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A Pinch-Based Approach for the Synthesis of Chilled Water Network

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This paper aims to address energy efficiency issue in the chilled water network (CHWN) system. Chilled water is a typical cooling agent used for heating, ventilating and air conditioning (HVAC) 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 this work, we attempt to address the problem from Process Integration perspective. The underlying principle of CHWN synthesis is to design the network in such a way that the chilled water is sent to the heat exchangers in a series fashion, rather than the conventional parallel arrangements. This enables the CHWN to be supplied with a lower flowrate of cooling water, which leads to less pumping work, and enables the chilled water return temperature to be maximized, thus increasing the chillers efficiency. A chilled water composite curve (CHWCC) is presented to determine the minimum chilled water flowrate needed for a CHWN. A network design algorithm is then used to design the CHWN to achieve the minimum chilled water flowrate. A hypothetical example is used to illustrate the newly proposed algorithm.

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. 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 (Hu and Chuah, 2003). Hence, it is of importance to optimise the CHWN system, in order to maintain business competitiveness, while trying to achieve the goal of sustainable development.

To optimise the CHWN system, common industrial practices include reducing cooling duties of individual chillers, lowering chilled water flowrate and rising the chilled water return temperature (Bell, 2008). Wulfinghoff (1999) reported that approximately 4 % energy saving is achieved per degree Celsius the chilled water temperature is raised. In addition, Bell (2008) 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. Some mathematical optimisation techniques have been proposed to optimise the CHWN

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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 (Chang, 2004), optimal operation settings for HVAC (Fong et al., 2006) and chilled water systems (Lee and Cheng, 2012).

In this work, we attempt to address the problem 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 (El-Halwagi, 1997). 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 (2001), 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.

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 the 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 (Kim and Smith, 2001). 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 efficiency of the chiller. An earlier attempt to demonstrate this concept has been recently presented by Lee et al. (2013) using mathematical optimisation techniques. In this paper, the above concept will be explored using a conceptual approach based on pinch analysis.

In the following section, a 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. Next, a network design procedure is then presented to design the CHWN that achieves the established flowrate targets.

2. Problem statement

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

Given is a set of chilled water-using units $m \epsilon M$, each with a fixed heat load Q_m to be removed by chilled water, and with specified maximum inlet ($T_{\mathrm{in},m}$) and outlet ($T_{\mathrm{out},m}$) 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 (2001) 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 temperature as a pivot, until it touches the CHWCC. The inverse slope of this chilled water supply line gives the minimum flowrate of the chilled water needed for the CHWN.

A hypothetical example is next used to illustrate the procedure.

4. Hypothetical example

This is a hypothetical example that consists of four chilled water-using units, whose limiting data are shown in Table 1. The last entry of the fourth column shows that the total heat removal from all units ($\sum_m Q_m$) is 2,800 kW. The chilled water supply temperature (T_{CHW}) is set at 7 °C.

In the conventional design of CHWNs, chilled water is supplied to the chilled water-using units in parallel configurations; in other words, all units receive chilled water at its supply temperature. For each chilled water-using unit m, its heat capacity flowrate requirement (F_m) can be determined using Eq(1).

$$F_m = \frac{Q_m}{\left(T_{\mathrm{out},m} - T_{\mathrm{CHW}}\right)} \qquad \forall m \tag{1}$$

The total heat capacity flowrate required ($\sum_m F_m$) can thus be determined as 293.33 kW/°C. We can also determine the chilled water return temperature to the chiller (T_{CHWR}) as 16.55 °C using Eq(2).

$$T_{\mathrm{CHWR}} = T_{\mathrm{CHW}} + \frac{\sum_m Q_m}{\sum_m F_m} \tag{2}$$

We next proceed to plot the CHWCC to determine the minimum flowrate of the CNWN. Following step 1 of the CHWCC procedure, the limiting profiles of the four chilled water units are given in Figure 1. As shown, these limiting profiles are located at their respective inlet and outlet temperatures. We then define three temperature intervals based on the inlet and outlet temperatures, i.e. 7 – 10 °C, 10 – 14 °C and 14 – 22 °C (see Figure 2). Following step 2 of the procedure, the individual segments of the chilled water profiles are merged within the temperature interval by adding their head loads. For instance, within the temperature interval 10 – 14 °C, three segments of the chilled water profiles for units 1, 2 and 3 exist, with respective heat loads of 400, 700 and 200 kW. These segments are merged into a single segment of 1,300 kW. A similar merger is carried out for the two segments of the chilled water profiles for units 3 and 4 in the temperature interval 14 – 22 °C. Note that no merger is needed within the interval 7 – 10 °C.

Table 1: Limiting data for hypothetical example

Unit, m	Inlet temperature, $T_{\mathrm{in},\,m}$ (°C)	Outlet temperature, $T_{\mathrm{out},\,m}$ (°C)	Load, Q_m (kW)	Limiting heat capacity flowrate, F_m (kW/°C)
1	7	14	700	100
2	10	14	700	175
3	10	22	600	50
4	14	22	800	100
Total			2,800	425

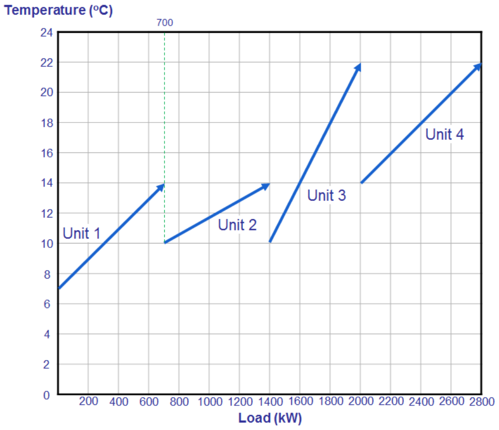

Figure 1: Limiting profiles of chilled water units for hypothetical example

The merging of the individual segments of chilled water profiles forms the CHWCC shown in Figure 3. The horizontal distance of the CHWCC gives the total heat removal required for all four chilled water units, i.e. 2,800 kW. A chilled water supply line is then drawn from the supply temperature of 7 °C. To lower the chilled water flowrate to its minimum, the supply line is rotated upwards with the supply temperature being the pivot, until it touches the CHWCC at 14 °C (Figure 3). The latter is termed the *pinch* temperature for the CHWN. In Figure 3, it can be seen that the chilled water will reach a temperature of 19.25 °C when returning to the chiller. The inverse slope of the supply line gives the minimum chilled water flowrate, which is 228.57 kW/°C (= 2,800 kW/(19.25 – 7 °C)), for the entire system. This corresponds to a 22 % reduction in the chilled water heat capacity flowrate (from 293.33 kW/°C), along with a 2.7 °C increase in the return temperature (which will eventually lead to higher chiller efficiency).

Note that the chilled water supply line that forms the pinch temperature with the CHWCC corresponds to case where the CHWN is serviced with chilled water at the minimum flowrate. However, sometimes this minimum chilled water flowrate is not desirable for the CHWN, due to other operational or practical constraints (e.g. the chiller has a specified return temperature that is lower than that determined by the CHWCC). In such cases, the chilled water supply line does not touch the CHWCC, and will have a slope lower than that of the minimum flowrate case, as shown dotted lines in Figure 3.

Note that for problems with many temperature intervals, it is more practical to perform the targeting step using the algebraic approach (e.g. Shenoy and Shenoy, 2013).

5. Network design

In this section, the network design procedure proposed by Shenoy and Shenoy (2013), i.e. the enhanced nearest neighbour algorithm (NNA) for CWNs is extended for use in CHWNs. Note that, in order to apply this procedure, each chilled water-using unit will be characterized as a pair of sink and source.

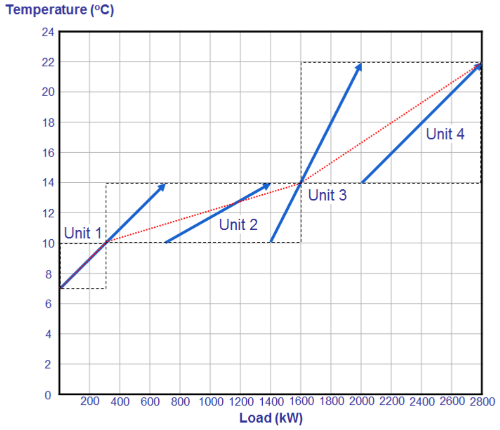

Figure 2: Temperature intervals and merger of individual segments of chilled water profiles

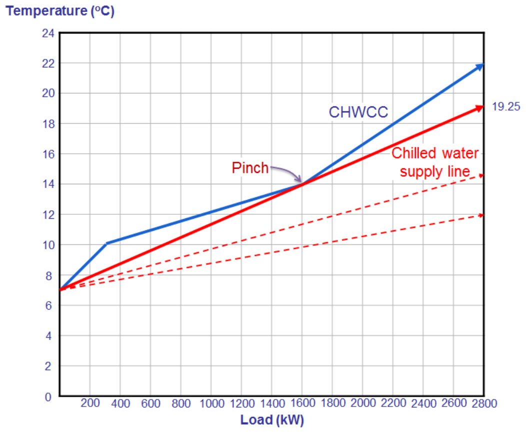

Figure 3: The CHWCC and chilled water supply line for hypothetical example

In this case, sink *j* corresponds to the inlet of chilled water-using unit *m*, with a flowrate requirement of $F_{\mathrm{SK}j}$ and a temperature limit of $T_{\mathrm{SK}j}$. On the other hand, the outlet of chilled water-using unit *m* corresponds to source *i*, with a flowrate of $F_{\mathrm{SR}i}$ and temperature of $T_{\mathrm{SR}i}$.

The procedure of enhanced NNA (Shenoy and Shenoy, 2013) may be summarized as follows:

1. Arrange all sources and sinks in column and row respectively in the matching matrix, from lowest to highest temperature levels. Grey out the cross-pinch regions where the allocation of sources to sinks is forbidden.
2. Allocate sources to sinks of the same temperature. If the source flowrate is less than that required by the sink, allocate the entire source, and make up the remaining flowrate of the sink with a pair of neighbour sources (see Step 4).
3. Prioritize the local recycle (LR) match between the source and sink of the same chilled water-using unit. Since the LR source will have higher temperature as compared to the sink, another available source of the lowest temperature level in the same region is to be paired with the LR source to be fed to the sink. The allocated flowrates of these sources are calculated using the following equations:

$$F_{\mathrm{SR}i,\ \mathrm{SK}j} + F_{\mathrm{SR}i+1,\ \mathrm{SK}j} = F_{\mathrm{SK}j} \tag{3}$$

$$F_{\mathrm{SR}i,\ \mathrm{SK}j}\, T_{\mathrm{SR}i} + F_{\mathrm{SR}i+1,\ \mathrm{SK}j}\, T_{\mathrm{SR}i+1} = F_{\mathrm{SK}j}\, T_{\mathrm{SK}j} \tag{4}$$

   where $F_{\mathrm{SR}i,\ \mathrm{SK}j}$ is the allocated heat capacity flowrate from SR_i to SK_j.
4. Identify two candidate sources SR_i and SR_{i+1} to satisfy the heat capacity flowrate and temperature constraints of sink SK_j. Note that SR_i and SR_{i+1} are the nearest available "neighbours" to sink SK_j, with temperature levels just lower and just higher than that of the sink, i.e. $T_{\mathrm{SR}i} < T_{\mathrm{SK}j} < T_{\mathrm{SR}i+1}$. The allocated flowrates of these sources are determined using Eq(5) and Eq(6). If SR_i has insufficient flowrate to fulfil the requirement of SK_j, i.e. $F_{\mathrm{SR}i} < F_{\mathrm{SR}i,\ \mathrm{SK}j}$, use whatever is available, and then a new pair of sources is used to make up the remaining flowrate.
5. Eliminate all LR matches of the CHWN (identified in Step 3) to decrease the flowrates that pass though the chilled water-using units. Flowrates and temperatures of the sinks and sources are adjusted accordingly.

Next, the enhanced NNA procedure is demonstrated using the hypothetical example.

6. Hypothetical example (revisited)

Following Step 1 of the enhanced NNA, the matching matrix for the hypothetical example is shown in Figure 4, where all sources (including the chilled water supply – FCHW) are listed in the first three columns, while all sinks (including chilled water return – CHWR) are listed in the first three rows. Note that during the targeting stage, the chilled water return temperature has been identified (19.25 °C), which is thus included in the second entry of the last column in Figure 4. Note also that the pinch temperature (14 °C, identified during the targeting stage) segregates the CHWN into higher and lower quality regions. Hence, sources in the higher quality region (with temperature lower than 14 °C) are forbidden to be allocated to sinks of the lower quality region (with temperature higher than 14 °C); the same principle applies to sources in the lower quality region and sinks in the higher quality region. Hence, these cross-pinch regions are greyed out in the matching matrix. However, the pinch-causing sources (i.e. SR1 and SR2 at 14 °C) are exceptional to this rule, as they may be allocated to sinks in both higher and lower quality regions.

		$F_{\mathrm{SK}j}$ (kW/°C)	100	175	50	100	228.57
		$T_{\mathrm{SK}j}$ (°C)	7	10	10	14	19.25
$F_{\mathrm{SR}i}$ (kW/°C)	$T_{\mathrm{SR}i}$ (°C)	SK_j $\mathrm{SR}i$	**SK1**	**SK2**	**SK3**	**SK4**	**CHWR**
228.57	7	**FCHW**	100	100	28.57		▨
100	14	**SR1**			21.43		78.57
175	14	**SR2**		$75^{(LR)}$		100	
50	22	**SR3**	▨	▨	▨	▨	50
100	22	**SR4**	▨	▨	▨	▨	100

		$F_{\mathrm{SK}j}$ (kW/°C)	100	**100**	50	100	228.57
		$T_{\mathrm{SK}j}$ (°C)	7	**7**	10	14	19.25
$F_{\mathrm{SR}i}$ (kW/°C)	$T_{\mathrm{SR}i}$ (°C)	SK_j $\mathrm{SR}i$	**SK1**	**SK2**	**SK3**	**SK4**	**CHWR**
228.57	7	**FCHW**	100	100	28.57		▨
100	14	**SR1**			21.43		78.57
100	14	**SR2**		~~$75^{(LR)}$~~		100	
50	22	**SR3**	▨	▨	▨	▨	50
100	22	**SR4**	▨	▨	▨	▨	100

Figure 4: Designing the CHWN for hypothetical example: (a) matching matrix for matching of sources and sinks; (b) elimination of LR match

We first look at the higher quality region that consists of all sinks (SK1 – SK4) as well as sources SR1, SR2 and chilled water supply (FCHW). For sink SK1, we can apply Step 2 of the procedure to allocate FCHW to SK1 of the same temperature (i.e. both at 7°C). For sink SK2, we can apply Step 3 of the procedure, where source SR2 is allocated to SK2 through an LR match. To fulfil the flowrate requirement of SK2, SR2 is to be paired with FCHW, as the latter is the lowest temperature source available in this region. Their allocated flowrates are determined using Eq(5) and Eq(6).

Next, we look at the matching of sources for sink SK3. Note that the LR match (Step 3) cannot be performed for SK3, as the source of this chilled water-using unit, SR3, belongs to the lower quality region. We hence apply Step 4 for SK3, where sources of just lower (7 °C) and just higher temperature (14 °C) are paired to be fed to SK3 at 10 °C. Note that since both SR1 and SR2 are available at 14 °C, either may be paired with FCHW to be sent to SK3, with the same allocation flowrates. For sink SK4 that has the same temperature as SR1 and SR2, one may allocate the entire SR1 or SR2 (see Figure 4(a)), or a mixture of both to this sink. Note that the latter alternative will incur an additional connection in the CHWN. For all cases, the unutilized chilled water will be sent back to the chiller (CHWR).

In Step 5 of the enhanced NNA, all LR matches of the CHWN are eliminated (Figure 4(b)), in order to reduce the source flowrate passing though the chilled water-using units. The final configuration of the CHWN is shown in Figure 5, where the LR match of SR2-SK2 is eliminated. The temperature level of SK2 and the flowrates of both SR2 and SK2 are hence adjusted, following the LR match elimination.

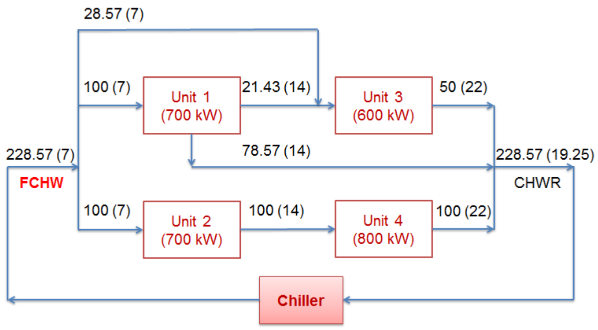

Figure 5: Final configuration of CHWN for hypothetical example

7. Conclusions

Targeting and design techniques based on Pinch Analysis have been presented for chilled water networks (CHWNs) in this paper. The targeting techniques make use of graphical tool to determine the minimum chilled water flowrate needed for a CHWN. The network design technique proposed recently has also been extended for designing the CHWN that achieves the minimum flowrate targets.

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