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Shortcut performance method for assessing the flexibility of cooling systems

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This paper presents a design methodology for the flexible operation of cooling systems. The main heat transfer equipment involved in a cooling system, namely: the cooling tower and the cooling network are analyzed using the thermal effectiveness method. For the design of a flexible system, the change in operating conditions such as plant throughput and wet bulb temperature are considered. The coolers in a cooling network can be arranged in parallel, series or a combination of both. However, it is demonstrated that the steady state response of any cooling network does not depend on the arrangement of the coolers.

1. Introduction

Cooling systems are normally designed for point conditions. However, in most cases, these point conditions lead to a considerable over-design of the system. The problem with over-design is that it is normally accompanied by an over-expenditure of power (Picón-Núñez, et al, 2004). One way of ensuring minimum energy consumption is to make sure that the water flow rate is reduced such that the required heat is removed from the process. However, typical plant production rates may vary during the year; this situation arises as a result of various situations, for instance: periods of maintenance, seasonal production, etc. Considering the variation in production rates, the way to keep pumping power consumption to a minimum is by means of a flexible cooling system. A flexible cooling system is the one that is able to adapt to the process heat removal demands regardless of the production rate. A basic model for the flexible operation of heat exchangers will be used and extended to the case of cooling systems.

A heat exchanger that exhibits flexible operation has two essential features. These are: larger surface area than required for normal operation and a bypass. During normal operation, a heat exchanger is subject to variations in operating conditions that may results is a reduction or increase of the exchanger heat duty. The way these two features are combined together during changed operating conditions in order to maintain the required heat load follows the next principles:

a) Normal operation: bypass partly open.
b) Changed operating conditions that result in increased heat load. Bypass further opened in order to reduce the water flow rate through the exchanger.

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c) Changed operating conditions that result in reduced heat load. Bypass fully shut in order to increase the water flow rate through the exchanger.

The size of the heat exchanger is determined for the expected set of conditions which will require the larger surface area. This corresponds to the case where throughput and cooling water temperature are increased. When operating conditions return to normal, the consequence of excess surface area is made up for by reducing the water flow rate. So, the bypass percentage of aperture is determined. As the operating conditions move in a direction that increases the heat duty, the bypass is further opened.

The same understanding described above, can be applied to cooling systems. Figure 1 shows a schematic of a cooling system designed for flexible operation. When the process operates under normal production rate, the bypass remains partly opened and with the coolers being designed for the larger production rate. As the production rate increases, the bypass closes making use of the full installed surface area. For the case of the lower production rate, the bypass is further opened and more water is recycled back to the cold water pond. When the point where the flow rate equals the pump flow rate, one of the pumps can be taken out of service. The analysis of the thermal performance of the individual heat transfer components of a cooling system is discussed below.

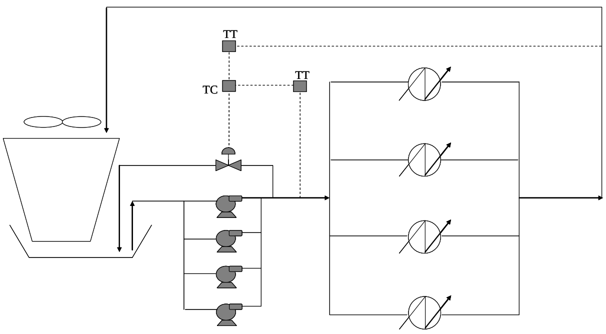

Figure 1: Cooling system structure for flexible operation.

2. Steady state response of cooling systems

Cooling systems are generally designed for point conditions such as: fixed heat load, fixed water flow rate and fixed ambient conditions (Bernier, 1994; Jameel–Ur–Rehman, et al., 2004). However, in operation these variables are subject to changes; the magnitude of the change can be easily calculated using the thermal effectiveness (ε) model (Jaber and 1989; Picón-Núñez, et al. 2007).

2.1 Thermal effectiveness model for cooling towers

It has been demonstrated that the thermal effectiveness of a counter-current evaporative cooing tower can be represented by Eq. 1:

$$\varepsilon_{\text{Tower}} = \frac{\left(T_{w1} - T_{w2}\right)}{\left(T_{w1} - T_{wb}\right)} \tag{1}$$

Where T_{w1} and T_{w2} are the tower inlet and outlet temperature respectively, and T_{wb} is the wet bulb temperature. Equation (1) indicates that if the wet bulb temperature and the inlet and outlet water temperature are known, the tower simplified effectiveness can be easily computed. This simplified tower effectiveness can be used to quickly evaluating the tower performance under changes in the process heat duty or changes in the wet bulb temperature. For instance, if a change in wet bulb temperature (δwb) enters the system, the new wet bulb temperature is given by $T^N_{wb} = T_{wb} + \delta_{wb}$, and the new water outlet temperature (T^N_{w2}) can be calculated from Eq 2 as:

$$T^N{}_{w2} = T_{w1}\left(1-\varepsilon_{Tower}\right)+\varepsilon_{Tower}\,T^N{}_{wb} \tag{2}$$

So the effect upon the outlet water temperature is:

$$\hat{T}^{(1)}_{w2} = \varepsilon_{Tower}\,\delta_{wb} \tag{3}$$

Where $\hat{T}^{(1)}_{w2}$ is the temperature change of the water that leaves the cooling tower. For Equation (3) to apply to the case above, the major assumption made is that the tower thermal effectiveness remains approximately constant under changes in the temperature operating conditions.

2.3 Cooling network thermal effectiveness

Cooling networks can be designed in parallel, series or a combination of them. Figure 2 shows various examples of these types of arrangements. The effect of a temperature disturbance (δ) upon a single phase heat exchanger, where the cold fluid has a larger heat capacity-mass flow rate can be calculated from:

$$\hat{T}_{out} = \varepsilon\left(1\text{-}\mathrm{C}\,\delta\right) \tag{4}$$

Where $\hat{T}$ is the change in temperature experienced by the cold fluid; C is the ratio of the hot fluid heat capacity-mass flow rate to that of the cold fluid. When a temperature disturbance enters a cooling network with all exchangers arranged in parallel, the temperature of the water after mixing in the return header can be calculated from:

$$\hat{T}^{(1)}_{w1} = \left[\frac{\sum_1^n m_n\left(1-C_n\varepsilon_n\right)}{\sum_1^n m_n}\right]\hat{T}^{(1)}_{w2} \tag{5}$$

Where m is the water mass flow rate. Eq. 5 can be rewritten as:

$$\hat{T}^{(1)}_{w1} = \varepsilon_{\mathrm{Network,parallel}}\,\hat{T}^{(1)}_{w2} \tag{6}$$

Where $\varepsilon_{\mathrm{Network,parallel}}$ represents the network overall thermal effectiveness for a parallel arrangement.

$$\varepsilon_{Network,parallel} = \frac{\sum_1^n m_n\left(1-C_n\varepsilon_n\right)}{\sum_1^n m_n} \tag{7}$$

Now, the disturbance $\hat{T}_{w1}^{(1)}$ enters the cooling tower and adds to the original wet bulb disturbance. So from Eq. 3 the new water outlet temperature can be calculated from:

$$\hat{T}_{w2}^{(2)} = \varepsilon_{Tower}\,\delta_{wb} + \hat{T}_{w1}^{(1)}\left(1-\varepsilon_{Tower}\right) \tag{8}$$

Substitution of Eq. 3 and 6 into Eq. 8 gives:

$$\hat{T}_{w2}^{(2)} = \delta_{wb}\,\varepsilon_{Tower}\left(1-\varepsilon_{System}\right) \tag{9}$$

Where,

$$\varepsilon_{System} = \varepsilon_{Network,parallel}\left(1-\varepsilon_{Tower}\right) \tag{10}$$

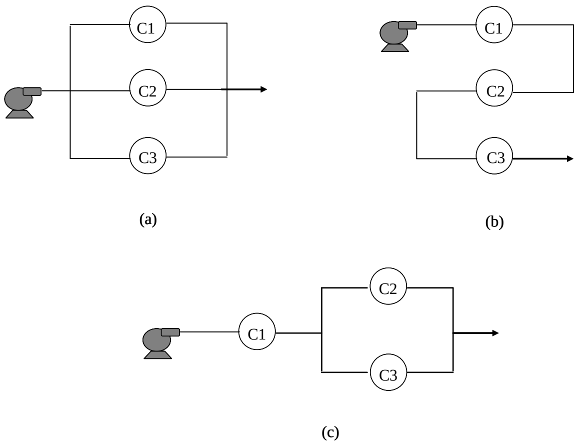

Figure 2: Cooling network arrangement: (a) parallel, (b) series, (c) series-parallel.

In the steady state we have that:

$$\hat{T}_{w2}^{(\infty)} = \delta_{wb}\,\varepsilon_{Tower}\left[1+\varepsilon_{System}+\varepsilon_{System}^{2}+\varepsilon_{System}^{3}+\ldots\right] = \delta_{wb}\,\varepsilon_{Tower}\sum_{n=0}^{n}\varepsilon_{System}^{n} \tag{11}$$

The summation of the ε_{System} terms can be approximated by the following expression:

$$\sum_{n=0}^{\infty} X^{n} = \left(\frac{1}{1-X}\right) \qquad \text{if} \quad X \langle 1 \tag{12}$$

So, Eq. 11 reduces to:

$$\hat{T}_{w2}^{(\infty)} = \delta_{wb}\,\varepsilon_{Tower}\left(\frac{1}{1-\varepsilon_{System}}\right) \tag{13}$$

Eq. 13 can be used to calculate the final change in the outlet temperature of the tower after a temperature disturbance has occurred. For an arrangement in series, it can be readily shown that the network effectiveness is:

$$\varepsilon_{Network,series} = \prod_{n=1}^{\infty} \left(1 - C_n \varepsilon_n\right) \tag{14}$$

For the combined arrangement of Figure 3c, the expression for the network effectiveness can be derived in various steps: coolers C2 and C3 are in parallel (Eq. 7 applies), and this structure is in series with cooler C1 (Eq. 14 applies).

$$\varepsilon_{2-3} = \frac{m_2\left(1 - C_2\varepsilon_2\right) + m_3\left(1 - C_3\varepsilon_3\right)}{m_2 + m_3} \tag{15}$$

$$\varepsilon_{Network,combination} = \left(1\text{-}C_1\varepsilon_1\right)\left(1 - C_{2-3}\,\varepsilon_{2-3}\right) \tag{16}$$

Where,

$$C_{2-3} = \frac{\sum_{n=2}^{n=3}\left(m_n\, C_p\right)_{process\ streams}}{\sum_{n=2}^{n=3} m_{water}} \tag{17}$$

In order to demonstrate the application of Eq. 13 to determine the steady state response of a cooling system to changes in wet bulb and return temperature the following example is used: A cooling tower has been designed for the following conditions: T_{w1}= 40 °C, T_{w2}= 20 °C, water flow rate= 29.4 kg/s, L/G= 0.8 and wet bulb temperature= 17 °C. The results for a wet bulb temperature change of 2°C and a change of 3°C in the process stream of cooler C3 are shown in Tables 1 and 2.

Table 1: Wet bulb temperature disturbance.

Disturbance on wet bulb temperature							
	T_{w1} (°C)	δ (°C)	ε_{tower} (°C)	$\varepsilon_{network}$ (°C)	ε_{system} (°C)	$\hat{T}_{w1}^{\infty}$ (°C)	$T_{w1}^{(\infty)}$ (°C)
Parallel	40	2	0.8696	0.4478	0.058	1.8	41.8
Series	40	2	0.8696	0.4787	0.062	1.8	41.8
Series – Parallel	40	2	0.8696	0.4721	0.061	1.8	41.8

Table 2: Cooling network response to temperature disturbance.

Disturbance on water inlet temperature							
	T_{w1} (°C)	δ (°C)	ε_{tower} (°C)	$\varepsilon_{network}$ (°C)	ε_{system} (°C)	$\hat{T}_{w1}^{(\infty)}$ (°C)	$T_{w1}^{(\infty)}$ (°C)
Parallel	40	2	0.8696	0.4478	0.058	1.3	41.3
Series	40	2	0.8696	0.4787	0.062	0.4	40.4
Series – Parallel	40	2	0.8696	0.4721	0.061	1.0	41.0

The results of Tables 1 and 2 show that the steady state response of cooling systems to changes in wet bulb temperature and process heat load is not significantly affected by the network structure. The advantages between the various structures have to be explored in terms of controllability and capital cost. The results have implications in design for flexible operation since the designer is able to predict the performance of the systems under different scenarios such as increased or decreased throughput and change in wet bulb temperature.

3. Conclusions

Cooling systems are, in most applications, designed for a maximum fixed heat duty. Flexible operation is the capacity of the system to deliver the required heat load within some specific bounds. For instance, specific bounds may be the following: plant throughput may vary between 80% and 120% from normal production rate and the wet bulb temperature experiences changes between seasons in as much as ±3°C. When a temperature or flow rate disturbance enters a cooling system, it propagates around until the steady state is reached. Since the steady state response of a cooling system is independent of the actual arrangement of coolers then the heat load removal of the exchanger network can be controlled through the use of a bypass scheme. For maximum cooling load, a closed bypass along with the full use of the installed heat transfer area is the mode of operation. During normal operation, the excess surface area is compensated for by partly opening the bypass valve thus reducing the heat transfer coefficients and as a consequence the heat load. When the production rate is reduced, the bypass is further opened. With the operation of a flexible cooling system, the pumping power consumption is a variable that can also be controlled. The thermal effectiveness model is a quick and reliable method for assessing the thermal performance of cooling systems. This model establishes the basis for the design of flexible cooling systems.

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