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Targeting and design of chilled water network

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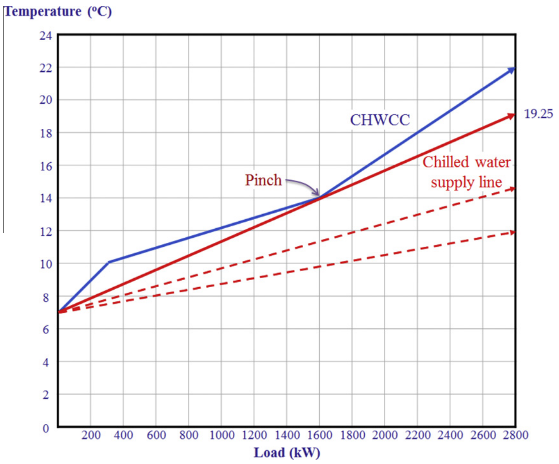
HIGHLIGHTS

- Minimum flowrate targeting for chilled water network.
- Mixed series/parallel configuration of chilled water-using units.
- Integrated cooling and chilled water networks.

GRAPHICAL ABSTRACT



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ABSTRACT

Chilled water is a common cooling agent used in various industrial, commercial and institutional facilities. In conventional practice, chilled water is distributed via *chilled water networks* (CHWNs) in parallel configuration to provide required air conditioning and/or equipment cooling in the *heating, ventilating and air conditioning* (HVAC) system. In this paper, *process integration* approach based on *pinch analysis* technique is used to address energy efficiency issues in the CHWN system for grassroots design problem. Graphical and algebraic targeting techniques are developed to identify the minimum chilled water flowrate needed to remove a given amount of heat load from the CHWN. Doing this leads to higher chilled water return temperature and enhanced energy efficiency of the HVAC system. A recent proposed network design technique is extended to synthesize the CHWN in a mixed series/parallel configuration. A novel concept of *integrated cooling and chilled water networks* (IWN) is also proposed in this work, with its targeting and design techniques presented. Hypothetical examples and an industrial case study are solved to elucidate the proposed approaches.

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1. Introduction

Energy efficiency has always been an aspect for continuous improvement for almost all industrial sectors, ranging from manufacturing to building and services. In recent years, apart from operation cost reduction, environmental sustainability has also been an important factor in promoting energy efficiency. Some reports have also identified quantitatively the contributions of energy efficiency enhancement towards carbon dioxide (CO_2) reduction along with other "technological wedges" [1,2].

This paper aims to address energy efficiency issue in the *chilled water network* (CHWN) system used for heating, ventilating and air conditioning (HVAC) in the industry. Chilled water is a typical cooling agent used in various industrial, commercial and institutional facilities. In the conventional setup of CHWNs, chilled water is distributed throughout the buildings via piping connection to various HVAC heat exchangers in order to provide required air conditioning and equipment cooling. In semiconductor manufacturing and electronic wafer production, the CHWN system is one of the most critical utility systems. Moreover, it has been reported to be the largest energy user among the various facility systems in semiconductor plant, accounting for almost 30% of the total power consumption [3]. Hence, it is of importance to optimize the CHWN system, in order to maintain business competitiveness, while trying to achieve the goal of sustainable development.

To optimize the CHWN system, common industrial practices include reducing cooling duties of individual chillers, lowering chilled water flowrate and rising the chilled water return temperature [4–7]. Wulfinghoff [4] reported that an approximately 4% energy saving is achieved per degree Celsius the chilled water return temperature is raised. By maximizing the return temperature, power saving in the range of 5–20% has been reported [5]. In addition, Bell [6] reported that reducing the chilled water flowrate will raise the chilled water return temperature (for the same amount of heat removal), leading to higher chiller efficiency. Gidwani [7] reported that a rise of 1–1.5% for coefficient of performance (COP) for every 1.8 °C rise for the chilled water supply temperature. Some mathematical optimization techniques have been proposed to optimize the CHWN system, focusing on energy management, in order to operate the chiller units with maximum efficiency and minimum power consumption/cost. These include those that determine the optimal loading of chiller [8,9], and the optimal operation settings for HVAC [10,11] and chilled water systems [12].

In this work, we attempt to address the grassroots design problem of CHWN synthesis from *process integration* perspective. Process integration can be defined as *a holistic approach to process design, retrofitting and operation which emphasizes the unity of the process* [13,14]. From the perspective of process integration, chilled water is a unique resource comprises of water and energy elements. Hence, some of the established tools of process integration for resource conservation may be extended for application for the CHWN system.

A closely related area of work reported in the past decade is the synthesis of *cooling water networks* (CWNs). In the seminal work of Kim and Smith [15], based on *pinch analysis*, a graphical tool termed the *limiting composite curve* was proposed to target the minimum cooling water requirement of a CWN. Furthermore, a network design methodology and options for debottlenecking cooling water systems were also proposed. In their later work [16], the authors explored the opportunity of reducing cooling water makeup by recovering process effluents. Apart from these works based on pinch analysis techniques, later works on this subject were mainly dominated by *superstructure-based mathematical optimization* techniques [17–20].

It should be noted that the underlying principle of CWN synthesis is to design the network in such a way that the cooling water is sent to the heat exchangers in a *series* fashion, rather than conventional *parallel* arrangement. This enables the CWN to be supplied with a lower flowrate of cooling water, which leads to less pumping work. Besides, the series arrangement also enables the return temperature of the cooling water to be maximized, thus increasing cooling tower efficiency [15]. These underlying principles of the CWN are readily extended to the CHWN system. The chiller unit in a CHWN is conceptually equivalent to the cooling tower in a CWN; both of them remove heat from the servicing fluid circulating through the various heat exchangers within the network. Hence, by arranging the heat exchangers in a series configuration, the chilled water flowrate in CHWN can also be minimized, leading to higher return temperature and hence improved COP of the chiller. An earlier attempt to demonstrate this concept has been recently presented by Lee et al. [21] using mathematical optimization techniques. In this paper, the above concept will be explored using a conceptual approach based on pinch analysis. Furthermore, a novel concept of the *integrated cooling and chilled water networks* (IWN) will be introduced in this paper.

In the following section, the formal problem statement for CHWN synthesis is first given. A graphical targeting technique is next presented to determine the minimum flowrate of chilled water needed for a CHWN. A hypothetical example is then used to illustrate the targeting technique. In the following section, an algebraic technique is presented to determine the minimum flowrate target. This technique is then illustrated with two examples. A network design procedure is then presented to design the CHWN that achieves the established flowrate targets. In the final section of the paper, the targeting and design techniques are extended for the IWN.

2. Problem statement

The formal problem for a CHWN may be stated as follows.

Given is a set of chilled water-using units $m \in M$, *each with a fixed heat load* Q_m *to be removed by chilled water, and with specified maximum inlet* ($T_{in,m}$) *and outlet* ($T_{out,m}$) *temperatures. To achieve the resource conservation objective and to enhance chiller efficiency, the chilled water is to be re-circulated among the chilled water-using units. The main objective is to synthesize an optimal CHWN that achieves the minimum chilled water flowrate while fulfilling the heat load removal of all chilled water-using units.*

3. Graphical targeting technique

In this section, a graphical technique known as the *chilled water composite curve* (CHWCC) is proposed to determine the minimum chilled water flowrate needed for a CHWN. Note that the CHWCC is extended from the *limiting composite curve* that was originally proposed by Kim and Smith [15] to target the minimum cooling water requirement of a CWN. The procedure for constructing a CHWCC is given as follows.

(1) Plot the *limiting profiles* of chilled water units on a temperature versus enthalpy diagram, according to their maximum inlet and outlet temperatures.
(2) Within each temperature interval, the individual segments of the chilled water profiles are merged by adding their heat loads. This forms the CHWCC.
(3) The *chilled water supply line* is then drawn from the chilled water supply temperature to remove the total heat load of the entire system. In order to minimize the usage of chilled water, the chilled water supply line is to have the steepest slope, but stays below the CHWCC. In other words, the chilled water supply line is rotated upwards using the supply