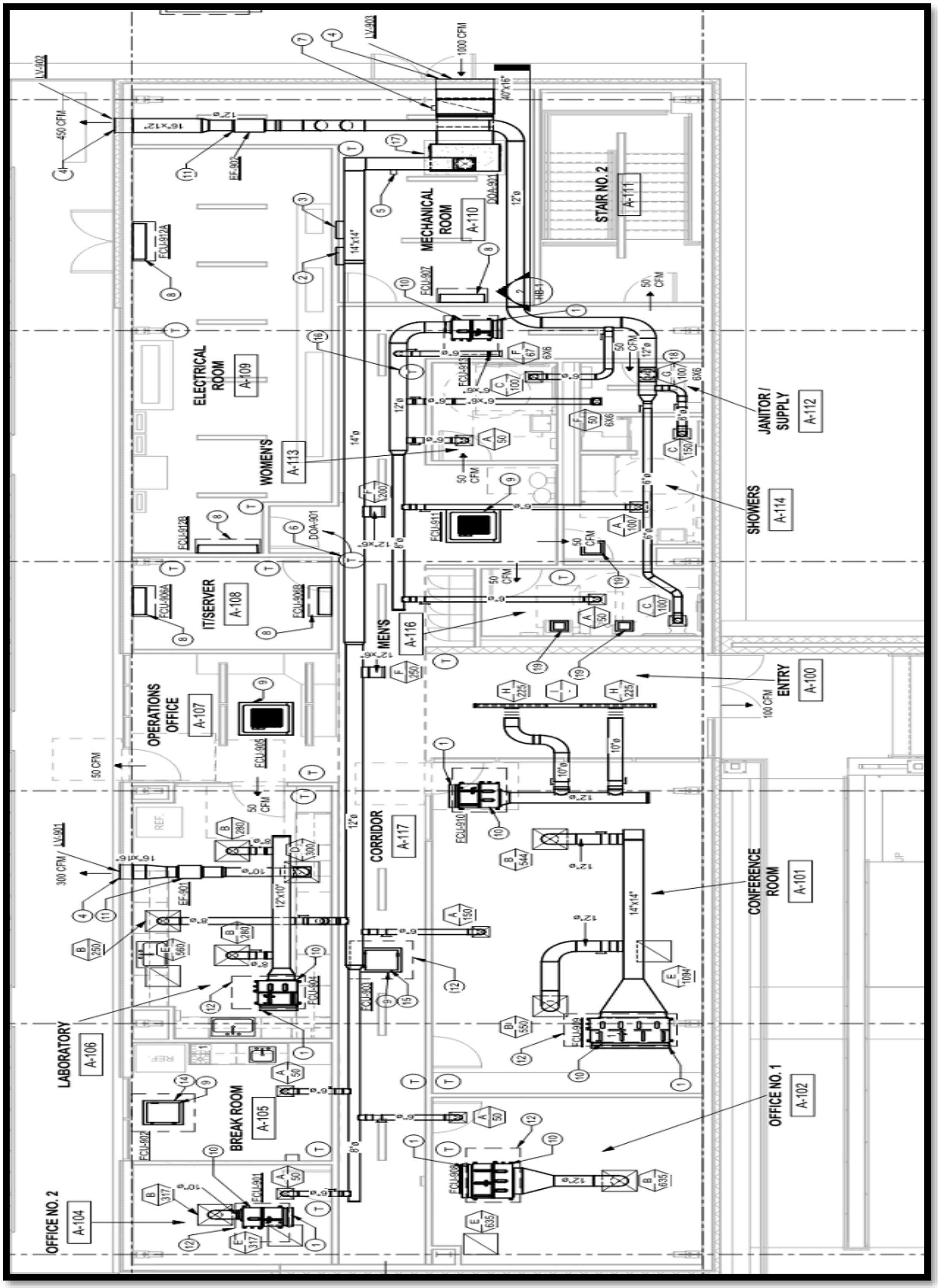


Fig 3-1 Manufacturing Complex facility

3.3 Plant Modeling

The optimized chilled water plant for the facility complex is shown below. Chilled water reset, condenser water reset, chiller staging, and variable pumping was used to arrive at the optimized design. The chilled water plant had the following components:

- CHWST Reset by two valve position from 42˚ F to 57˚ F
- Two stage chiller with 0.4, 0.6, and 0.75 KW/ton at AHRI conditions
- Towers with 3˚ F, 6˚ F, 9˚ F, & 12˚ F approach; 9˚ F, 12˚ F, & 15˚ F tower range; and efficiencies of 50,70, 90 gpm/hp.
- Condenser water pumps with VFDs.

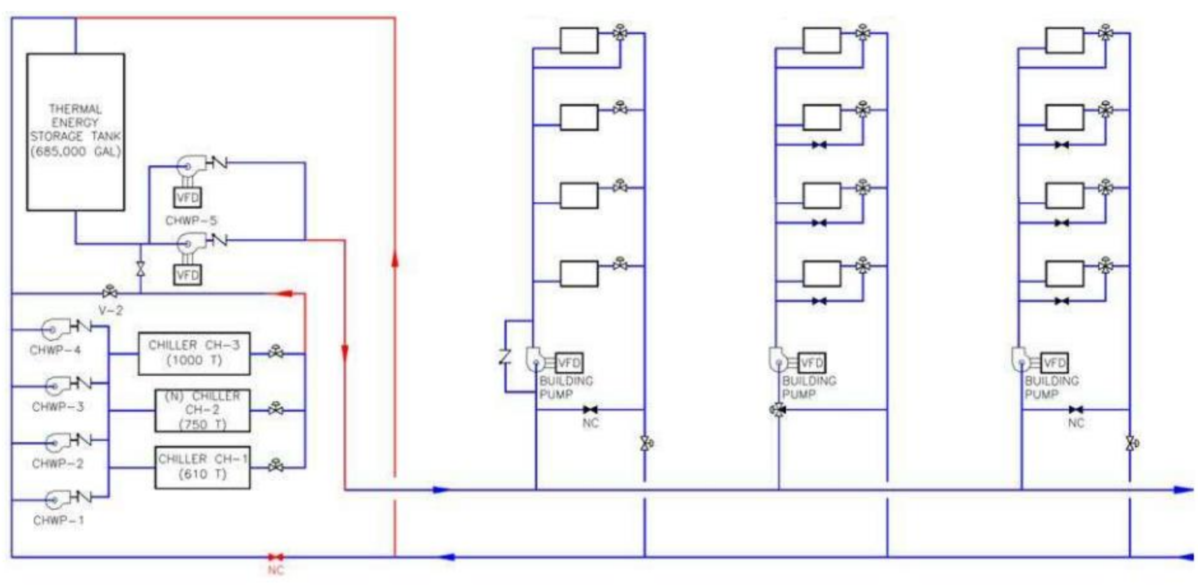


Figure 3-2 Chilled water plant for the complex facility.

CHAPTER 4

4.0 RESULTS AND DISCUSSIONS.

The following control equation coefficients obtained were obtained:

- Control CW return temperature to the set point is determined from equation 1:

  CWRT = CHWST + A*PLR + B …………………………………. (1)

  A = -70 + 0.0063*CDD65 – 0.0085*WBDD55 +1.74*WB +0.52*APPROACH – 0.032*GPM/HP.

  B = 16 – 0.0030*CDD65 + 0.0050*WBDD55 – 0.30*WB + 0.18*APPROACH – 0.016*GPM/HP

- Control CW flow ratio to the set point is determined from equation 2:

  CWFR = C*PLR + D………………………………………………. (2)

  C = 1.40 – 1.24E-05*CDD65 + 1.34*NPLV -0.0212*WB -0.012*APPROACH + 0.0775*RANGE.

  D = -0.167 + 7.04E-06*CDD65 - 0.120*NPLV + 0.0040*WB + 0.00140*APPROACH +0.00230*RANGE.

- One chiller is used when the PLR is less than SPLR determine from equation 3:

  SPLR = E*(CWRT – CHWST) + F………………………………. (3)

  E = 0.057 – 0.000569*WB – 0.0645*IPLV -0.00023*APPROACH - 0.000402*RANGE + 0.0399*KW/TON.

  F = -1.10 + 0.0145*WB – 2.14*IPLV + 0.0070*APPROACH + 0.0120*RANGE – 1.40*KW/TON.

These control sequence results only apply to this specific facility. No further analysis was done to validate it for similar climate conditions with thermal storage.

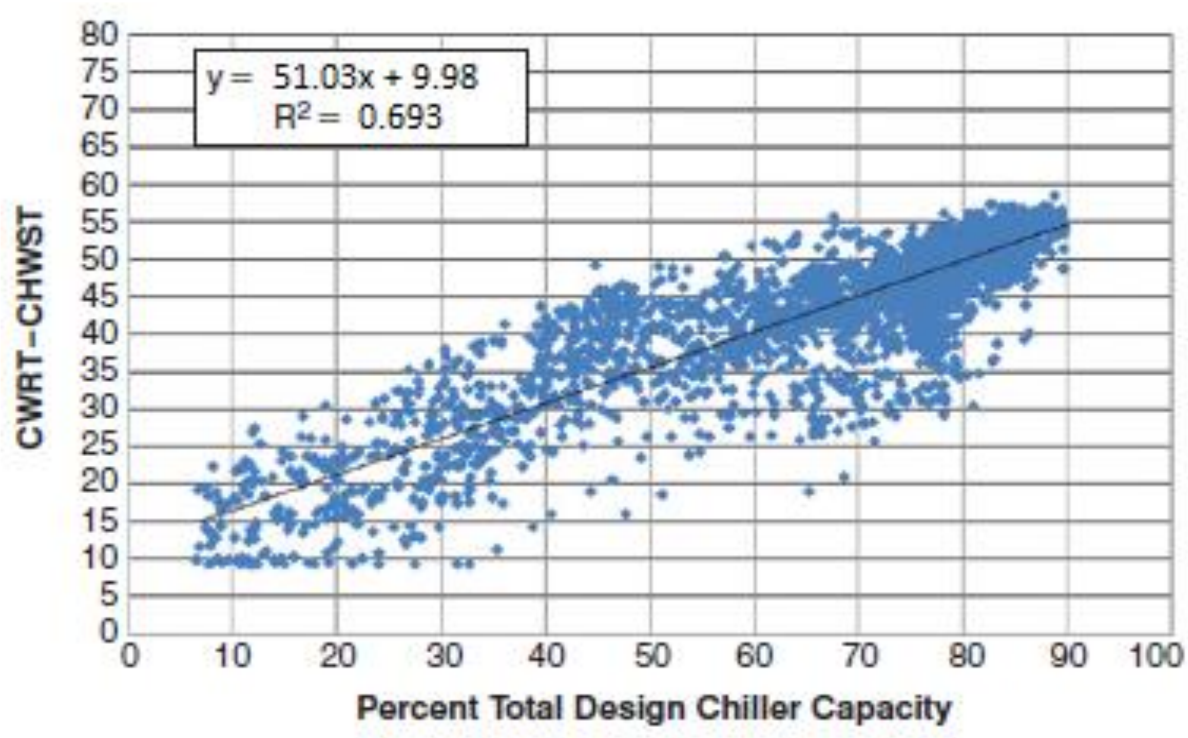


Figure 4-1 TOPP Optimum Condenser water supply temperature vs. wet-bulb temperature

The CWRT – CHWST difference which is an indicator of refrigerant lift can be fitted in a straight line as shown in figure 4-1 defined by:

CHWRT – CHWST = A x PLR + B

Where A and B the climate and plant design conditions. The optimum CWRT can be obtained by solving the above and for this facility, its 17˚ F. This shows that the CHWRT can be controlled by controlling the tower fan speed. This is usually done by oil bearing management design.

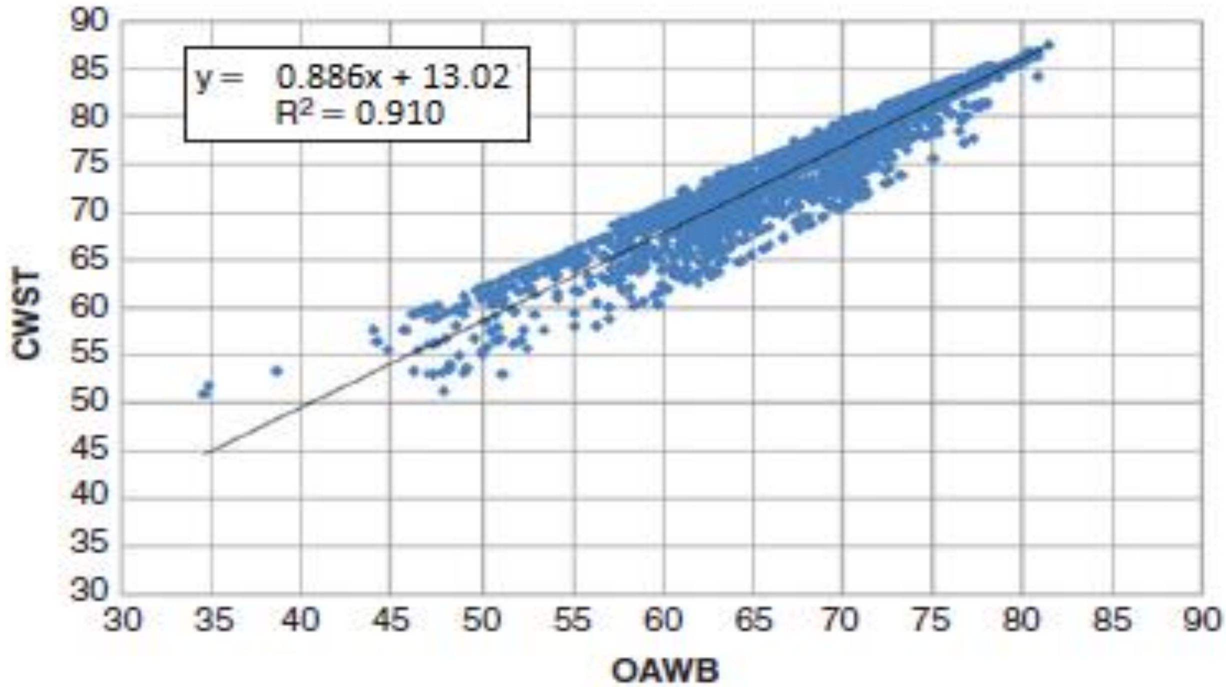


Figure 4-2 TOPP [CWRT – CHWST] Vs. plant load ratio

By resetting the condenser water supply temperature based on outdoor, the cooling tower can effectively be controlled as shown be the simulation from figure 4-2. The simulation shows good correlation between part load ratio and the difference between the condenser return temperatures.

From figure 4-4, the savings by the optimized design = 13.5 Kw X 4667 x $0.14/kwh = $8,900 annually.

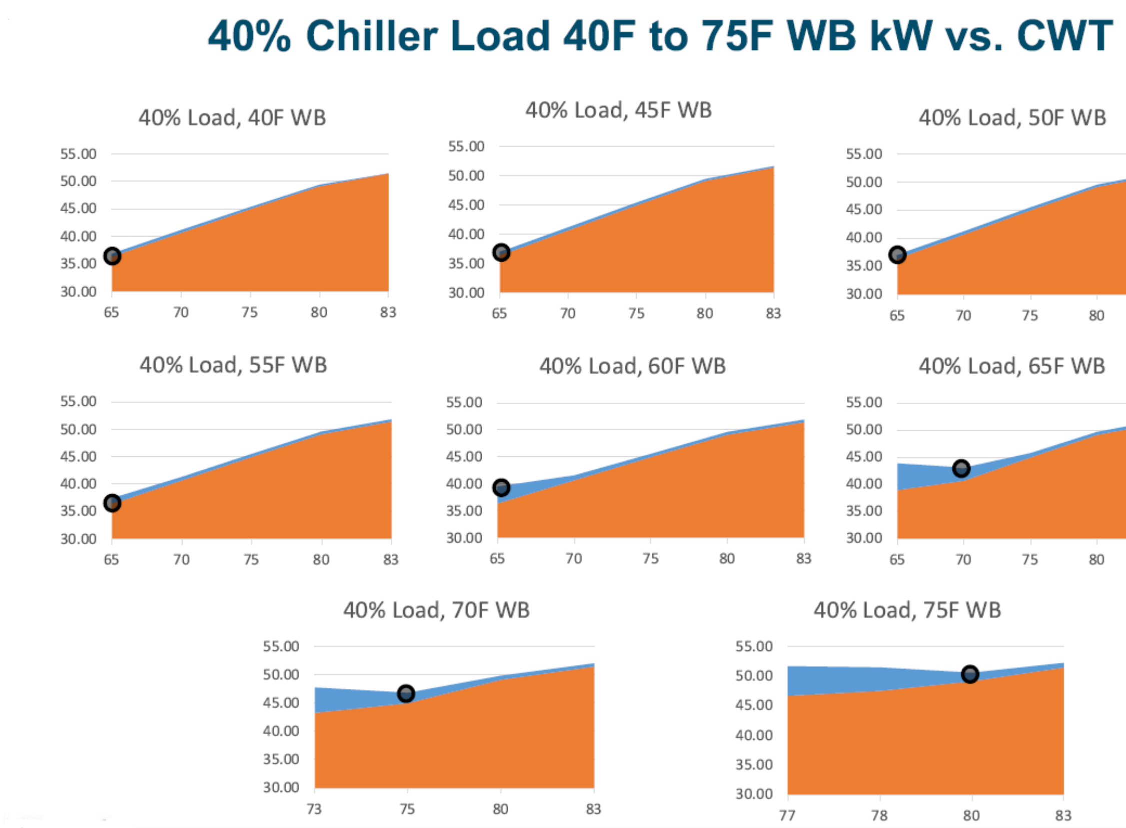
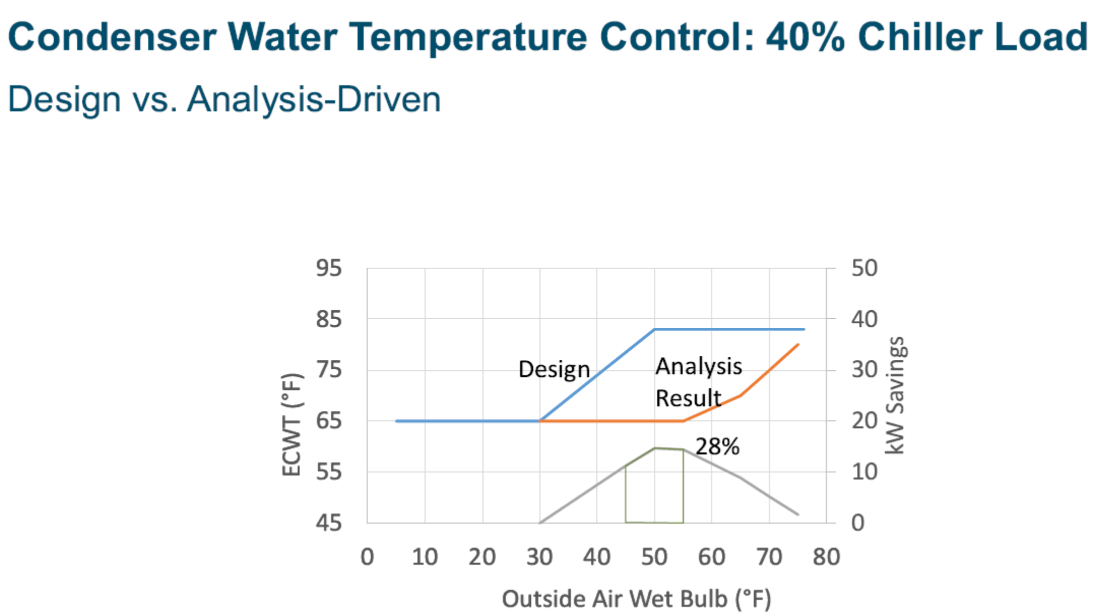


Figure 4-3 Chiller operation at part load



CHAPTER 5

CONCLUSIONS.

Though as demonstrated by the results of this research and the work of Taylor [2] that simulations of chilled water plants seldom indicate a good fit to optimal operation, implementation chilled water supply temperature resets with provides considerable savings on the overall energy usage of the plant during peak loads.

This research also confirms that operating chilled water plants at or near the AHRI standard 550/590 of 40 ˚F also rarely results in optimized operation. This research has shown that as the CHWST is set upwards, though the pump energy consumption will increase because of the need to increase fluid flow to balance the change in temperature, the chiller energy consumption is always reduced, resulting in a net positive gain and savings in energy costs.

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BIOGRAPHICAL INFORMATION

Cliff Odhiambo Nudi received his bachelor's degree (BSME) in Mechanical Engineering from the University of Texas at Arlington in August 2015. In September 2015, he began his graduate studies at the University of Texas at Arlington. His master's research focused on optimization of chilled water plant systems. Cliff received his MSc in Mechanical Engineering in December 2017. Cliff is a practicing engineer and his areas of expertise is the design of HVAC, fire, and plumbing systems.