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Guided Design of Heating and Cooling Mains for Lower Water and Energy Consumption and Increased Efficiency

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Water cooling and water heating is an important source of energy consumption, accounting for more than 20% of all energy consumption in manufacturing industry. It is clear that the development of heat recycling schemes and better structural design can allow reaching significant savings. It is also known from power generation and from the bulk chemicals production that the cooling water systems are generally designed with a set of heat exchangers arranged in parallel. This arrangement results in higher cooling water flowrate and low cooling water return temperature thus reducing cooling towers efficiency. This indicates the importance of the system structure, the possibility of mixing of heating or cooling water; recycling and reuse of heating and cooling resources and finally the importance of distribution of the driving forces to heat transfer. This paper reports a technique for grassroot design of centralised cooling and heating water system for water and wastewater minimization which incorporates the performances of the cooling/heating providers involved. The study focuses on cooling/heating systems consisting of multiple chillers and/or boilers that supply a common set of heat exchangers. The paper takes a conceptual approach to the stated problems, but traces the way for exact solution using the superstructure based mathematical approach (formulating the problem). It explores cooling/heating water reuse opportunity and predicts thermal performance of thermal systems involved.

1. Introduction

Cooling water systems are used to remove waste energy from the process to the atmosphere. The systems consist of cooling towers, re-circulating system and cooling water network. Water is used as a medium to remove energy from the process through the cooling towers into the atmosphere.

Previous research on cooling water systems has focused mainly on debottlenecking the cooling towers through synthesis and optimization of the cooling water networks. The common technique used in this regard was based on graphical analysis approach (Kim and Smith, 2001; Kim et al., 2002). This technique was derived from the principles of pinch analysis developed for heat exchanger networks synthesis by Linnhoff and coworkers (Linnhoff and Flower, 1978; Linnhoff et al., 1979; Flower and Linnhoff,

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1980). The principles of pinch analysis were also adapted for mass exchange network synthesis (EL-Halwagi and Manousiouthakis, 1989) and later applied for targeting and synthesis of wastewater minimization problems (Wang and Smith, 1994). Few authors used the superstructural modelling techniques to optimize the cooling water systems (Majozi & Moodley, 2008; Kim and Smith, 2003).

This paper presents a technique for synthesis and optimization of cooling water system which incorporates the performances of the cooling towers involved. The study focuses mainly on cooling systems consisting of multiple cooling towers that supply a common set of heat exchangers. The heat exchanger network is synthesized using the mathematical optimization technique. The cooling tower model is used to predict the thermal performance of the cooling towers whilst taking the thermal conditions of the associated heat exchanger network into account.

2. Cooling water systems model development

The cooling water system consists of cooling towers and heat exchanger network. Therefore the mathematical model for designing cooling system entails the heat exchanger network model and the cooling tower model. The heat exchanger model entails a superstructure in which all possible cooling water reuse opportunities are explored. The mathematical optimization formulation was developed from the superstructure given in Figure 1 by considering energy and mass balance equations across each cooling water using operation and at each node.

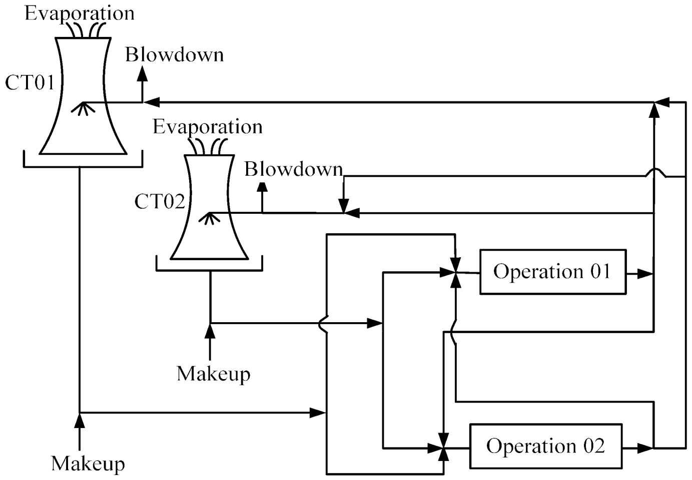

Figure 1: Superstructure for a cooling water system

The optimum heat exchanger network design is found by minimizing the cooling tower inlet flowrates. The interaction between the heat exchanger network and the cooling towers is investigated using the cooling tower model derived by Kröger (2004) using the control volume in Figure 2. The governing equations that predict the thermal performance of a cooling tower are given by Equations (1), (2) and (3). Equations (1) and (2) define the mass and energy balance for the control volume, respectively. Equation (3) defines the air enthalpy change for the control volume.

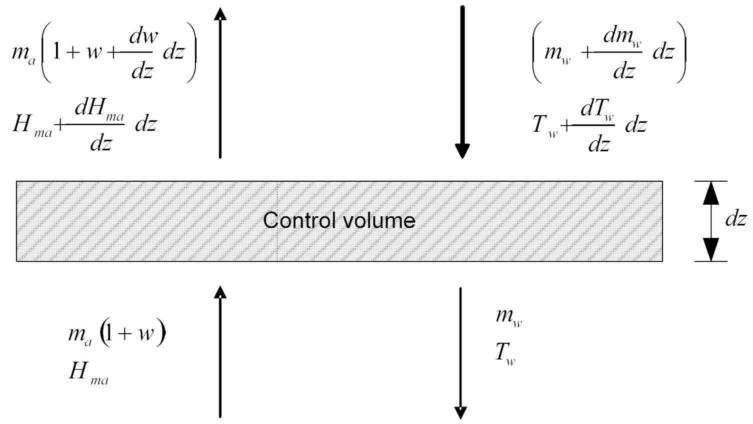

Figure 2: Control volume

$$\frac{dm_w}{dz}=m_a\frac{dw}{dz} \tag{1}$$

$$\frac{dT_w}{dz}=\frac{m_a}{cp_w m_w}\left(\frac{1}{cp_w}\frac{dH_a}{dz}-T_w\frac{dw}{dz}\right) \tag{2}$$

$$\frac{dH_a}{dz}=\frac{Ka_{fi}A_{fi}}{m_a}\left(Le_f(H_{as}-H_a)+(1-Le_f)H_v(w_s-w)\right) \tag{3}$$

The heat exchanger network model is based on the following a possible practical case study.

3. Case study

A set of cooling towers with specified maximum cooling water return temperature to the cooling towers without a dedicated source or sink for any cooling water using operation is given. This situation arises when packing material inside the cooling tower is sensitive to temperature and any cooling tower can supply any water using operation whilst the water using operation can return to any cooling tower.

The application of the proposed technique is demonstrated by considering one example. This example was extracted from the paper by Majozi and Moodley (2008). The formulation for the Case study consists of bilinear terms which are nonconvex thus rendering the model NLP. This model is difficult to initialize because the starting point might be infeasible or the solution might be locally optimum (Gololo & Majozi, 2010). To overcome these difficulties the technique proposed by Quesada and Grossmann (1995) was used to linearize the bilinear terms. This technique uses the upper and the lower bounds to create a convex space for the bilinear terms.

3.1 Base case

Cooling water system in Figure 3 shows a set of heat exchanger networks which are supplied by a set of cooling towers. Each cooling water using operation is supplied by freshwater from the cooling tower and return back to the cooling tower. The implication of these arrangements results in higher return cooling water flowrate and low return cooling water temperature thus reducing cooling tower efficiency (Bernier, 2004).

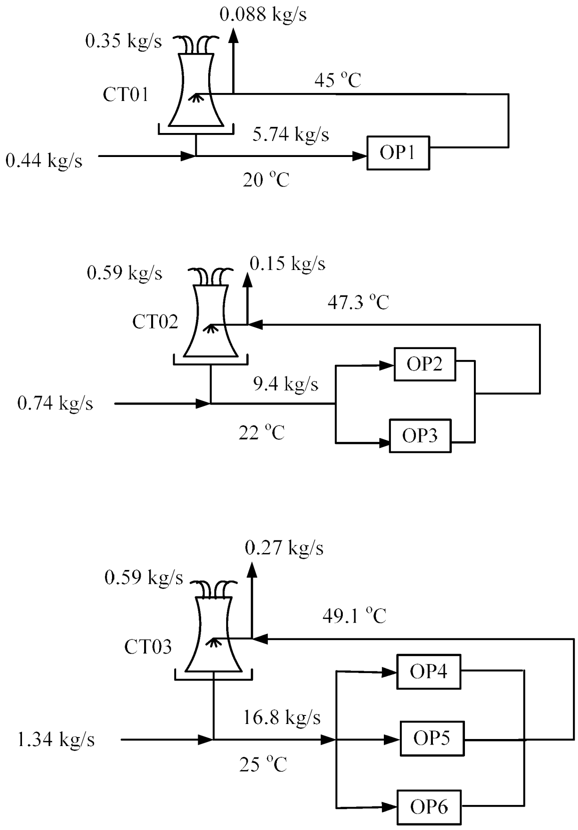

Figure 3: Base case (Majozi and Moodley, 2008)

3.2 Case study

In this case each cooling tower can supply any cooling water using operation. The return streams from any cooling water using operation can go to any cooling tower. The return temperature to any cooling tower is however specified.

Figure 4 shows the heat exchanger network after applying the methodology described above. By exploiting the opportunity for cooling water reuse, the overall circulating water decreased by 22 % and one cooling tower was eliminated. The cooling tower inlet temperatures are at their maximum values.

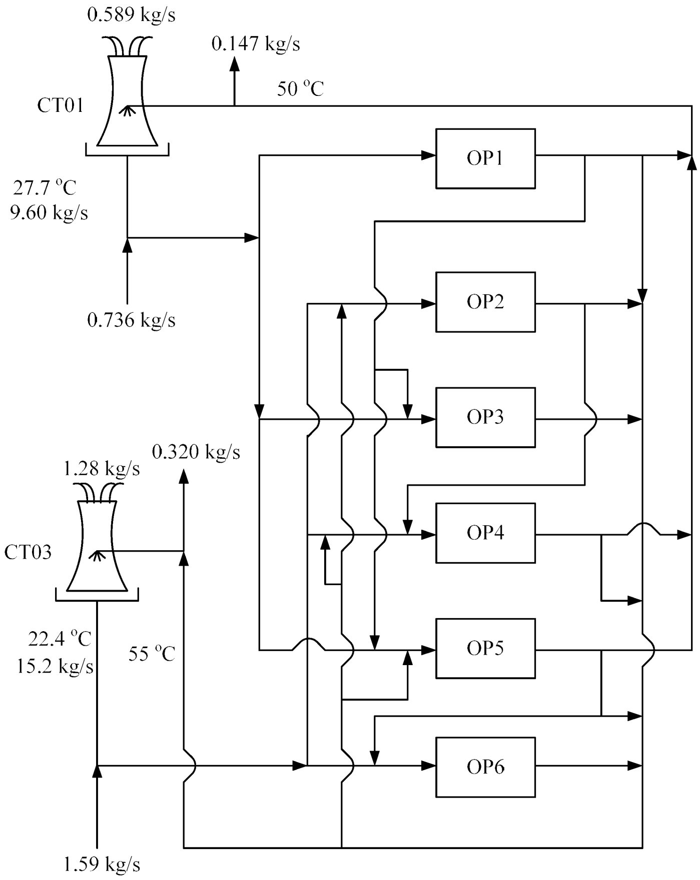

Figure 4: Final design of the cooling water system

These results show the opportunity to increase the heat duties, through expansions, without investing on a new cooling tower. The only additional investment required is on piping for reuse streams. For this case study the makeup and the blowdown was also decreased by 7 %. However the decrease in makeup and blowdown cannot be guaranteed for all practical case studies and this is not the intended purpose in this study. The results summary is shown in Table 1.

Table 1 Results summary

Stream	Base case(kg/s)	Results(kg/s)
Makeup	2.52	2.33
Blowdown	0.50	0.47
Circulating water	31.94	24.80

4. Conclusions

The mathematical technique for cooling water system synthesis with multiple cooling towers has been presented. This technique is more holistic because it caters for the effect of cooling tower performance on the heat exchanger networks. The cooling tower thermal performance is predicted using the mathematical model.

The proposed technique debotllenecked the cooling towers by decreasing the circulating water flowrate. This implies that a given set of cooling towers can manage an increased heat load. From the case study, 22 % decrease in circulating water flowrate was realized. This decrease in the overall circulation water has an added benefit of decreasing the overall power consumption of the circulating pumps. The blowdown and makeup were also decreased by 7 %, however this cannot be guaranteed for all practical case studies.

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