Identification of design criteria for district cooling distribution network

Gerardo L. Augusto[1,*], Alvin B. Culaba[1], Raymond R. Tan [2]

[1]Department of Mechanical Engineering, De La Salle University, Manila, Philippines
[2]Department of Chemical Engineering, De La Salle University, Manila, Philippines

The hydraulic calculation and system simulation of two (2) district cooling distribution network models with and without secondary lines are presented in which the theoretical system pressure drop, system flow rate and flow rate requirements in each energy transfer station were determined considering a temperature difference set-point of 9°C. Variable primary flow of chilled water pumping arrangement was used to improve energy usage and to eliminate the need for a separate distribution pump in the network.

Pipe sizing and friction factor identification were necessary to determine the frictional coefficients of distribution network components. Implicit Colebrook-White equation was used to determine the pipe friction factor. The method of least squares and Cholesky decomposition method were also adopted to derive new set of pump characteristic curve considering that pumps are modulated at its best efficiency points. The governing equations consisted of mass conservation and energy equations in the form of pump characteristic curve and distribution network characteristics. The system of nonlinear equations was solved using multivariable Newton-Raphson method. The linearized equations revealed that coefficient matrices formed between the two networks were different from each other which suggested that different decomposition algorithms must be used to ensure that solution vectors are properly determined. Distribution networks with and without secondary lines showed that Jacobian matrix can be solved using singular-value decomposition and LU decomposition methods, respectively. The results of system simulation defined the coordinates of system characteristic curve which indicated the best efficiency points during selected part load and full load conditions.

An optimization technique such as exhaustive search method was used to determine the piping network design criteria that could give minimum overall costs of construction and maintenance of piping system. Numerical results show that distribution network with secondary lines yields minimum overall costs as compared with piping network without secondary line considering that nominated loads, pipe lengths and fittings, normalized annual demand factor and costs parameters associated with components of objective function are held constant.

*Corresponding author
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INTRODUCTION

District cooling system (DCS) uses thermal energy in the form of chilled water from a central plant to multiple buildings through a distribution network of underground pipes for use in space cooling. The cooling process takes place in the central plant which eliminates the use of separate conventional cooling system from each building.

The district cooling system primarily consists of three (3) components, namely; the central cooling plant, the distribution system and the customer's energy transfer station (ETS). The cooling equipment, cooling towers, power generation, and thermal storage if any, are the main components of a central cooling plant. The distribution system is a piping network that transfers the cooling medium or chilled water from the central cooling plant to different energy transfer stations of individual building at controlled rates. The customer's energy transfer station consists of plate type heat exchangers (PHE), secondary pumping system, and chilled water piping for the building.

A large-scale district cooling plant could save energy consumption costs from 25% to 40% as compared with the sum of conventional centralized air-conditioning system of each building (Bin Shafar 2011). However, as the distribution network is often the most expensive portion and requires large initial investment cost of the district cooling system, careful design is needed to optimize its use.

Over the years, the codes, standards and regulations essential for the piping industry are well established (ASHRAE 2008; ASME 1997; ASME 2009). Studies on pipeline design, installation, and operation are widely discussed by several investigators in which application of appropriate codes and system hardware components to meet safety standards are specified (Antaki 2003; McAllister 2005). Antaki (2003) discussed the fundamental principles in materials, design, fabrication, inspection, testing, operation, maintenance and integrity of plant piping. However, even prior to construction, a thorough investigation using system simulation and optimization is needed to imitate the configuration of real system and to understand the performance of distribution network at different operating conditions with minimum cost.

Stoecker (1989) used system simulation of a simple water pumping system which transfers fluid from one reservoir to another. The flow rates and pressure drop were obtained from a determined system of equations using multivariable Newton-Raphson method. In a separate study, he also introduced optimization procedures of water chilling unit (e.g., refrigeration system with cooling tower) being optimized for minimum first cost.

For several decades, numerical optimization techniques have been widely used on structural applications but their use in distribution network is quite new (Schmit 1960; Vanderplaats 1999). Combining both system flow analysis and optimization techniques yields a powerful approach to minimize costs and to increase performance during piping system design (Hodgson and Walters 2002; Walters 2002). To implement optimization methods in pumping system design, Hodgson et al. introduced hydraulic solver and optimizer for flow analysis and optimization technique, respectively. The hydraulic solver operated as a subroutine which is called repeatedly by the optimizer to evaluate a series of designs. However, the details of hydraulic calculation were not specified.

Recent study of distribution network used numerical optimization to determine the optimal pipeline size and pump combination for a 90.4 mile long, treated-seawater transfer line in the Kingdom of Saudi Arabia. The design study described the best configuration of pipeline material and sizes including pumps to meet both seawater requirements and the flexibility to accommodate an increased demand in the future. The system constraints were maximum pipe operating pressure and minimum thickness for a given pipe diameter (Thorp and Olsen 2008).

In district cooling with closed-loop system, the appropriate pipe size of distribution network shall be determined by the economic standpoint of life-cycle cost for construction, operation and maintenance. However, this study is seldom done because the calculation requires tedious works. Instead, the criteria that have evolved from practice are usually used for design. These design criteria are maximum flow velocity and pressure drop limits (ASHRAE 2008; ASHRAE 2013).

This study aimed to determine the piping network design criteria that would minimize the sum of initial investment, maintenance, and operational costs. The criteria that have evolved from practice were still used in the piping design. The design constraints were pressure drop limit, maximum flow velocities at primary line, secondary line, tertiary line if any, and at plot take-off (PTO). The calculation method was divided into three (3) modules namely; friction factor identification, chilled water pumping system simulation, and optimization. The system pressure drop, system flow rate and flow rate requirements in each energy transfer station (ETS) were determined to properly evaluate the performance of complex piping system before any hardware is procured. Optimization technique such as exhaustive search method was used to solve the objective function and to identify the piping network design criteria.

MATERIALS AND METHODS

District Cooling System and Distribution Network Models

Figure 1 shows an overall view of district cooling system with temperature limits at full load condition. Variable primary flow pumping scheme was used to reduce operating and investment costs since it requires smaller space due to fewer plant components. The pumping arrangement is shown in Fig. 2. The distribution network with temperature difference set-point of 9°C was used as the reference for plant design and operation for chilled-water systems. To compare the piping network design criteria of two distribution network models, the schematic diagrams DNModel-01_12 and DNModel-03_12 were used as shown in Fig. 3 and Fig. 4, respectively. Figure 4 shows the presence of secondary lines in the network. These network models were used as benchmarks for fluid flow analysis. In both cases, twelve (12) energy transfer stations (ETS) in each network were used with total pipe length of approximately 5.2 km. The nominated cooling loads are listed in Tab. 1. Table 2 shows the breakdown of pipe lengths installed in two (2) distribution network models. To properly accommodate the cooling loads, three (3) plate type heat exchangers were placed in each building.

Identification of Piping Network Design Criteria

Methods of hydraulic calculation have been developed primarily for domestic water distribution system (Jeppson 1977; Stephenson 1981). However, these may apply to chilled water distribution network of district cooling system with appropriate modifications in which the algebraic sum of head losses around any closed loop is neglected. Prior to head loss calculation, the friction factor is determined using an implicit Colebrook-White method (GL Augusto, unpublished observations). Pertinent variables such as system pressure drop and volume flow rates of chilled water in a thermal system operating at steady-state must be calculated to determine the required pumping performance characteristics. Calculating flow rates and system pressure in a piping network with branches, fittings, pumps and plate type heat exchangers could be difficult without the aid of a computer. Computer tools needed for the source codes are written in Fortran programming and Basic programming using macro platform of MS Excel. The hydraulic calculation and chilled water pumping system simulation were carried-out in an iterative fashion considering that chilled water supply and return temperatures throughout the network were maintained. Initial estimates of system pressure and system flow rate were determined. Refined values of these parameters including flow rate in each energy transfer station were calculated, and adjusted to ensure that the cooling loads were met. The system simulation was treated as continuous and deterministic. This research work is based on the following fluid mechanics assumptions namely; one-dimensional flow, incompressible flow, steady-state condition, and no chemical reactions. An optimization approach commonly known as exhaustive search method was used to determine the piping network design criteria that provided the minimum overall cost. Figure 5 shows the logical structure of identifying the piping network design criteria using the combined fluids engineering and optimization approach.

Identification of Governing Equations

Prior to chilled water pumping system simulation, pipe sizing and friction factor identification were necessary to determine the frictional coefficients of distribution network components. Knowing these coefficients, the energy equations due to pipe friction can be derived. Combining mass conservation, pump performance curve and energy equations yielded a system of nonlinear equations. The results of calculation defined the coordinates of system characteristic curve at full load and part load conditions. The coordinates of system characteristic curve were sets of system pressure drop, system flow rate, and individual flow rate in each energy transfer station at selected operating conditions.

Mass Conservation. Mass conservation was introduced at district cooling plant main entry point and at the nodes where the intersection between primary and secondary lines existed. The continuity equation included the time rate of change of mass within the control volume and mass flux as shown below.

$$\frac{dm_{cv}}{dt} = \int \frac{\partial \rho}{\partial t} dV + \int \rho(\boldsymbol{q}.\boldsymbol{n})\, dS$$

$$0 = \int \left[\frac{\partial \rho}{\partial t} + \rho \nabla.\boldsymbol{q} + \boldsymbol{q}.\nabla \rho\right] dV$$

In an incompressible fluid, the chilled water density is constant. If a steady-state condition exists then the continuity equation at any arbitrary volume can be reduced to Eq. 1 which means that the divergence of velocity field ***q*** is zero everywhere.

$$0 = \nabla.\boldsymbol{q} \qquad \text{Eq. 1}$$

The simplified mass balance equations are shown below

$$\omega = \textstyle\sum_j \omega_j \qquad \text{Eq. 1a}$$

$$\omega_s = \textstyle\sum_j \omega_j \qquad \forall_s \qquad \text{Eq. 1b}$$

Pump Performance Curve. The pump performance curve was taken from the technical data sheet of pump model that satisfies the chilled water cooling flow rate requirements of water-cooled chiller with temperature difference of 9°C. The pump flow curve can be generally expressed as a function of volume flow rate as shown in Eq. 2.

$$\delta p_1 = g(\omega) \qquad \text{Eq. 2}$$

Energy Equations due to Pipe Friction. The energy equations due to pipe friction were derived based on the

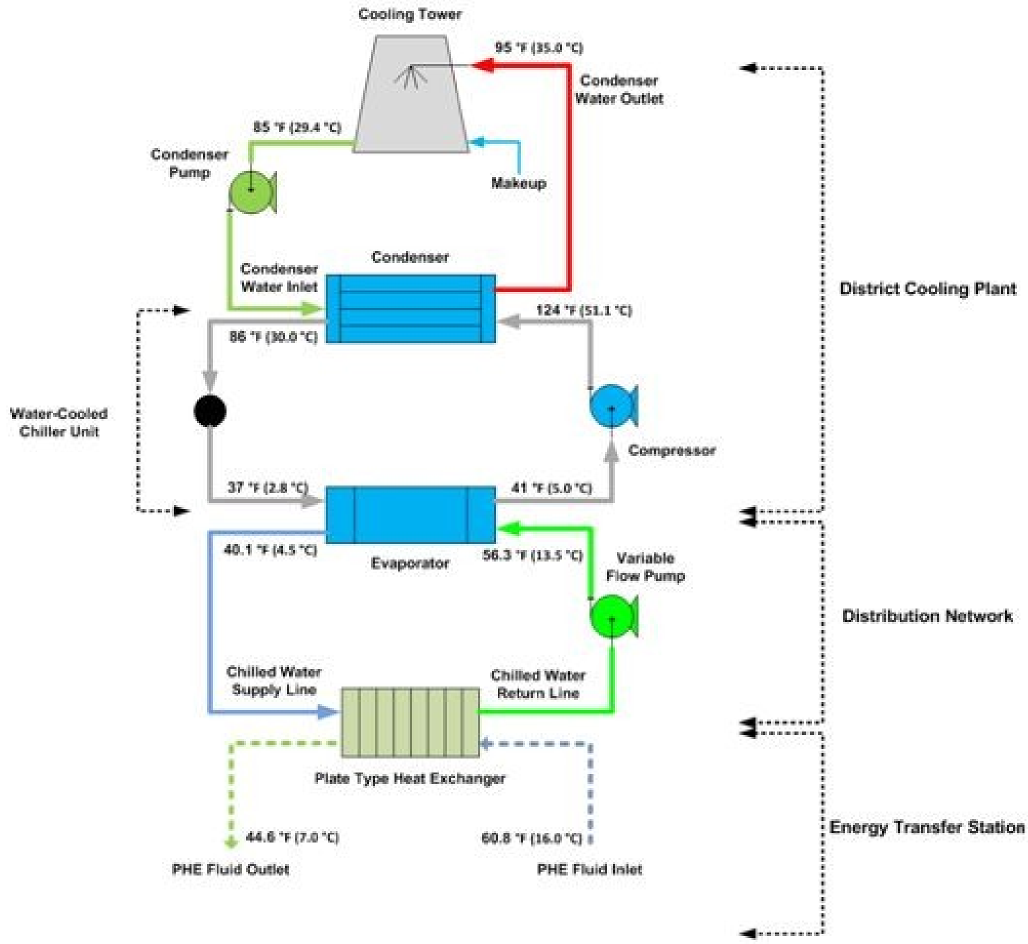

Figure 1. Overview of district cooling system with temperature limits

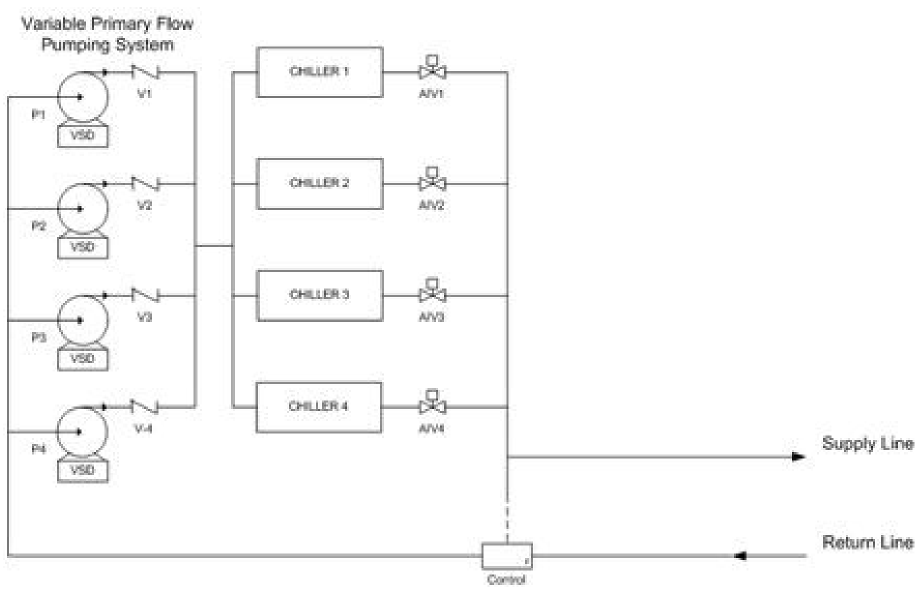

Figure 2. Variable primary flow of chilled water pumping arrangement

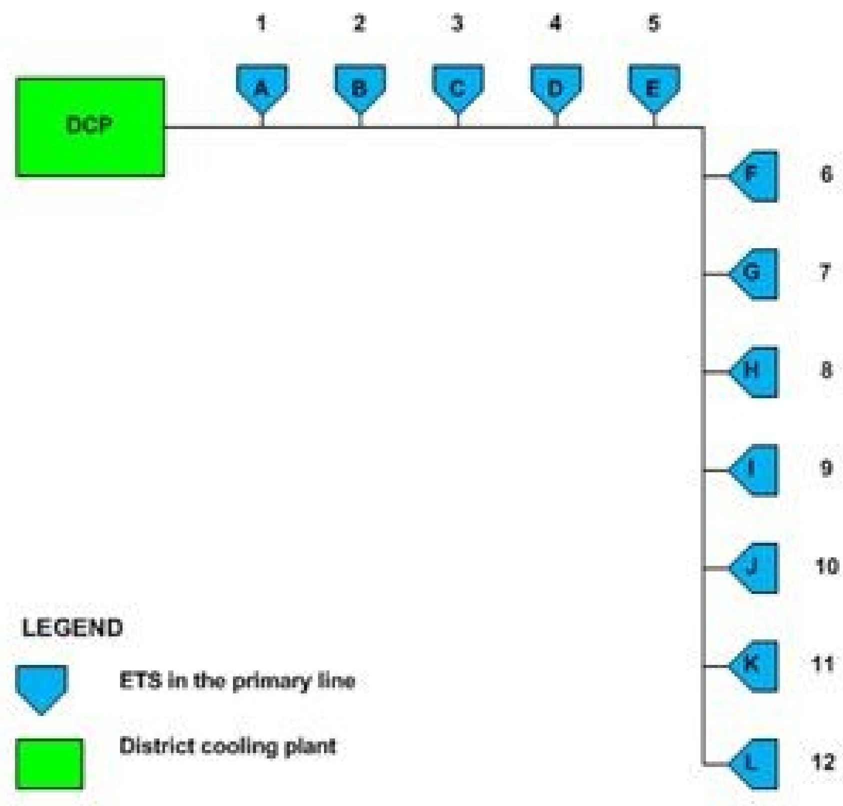

Figure 3. Schematic diagram of distribution network DNModel-01_12

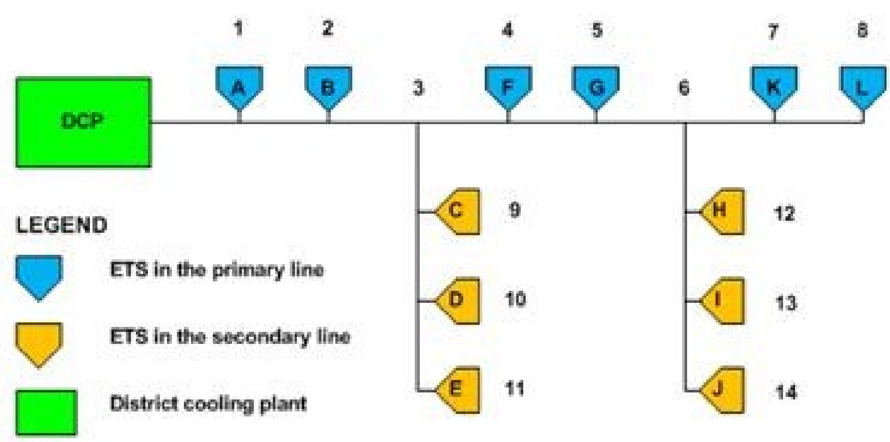

Figure 4. Schematic diagram of distribution network DNModel-03_12

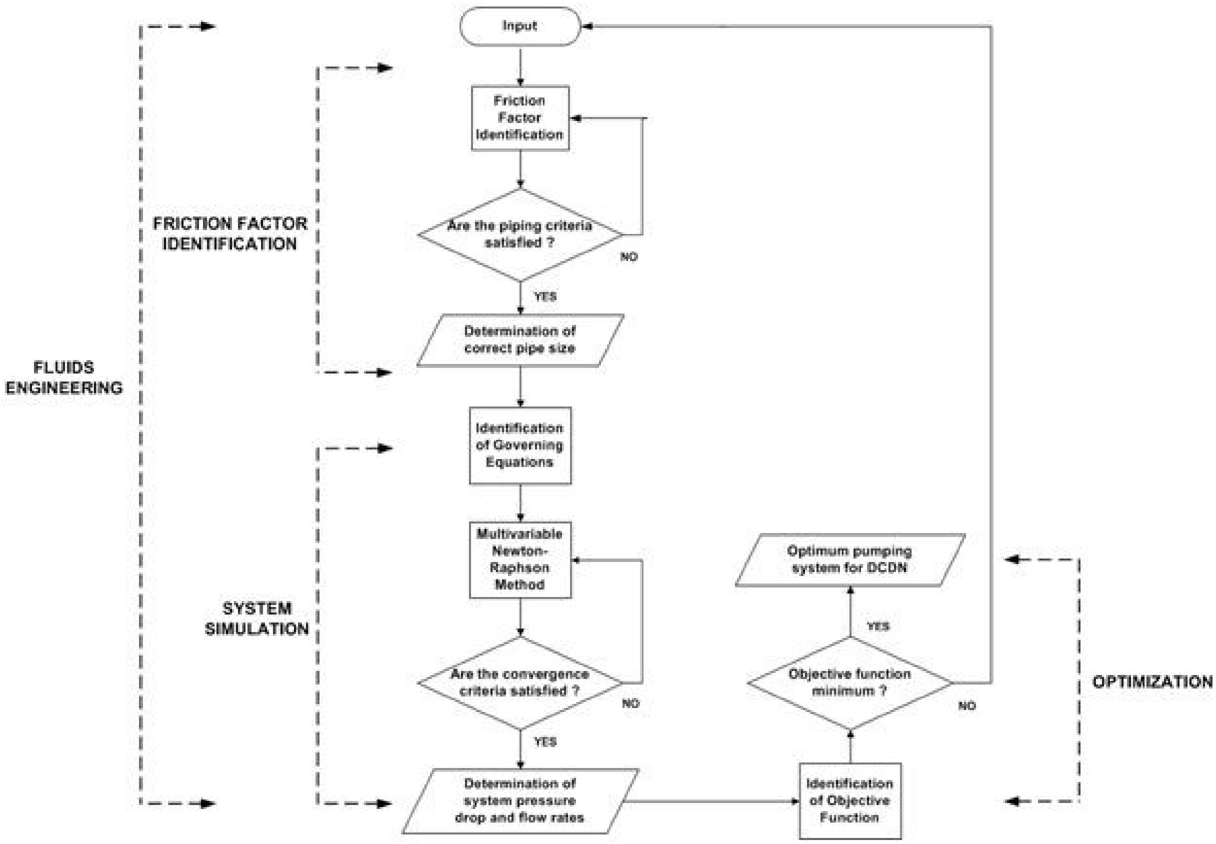

Figure 5. Logical structure of optimum pumping system for distribution network

configuration of distribution network from central cooling plant to respective energy transfer station of each building which can be generally expressed as

$$\delta p_j = \sum_i c_i \omega_i^2 \qquad \forall_j \qquad \text{Eq. 3}$$

where, i indicates the number of pipe components and j the number of ETS in the distribution network. The notations c_i and ω_i denote the frictional coefficients of each pipe components and flow rate along the distribution network, respectively. The friction factor denoted by f is a function of Reynolds number and pipe relative roughness. The frictional coefficient can be expressed in terms of friction factor and a ratio of pipe length and pipe diameter. These parameters are given by

$$f = h\left(R, \frac{\varepsilon}{D}\right) \qquad \text{Eq. 3a}$$

$$c = k\left(f, \frac{L}{D}\right) \qquad \text{Eq. 3b}$$

Enthalpy Balance at Return Line. The enthalpy balance was neglected because chilled-water supply temperature (T_s) and temperature difference set point (δT) were held constant throughout the network at 4.5 C and 9°C, respectively. Evaluating the enthalpy balance of return line at the junction before entering the district cooling plant reduced the equation to mass conservation.

$$\rho \omega C_p\left(T_j + \delta T_j\right) = \rho \omega_1 C_p\left(T_j + \delta T_j\right) + \sum_{j=2}^{m} \rho \omega_j C_p\left(T_j + \delta T_j\right) \qquad \text{Eq. 4}$$

The above equations require that the following conditions are satisfied.

$$T_j = T_s \qquad \forall_j$$

$$\delta T_j = \delta T \qquad \forall_j$$

$$\omega_j = h\left(L_{c_j}, \delta T\right) \qquad \forall_j \qquad \text{Eq.4a}$$

The fluid thermal properties such as mass density, absolute viscosity and specific heat at constant pressure are functions of chilled water supply temperature.

$$\rho = \hat{g}(T_s) \qquad \text{Eq. 5a}$$

$$\mu = \hat{h}(T_s) \qquad \text{Eq. 5b}$$

$$C_P = \hat{k}(T_s) \qquad \text{Eq. 5c}$$

Dimensional Analysis

Buckingham Π Theorem. As variable primary flow pumping system was used, the pumps were modulated at its best efficiency point at different operating conditions. Dimensional analysis with a generalized approach commonly known as Buckingham Π Theorem was adopted to derive pertinent parameters to predict the performance of pump model under selected conditions of operation. When the length scale was neglected the following variables were used:

$$\hat{f}\left(\dot{h}, Q, n, \emptyset, \varepsilon, \rho, \mu, \dot{T}, \eta, g\right) = 0 \qquad \text{Eq. 6}$$

The dimensionless parameters can be expressed as

$$\theta\left(\frac{\dot{h}}{\emptyset}, \frac{\dot{T}}{\rho n^2 \emptyset^5}, \frac{Q}{n\emptyset^3}, \frac{\rho n \emptyset^2}{\mu}, \frac{\varepsilon}{\emptyset}, \eta, \frac{g}{n^2 \emptyset}\right) = 0 \qquad \text{Eq. 7}$$

Simplifying the above parameters, the new functional relations yield

$$\frac{g\dot{h}}{n^2 \emptyset^2} = \theta_1\left[\frac{Q}{n\emptyset^3}, \frac{\rho n \emptyset^2}{\mu}, \frac{\varepsilon}{\emptyset}\right] \qquad \text{Eq. 8a}$$

$$\frac{\dot{T}}{\rho n^2 \emptyset^5} = \theta_2\left[\frac{Q}{n\emptyset^3}, \frac{\rho n \emptyset^2}{\mu}, \frac{\varepsilon}{\emptyset}\right] \qquad \text{Eq. 8b}$$

$$\eta = \theta_3\left[\frac{Q}{n\emptyset^3}, \frac{\rho n \emptyset^2}{\mu}, \frac{\varepsilon}{\emptyset}\right] \qquad \text{Eq. 8c}$$

Subsequently, based on the above equations, the Affinity Laws for geometrically similar pumps such as head, torque and volume flow rate were derived as shown in Eq. 9a, Eq. 9b and Eq. 9c, respectively.

$$\left[\frac{g\dot{h}}{n^2 \emptyset^2}\right]_1 = \left[\frac{g\dot{h}}{n^2 \emptyset^2}\right]_2 \qquad \text{Eq. 9a}$$

$$\left[\frac{\dot{T}}{\rho n^2 \emptyset^5}\right]_1 = \left[\frac{\dot{T}}{\rho n^2 \emptyset^5}\right]_2 \qquad \text{Eq. 9b}$$

$$\left[\frac{Q}{n\emptyset^3}\right]_1 = \left[\frac{Q}{n\emptyset^3}\right]_2 \qquad \text{Eq. 9c}$$

Numerical Methods

Cholesky Decomposition Method. In a large-scale district cooling plant, the chilled-water pumps are connected in parallel. To derive the pump performance curve that would represent a set of similar pumps operating at full load, the method of least squares was used. But, if the total cooling load downstream of the network decreases then the pumps operate at part load condition. In this case, the pressure rise developed by the pumps is a function of both flow rate and number of operating pumps. As system equilibrium occurs at pump's best efficiency point, the pump rotational speed can be identified using Affinity Laws.

The method of least squares can be expressed as

$$u = \sum_k \left[\dot{h}_k - p_k(Q)\right]^2 \qquad \text{Eq. 10}$$

where, $p_k(Q)$ is a theoretical pump curve which is a polynomial function of flow rate with an exponential index, m=3.

$$p_k(Q) = a_0 + a_1 Q + \ldots + a_m Q^m \qquad \text{Eq. 11}$$

As the pump curve should be fitted through new sets of coordinates, a necessary condition for u to be minimum is to satisfy the following:

$$u_{a_l} \text{ or } \frac{\partial u}{\partial a_l} = 0 \qquad \forall_l \qquad \text{Eq. 12}$$

$$\text{where, } \frac{\partial u}{\partial a_l} = -2\sum_k Q^l\left[\grave{h}_k - p_k(Q)\right] = 0$$

In matrix form, the normal equations are shown below.

$$\begin{bmatrix} \sum \grave{h} \\ \sum Q\grave{h} \\ \sum Q^2\grave{h} \\ \sum Q^3\grave{h} \end{bmatrix} = \begin{bmatrix} n & \sum Q & \sum Q^2 & \sum Q^3 \\ \sum Q & \sum Q^2 & \sum Q^3 & \sum Q^4 \\ \sum Q^2 & \sum Q^3 & \sum Q^4 & \sum Q^5 \\ \sum Q^3 & \sum Q^4 & \sum Q^5 & \sum Q^6 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} \qquad \text{Eq. 13}$$

In vector form, it can be rewritten as

$$\grave{\boldsymbol{h}} = \boldsymbol{A}\boldsymbol{a}$$

$$\boldsymbol{A}^{-1}\grave{\boldsymbol{h}} = \boldsymbol{a} \qquad \text{Eq. 14}$$

As the elements of coefficient matrix are symmetric and positive-definite, then it has positive real eigenvalues which suggests that the inverse of coefficient matrix is equal to its transpose. Hence, Cholesky decomposition method can be used in solving the unknown vector parameter denoted as a.

Multivariable Newton-Raphson Method. The continuity equation, pump performance curve and energy equations due to pipe friction can be expressed as functional relations to be zeroed as shown in Eq. 15.

$$f_{ii}(\delta p, \omega, \omega_1, \omega_2, ..) = 0 \qquad \text{Eq. 15}$$

The independent variables were system pressure drop, system flow rate and cooling flow rate requirements in each ETS. The above equation can be rewritten as

$$F_{ii}(s_1, s_2, .., s_n) = 0 \qquad \text{Eq. 16}$$

Simplifying the governing equations could lead to system of nonlinear equations in which the variables $\underline{s}$ be an entire vector denoted as $s_{jj}$and F be the entire vector of functions F_{ii}. It can be solved using multivariable Newton-Raphson (MNR) method where the functions can be expanded in Taylor series of the form

$$F_{ii}(\boldsymbol{s} + \delta\boldsymbol{s}) = F_{ii}(\boldsymbol{s}) + \sum_{jj=1}^{n} \frac{\partial F_{ii}}{\partial s_{jj}} \delta s_{jj} + O(\delta\boldsymbol{s}^2) \qquad \text{Eq. 17}$$

Neglecting higher order terms O(δs_2)and by considering the left-hand side equation equal to zero, a set of equations for the corrections δ_s that move each function closer to zero is simultaneously obtained. Hence, Eq. 17 can be reduced to an equation with Jacobian matrix J as shown below.

$$\boldsymbol{J}.\delta\boldsymbol{s} = -\boldsymbol{F} \qquad \text{Eq. 18}$$

If matrix Eq. 18 is a determined system of equations, then LU decomposition method can be used. Otherwise, it would be more appropriate to use singular-value decomposition method where the corrections δs_{ll} are then added to the solution vector and the process is iterated to convergence. The convergence criteria are function convergence and root convergence with tolerance values of $1.0\text{x}10^{-8}$.

$$\boldsymbol{s}_{ll+1} = \boldsymbol{s}_{ll} + \delta\boldsymbol{s}_{ll} \qquad \text{Eq. 19}$$

Optimization Method

In optimization using exhaustive search method, the values of objective function were determined and conclusions were drawn from the results of the calculation at various combinations of independent variables. The objective function denoted as $\epsilon(\boldsymbol{x})$ is a cost function derived from engineering economics. Comparative cost analysis such as present worth pattern method was used. To further verify the results of computation, the annual cost pattern method was also adopted for comparison. The cost function variables included the (a) the initial investment costs for pumps, plate type heat exchangers (PHE), and distribution network, (b) installation costs for item (a), (c) excavation cost for distribution network including backfill and surface restoration, (d) operation and maintenance costs, (e) payroll taxes including taxes for property and insurance, and (f) depreciation cost. The optimization problem can be written as

$$\underset{\boldsymbol{x} \in R}{minimize}\, \epsilon(\boldsymbol{x}) \qquad \text{Eq. 20}$$

subject to the following design constraints,

$$\beta(\boldsymbol{x}) = \delta p_{l.v.} \qquad \text{Eq. 21}$$

$$\gamma_{kk}(\boldsymbol{x}) \leq v_{u.l.} \qquad \forall_{kk} \qquad \text{Eq. 22}$$

The equality and inequality design constraints were piping network design criteria such as pressure drop limit and velocity limits, respectively. The pressure drop limit was set at 100 Pa/m (ASHRAE 2008). The velocity limits for primary line, secondary line and plot take-off should not exceed 3.0 m/s with a search interval of 0.05 m/s. Table 3 shows the normalized annual power load demand factor.

RESULTS AND DISCUSSIONS

Hydraulic Calculation

A determined system of nonlinear equations was formed when consolidating all the governing equations using distribution network DNModel-01_12. An overdetermined system of nonlinear equations was derived when evaluating distribution network DNModel-03_12. In system simulation, multivariable Newton-Raphson method with LU decomposition and singular-value decomposition methods were used in calculating the independent variables for DNModel-01_12 and DNModel-03_12, respectively.

The results of system simulation indicate the best efficiency points during selected part load and full load conditions for distribution network models DNModel-01_12 and DNModel-03_12 as shown in Fig. 6 and Fig. 7, respectively. Table 4 summarizes the description of best efficiency points at different operating conditions. $PC_{\_1}$ indicates the general pump curve of all pumps operating at rated speed. Pump curves denoted as $PC_{\_2}$ and $PC_{\_3}$ represent the upper and lower limits with six (6) and five (5) number of pumps operating at rated speed. $PC_{\_Predicted}$ illustrates the pump curve when operating at full load with a diversity factor of 80%. $PC_{\_Mod}$ shows the pump curve when operating at part load with nominated loads reduced to 72% and diversity factor of 80%. At full load, distribution network DNModel-01_12 requires higher pump head i.e., 28.3 m as compared with DNModel-03_12 which is 21.7 m.

Optimization Method

Optimization technique commonly known as exhaustive search method was used in identifying the piping network design criteria that would give minimum overall costs of construction and maintenance of two (2) distribution network models. Table 5 shows pertinent cost parameters that are associated with components of objective function. The optimization results for distribution network models are listed in Tab. 6. Pipe sizes for two (2) distribution network models were obtained when the network design criteria became known. The results are listed in

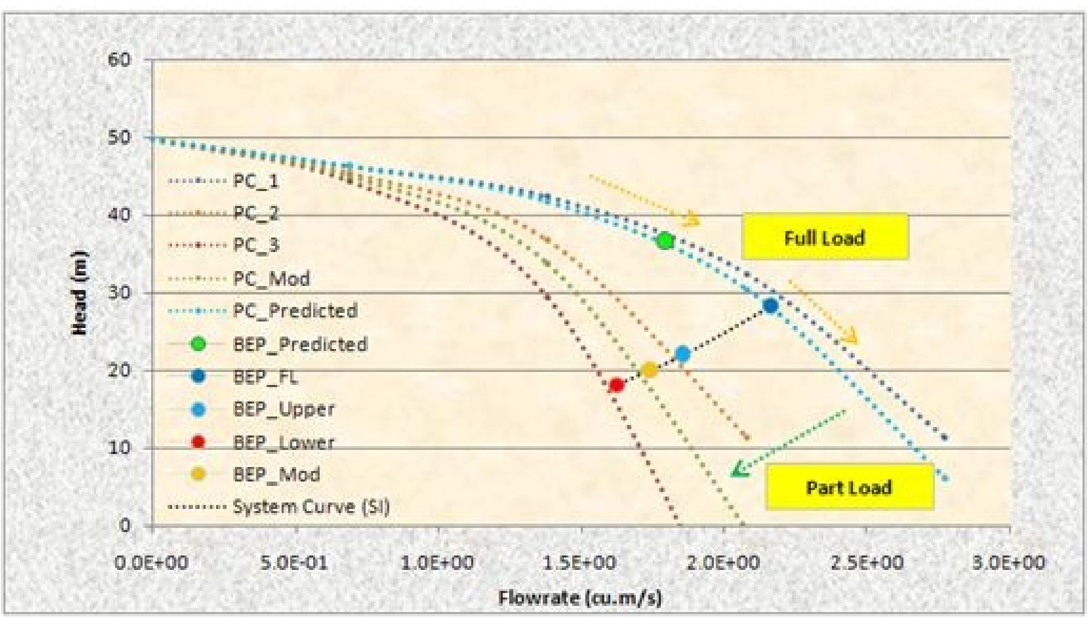

Figure 6. Best efficiency points at part load and full load conditions for DNModel-01_12

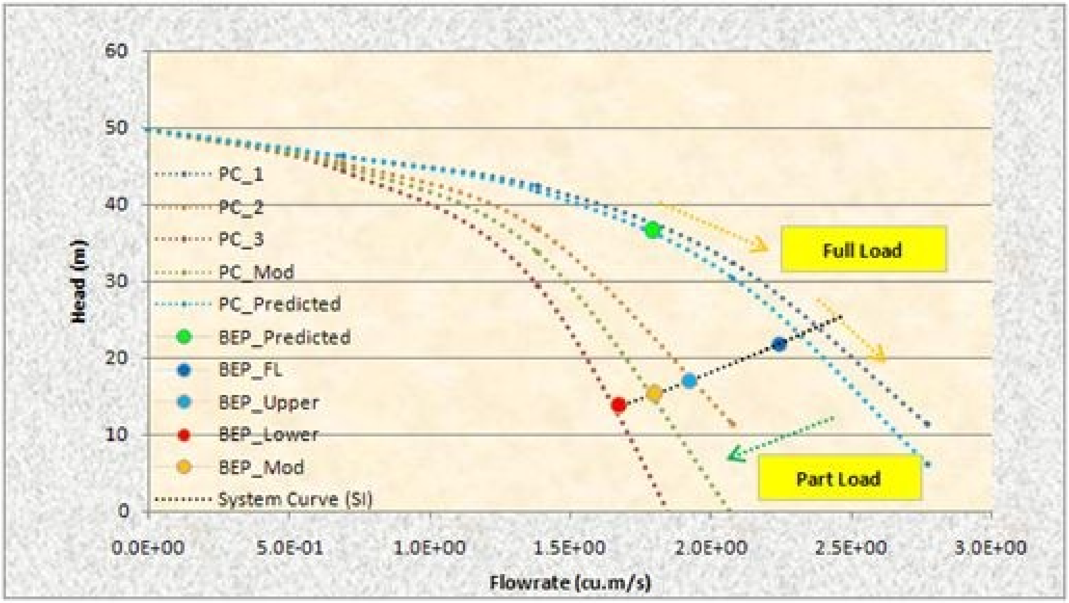

Figure 7. Best efficiency points at part load and full load conditions for DNModel-03_12

Tab. 7.

Figure 8 illustrates the profile of overall costs for distribution network DNModel-01_12. This is based on present worth pattern method as a function of limiting velocity at primary line considering the velocity limit of 1.75 m/s at plot take-off is held constant. The annual cost pattern method was also adopted for comparison as shown in Fig. 9. The results suggest that minimum overall cost occurred when the velocity limit at primary line was 3.0 m/s.

The overall costs profiles for distribution network DNModel-03_12 based on present worth and annual cost pattern methods are shown in Figures 10 and 11. The results indicate that minimum overall cost occurred when the velocity limit at primary line was 2.7 m/s considering that the velocity limits at secondary line and plot take-off were held constant at 3.0 m/s and 1.9 m/s, respectively.

CONCLUSIONS

The method of identifying the piping design criteria of district cooling distribution network was developed. To determine the piping design criteria involved three (3) research areas namely; friction factor identification, chilled water pumping system simulation, and optimization. In this study, two (2) distribution networks models with and without secondary lines and total pipe length of approximately 5.2 km. were used as benchmarks for fluid flow analysis. Both networks had twelve (12) energy transfer stations with total nominated load of 24,000-ton of refrigeration and diversity factor of 80%. Main results are summarized as follows:

1. Prior to chilled water pumping system simulation, pipe sizing and friction factor identification were necessary to properly determine the frictional coefficients of distribution network components. The pipe friction factor was calculated using an implicit Colebrook-White equation.

2. A determined system of equations was formed when evaluating all the governing equations derived from a distribution network without secondary line. Multivariable Newton-Raphson and LU decomposition methods were used to determine the independent variables.

3. An overdetermined system of nonlinear equations was created when consolidating all the governing equations derived from a distribution network with secondary lines. The independent variables were identified using multivariable Newton-Raphson and singular-value decomposition methods.

4. The results of system simulation defined the coordinates of system characteristic curve which indicated the best efficiency points during selected part load and full load conditions.

5. At full load, distribution network DNModel-01_12 required higher pump head of 28.3 m as compared with distribution network DNModel-03_12 which was only 21.7 m.

6. Optimization results using exhaustive search method

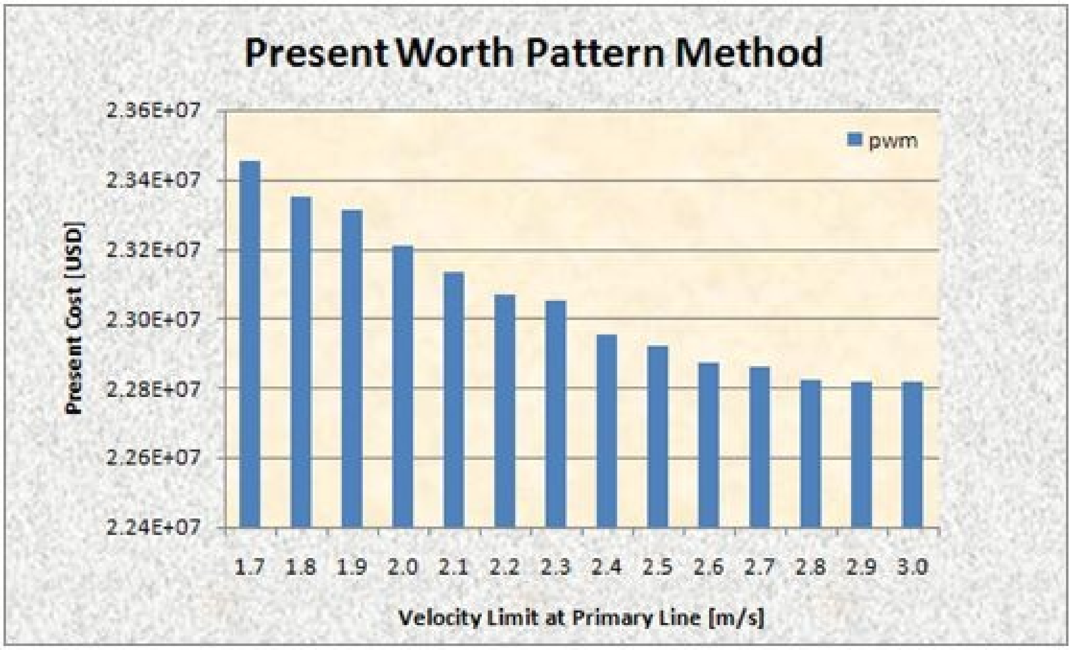

Figure 8. Optimization based on present worth pattern method for DNModel-01_12

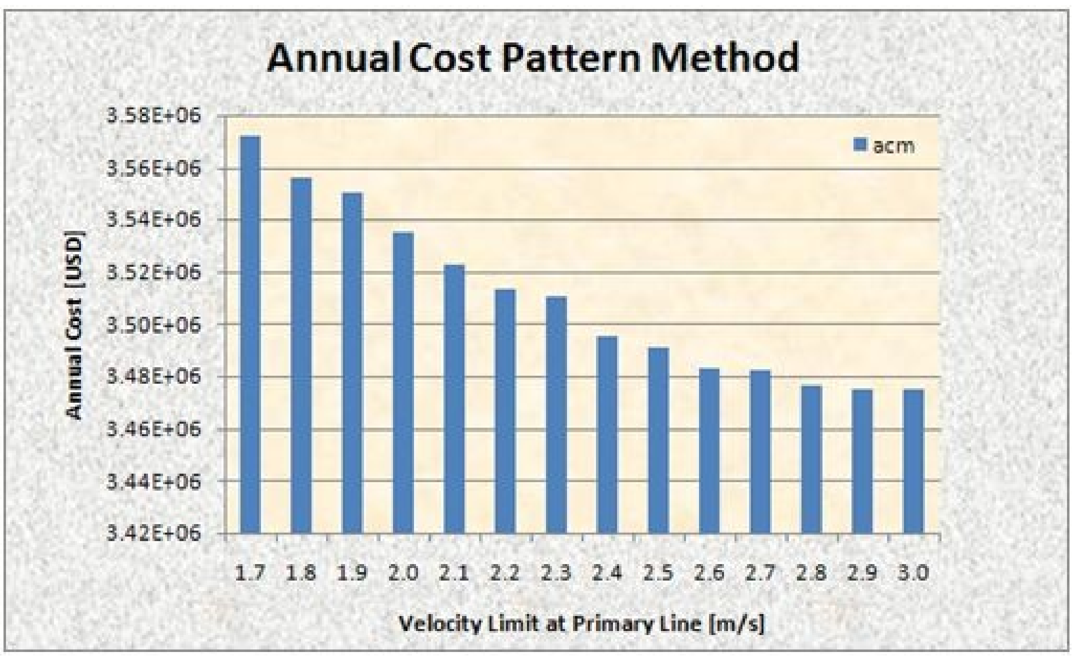

Figure 9. Optimization based on annual cost pattern method for DNModel-01_12

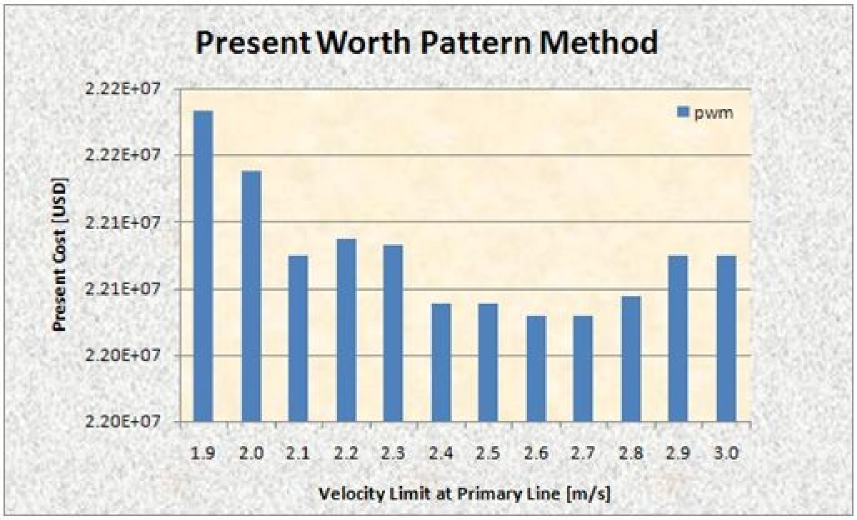

Figure 10. Optimization based on present worth pattern method for DNModel-03_12

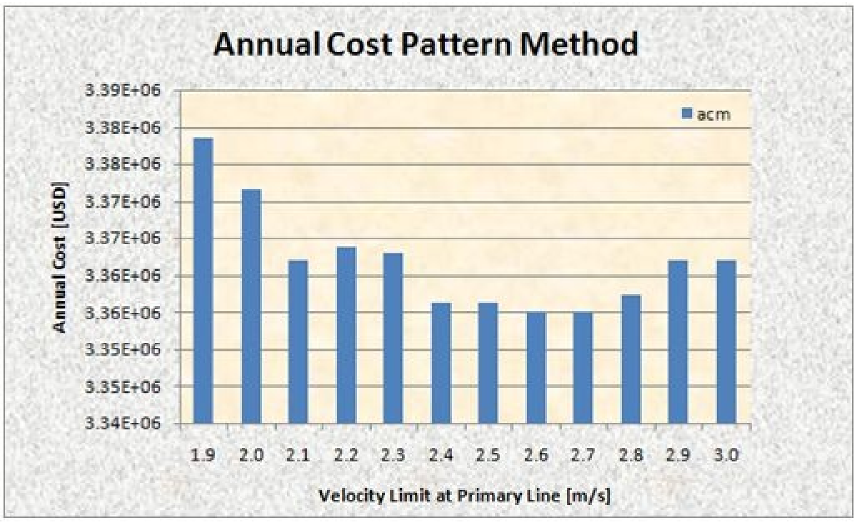

Figure 11. Optimization based on annual cost pattern method for DNModel-03_12

suggest that piping network design criteria for distribution network DNModel-01_12 without secondary line have velocity limits at primary line of 3.0 m/s and at plot take-off of 1.75 m/s considering a pressure drop limit of 100 Pa/m.

7. Furthermore, the piping network design criteria for distribution network DNModel-03_12 with secondary lines had velocity limits at primary line of 2.7 m/s, at secondary line of 3.0 m/s and at plot take-off of 1.9 m/s considering a pressure drop limit of 100 Pa/m.

The piping network design criteria discussed in item nos. 6 and 7 can only be achieved provided that input parameters such as nominated cooling loads, pipe lengths, normalized annual power load demand factor and interest rates associated with components of objective function as listed in Tab 1, Tab. 2, Tab. 3 and Tab. 5, respectively will be used.

NOMENCLATURE

μ	absolute viscosity
T_s	chilled-water supply temperature
δs	correction vector
dm	elemental mass
dv	elemental volume
ds	elemental surface
c	frictional coefficient

Table 1. Nominated cooling loads

Building ID	Cooling Load (TR)	Building ID	Cooling Load (TR)
Tower A	3000	Tower G	1500
Tower B	2800	Tower H	1800
Tower C	2500	Tower I	1800
Tower D	2500	Tower J	1500
Tower E	2000	Tower K	1400
Tower F	1800	Tower L	1400

Table 2. Pipe lengths for two (2) distribution network models

DNModel-01_12			
Building ID	Main Line (m)	PTO Line (m)	ETS/PHE (m)
Tower A	500	100	8
Tower B	500	100	8
Tower C	300	100	8
Tower D	300	100	8
Tower E	300	100	8
Tower F	300	100	8
Tower G	300	100	8
Tower H	300	100	8
Tower I	300	100	8
Tower J	300	100	8
Tower K	300	100	8
Tower L	300	100	8

DNModel-03_12			
Building ID	Main Line (m)	PTO Line (m)	ETS/PHE (m)
Tower A	500	100	8
Tower B	500	100	8
Node 3	50	-	-
Tower C	300	100	8
Tower D	300	100	8
Tower E	300	100	8
Tower F	300	100	8
Tower G	300	100	8
Node 6	50	-	-
Tower H	300	100	8
Tower I	300	100	8
Tower J	300	100	8
Tower K	300	100	8
Tower L	300	100	8

Table 3. Normalized annual power load demand factor

Month	%	Month	%
January	47.14	July	85.71
February	44.29	August	88.57
March	54.29	September	80.00
April	64.29	October	71.43
May	71.43	November	57.14
June	78.57	December	51.43

Table 4. Description of best efficiency points at part load and full load conditions

Legend	Description
$BEP_{\_Predicted}$	Initial set of pressure drop and cooling flow rate requirements
$BEP_{\_FL}$	Best efficiency point at full load when all pumps are running with diversity factor of 80%
$BEP_{\_Upper}$	Best efficiency point at part load when 6 no. of pumps are operating at rated speed
$BEP_{\_Lower}$	Best efficiency point at part load when 5 no. of pumps are operating at rated speed
$BEP_{\_Mod}$	Best efficiency point at part load when cooling loads reduced to 72%

f	friction factor
g	gravity
$\boldsymbol{J}$	Jacobian matrix
ρ	mass density
LC	nominated cooling load
D	pipe diameter
L	pipe length
ε/D	pipe relative roughness
PHE	plate-type heat exchanger
PTO	plot take-off
δp_I	pressure drop due to pump curve
δp_j	pressure drop due to piping configuration
$\delta p_{l.v.}$	pressure drop limiting value
η	pump efficiency
$\grave{h}$	pump head
ϕ	pump impeller diameter
ε / ϕ	pump relative roughness
n	pump rotative speed
Q	pump volume flow rate
R	Reynolds number
$\boldsymbol{S}$	solution vector of MNR
C_p	specific heat at constant pressure
δT	temperature difference set point
t	time
$\grave{T}$	torque
$\boldsymbol{n}$	unit vector
$\boldsymbol{q}$	velocity field
$v_{u.l.}$	velocity upper limit
ω	volume flow rate

Subscript

cv	control volume
i	indicates the number of pipe components
j	refers to the number of ETS in the distribution network
k	number of data points
l	number of pump curve coefficients
ii	number of functional relations to be zeroed in MNR
jj	number of independent variables in MNR
kk	number of velocity limits
ll	number of iteration in MNR
s	number of secondary lines

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CONFLICTS OF INTERESTS

The authors certify that there is no conflict of interest in the conduct, preparation and submission of this manuscript.

Table 5. Cost parameters associated with components of objective function

Description	Value
Estimated life of district cooling distribution network	30 years
Contractor fee for installation of pumps, pipe works	7%
Interest for capital before taxes	15%
Interest for maintenance cost	10%
Interest for payroll taxes	4%
Interest for property and insurance taxes	3%

Table 6. Piping network design criteria for distribution network models

Description	Variable	DNModel-01_12	DNModel-03_12	Unit
Velocity limit at primary line	v_{pl}	3.00	2.70	m/s
Velocity limit at secondary line	v_{sl}	-	3.00	m/s
Velocity limit at plot take-off	v_{pto}	1.75	1.90	m/s
Pressure drop limit	$\delta p_{l.v.}$	100	100	Pa/m

Table 7. Pipe sizes for two (2) distribution network models

DNModel-01_12			
Building ID	Main Line (mm)	PTO Line (mm)	ETS/PHE (mm)
Tower A	900	450	300
Tower B	900	450	250
Tower C	800	400	250
Tower D	750	400	250
Tower E	700	350	250
Tower F	700	350	250
Tower G	600	300	200
Tower H	600	350	250
Tower I	500	350	250
Tower J	450	300	200
Tower K	400	300	200
Tower L	300	300	200

DNModel-03_12			
Building ID	Main Line (mm)	PTO Line (mm)	ETS/PHE (mm)
Tower A	1000	450	300
Tower B	900	400	250
Node 3	900	-	-
Tower C	600	400	250
Tower D	450	400	250
Tower E	350	350	250
Tower F	700	300	250
Tower G	600	300	200
Node 6	600	-	-
Tower H	500	300	250
Tower I	400	300	250
Tower J	300	300	200
Tower K	400	300	200
Tower L	300	300	200

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Gerardo L. Augusto The main author and researcher of this study. This research work is part of his doctoral dissertation at De La Salle University – Manila.

Alvin B. Culaba He guided the main author in conceptualizing design optimization in district cooling system. He is the adviser of the main author in his PhD work at De La Salle University – Manila.

Raymond R. Tan Provided lectures on engineering optimization and discussed some key points of heuristic and metaheuristic algorithms with the main author.

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