TECHNIQUES FOR ESTIMATING COEFFICIENT OF PERFORMANCE OF INDUSTRIAL COOLING SYSTEMS

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ABSTRACT OF THE THESIS

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Chiller plant systems often have the highest consumption of energy in a facility. Hence, it becomes essential for estimating the coefficient of performance (COP) of an industrial cooling system to ensure efficient use of resources. Various chiller plant systems have been analyzed to establish techniques or methodologies for determining the COP. Performance degradation with age and recent new technologies create an enormous range of COPs from 2 to 8 or more. After analyzing, it is found that the critical parameter for determining the COP of any type of chiller plant system is the mass flow rate. Remarkably, many industrial cooling systems do not measure mass flow rate in any part of the chilled water system and therefore cannot calculate COP. Good energy efficiency practice then requires that techniques be developed to estimate mass flow rate in industrial cooling systems in situ, without shutting down the system and installing measurement equipment.

Three methodologies have been examined for measuring the mass flow rate of the condenser water loop. The first method looks at the cooling tower part of the condenser water loop to determine the mass flow rate of the condenser water by isolating some of

the valves. The second method makes use of pump curves with relation to the differential pressure to calculate the flow rate of either the chilled water or the condenser water. Lastly, an ultrasonic flow meter is considered as a means to determine the flow rate in a running system. The mass flow rate is then used in the estimation of COP of the chiller cooling tower system.

DEDICATION & AKNOWLEDMENT

This thesis is dedicated to my family, friends and faculty that were by my side throughout my master's program. I would like to thank Rutgers University facilities for allowing us to use Rutgers Livingston and Busch Campus as a living laboratory. In addition, I would also like to thank Attila Bartalis – Associate Director of Utilities for coordinating with everything required.

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Chapter 1. Introduction

Heating, Ventilation and Air-Conditioning (HVAC) is the technology that provides suitable air quality and thermal comfort indoors. HVAC systems form an integral part in medium to large office and industrial buildings, apartments, hotels, hospitals, vehicles and marine environments. Heating systems consists of heaters that generate heat via central heating in a building. Such systems contain a heat pump, boiler or furnace for heating air, water or steam in a central location and transferred to rooms with the help of pumps and pipes. Air-Conditioning systems consists of a chiller plant wherein chilled water is distributed to Air Handling Units (AHUs) that cools the air in their respective places. Ventilation systems remove odors, smoke, moisture, dust, bacteria or carbon dioxide and replenish with oxygen by replacing or changing air in any space. Out of these three systems, almost half of the consumption is done by the chiller plant itself[1] and hence, it becomes crucial to determine the energy performance of the chiller plant system. Chiller plant systems vary a lot as per their applications and are therefore categorized into numerous types based on chilled water distribution. This chapter analyzes the chiller plants and its types completely before proceeding with the examination of its performance as the measurement criteria of performance varies along with the type of chiller plant.

1.1 Literature Review:

According to Huyen Do et.al. [2], "In the USA, the heating, ventilation, and air conditioning (HVAC) system is usually the largest consumer in a residential building". Approximately 50% of the total power in a building is consumed by the HVAC systems [3]. The chiller plant equipment consists of cooling towers, chillers, chilled water and condenser water pumps supplying chilled and condenser water to the chillers. Any additional chilled water pumps if used for supplying chilled water to the AHU's are not included as they are not part of the equipment that produces cooling in these plants. A typical chilled water system schematic is shown in the below figure.

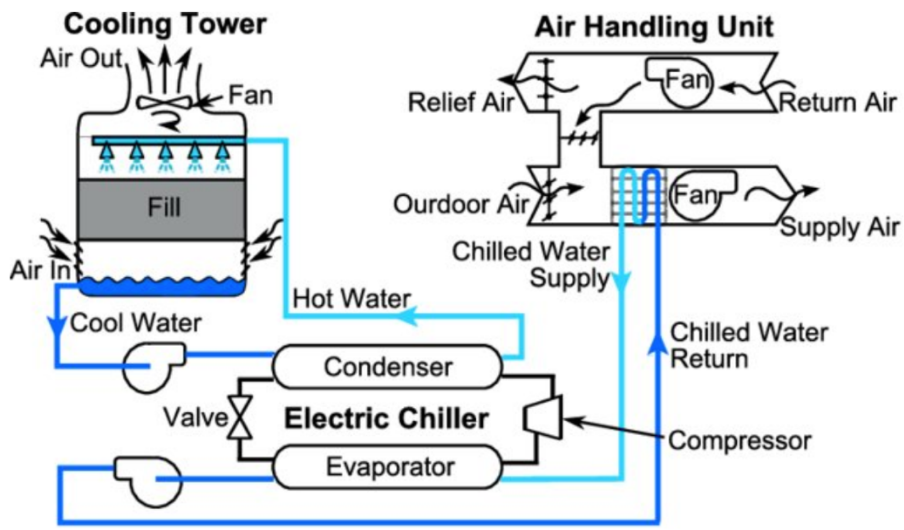

Figure 1. Schematic of a typical chilled-water system.[4]

According to [5], "The assumptions for building systems are based on theoretical values or equipment ratings based on static laboratory conditions rather than "real world" data reflecting part load operations, weather variations, operator inputs and system depreciation." These assumptions have a significant impact on the analysis of efficiency and related environmental impacts. However, when considering the relative frequency of part-load vs. full-load operating conditions and auxiliaries (e.g. pumps, cooling tower fans), the actual annual efficiency will be much different than that stated as per the design conditions [5]. A strong negative impact is created by the auxiliaries on the annual efficiency of the chiller plant system, especially if the pumps and fans are driven by constant speed motors rather than variable frequency drives (VFDs)[5].

Very few studies are available that focus on the total plant efficiency, including the auxiliaries[5]. In the USA, cooling system efficiency is commonly quantified in terms of COP or kW/Ton. One ton of cooling is equivalent to the removal of 3.516 kW or 12000 Btu per hour of heat. COP is the ratio of the refrigeration effect produced by the chiller against the amount of electrical energy that went into the machine to produce this[5]. More efficient systems have a higher COP.

This thesis aims at measuring the in-situ COP of the chiller plant system by developing methodologies that can be used during energy conservation assessments.

1.2 Types of Chillers

Chillers fall under two main categories: vapor compression and vapor absorption chillers. Both categories are further categorized according to three types of condenser systems: air-cooled, water-cooled and evaporatively-cooled. Although all three condenser types cool process fluids, how the system rejects the extracted heat differs. Air-cooled chillers have condensers that use the ambient air to cool the refrigerant, whereas water-cooled chillers use water for cooling the refrigerant in the condenser. Evaporative-cooled chillers have condensers that use the evaporation principle for cooling the refrigerant.

Vapor compression chillers consist of a compressor, condenser, expansion valve and an evaporator. They use a vapor compression cycle wherein a compressor pressurizes the refrigerant, which gets cooled in the condenser by the cooling water supply coming from the cooling tower. The refrigerant then passes through an expansion valve reducing its temperature and pressure to finally pass through an evaporator for absorbing heat from the chilled water loop. This chilled water then flows in the loop between the evaporator and Air Handling Units (AHUs).

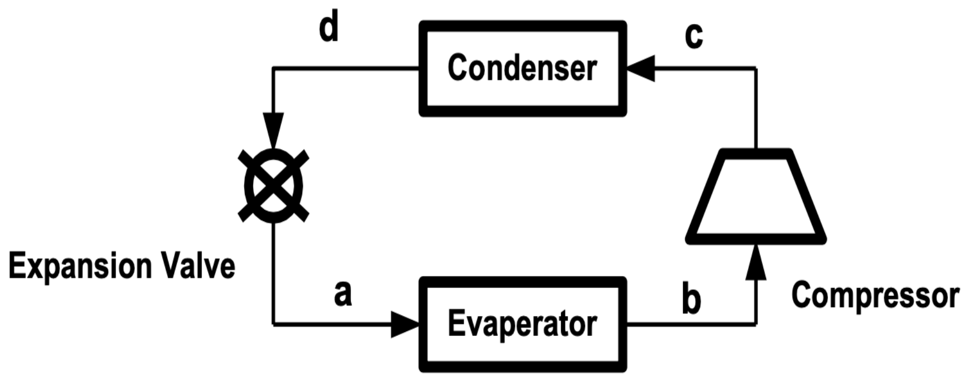

Figure 2. Vapor compression chiller and cooling tower plant system[6]

Absorption refrigeration chillers consist of a generator, pump, absorber, condenser and an evaporator. In the absorption cycle, the refrigerant vapor is dissolved in a liquid suitable for operation. The refrigerant fluid is then pumped around the cycle. Generally, there are two commonly used fluid pairings. In case of a smaller equipment, ammonia is used as a refrigerant and water as absorbent. For larger equipment, water is used as a refrigerant and lithium bromide solution as an absorbent. The Heat from the energy source is absorbed by the evaporator which evaporates some of the refrigerant vapor from the liquid absorbent. The vapor then passes into the absorber concentrating the diluted absorbent and releasing some energy. Outlet water from the cooling tower first passes through the absorber, collecting this released energy before going through the condenser. Some of the concentrated solution is pumped from the absorber to the generator, which raises the pressure to the condenser pressure. Heat (e.g., waste heat from factories, a fossil-fueled flame, solar energy) is added to the generator that raises the solution temperature evaporating the refrigerant vapor out of it diluting the solution. This weaker solution passes back to the absorber via an expansion valve equalizing the absorber pressure. This high pressure, high temperature vapor passes to the condenser rejecting heat to the cooling water from the tower and gets condensed back to saturated liquid at constant pressure. This refrigerant vapor then passes through an expansion valve reducing its temperature and pressure to flow in the evaporator. Cooling towers are used that supply cold water to condenser for cooling the refrigerant. COP of absorption chillers typically ranges from 0.5 to 0.9[7], [8]. There are two applications where absorption chillers can be advantageous. One is to use the absorption chiller during peak electric rates to improve the total system cost. They are also effective in combination with chiller plants as partially chilling at higher temperature increases the absorption chiller's efficiency and capacity while reducing the cooling load on an electric chiller. Operators can also preferentially load the absorption chiller during peak hours.[7], [8].

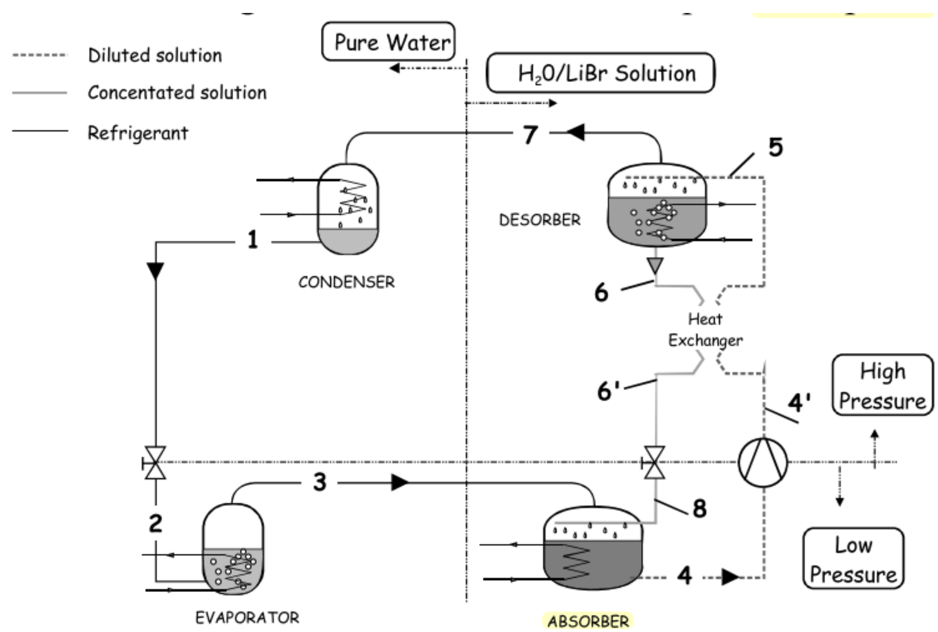

Figure 3. Absorption refrigeration chiller and cooling tower plant system[8]

1.3 Overview of Cooling Towers

The longstanding use of cooling towers within industrial HVAC systems, and the decades of literature corresponding to this topic indicates that cooling towers are quite important in the annual efficiency of the chiller plant system[9]. Cooling towers are a type of heat exchanger that lowers the temperature of hot water by allowing air and water to come in contact with each other, which induces the evaporation of small volumes of water. Usually designed for specific applications, cooling towers come in many types. Cooling towers are characterized into two main types: natural draft cooling towers and mechanical draft cooling towers. Natural draft cooling towers circulate air throughout them by natural convection phenomenon, which then cools the water. Natural draft cooling towers use the principle of evaporative cooling. Much of the heat is rejected by evaporating a portion of the circulating water, whereas a lower level of heat is also lost by heat transferring to the air.

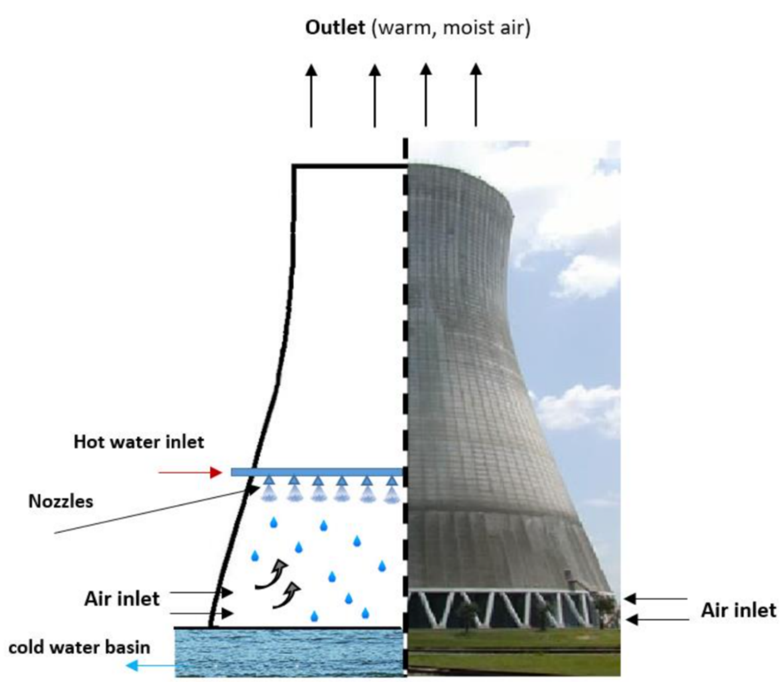

Figure 4. Natural draft cooling tower [10]

Mechanical draft or also called as induced draft cooling towers, come in two types, both based on the flow of incoming water: crossflow cooling towers and counterflow cooling towers. In crossflow cooling tower systems, the air flows horizontally while the water flows vertically. The hot water flows due to gravity in the distribution basins from the top of the tower. In counterflow cooling tower, the air flows vertically upwards, counter to the flow of water. Unlike natural draft, mechanical draft cooling towers have centrifugal or axial fans to circulate air throughout the tower.

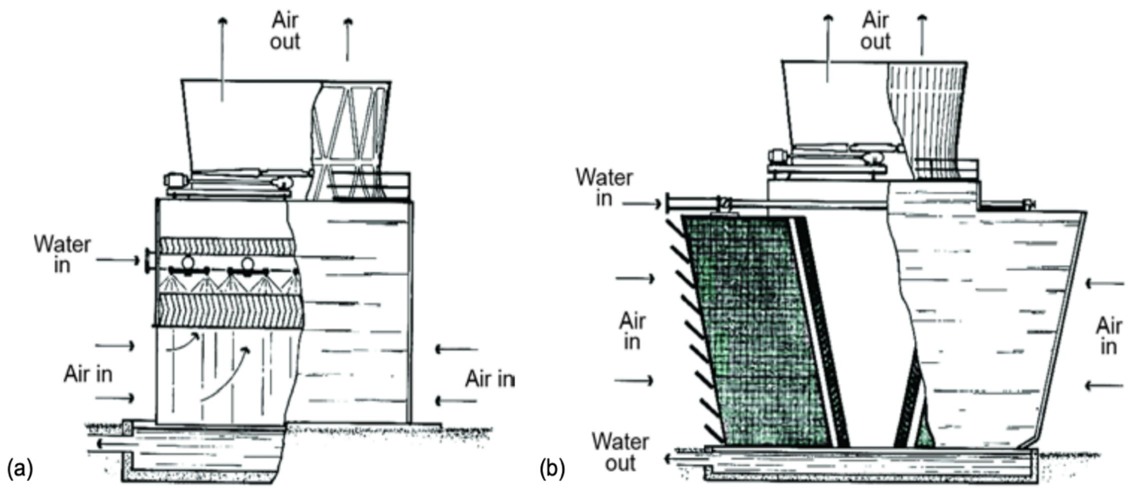

Figure 5. Counter-flow (left) and crossflow (right) cooling towers [11]

Both types of mechanical draft cooling towers consume more power than natural draft cooling towers; however, they are much more effective[10][11].

1.4 Factors affecting the efficiency of chiller plant system

The Factors that affect the efficiency of the chiller plant system are discussed below

- Type of Chiller equipment
- Sizing of cooling towers and chillers relative to seasonal loads
- Use of VFDs

- Maintenance history and age of equipment
- Pump arrangement
- Type of Chilled water system
- Condenser system operation

1.4.1 Chiller compressor type

The three types of compressors that are used in vapor compression chillers are rotary, reciprocating and centrifugal. Amongst these three, centrifugal chillers being most efficient are the likely option to be considered in buildings and facilities[12]. The table below indicates the size ranges of chiller compressor types.

Chiller types	Size Range in Tons	Size Range in KW
Reciprocating	50 - 230	175-800
Rotary	70 - 400	240-1400
Centrifugal	200 - 2500	700-8800

Table 1: Size ranges of Chiller compressor types[5]

A reciprocating compressor also called as the piston compressor is a positive-displacement compressor that uses a piston driven by a crankshaft to deliver gases at high pressure. A Rotary screw compressor uses a rotary-type positive-displacement mechanism. The gas compression process of a rotary screw compressor is a continuous sweeping motion, so there is very little pulsation or surging of flow. The more common type of rotary compressor used in water chillers is the helical screw type[5]. For commercial purposes, centrifugal compressors serve the need of large cooling loads.

Usually, the compressors are equipped with electric motors, but they can also be driven directly with steam or combustion turbines or reciprocating engines. Since 1990, there have been significant improvements in the part load efficiency of chillers, and with the chillers that use VFDs, maximum efficiency occurs at around 50% load[5]. The efficiency of chillers rapidly reduces below 40% loading[5]. The figure below indicates chiller COP using centrifugal compressors and screw compressors with the variation of load[12].

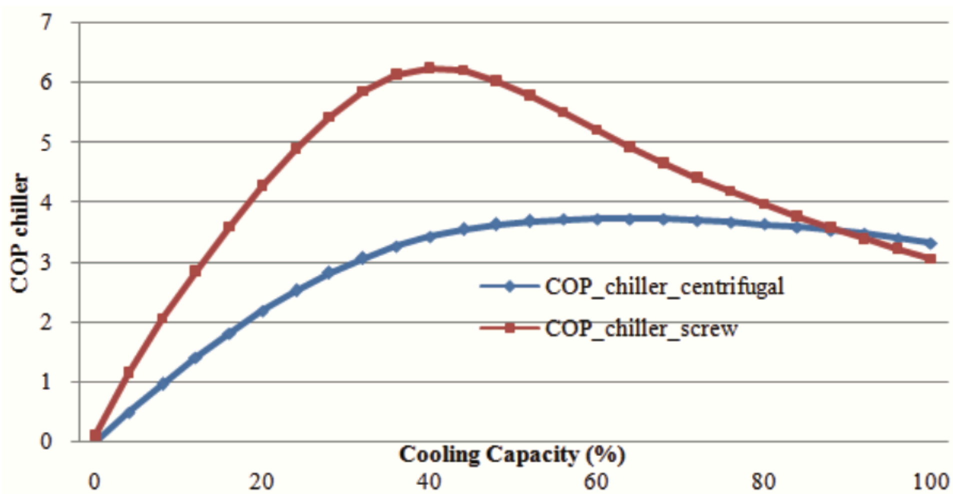

Figure 6. Performance curves of chillers operating at different loads [12]

At first, it seems like running chillers at part load results in higher energy efficiency; however, this performance does not account for the part load operation of pumps and fans in the condenser circuit, which can greatly reduce the total plant efficiency if they are not equipped with VFDs[5].

1.4.2 Sizing of cooling towers and chillers with respect to load

The conventional load estimation software and methodologies often overstake peak loads[5]. Considering the consequences of underestimating loads for the purposes for which these methods are designed, this is quite understandable. Design practices that contribute to such high load estimation include:

- Inadequate recognition of load variation within a particular building;
- Assuming peak wet bulb and dry bulb temperatures to be coincident;
- Using high design temperatures inappropriately for dry bulb and wet bulb; and
- Compounding additional safety factors.

This overestimation of the above parameters results in oversizing of chillers and cooling towers, which further contributes to the system operating at suboptimal levels during much of the year[5]. Lack of attention to the staging of chillers, poor operations in particular, can aggravate the problem.

1.4.3 Variable frequency drives

Apart from the chiller, condenser pumps and cooling tower fans have a considerable impact on the total efficiency of a chiller plant[5]. Annual performance of the plant is degraded when constant speed pumps and fans are operated at lower loads[5]. Variable speed drives or variable frequency drives (VFDs) are continuously been recommended to manufacturing facilities. These drives have higher capital cost; however, they can prove to be a cost-effective technique in the long run[5]. Significant impact on efficiencies of VFD installed centrifugal chiller plant is shown in table below.

Types of chiller plants	kW/ton		
	Low	High	Average
New all-variable-speed chiller plants	0.45	0.65	0.55
High-efficiency optimized chiller plants	0.65	0.75	0.70
Conventional code-based chiller plants	0.75	0.90	0.83
Older chiller plants	0.90	1.00	0.95
Chiller plants with design or operational problems	1.00	1.30	1.15

Table 2. Generalized centrifugal chiller plant efficiencies in S. California[5]

Significant improvements have been made over the past decade in the part-load efficiency of commercial chillers[5]. Chillers part-load performance is represented in the below figure 7 based on certain fixed entering condenser water temperature (ECWT) as the load varies. The efficiency of older chiller compressors drops greatly at lower loads for a fixed ECWT[5]. However, modern constant-speed chillers have very little efficiency degradation until the load drops to about 40%[5]. With the installation of VFDs, efficiency is maximized at about 50% loading[5]. These data points are only for chiller compressor. Cooling tower fans and condenser pumps are not taken into consideration[5].

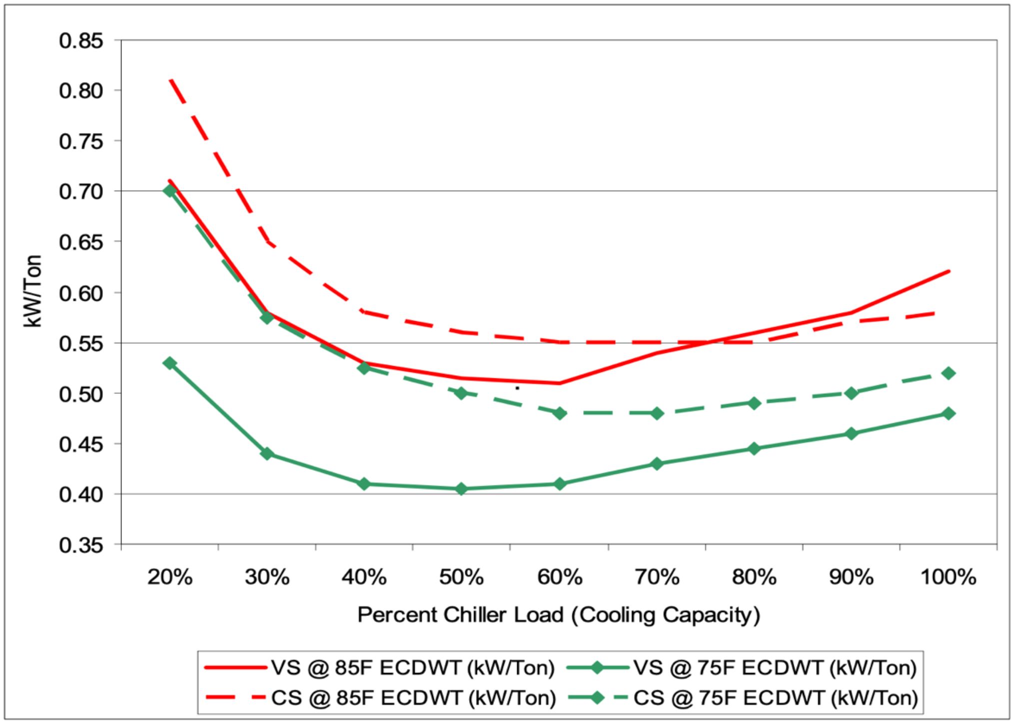

Figure 7. Part-load efficiency of variable-speed and constant-speed chiller compressors at fixed ECWT [5]

1.4.4 Age and Maintenance

Older chillers were typically designed for lower efficiencies[13]. The ageing of the chiller is affected by system maintenance. The ageing effect is delayed with the help of annual maintenance while no maintenance ages the equipment sooner[13]. The primary ageing factors of concern for chillers include vibration, excessive pressures and temperatures, chemical attack, thermal cycling and poor-quality cooling water[13]. Moisture, non-condensable gases and other contaminants within the refrigerant containment accelerates the ageing effect [13]. Underloading of chillers and excessive start/stop can cause rapid ageing[13]. Corrosion and fouling of condenser and evaporator tubes is also an important factor causing ageing of the chiller system[13]. The principal cause of chiller failures is lack of monitoring[13]. Trending and recording of operating temperatures and pressures on a daily basis becomes important and the refrigerant chemistry and lubricant oil should be analyzed routinely. Omission of scheduled maintenance and human errors should be avoided. Most failures can be minimized or eliminated by monitoring equipment and following vendor procedures carefully. Equipment performance should be trended and recorded. Routine maintenance staff should be well-trained. Maintenance and major overhauls, which require opening of refrigerant containment section should be performed by experienced and well-trained technicians. A misaligned or damaged part or even a small amount of contamination can cause severe problems in the operation of chiller[13]. It becomes important to keep equipment internals clean and prevent leakage of air, water and other contaminants into the sealed refrigerant containment[13].

1.4.5 Pump Arrangement

In chilled water systems, pumping arrangement plays a significant role when sequencing of chillers is required as per the cooling load. There are two ways to arrange pumps: tandem and headered as shown in the figure below.

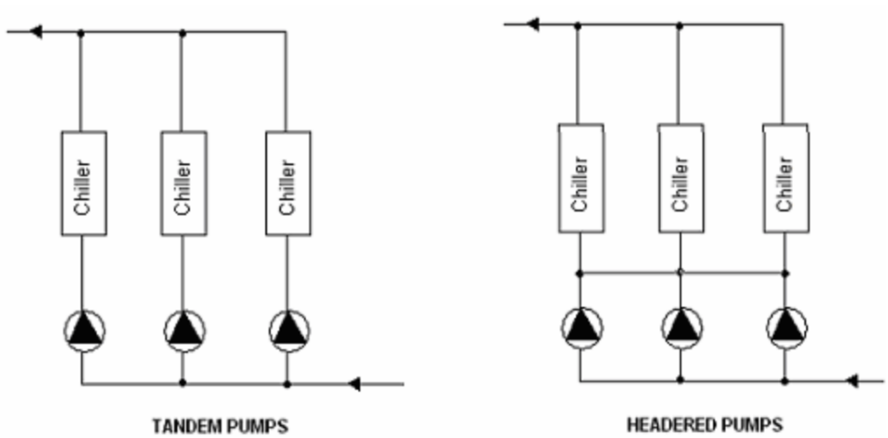

Figure 8. Pump arrangement types[14]

In tandem arrangement, each pump is dedicated to its respective chiller and whenever a particular chiller is operating its dedicated pump should be operating too[15]. Apart from its simple arrangement, it also proves beneficial to have less number of chillers operating to save pump power [16]. The disadvantage of such arrangement is that standby pump should be installed to every chiller, which becomes a very costly affair. For chiller plants that do not have standby capacity, this arrangement can cause a chiller to fail if one of the pumps fails[14].

In case of headered arrangement, discharge of multiple pumps is connected to a common manifold before the flow enters the chiller. Such arrangement gives plant operators the ability to operate any chiller with any primary chilled water pump. It also gives ability to operate more than one pump for a single chiller. Operators can have only one standby pump for the entire setup. The major disadvantage of headered arrangement is that an entire plant can fail due to the failure of single pump. For example, consider a typical plant having three manifolded pumps and three chillers with only two chillers and two pumps operating. If one of the pumps fails, then the flow rate drops across each chiller significantly at the time of pump failure[14]. The chiller's flow switch gets tripped due to this sudden flow rate drop across the evaporator even before the building control software turns on the backup pump [14].

1.4.6 Types of chilled water system

A chilled water system is a cooling system used to provide space cooling by circulating chilled water throughout the building. The objective behind selecting chilled water pumping system is to provide required cooling capacity based on its application, make efficient use of refrigeration capacity in the plant and also for minimizing the usage of pumps. In HVAC systems, pumping usually draws around 15% to 20% of the total annual plant energy consumption[17]. Conventionally, regardless of the demand load, chilled water plants circulate water at constant flow rate [14]. Air-conditioning systems reach peak load for only few hours in an entire year. Hence, a considerable amount of energy is wasted by continuous running of pumps at constant speed. Due to this, retrofitting the existing pumps with VFDs is taken into consideration while new pump systems are designed with the VFDs at the time of installation.

Chilled water pumping systems are divided into two categories.

1) Constant Primary Flow Chilled Water Systems
2) Variable Primary Flow Chilled Water Systems

1.4.6.1 Constant Primary Chilled Water System

A constant primary chilled water system is the most simplified chilled water distribution system where a fixed amount of water is circulated at all times by a set of constant flow pumps. During part load conditions, flow is restricted through the air handler cooling coils by bypassing some water with the help of a 3-way control valves. Even then, the total quantity of flow returned to the chiller remains constant. The below figure shows the constant flow chilled water system.

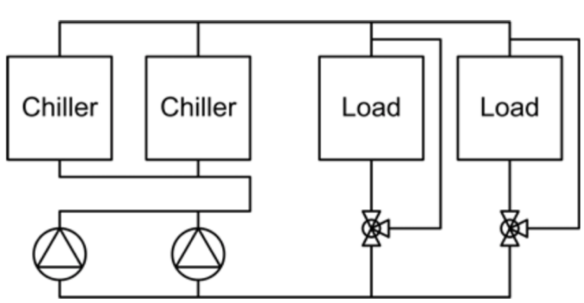

Figure 9. Constant flow chilled water system[18]

Flow rate in GPM is determined as per below equation for peak design conditions in case of constant flow systems.

Chiller Capacity (BTU/hr) = GPM x 500 x ΔT, where ΔT is the difference in temperature between the entering and leaving chilled water[19].

ΔT varies in response to the load that is (BTU/hr). As discussed above, since the peak load only happens for a few hours in an entire year, some part of the chilled water flow rate will always be bypassed through the 3-way valve. If high quantity of chilled water is bypassed, then it mixes with the leaving water coming from the cooling coils and yields lower chilled water return temperature to the plant. As the supply water temperature is fixed to a setpoint, the overall differential temperature ΔT across the chiller gets reduced. This is termed as low delta-T syndrome in HVAC industry[20]. Low delta-T syndrome can cause major problem for constant flow system by wasting its useful energy. Due to this, the chiller will always be loaded less than the capacity actually required. Hence, for overcoming the capacity deficiency, the plant operators switch on additional chillers and pumps associated with them. This causes the entire chiller plant operation to become inefficient. To overcome such a scenario, variable flow systems are used for increasing the efficiency of the chiller plant system.

1.4.6.2 Variable Primary Flow System

In a variable primary flow system, chilled water flow varies throughout the loop along with the chiller evaporators[21]. The entire flow is supplied by the variable primary pumps according to the cooling demand of the chillers. The pumps in the variable primary system maintain its flow as per the set differential pressure or ΔP. ΔP varies when the 2-way control valves of air-handlers or fan coils operate in response to varying loads. Accordingly, to restore the ΔP, the controller varies the pump speed[21]. The below figure shows typical Variable primary flow system arrangement.

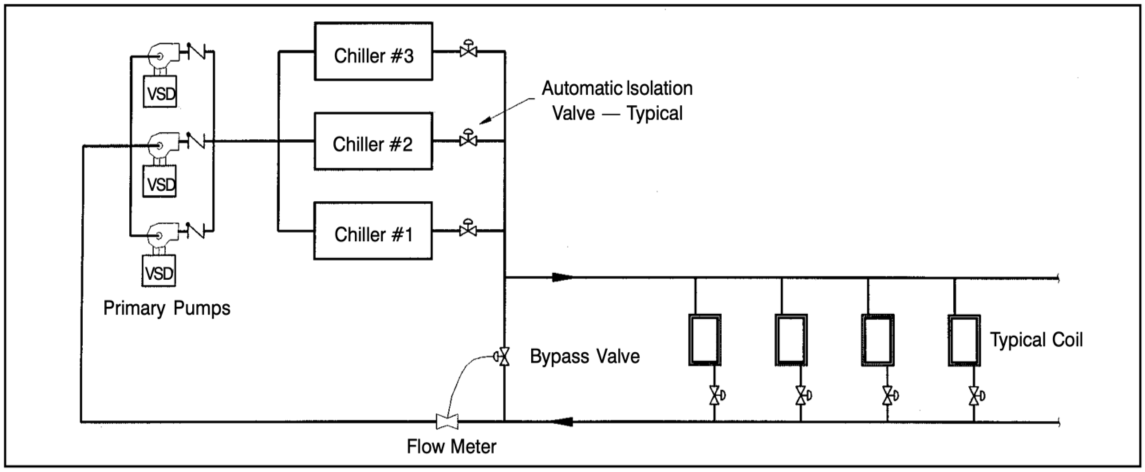

Figure 10. Variable Primary Flow System[22]

Variable primary flow systems do not have a neutral bridge dividing the plant into primary and secondary loops. Hence, there is no mixing of supply and return water as the flow is better matched to the cooling load with the chiller plant.

1.4.7 Condenser System Operation

The heat absorbed from the chilled water in the evaporator loop by the refrigerant along with the compressor work done is rejected into the condenser water loop[23]. A typical condenser water loop is shown in the below figure.

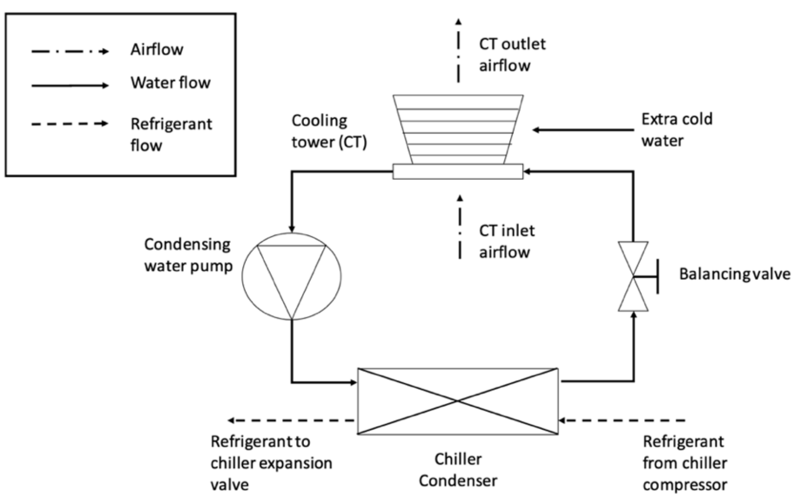

Figure 11. Typical condenser cooling tower loop[24].

The condenser water from the chiller flows to the cooling tower and back. The water from the cooling tower is pumped again to the chiller and the cycle repeats. The heat absorbed by the condenser water is rejected in the cooling tower.

1.4.7.1 Impact of scale buildup

Condenser water pumps can be of two types: constant flow pumps and variable flow pumps. Similar to chilled water pumps piping arrangement, condenser water pumps also have dedicated pumping and headered pumping systems. Retrofitting a VFD to an existing plant is a concern of scale buildup in the condenser barrel owing to low fluid velocity[25]. Mineral scale in water gets deposited and begins to build up in the condenser barrel increasing the head and reducing the flow rate[26]. The below figure represents the variation in the performance due to change in flow rate caused by the fouling effect in the condenser.

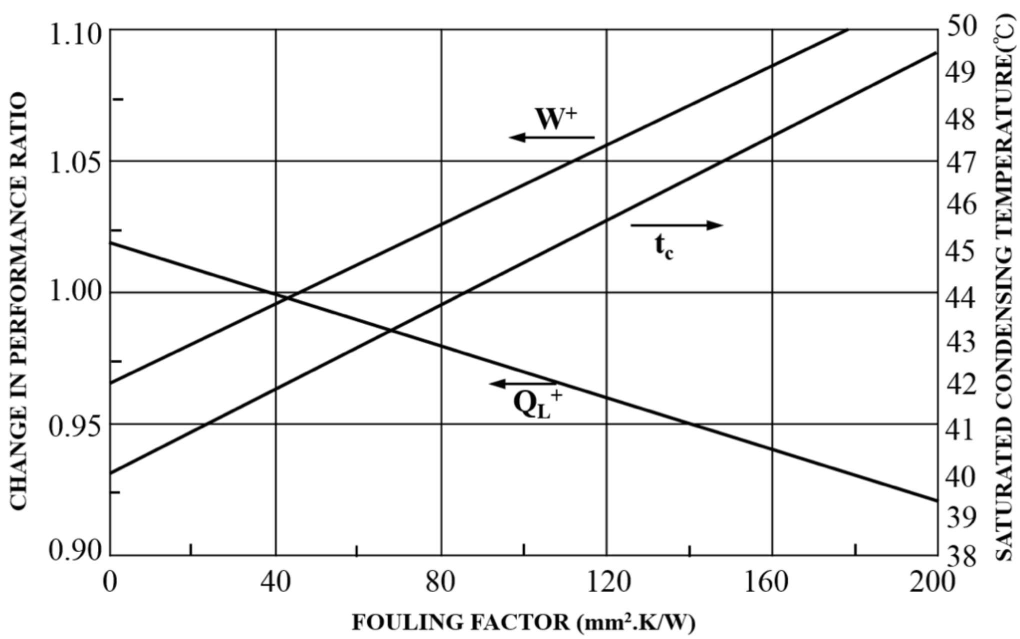

Figure 12. Variation of performance due to fouling factor[26]

Performance of the chiller drops as the deposits increase overtime in the heat transfer surfaces. Chillers have a low flow prevention system in order to avoid such problem[26]. Modern chillers nowadays have a minimum condenser water flow of 30%-50% of the maximum condenser water flow[26].

1.4.7.2 Condenser water components and its impact on Chiller performance

The condenser water system components consist of cooling towers, condenser water pumps and chillers. The cooling of the condenser water in the cooling tower depends on the web bulb temperature outside, flow rate of the pumps and the cooling tower fan speed[27]. The below table indicates an increase in delta T or range (temperature difference between entering and leaving cooling tower water) with a reduction in flow rate according to AHRI and GreenGuide recommendation.

Condition	Load (%)	WB (°F)	Range (°F)	Flow (gpm)	Approach (°F)	LWT (°F)	EWT (°F)	Fan speed (%)	Tower power (hp)
AHRI flow rate	100	78°F	9.3°F	2100	7	85°F	94.3	100	40
Same tower, GreenGuide recommended flow rate	100	78°F	14°F	1400	5.1	83.1°F	97.1	100	40
Oversized cooling tower (37% more cost)‡	100	78°F	14°F	1400	5.5	83.5°F	97.5	100	20

Table 3: Cooling tower operation with reduced flow

The chiller compressor power depends on the pressure difference or also called as lift between the evaporator and condenser refrigerant pressure. The evaporator refrigerant pressure depends on the leaving chilled water temperature whereas the condenser refrigerant pressure depends on the leaving condenser water temperature or entering tower water temperature[27]. It can be analyzed from the above table that reducing the flowrate increases the entering tower water temperature. Even though reducing the flowrate decreases condenser pumps and cooling tower power consumption; however, the chiller power increases due to increase in leaving condenser water temperature[27]. In order to set up an optimal point to have an improved overall efficiency, determination of performance of each condenser water component becomes essential. Out of these, cooling tower fan and pump loads can be known my measuring their kW consumption. However, determination of chiller COP becomes the challenge for optimization.

1.5 Coefficient of performance (COP)

The COP of a vapor compression chiller plant is the refrigeration effect produced by the chiller against the amount of electrical energy required to produce that effect. The refrigeration effect is basically the cooling load denoted by

$$Q = c_p \, m_{chw} \, (T_{chw,ent} - T_{chw,lea}), \quad (1)$$

where Q denotes cooling load, cp is the specific heat of water, m_{chw} is the mass flow rate of chilled water that flows in the loop between evaporator and AHUs, $T_{chw,ent}$ is the temperature of chilled water entering the evaporator and $T_{chw,lea}$ is the temperature of chilled water leaving the chiller. The electrical energy is consumed by the compressor, which is denoted by W_{comp}. Hence, the COP of the chiller is calculated as

$$COP = Q/W_{comp}. \quad (2)$$

The chiller control panel shows the temperatures of entering and leaving chilled water as well as the electric power supply required for the compressor. The only unknown that remains is the mass flow rate of the chilled water system. The chiller control panel usually sets the condenser water temperature setpoint, $T_{cw,set}$ according to the design conditions. The chilled water loop is always insulated to avoid any variation in temperature. Along with the pipes, the chilled water pumps are also completely insulated. Hence, it is not quite feasible to estimate the mass flow rate of the chilled water loop. If the chilled water pump's design characteristics and model number are noted at the time of installation, the mass flow rate of the chilled water can be measured with the help of pump curve. This research focusses on different methodologies if the mass flow rate of chilled water loop cannot be measured by the above technique. These methodologies focus on measuring the mass flow rate of condenser water flowing in the loop between the chiller and the cooling tower. The temperatures of entering and leaving condenser water are displayed on the chiller panel. If the mass flow rate is estimated, the total heat that is rejected by the refrigerant in the condenser water can be calculated. This heat comprises of the building heat absorbed by the chilled water loop and of the compressor work that is done on the refrigerant. Since, the compressor work is known from the chiller panel, the evaporator load can be estimated, and therefore, the COP can be measured. So, the real problem in the estimation of COP is the condenser water mass flow rate measurement. Majority of the facilities are not equipped with mass flow meters. In such cases, estimating mass flow rate of the running system becomes difficult. It is possible to increase the chiller plant efficiency by continuously optimizing the control parameters, such as building load and the wet bulb temperature, during the operation. For this purpose, real-time measurement of COP becomes extremely important.

1.6 Conventional methods of finding the mass flow rate.

Mass flow rate can be measured by an orifice plate, venturi tube, flow nozzles, pitot tube and mass flow meters. The major problem with the orifice plate is that it bends after operating for a certain time[28]. A mass flow meter, also called an inertial flowmeter, is a device that measures the mass flow rate of a fluid flowing through a tube. Many types of mass flowmeters are available that can serve the purpose of measuring the flow rate, like the Coriolis mass flowmeters, thermal mass flowmeters, gyroscopic mass flow meters, velocity flowmeters, calorific flowmeters, turbine flowmeter, vortex flowmeter, electromagnetic flowmeter, ultrasonic doppler flowmeter, positive displacement flowmeters and open channel flowmeters. Out of these, the Coriolis flowmeter is considered to be most accurate, and it is sometimes used to check accuracy of other flowmeters[29]. However, for existing installations of chiller plant systems there are generally no flowmeters connected to pipes. In such a case, hot tapping becomes the only option, wherein a new connection is added to an existing pipeline without emptying or interrupting that particular section of pipe. Apart from these ultrasonic flowmeters can be used as they can measure the flow rate without interrupting the process.

1.7 Problem Statement

Measurement of mass flow rate of cooling water in an operating system is a difficult task since many facilities do not install them on pipelines at the time of installation. It is also not feasible to install mass flow meters on an existing system as it requires drilling holes on pipelines. The chiller panel indicates the power usage at all times and temperatures of different components in the chiller, but those are not sufficient enough to calculate performance of chiller system. As discussed earlier, estimation of condenser water loop becomes the top priority in the measurement of coefficient of performance. Hence, we have set up three techniques to determine the flow rate of the condenser water loop.

1.8 Overview of the objective

In response to the problem outlined above, the objective of this research is to accurately measure the mass flow rate of condenser water loop of the chiller cooling tower plant system as it is an important parameter in finding the COP of the chiller system. The current systems are not equipped with COP estimation on the chiller panel as the actual evaporator load of the building is an unknown factor. The techniques this thesis uses to measure the flow rate is quite feasible to use by all facility workers as well as by energy audit professionals in assessments. When energy auditing is done by the Industrial Assessment Centers, chiller systems performance is often neglected as it is not feasible to measure real-time mass flow rate in a running system and estimate the COP. This negligence often happens with the facility personnel as well, since they don’t have accessible means of checking the performance and improve it. DOE’s Industrial assessment program visits numerous facilities every year, however, recommendations for chiller efficiency improvement are seldom made. Hence, the need for estimating COP arises as chiller plant system is basically the largest part in the energy consumption of organizations. Three feasible methodologies have been discussed ahead that gives accurate determination of mass flow rate of the condenser water loop in order to estimate the coefficient of performance. These methodologies are devised with a focus on Industrial assessments such that energy audit professionals can use these techniques to estimate COP of the chiller plants.

Chapter 2 Methodologies to estimate mass flow rate

2.1 Mass flow measurement through cooling tower manipulation

In this section, a methodology is described by which mass flow rate can be measured of the cooling tower outlet water that flows through the condenser of the chiller, which is an essential parameter in determining COP of the chiller. This methodology has been performed on a mechanical draft cross flow cooling tower. Cross flow cooling towers distribute the hot water perpendicularly to the air flow. There are two inlet water entries on the top of the cooling tower as shown in the figure below. Inlet water from the top of the cooling tower flows due to gravity through the distribution basin into the fill while air is drawn horizontally across the fill by the cooling tower fan. On the side opposite to the cold-water outlet, there is a makeup water float valve. The evaporation and the drift losses from the cooling tower are overcome by the makeup water. Outlet at the bottom provides cold water to the condenser. Overflow and drain outlets are available at the sump water basin so that the outlet sump water level is maintained. Warm moist air is ejected from the top of the cooling tower. Cooling tower fan is operated by a variable frequency drive. Its working is based on outside wet bulb temperature, flow rate of the incoming water to the tower and the cooling load of the building. This experiment works for single cell or multiple cooling tower cells working together. Procedure for both of these setups is described below

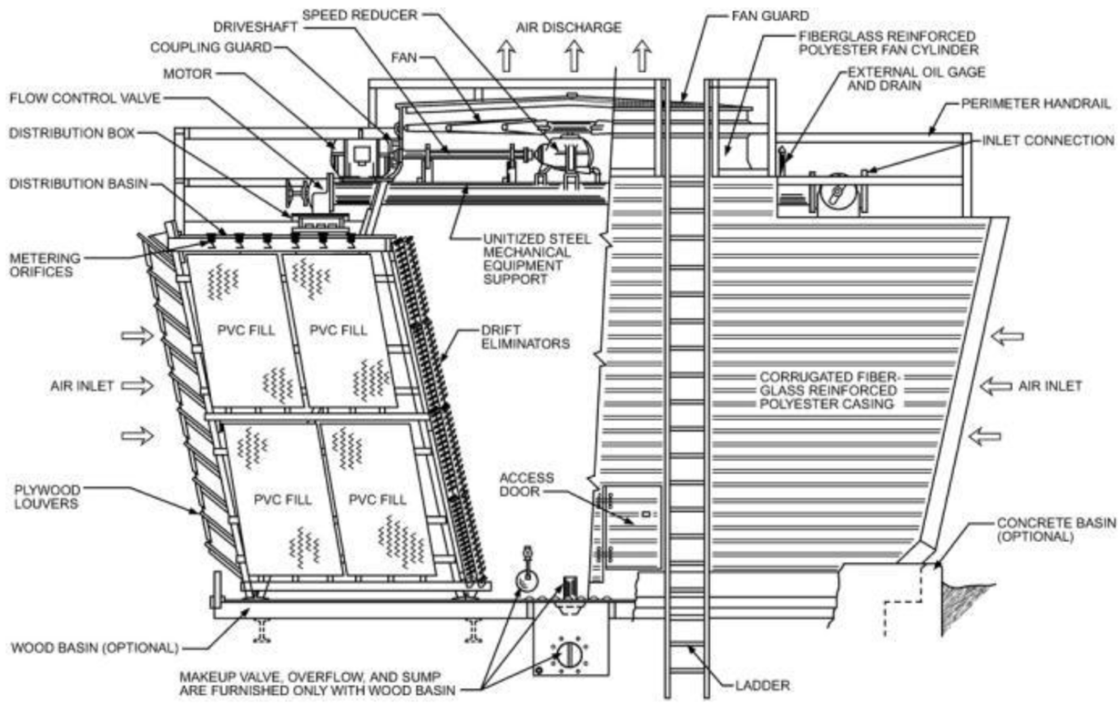

Figure 13. Mechanical draft cross flow cooling tower [30]

2.1.1 Multiple cell cooling towers

Generally, two or more number of cooling towers work together for cooling the condenser water and rejecting heat to the atmosphere. Valves of only one of this cooling towers is operated for measuring the flow rate so that it does not affect the working of the chiller system. A long stainless-steel ruler of 36 inches is used along with a stopwatch for taking readings. The water collection sump area dimensions (length and width) are measured before beginning with the procedure. This procedure is divided into four steps.

- Firstly, the makeup water is turned off. Now, the incoming and outgoing water is not balanced because of evaporation and drift losses and hence, the water level in the sump area starts dropping at a slow rate.
- The drop in water level is measured with respect to time. As the drop-in water level is quite slow, a ten-minute timer has been set and measurements are taken on the ruler

before and after the time span. The level drop with respect to time is multiplied with the area of water collecting sump to get the volumetric flow rate. The mass flow rate of the makeup water is known from this step.

- In this step, along with the makeup water valve the outgoing water supply is also cut off. Now, only the incoming water valve is on which causes the level rise of the sump water.
- In the final step, the level rise is measured with respect to time to get the volumetric flow rate of the incoming water. The level rise in this case is too fast that the outlet water valve should be turned on in thirty seconds without having the water to overflow.

Repetition of this methodology should be carried out at other cooling tower cells as well that are running together. The mass flow rate of the incoming water measured can be added to the flow rate of makeup water for getting the total flow rate of condenser water loop. From the chiller display condenser water entry and exit temperature can be noted. COP of the chiller plant system can be estimated with the help of this methodology. This can be used for both cross flow as well as for counter flow cooling towers.

2.1.2 Single cell cooling tower

Similar to the multiple cell, a single cooling tower setup can also be used for cooling the condenser water. The procedure slightly differs than that of the multiple cell cooling tower. This procedure for the single cell tower is also divided into four steps. The first two steps for measuring the makeup water are exactly the same as multiple cell cooling tower. However, the final two steps differ as for a single cell tower, isolation occur at the incoming water valves at the top of the cooling tower. The final two steps are described below.

- In this third step, along with the makeup water, one of the inlet water valves can be turned off, which causes a drop in flow level.
- This level drop can be measured with respect to time and doubled to get the total flow rate of the incoming water.

This incoming water flow rate can then be added to the makeup water flow rate to get the total flowrate of the condenser water loop.

2.2 Flow rate estimation from pump curves

Another approach towards finding the mass flow rate of condenser water is through the differential pressure of the pump that is used to supply condenser water to the cooling tower. Since it is not feasible to physically measure the flow rate through this methodology, estimation of flow rate has been made. Commercial centrifugal pumps are available in a variety of capacities, sizes and designs. Pump's performance is characterized by the increase in pump efficiency, pump power and pump head. These three properties vary with respect to flow rate[31]. Pump manufacturers test these properties and construct a pump curve for each pump.

2.2.1 Generic Pump Curve

Pump curves provide an essential data about a pump's ability to produce flow against certain head or also called as differential pressure. A condenser water pump curve has been shown below.

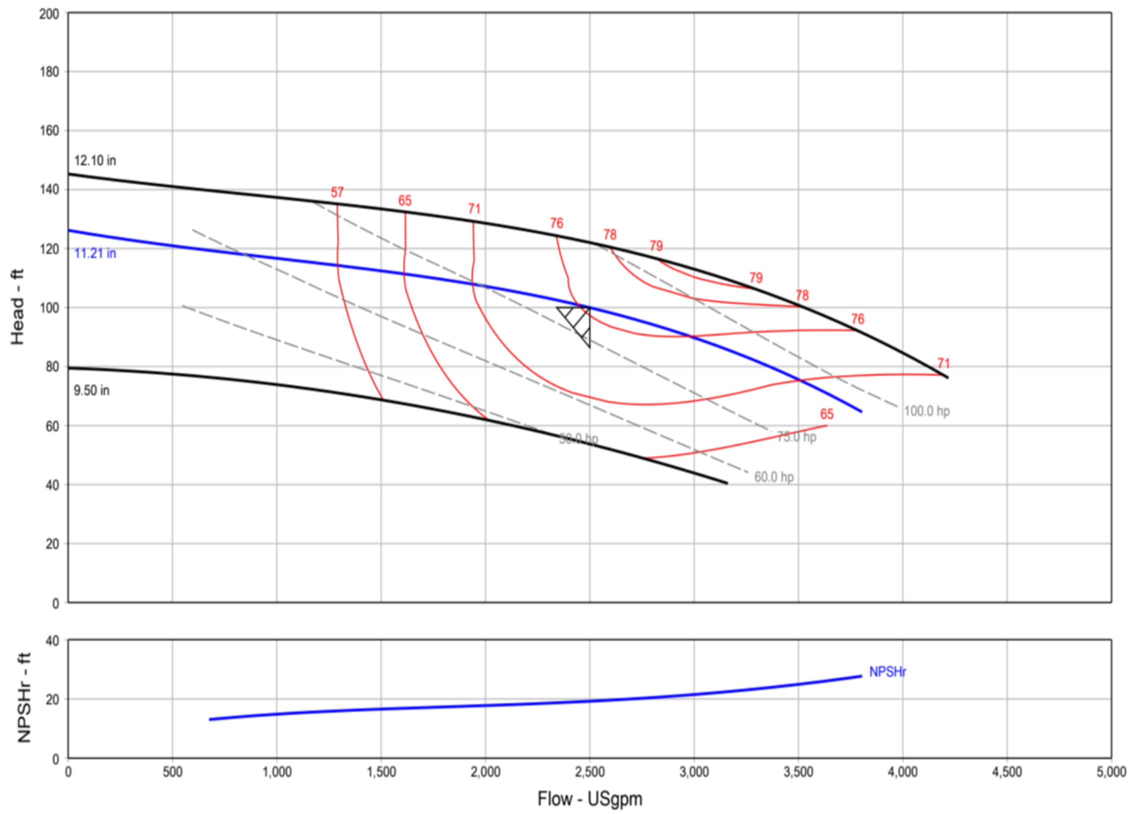

Figure 14. A condenser water pump curve with design flow of 2500 GPM at 100 ft. head

Flow rate is represented on the x-axis of the pump curve whereas differential pressure or head is shown on the y-axis. The red lines are the pump efficiency lines. Differential pressure of the pump can be measured with the help of pressure gauges before and after the pump. This differential pressure can be used to find the flow rate of the condenser water loop. While some systems don't have pressure gauges installed, this is rare and, in those cases, a first step would be to have gauges installed. The pump curve can be found in the pump manufacturer's catalogue for any particular type of pump.

2.2.2 Adjustment of pump curves for variable frequency drives

If the pump is equipped with a variable frequency drive, then it may run at lesser than its design speed.

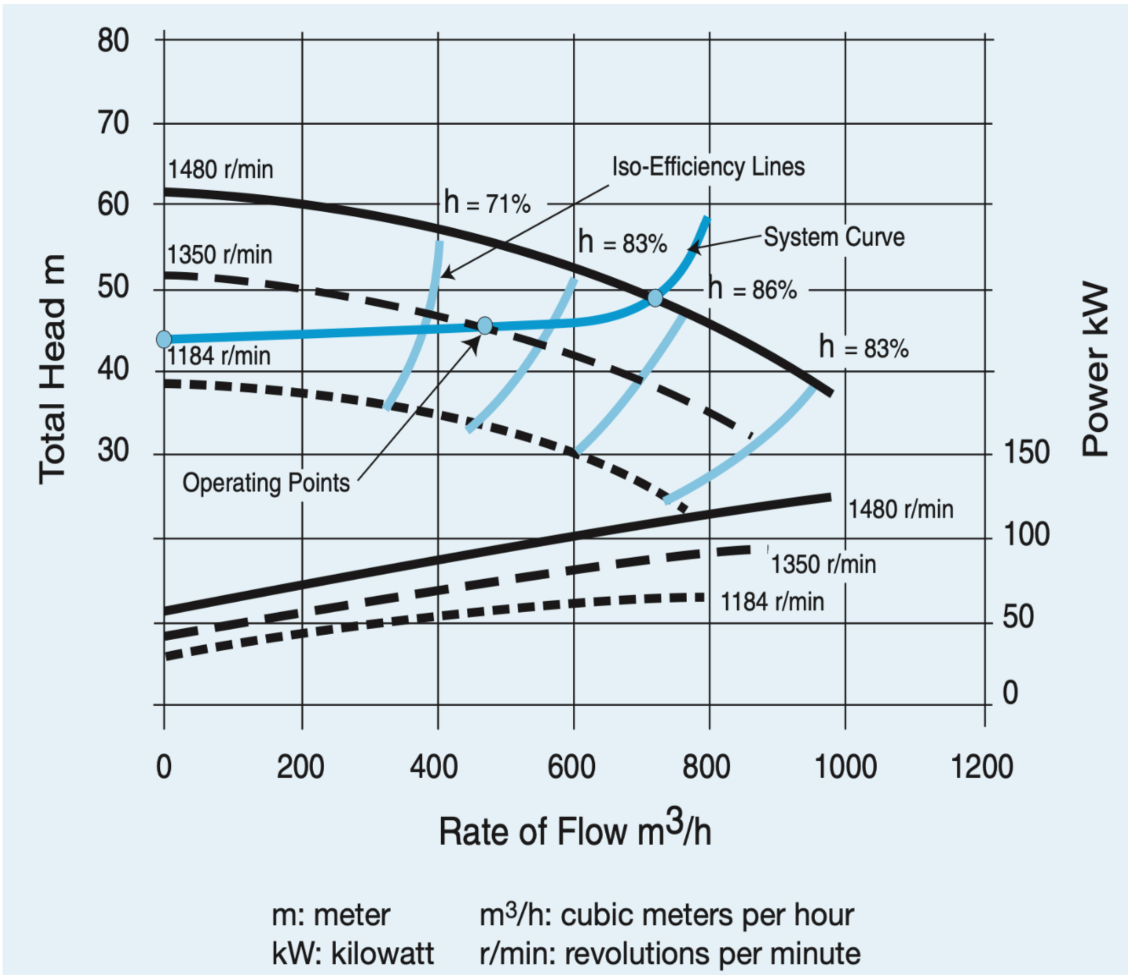

Figure 15. Pump curve at different RPM [31]

The VFD control panel normally shows the percentage load of the pump that it is currently operating at. Along with the decrease in pump speed, there is a different curve that needs to be seen for getting the flow rate corresponding to head as seen in the above figure. The pressure differential reading taken from the pressure gauges can be multiplied with 2.31 to convert into head. The flow rate can be estimated with the help of this technique. This method can be directly applied to chilled water pumps as well to get the chilled water flow rate. The chilled water pump model number, motor hp, design flow rate and design head are required for flowrate estimation. The affinity laws promise significant energy savings with the installation of VFD[31]. There are three affinity laws as discussed below.

1) $Q1/Q2 = N1/N2$

2) $H1/H2 = (N1/N2)^2$

3) $P1/P2 = (N1/N2)^3$

In these equations Q denotes the flow rate, N is the pump speed, H is head and P is Power.

This states a 50% reduction in pump speed reduces the power input by 87.5%. The first two equations of affinity laws provides a good approximation of actual pump behavior over a wide range of speeds[32]. However, in case of power relationship, the approximation is larger, particularly for smaller pumps[32]. It has been observed that the affinity laws provide a correct estimate of energy savings when the pump delivers fluid against frictional resistance of the piping system[31]. According to the speed of pump shown on the VFD, the affinity laws and the pressure differential, the flow rate of the chilled water or the condenser water can be estimated.

2.3 Using an Ultrasonic flow meter

Clearly, measuring liquid flow in a pipe would be the preferred method but turns out to be challenging. There is an assortment of in-flow methods which could work but all require penetrating the pipe with a hole for insertion. This does not necessarily require shutting the system down as this insertion could be accomplished with “hot tapping”.

However, there are risks and most facilities will balk at doing this. This leaves non-invasive techniques, which normally means an ultrasonic flow meter.

The ultrasonic flow meter is designed to measure the fluid velocity of liquid within a closed conduit. Ultrasonic flowmeters are affected by density, viscosity, temperature, suspended particles and acoustic properties of the liquid depending on the flow meter. The transducers are a non-contacting, clamp-on type, which provides benefits of easy installation and non-fouling operation. Using ultrasonic transducers, the flow meter can measure the average velocity along the path of an emitted beam of ultrasound. The ultrasonic flowmeter can be categorized into two types: transit type and doppler type flowmeter.

2.3.1 Transit type flowmeter

In transit type flowmeter, time difference from the transmission of ultrasound signal is measured until it is received by the second transducer. Transit time flow meter utilizes two transducers that function as both ultrasonic transmitters and receivers. As both the transducers sends and receives signals simultaneously, a comparison between the upstream and downstream measurements is done. The time travel remains same when there is no flow. The sound waves travel faster in the direction of flow and slower when the flow is in opposite direction. The fluid cannot contain a high concentration of bubbles or solid particles, which would reduce the frequency of the sound signal and make it too weak to travel. A typical representation of the transit type ultrasonic flowmeter is displayed below.

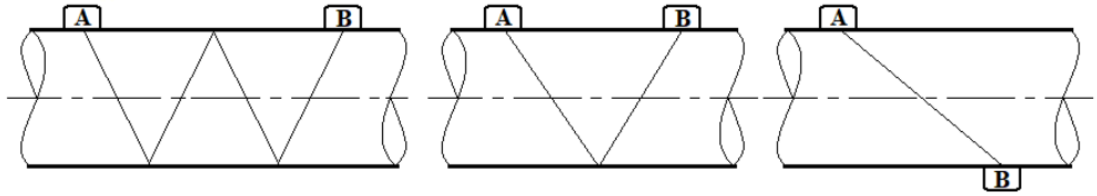

Figure 16. Arrangement of Transit type ultrasonic transducers. (a) W-type; (b) V-type; and (c) Z-type [33]

There are three methods of mounting the transducers on a particular pipe: V-method, Z-method, W-method and N-method. V-method and W-method are the most commonly used methods for pipes as the time required is larger due to longer path thereby providing higher accuracy for measurement[33]. In v-method and w-method, the transducers are attached on the same side of the pipe. The sound traverses twice in v-method and four times in case of w-method. In the Z-method, the transducers are attached on the opposite side of the pipe and sound transverse only one time through the pipe. A pipe region is selected such that the fluid flow should be fully developed where the velocity profile remains same throughout. For turbulent flow in a pipe, the hydrodynamic entry length is approximately ten times the diameter beyond which the flow is fully developed. The transducers are clamped on the outside of a closed pipe at a calculated distance from each other according to the pipe geometry. The transducer spacing is displayed on the ultrasonic flow meter depending on the pipe material, outside or inside diameter and the thickness of the pipe. If some liner is present, its thickness is also required to be specified in the flow meter. Accuracy of all these parameters is quite important for receiving strong signals. The mass flow rate of condenser water can be estimated from the ultrasonic flow meter. If the flow consists of bubbles, particulate matter, the transit type ultrasonic flow meter will not receive any signal[34]. In such as case, doppler ultrasonic flow meter can be used for estimating the flow rate.

2.3.2 Doppler type flowmeter

Doppler flowmeter works on the principle of doppler effect where frequency change of the signal that is sent into the flowing liquid across the pipe is measured. This frequency change happens across solid particles or bubbles in the flow stream creating an echo, which is returned to the transducer. Accuracy increases with the increase in concentration of suspended particles or bubbles. Recommended size of particles is above 100 micrometers and the concentration is required to be greater than 100 parts per million. Similar to transit type flowmeter, fully developed flow is required to minimize errors in flow measurement.

A doppler flowmeter has only one transducer that transmits and receives signals. A typical representation of doppler flow meter has been shown in the below figure.

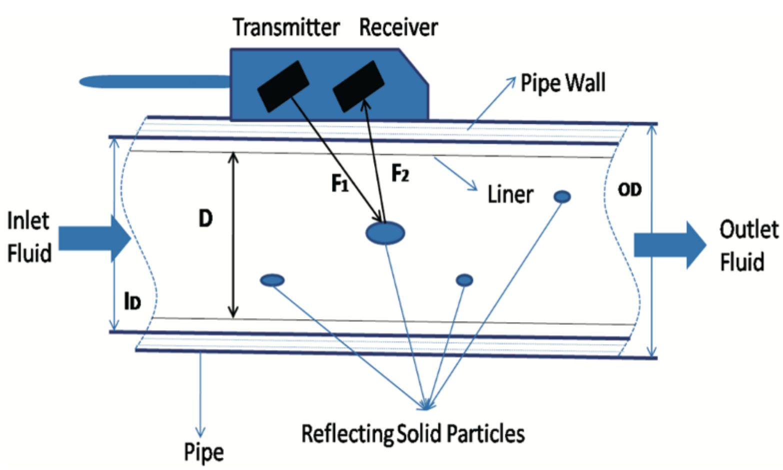

Figure 17. Doppler flow meter working principle [35]

The doppler flow meter either displays velocity or the flow rate in GPM. If the doppler flow meter only displays velocity, then possible correlation to get the flow rate according to pipe diameter will be provided by the manufacturer. A doppler flowmeter is not suitable for clear and clean fluid. In case of accuracy, transit flowmeters are reported as more accurate than doppler type[34].

Chapter 3 Results and Discussion

Data gathering for the cooling tower and ultrasonic flow meter methodologies were limited to mass flow rate measurement due to Covid-19 restrictions. Mass flow rate measurement of these two methodologies is not cross correlated with the load on the chiller.

3.1 Cooling tower methodology

As per the method discussed above, a two-cell cooling tower has been selected for the purpose of mass flow rate measurement.

Figure 18. A two-cell crossflow cooling tower

The level drop after shutting the makeup water valve was observed for one of the cells. Due to slow drop in water level, a 10 minute was set. A 25 millimeter drop in water level was observed in the span of 10 minutes. This procedure was repeated for 5 times and the readings were measured. Same procedure was carried out on the other cell of the cooling tower as well. Readings of both the cells are shown in the table below.

Sr. No.	Cell 1 level drop in mm.	Cell 2 level drop in mm.
1	25.5	24.5
2	24.5	25
3	24.5	24.5
4	25	25.5
5	25.5	25

Table 4. Level drop due to no makeup water for 10 minutes

The difference in the readings can be due to human errors. The average can be taken as 25 mm of level drop in 10 minutes. The geometry of the water sump was measured as 5 feet by 4 feet.

Mass flow rate of makeup water = 1.524 m x 1.219 m x 0.0025 m/min = 0.00464 m^3/min.

= 1.227 GPM.

The combined makeup water flow rate for both the cooling tower cells equals to 2.454 GPM.

For measuring the mass flow rate of the incoming water to the cooling tower, outlet water valve was shut off along with the makeup water valve of one cooling tower. A significant level rise was observed before overflowing of the water sump in a few seconds. Similar to the makeup water step, five readings were taken for each of the cooling tower cell. The level of water below the overflow point is measured prior to the shutting off of the valve. After shutting off the valve, the time is measured with a stopwatch until the water reaches the overflow point and then the valve is opened. Five readings are taken for each cooling tower cell. Readings for the above step are shown in the table below.

Sr. No.	Time to overflow	Cell 1 level rise in mm.	Level rise per second
1	18	60	3.33
2	16	53	3.31
3	18	58	3.22
4	15	51	3.4
5	17	56	3.29

Table 5. Cell 1 level rise with respect to time for incoming water.

Sr. No.	Time to overflow	Cell 2 level rise in mm.	Level rise per second
1	19	62	3.26
2	16	55	3.43
3	15	48	3.2
4	17	57	3.35
5	16	52	3.25

Table 6. Cell 2 level rise with respect to time for incoming water.

The average level rise per second of both the cells of cooling comes around 3.3 mm/sec. Mass flow rate of the incoming water = 1.524 m x 1.219 m x 0.0033 m/s = 0.00613 m^3/s. This is equivalent to 97 GPM from 1 cell of cooling tower. Since the level rise is same for both the cooling tower cells, we get the total incoming flow of water to be 194 GPM. Adding the makeup water flow rate to the flow rate of the incoming water, the total flow rate of the return water from the cooling tower can be calculated as 196.2454 GPM. This cooling tower set is not connected to chiller and works as a free cooling medium for a data center. This experiment was performed on these cooling tower cells just for knowing the feasibility of performing this methodology. In case of a chiller-cooling tower plant system, same procedure mentioned above should be followed along with the steps mentioned below for determining the COP of the system.

Further steps required for measuring the COP of the system are as follows:

1) The compressor power and the chiller water entering and leaving temperature should be noted from the chiller control panel that is associated with the cooling tower at the time of experimentation.
2) The mass flow rate measured can be multiplied with the ΔT (difference in entering and leaving chilled water temperature) to get the cooling load on the evaporator.
3) COP can be determined by dividing the evaporator load with the compressor power noted from the chiller control panel.

3.2 Pump Curve Methodology

As discussed earlier, pump curves provide an estimate of the actual flow rate running in the system. A variable primary flow chilled water system has been selected for testing this methodology. This chilled water system consists of two 950-ton chillers with 4 cell cooling towers. Each chilled water and condenser water loop consist of three pumps. At the time of measurement, one of the chillers was operating at part load of 49% with only one chilled water pump operating. Since the chilled water pump characteristics and model number were known, pump curve was obtained from the manufacturer. Figure 27 shows the pump curve for a 1650 GPM, 70 feet head centrifugal chilled water pump.

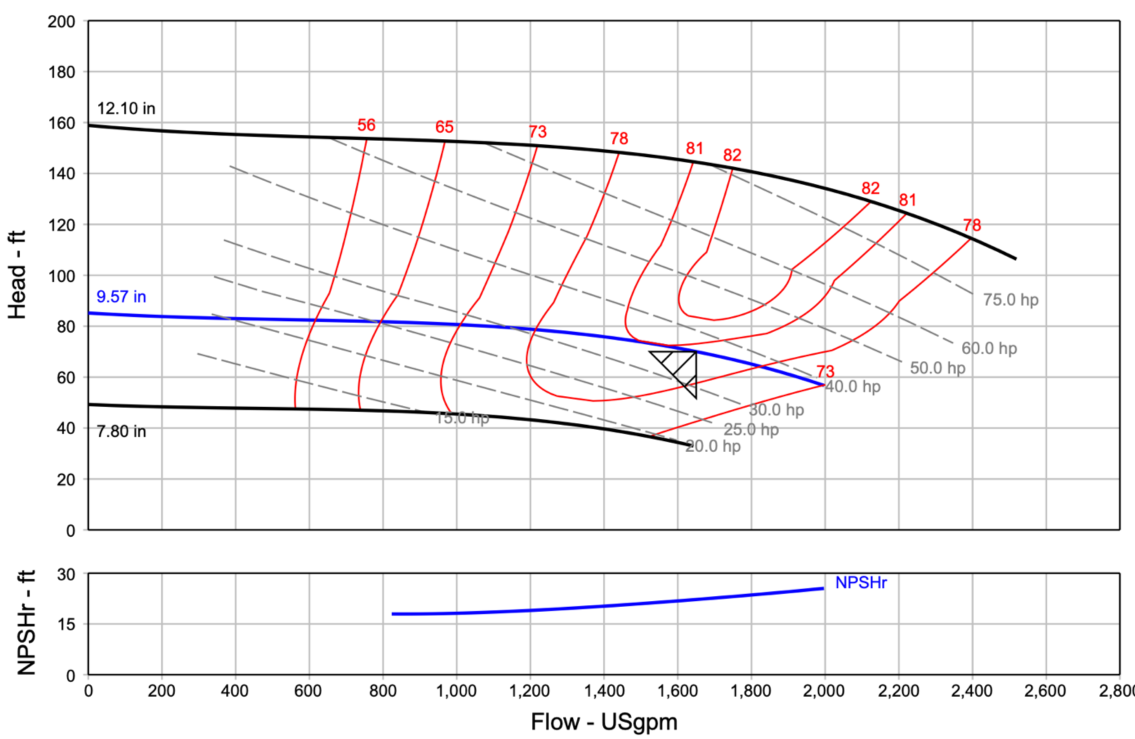

Figure 19. Centrifugal chilled water pump curve with design flow of 1650 GPM at 70 ft. head

If the pump is running at 100% speed, the flow rate will be 1650 GPM corresponding to 70 ft. head. In this case, the head is known to us that is 30.26 ft. from the building management system (BMS). Now, using the affinity laws, we have,

(Q2/Q1) = (N2/N1). However, (N2/N1) is unknown which can be calculated from

(H2/H1) = $(N2/N1)^2$. Here, H2 =30.26 ft (design head), H1 = 70.1 ft (from BMS) and N1 = 1780 RPM (design speed). Hence, N2 can be calculated which comes out to be 1169.51 RPM. Substituting in the flow rate affinity law, Q2. = 1084.1 GPM. Along this flow rate and head region in the pump curve, the efficiency drops from 81% to 73%. Therefore, adjusting the value of calculated Q2 with respect to lesser efficiency, we get, Q2 = 977 GPM.

In order to calculate COP, the chiller water evaporator entering and leaving temperature as well as compressor power is taken from the chiller panel. These readings are taken in winter at part load condition. In this case, only one chiller is running at 49% load from the three-chiller set. Also, only one pump is running from three-pump system whose flowrate has been calculated above.

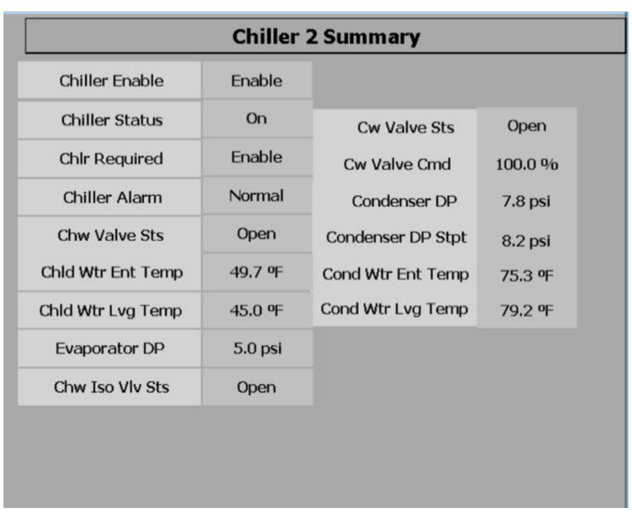

Figure 20. Chiller summary showing chilled water temperatures.

Converting Fahrenheit into degree Celsius and GPM to Kg/s, evaporator load is calculated as Q_{evap} = 61.6 kg/s x 4.18 x (9.833 – 7.22) = 672.82 kW.

The compressor power has been known from the building management system at 49% load as per the below figure.

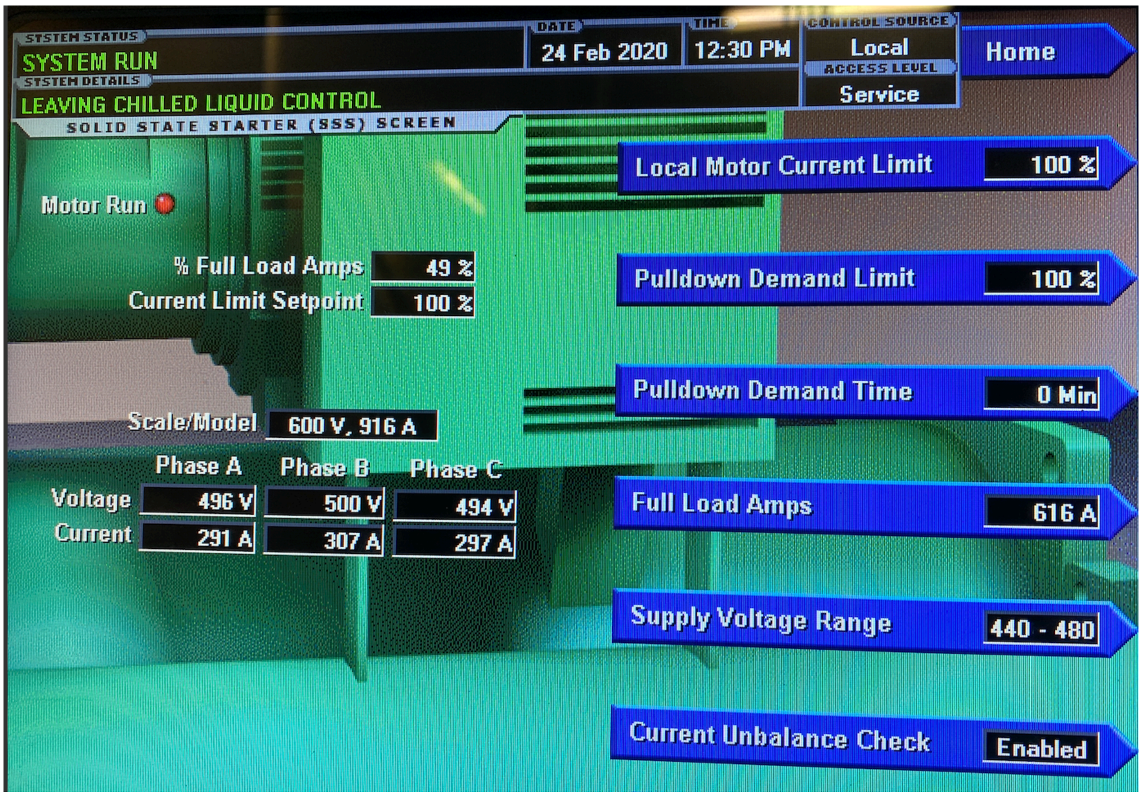

Figure 21. Chiller panel indicating Compressor load and power consumption.

Three phase Compressor Motor power W_{comp} has been calculated as 218.63 kW.

The COP of the system can be calculated as Q_{evap}/W_{comp} = 3.08

The chiller is designed for 950 tonnes of refrigeration with 14-degree Fahrenheit delta T for the chilled water loop. The nameplate motor power of the compressor is given as 569 KW. The COP of the chiller from the above data should be 5.87. Hence, from the above-mentioned methodology real-time COP of the chiller can be calculated. In this examination, we have used variable primary flow chilled water system. However, this technique can also be used on any type of constant primary flow system as well wherein, the flowrate will directly correspond to the head or the differential pressure.

3.3 Ultrasonic flow meter Method

As discussed earlier ultrasonic flow meter are of two types: transit and doppler type flowmeter. Both of these types have been tested for the measurement of flowrate. A four-cell cooling tower's outlet manifold is used for getting the total flow rate of all the cooling tower cell's leaving water. A long section of horizontal pipe has been selected in order to have a fully developed flow for measurement.

3.3.1 Transit principle

The transit type flowmeter didn't receive any signal even after proper calibration of distance between transducers. There can be two problems behind this: firstly, if the fluid contains solid particles or bubbles and secondly due to interior condition of pipe. The interior pipe condition is affected by wall roughness, corrosion and scale buildup[34]. These three factors increase turbulence inside the pipe and also the signal has to reflect of or penetrate through an extra thick layer of corrosion or scale. Hence, for resolving such issue, doppler flowmeter has been used on the same section of pipe.

3.3.2 Doppler principle

The doppler flow meter received strong signal and provided a constant reading number of times. Reading of the doppler flowmeter is shown in the below figure.

Figure 22. Ultrasonic doppler flowmeter reading.

The pipe section has an outer diameter 18 inches. The doppler flowmeter measured a velocity of 1.65 m/s. Considering the pipe's inner diameter, the flowrate can be estimated as 3750 GPM. Further steps required for determining the COP of the system are same as mentioned for the first methodology

1) The compressor power and the condenser water entering and leaving temperature should be noted from the chiller control panel that is associated with the cooling tower at the time of experimentation.

2) The mass flow rate measured can be multiplied with the ΔT (difference in entering and leaving chilled water temperature) to get the cooling load on the evaporator.
3) COP can be determined by dividing the evaporator load with the compressor power noted from the chiller control panel.

CHAPTER 4. CONCLUSION AND FUTURE SCOPE

From this thesis, new techniques or methodologies have been developed for estimating the in-situ mass flow rate of the running chiller plant system without affecting its operation. Mass flow rate measurement was achieved with the help of all three methodologies. The cooling tower and ultrasonic flowmeter methodology provided measurement of condenser water flowrate whereas chilled water flowrate was obtained through pump curve methodology. COP was measured for the pump curve technique as well due to the availability of chiller data. COP of any type of chiller plant systems can be estimated with the help of these methodologies. Energy assessments for small to medium size manufacturing facilities can be done with new recommendations involving COP estimation as these methods are quite feasible and can be performed by facility operators or energy audit professionals themselves. Facility operators can keep track of their energy consumption my monitoring COP at various load percentage of the chiller and finding the optimum configuration that gives most efficiency. Observation of COP variation with respect to change in system parameters can be done which would help to maximize efficiency. As discussed earlier, the condenser water entering and leaving temperature has a major impact on the COP of the system and should be monitored on regular basis. At the time of maintenance, mass flow meters should be installed that can monitor the flow rate directly. Building management system software can be further optimized to modulate flow rate of chilled water and condenser water loop such that maximum COP can be achieved at any given point of time. Timely maintenance of the entire chiller plant along with all the pumps and cooling tower should be done for delaying ageing of the equipment. Retrofitting existing constant flow systems with variable flow systems should be considered to increase annual efficiency of the entire plant and to avoid low delta-T syndrome issues. All of these can help industrial assessment professionals to implement new recommendations that would optimize the energy consumption of existing facilities and save in terms of annual consumption.

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