Pipe sizing of district cooling distribution network including in energy transfer station

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Abstract. A district cooling system (DCS) distributes chilled water to different buildings connected to the main plant. The benefits of a DCS include greatly increasing energy efficiency and decreasing life cycle operation costs. The installation, maintenance, and design of a DCS can be expensive, however. Therefore, means of decreasing costs without cutting quality is necessary. Given this, a hypothetical DCS is presented with a constant temperature difference set-point of 9°C. The DCS was set to have a system diversity of about 80%. Hydraulic calculation will be used in the study in order to determine the smallest possible pipe sizes that would permit normal operation below allowable limits. The network is divided into 3 parts; namely the main line (ML), the plot take-off (PTO), and the plate-type heat exchangers (PHEs). The DCS will have a piping network connected to 12 energy transfer stations, each with 3 sets of PHEs. Initial guess values of pipe dimensions and friction factors will first be calculated using continuity and the Von Karman equation. A single-variable Newton-Raphson method is then used on the implicit Colebrook-White equation to estimate the actual friction factor for each pipe. Then, the calibrated pipe sizes will be determined by cross-referencing theoretical values with industry-standard sizes as specified in ASHRAE. In calculating the friction factor, it was found that the values increase as the given tonnage decreases, thus implying a decrease in pipe size as the chilled water flows toward the last building. The entire study was conducted on MATLAB. It must be noted that the study is only limited to the selection and design of a simple DCS.

1. Introduction

According to Dincer & Abu-Rayash [1], a district cooling system (DCS) distributes chilled water to different customer energy transfer stations through the use of a network of underground pipes. The installation of a district cooling system eliminates the need for separate buildings and rooms to have their own climate control devices such as air conditioners and heaters. Given this, a DCS helps save a significant amount from both initial and maintenance costs. DCS technology allows for an increase in energy efficiency by 40% and a decrease in lifecycle cost by 20%.

Krarti [2] states that a DCS can utilize three main technologies that will generate the chilled water necessary for distribution. First, electric chillers can be used since they have a lower global warming potential. The second option is through the use of free cooling, which involves using cold water from nearby bodies of water. Finally, absorption chillers can also be used by DCS from nearby sources of free heat, such as power plants and industrial works.

A district cooling system has three major components, namely the central plant, the network, and the energy transfer station (ETS). The central plant produces the chilled water through means of harvesting thermal energy using the technologies stated earlier. The water is then pumped through the network, or
a series of pipes that connect the production facility to the customer ETS. Finally, the ETS, also called the customer-building interconnections, transfers heat to the network through the use of plate-type heat exchangers or PHEs [3]. It must be known that conventional methods of cooling, such as air conditioning units, constitute up to 50% to 70% of electricity demand within a building. The use of an ETS with secondary lines going throughout the building not only allows for a more environmentally friendly solution to large-scale climate control, but also for a more economic opportunity to reduce costs during its operating life cycle.

The projected friction factors present within the different sections of the network will be estimated using numerical optimization techniques. Previous studies have incorporated such techniques in distribution network design. For example, Augusto et al. [4] used exhaustive search methods in order to find the optimal pipe sizing dimensions that will yield the lowest overall cost. Another study by Liao [5] assigned confidence values to corresponding accuracies and uncertainties within a distribution system. Finally, in selecting the appropriate pipe sizes within a network, it was recommended by ASHRAE [6] to base design criteria off fluid velocity and pressure drop limits.

Given that the study will be performed on a hypothetical DCS, a change in temperature of about 9°C will be assumed between the chilled water return and supply lines. This is to follow the standards set by ASHRAE [7]. The ASHRAE Standard 90.1, published in 2016, dictates that the chilled-water cooling coils within the heat exchangers must allow for a minimum change in temperature of about 9°C between the supply and return lines. Any change in temperature that is lower than 9°C may suffer from “low delta-T syndrome.” A study by Yan [8] has provided a mathematical explanation for this phenomenon. Put simply, lower values would result in chilled water systems to consume more energy, thus causing it to operate less efficiently. This can be the result of improper load distribution.

The installation of a DCS is an expensive venture. Mistakes can further amplify that cost in terms of wasted time and resources. Therefore, it is imperative to determine the necessary pipe dimensions given the physical limitations of the setup that would not only allow optimal running conditions, but to also ensure the lowest cost possible. This way, optimal pipe sizes can be pinpointed quickly through system simulation. A study by Walters [9] has shown that the costs for pump and pipe sizing can be cut by a substantial amount once numerical optimization methods have been introduced to fluid flow analysis. Numerical methods have proven to reduce costs without compromising system performance.

This study aims to create a program that will calculate the appropriate pipe sizing when designing a DCS for a system with twelve ETS. The program must first calculate the friction factor present in each pipe. This will be done using the Newton-Raphson Method (NRM) on the implicit Colebrook-White Equation as a function of the Reynolds Number (Re) and the pipe relative roughness ($\varepsilon/D$). Using the calculated friction factors, the calibrated main line pipe sizing will be determined using the pressure drop and velocity limit as reference. It must be stated that this study is limited to only selecting the cheapest possible pipe sizes. The costs of installation and maintenance are not covered nor considered. Furthermore, the study will be done on a DCS without secondary lines flowing throughout each building. The final pipe sizes will then be compared with the results obtained by Augusto et al.

2. Methods and Data

2.1. DCP Schematic

The district cooling plant (DCP) is composed of three different sections, namely the main line (ML), the plot take-off (PTO), and the plate-type heat exchanger (PHE). In this study, the appropriate pipe sizing for each section was determined. Figure 1 below shows the district cooling schematic to be used. It can be seen that there are twelve buildings, each with their respective energy transfer stations. The main line is represented by the solid line extending from the district cooling plant (DCP) to the rest of the buildings. Each building has a plot take-off line that connects them to the main line. Lastly, given that there is an ETS in each building, three PHEs connect it to the rest of the building. It must be noted that all three sections in the schematic were simplified, and that one line represents one pair of supply and return lines.
2.2 Initial Pipe Dimensions

In calculating the initial pipe dimensions per sector, the flowrate $\omega$ passing through each pipe was determined. Eq. 1 below determines the flowrate in gallons per minute given the tons of refrigeration. It must be noted that the $\Delta C$ is the change in temperature between supply and return lines. This value was kept at a constant 9°C for all pipes in the system. After converting to cubic meters per second, the continuity equation, as shown in Eq. 2, was used to calculate the theoretical pipe size $D_{theo}$ in terms of millimeters.

$$\omega = \frac{24TR}{1.8\Delta C} \quad (1)$$

$$D_{theo} = \sqrt{\frac{4\omega}{V\pi}} \quad (2)$$

The theoretical values were then cross-checked with possible pipe sizes within that range. The initial pipe sizing for each section was based on the smallest possible pipe sizes that could accommodate the velocity and pressure drop limits at particular sections in the DCS without failing. More specifically, the pressure drop within each pipe must not exceed 100 Pa/m. In Eq. 2, the velocity limit $V$ within each pipe is different per section in the network. In the main line, the velocity limit was set to 3 m/s. The velocity limits at PTO and PHE were both set to 1.75 m/s. The values for these velocity limits, pipe lengths, and the tons of refrigeration per pipe were taken from the aforementioned study conducted by Augusto et al. Finally, the industry-standard pipe sizes were taken from the 2017 ASHRAE handbook [10].

Figure 1: Basic schematic diagram of a DCP

Figure 2: Friction factor calculation algorithm
2.2 Friction factor calculation
After acquiring the initial pipe sizes, the Newton-Raphson Method (NRM) was used to find the finalized friction factor for each section. Initial values were set first, and this was done by calculating the pipe relative roughness ($\frac{\varepsilon}{D}$) as shown in Eq. 3. The Von Karman Equation (Eq. 4), was then used to find the initial friction factor values. Eq. 5 then shows the Reynolds number calculation given a constant kinematic viscosity $\nu$ of $1.547E - 6$ m$^2$/s. It must be noted that the theoretical velocity $V_{theo}$ was calculated using the theoretical diameter $D_{theo}$. The theoretical velocity is expressed in meters per second. Lastly, the inner diameter $D_{in}$, expressed in meters, was determined using the initial pipe size calculated earlier. The algorithm can be more easily seen in Figure 2.

\[
\frac{\varepsilon}{D} = (6.571429E - 6) \times \left( \frac{D}{7000} \right)^{-1}
\]

\[
\frac{1}{\sqrt{f_{initial}}} = 2 \log \log \left( \frac{D}{\varepsilon} \right) + 1.14
\]

\[
Re = \frac{V_{theo}D_{in}}{\nu}
\]

\[
\frac{1}{\sqrt{f}} = -2 \log \log \left( \frac{\varepsilon}{D} \right) \frac{2.51}{3.7} + \frac{2.51}{Re\sqrt{f}}
\]

NRM was then used on the implicit Colebrook-White equation by following Eq. 7 below, where $F$ is the original equation and $dF$ is the derivative with respect to $f$. The process will start from the initial friction factor calculated earlier. The process will keep iterating until the relative approximate error is less than the tolerance value of $10^{-6}$.

\[
f_{new} = f_{old} - \frac{F}{dF}
\]

2.3 Calibrated Pipe Sizing
Using the finalized friction factors, the calibrated pipe sizing was then acquired by following the same process used in finding the initial diameter. The finalized pipe sizes were determined by implementing the final friction factor in solving for the allowable velocity limit and pressure drop. The process will stop iterating once the smallest possible pipe size provides values that are within the acceptable range. The pressure drops $\Delta P$, in terms of Pascals per meter, were calculated using the modified Darcy-Weisbach equation (Eq. 8) below. The variable $V_{pipe}$ is the velocity within the pipe that is compared with the velocity limit and is expressed in meters per second. Similarly, $D_{test}$ is the pipe size being tested expressed in meters. Figure 3 shows the algorithm for obtaining the calibrated pipe sizes.

\[
\Delta P = f\frac{\rho}{2} \left( \frac{V_{pipe}^2}{D_{test}} \right)
\]
3. Results and Discussion

3.1 Estimated Friction Factors per Section

It must be noted that the entire study was done on MATLAB. The calculated friction factors for the main line, PTO, and PHE are shown in Tables 1a, 1b, and 1c below, along with the tons of refrigeration gathered from Augusto et al. Additionally, the study used a diversified flowrate of 80% given that the buildings will be assumed to not operate at full load at the same time. The system diversity of 80% applies to the ML, PTO, and PHE lines. Additionally, the flowrate going through one PHE is the PTO flowrate divided by 3. It can be seen that as the flowrate decreases, the friction factor increases. This corresponds to a decrease in the pipe size, which can be seen later on.

| Pipe Designation | Tons of Refrigeration | Flowrate (gpm) | Initial Friction Factor | Calibrated Friction Factor |
|------------------|-----------------------|----------------|-------------------------|---------------------------|
| DCP – Tower 1    | 24,000                | 28444.44       | 0.01060                 | 0.01204                   |
| Tower 1 – Tower 2| 21,000                | 24888.89       | 0.01060                 | 0.01219                   |
| Tower 2 – Tower 3| 18,200                | 21570.37       | 0.01082                 | 0.01235                   |
| Tower 3 – Tower 4| 15,700                | 18607.41       | 0.01095                 | 0.01252                   |
| Tower 4 – Tower 5| 13,200                | 15644.44       | 0.01109                 | 0.01272                   |
| Tower 5 – Tower 6| 11,200                | 13274.07       | 0.01109                 | 0.01293                   |
| Tower 6 – Tower 7| 9,400                 | 11140.74       | 0.01142                 | 0.01314                   |
| Tower 7 – Tower 8| 7,900                 | 9362.96        | 0.01142                 | 0.01337                   |
| Tower 8 – Tower 9| 6,100                 | 7229.63        | 0.01183                 | 0.01369                   |
| Tower 9 – Tower 10| 4,300                | 5096.30        | 0.01208                 | 0.01418                   |
| Tower 10 – Tower 11| 2,800                | 3318.52        | 0.01237                 | 0.01483                   |
| Tower 11 – Tower 12| 1,400                | 1659.26        | 0.01296                 | 0.01599                   |

| Pipe Designation | Tons of Refrigeration | Flowrate (gpm) | Initial Friction Factor | Calibrated Friction Factor |
|------------------|-----------------------|----------------|-------------------------|---------------------------|
| ML – Tower 1     | 3,000                 | 3555.56        | 0.01208                 | 0.01479                   |
| ML – Tower 2     | 2,800                 | 3318.52        | 0.01208                 | 0.01492                   |
| ML – Tower 3     | 2,500                 | 2962.96        | 0.01237                 | 0.01504                   |
| ML – Tower 4     | 2,500                 | 2962.96        | 0.01237                 | 0.01504                   |
| ML – Tower 5     | 2,000                 | 2370.37        | 0.01271                 | 0.01536                   |
| ML – Tower 6     | 1,800                 | 2133.33        | 0.01271                 | 0.01556                   |
Table 1c: Friction Factor Values at a Single Plate-Type Heat Exchanger

| Pipe Designation | Tons of Refrigeration | Flowrate (gpm) | Initial Friction Factor | Calibrated Friction Factor |
|------------------|-----------------------|----------------|-------------------------|---------------------------|
| Tower 1 – PHE 1  | 1000                  | 1185.19        | 0.01344                 | 0.01654                   |
| Tower 2 – PHE 2  | 933.33                | 1106.17        | 0.01344                 | 0.01669                   |
| Tower 3 – PHE 3  | 833.33                | 987.65         | 0.01344                 | 0.01695                   |
| Tower 4 – PHE 4  | 833.33                | 987.65         | 0.01344                 | 0.01695                   |
| Tower 5 – PHE 5  | 666.67                | 790.12         | 0.01343                 | 0.01751                   |
| Tower 6 – PHE 6  | 600                   | 711.11         | 0.01408                 | 0.01749                   |
| Tower 7 – PHE 7  | 500                   | 592.59         | 0.01408                 | 0.01794                   |
| Tower 8 – PHE 8  | 600                   | 711.11         | 0.01408                 | 0.01748                   |
| Tower 9 – PHE 9  | 600                   | 711.11         | 0.01408                 | 0.01748                   |
| Tower 10 – PHE 10| 500                   | 592.59         | 0.01408                 | 0.01794                   |
| Tower 11 – PHE 11| 466.67                | 553.08         | 0.01408                 | 0.01812                   |
| Tower 12 – PHE 12| 466.67                | 553.08         | 0.01408                 | 0.01812                   |

3.2 Calibrated Pipe Sizes per Section

After acquiring the needed friction factor values, the calibrated pipe sizing was then determined. Tables 2a, 2b, and 2c below show the final pipe sizes needed for the DCP installation for each section. The calibrated pipe sizing was based on available industry-standard sizes according to ASHRAE. The final pipe sizes were then compared with the values obtained by Augusto et al.

Table 2a: Calibrated Pipe Sizes for the Main Line

| Pipe Designation | Initial Pipe Size (mm) | Final Pipe Size (mm) | Augusto et al. (mm) |
|------------------|------------------------|----------------------|---------------------|
| DCP – Tower 1    | 872.72                 | 900                  | 900                 |
| Tower 1 – Tower 2| 816.35                 | 900                  | 900                 |
| Tower 2 – Tower 3| 759.98                 | 800                  | 800                 |
| Tower 3 – Tower 4| 705.86                 | 750                  | 750                 |
| Tower 4 – Tower 5| 647.23                 | 700                  | 700                 |
| Tower 5 – Tower 6| 596.18                 | 600                  | 700                 |
| Tower 6 – Tower 7| 546.18                 | 600                  | 600                 |
| Tower 7 – Tower 8| 500.71                 | 600                  | 600                 |
| Tower 8 – Tower 9| 439.98                 | 500                  | 500                 |
| Tower 9 – Tower 10| 369.40                | 450                  | 450                 |
| Tower 10 – Tower 11| 298.09                | 400                  | 400                 |
| Tower 11 – Tower 12| 210.78                | 300                  | 300                 |

Table 2b: Calibrated Pipe Sizes for the Plot Take-Off

| Pipe Designation | Initial Pipe Size (mm) | Final Pipe Size (mm) | Augusto et al. (mm) |
|------------------|------------------------|----------------------|---------------------|
| ML – Tower 1     | 403.99                 | 450                  | 450                 |
| ML – Tower 2     | 390.29                 | 400                  | 450                 |
| ML – Tower 3     | 368.79                 | 400                  | 400                 |
| ML – Tower 4     | 368.79                 | 400                  | 400                 |
| ML – Tower 5     | 329.86                 | 350                  | 350                 |
| ML – Tower 6     | 312.93                 | 350                  | 350                 |
Table 2c: Calibrated Pipe Sizes for a Single Plate-Type Heat Exchanger

| Pipe Designation | Initial Pipe Size (mm) | Final Pipe Size (mm) | Augusto et al. (mm) |
|------------------|------------------------|----------------------|---------------------|
| Tower 1 – PHE 1  | 233.24                 | 250                  | 300                 |
| Tower 2 – PHE 2  | 225.32                 | 250                  | 250                 |
| Tower 3 – PHE 3  | 212.90                 | 250                  | 250                 |
| Tower 4 – PHE 4  | 212.90                 | 250                  | 250                 |
| Tower 5 – PHE 5  | 190.43                 | 250                  | 250                 |
| Tower 6 – PHE 6  | 180.66                 | 200                  | 250                 |
| Tower 7 – PHE 7  | 164.91                 | 200                  | 200                 |
| Tower 8 – PHE 8  | 180.66                 | 200                  | 250                 |
| Tower 9 – PHE 9  | 180.66                 | 200                  | 250                 |
| Tower 10 – PHE 10| 164.91                 | 200                  | 200                 |
| Tower 11 – PHE 11| 159.33                 | 200                  | 200                 |
| Tower 12 – PHE 12| 159.33                 | 200                  | 200                 |

3.3 Comparison of Data Values

The results show that there are slight differences between the calculated pipe sizes. It can also be seen that the values obtained seem to deviate even more as the water flows farther away from the plant. Additionally, the new values are one size smaller compared to those by Augusto et al. However, the majority of the data remains the same. A possibility of why the values do not match is because this study did not take into consideration the minor losses present in an actual network. The inputs that are common to both studies are only the flowrates through each building, system diversity, velocity limits, and water density. Furthermore, the code was written in such a way that it would terminate once it finds that both fluid velocity and pressure drop values are below their respective limits. Given that the minor losses were not considered, the friction factor within each pipe has deviated by a slight amount, thus causing discrepancies in the finalized pipe sizes.

4. Conclusion

This study was divided into two main parts. The first was to estimate the friction factor that exists in each pipe using the given tons of refrigeration. The second task was to determine the required pipe sizes using the calculated friction factors. It must be noted that the study was performed on a hypothetical DCS with a constant change in temperature of 9 degrees Celsius between the supply and return lines. In conducting the study:

The district cooling plant schematic outlines 12 buildings. Each of these buildings has one energy transfer station (ETS) that is connected to 3 plate-type heat exchangers (PHEs). Additionally, the system diversity was set to 80%.

The total tons of refrigeration outputted by the DCP was set to 24,000 TR. The flowrate going through each pipe, as well as the pressure drop and velocity limits, were taken from a study by Augusto et al. The pressure drop limit was set to 100 Pa/m. The velocity limit in the main line was set to 3 m/s, while those in the PTO and PHE were set to 1.75 m/s.
The initial values of the pipe size were found using the tonnage and theoretical flowrate. Similarly, initial values of pipe friction factor were found using the pipe relative roughness equation and the Von Karman Equation.

A single-variable Newton-Raphson Method was then used on the implicit Colebrook-White equation to find the finalized friction factors of each pipe. This was done using the initial friction factor values.

Using the ASHRAE 2017 Handbook as a guide, the calibrated pipe sizes were found. The algorithm was to use the theoretical pipe sizes as a guide to narrow down the range of potential sizes starting from the smallest to the largest. The final pipe dimensions were then selected once the fluid velocity and pressure drop are below the aforementioned limits.

The entirety of the study was conducted on MATLAB. Utilizing the smallest possible pipe diameters that permit allowable velocity and pressure values will ensure the lowest possible overall price in selecting the needed pipe sizes for a district cooling system.

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