Design of Coolers for Use in an Existing Cooling Water Network

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It is usual practice to design coolers without considering how they will behave when they are installed in a cooling water network and the effect that they will have upon the performance of the coolers already operating in the system. The dangers of this practice have recently been highlighted by Tavares et al. (2010). These workers presented a study in which a new exchanger was installed in an existing network. The unit had been over-designed. However, it still did not provide adequate performance. The hot stream outlet temperature was 5 °C above the required value. This study is a clear demonstration of the need to specify the design objectives for coolers in a systems context. Unlike the recent work of Picon Nunez et al. (2009), Giorgia et al. (2009) and Castro et al. (2000) the work of Tavares et al. (2010) did not include a consideration of cooling tower performance. This is unfortunate for the installation of a new exchanger generally results in increase in the temperature at which the cooling water is returned to the tower. This increase, in turn, results in an increase in the temperature of the cooling water returning from the tower and being fed to the coolers constituting the network. Another shortcoming, in this otherwise important work, is that a very detailed model of heat exchanger performance is used. This model is restricted to shell-and-tube heat exchangers. This restricts the practical application of the work for it cannot be applied where other exchanger types (such as plate-and-frame units, spiral units and CompablocTM units) are often employed and where tube inserts can often be used to rectify the adverse effects of installing a new exchanger into an existing system. In this work we show how thermo-hydraulic simulation can be applied to cooling water systems incorporating a wide range of different exchanger types. We then demonstrate how coolers for installation into existing cooling water networks can be approached using systems analysis. However, we start by demonstrating the need for such an approach by considering how coolers are currently designed.

1. Current Approach to Cooler Design

Coolers are generally designed without any reference being made to the structure of the network in which they are being installed. The process engineer will provide a specification of the required duty. This consists of specification of the mass flow rate of the process stream passing through the unit, the inlet and outlet temperatures of this stream (these three parameters set the amount of heat that must be exchanged) and the usually the inlet and outlet temperatures of the cooling water. It also contains a specification of the maximum pressure drop that each stream can encounter during its passage through the exchanger. A typical water side specification could be an inlet temperature typical of local ambient conditions, a cooling water temperature rise of 5 °C and an allowable pressure drop of 50 kPa. The exchanger design would then seek an exchanger geometry that at least transferred the required quantity of heat whilst observing the pressure drop constraints.

2. Hydraulic Simulation of Cooling Water Networks

Cooling water networks can usually be assumed to have one useful property. The amount of water entering the system equates with that being returned to the cooling tower. The flow distribution through such network is governed by the "momentum equation". This equation has relates local pressure to three individual factors: gravitational head, fluid momentum and frictional losses. Two of these factors (gravitational head and fluid momentum) are reversible. Only the frictional losses are irreversible. This means that provided flow is established throughout a cooling water network (that it flows through the coolers positioned in elevated positions) then the distribution can be determined from solution of equations for frictional loss alone. The equations given for pressure losses through pipelines usually relate pressure drop with velocity. For instance, for flow through a tube we have:

$$\Delta P = 2f\left(\frac{L}{d}\right)\frac{\rho u^2}{g_c} \tag{1}$$

However, we could write such equations in terms of volumetric flow rate:

$$\Delta P = \left[\frac{32}{\pi^2} f\left(\frac{L}{d}\right)\left(\frac{\rho}{g_c d^4}\right)\right]V^2 \tag{2}$$

This can be written:

$$\Delta P = KV^2 \tag{3}$$

In the case of flow through a tube the constant K is a function of velocity. However, this function is not a strong one and when the equation is used in a model of network behaviour solution by iteration is very rapid. Pressure loss during flow through valves is usually calculated from tables listing the loss in terms of velocity heads. Such tables (Reference) contain numbers for a number of valve types and differing degrees of opening. These numbers are easily converted to K values. Other pipe fittings (bends, junctions etc.) are handled in terms of equivalent pipe lengths. The use of equations based on volumetric flow rate has a major advantage where a number of components (valves, pipes and exchangers) occur in series. For we do not need to track velocity changes, we simply add the individual K values.

So for a single pipe branch:

$$\Delta P = V^2 \sum K_i \qquad (4)$$

This form of equation also has advantages where parallel branches are to be analysed. Consider a system consisting of two branches fed from a common main and returning to another common main. The volumetric flow rates are:

$$V_A = \sqrt{\frac{\Delta P}{K_A}} \qquad V_B = \sqrt{\frac{\Delta P}{K_B}} \qquad (5)$$

Now the pressure drop across each path is the same and the total flow is the summation of the flows through the individual branches. So:

$$\sqrt{\frac{\Delta P}{K_{AB}}} = \sqrt{\frac{\Delta P}{K_A}} + \sqrt{\frac{\Delta P}{K_B}} \qquad (6)$$

a simple equation characterising flow through a system having two separate branches. Using these equations it is possible to derive a system of equations that can be rapidly solved to yield the flow distribution through a cooling water network. Since this also provides frictional losses for every branch in the network it allows us to calculate the distribution of hydro-static head throughout the network. Consequently, we can not only check that flow is established throughout a network but determine the conditions within coolers positioned at high elevations. We can check that such units do not operate under vacuum or become “vapour logged”.

3. Simple Means of Representing the Hydraulic Behaviour of an Exchanger

It is possible to characterise a heat exchanger in terms of nozzle losses and bundle losses) using the equation:

$$\Delta P = (2K_N + K_B)V^2 \qquad (7)$$

In many cases the nozzle losses will be small relative to bundle losses (designers often size nozzles on the basis of using less than 10% of the allowable losses) and we can use the equation:

$$\Delta P = K_X V^2 \qquad (8)$$

As with flow through a tube this equation is a weak function of velocity that can be solved iteratively. The K values, and their dependency on throughput, can be determined by using exchanger analysis software (such as the commercial codes used for shell-and-tube exchangers, or the in-house codes used by manufacturers of proprietary exchanger types) at two separate throughputs.

4. Design of Exchanger on Basis of Systems Analysis: a Case Study

A new cooler is to be installed in the network illustrated in Figure 1. The geometry of the existing exchangers, details of the existing pipe-work, the pump curve and cooling tower characteristics are given in the Appendix. A new cooler is to be installed in the network. The load on this cooler is 1 MW. This is a significant increase on the amount of heat extracted from the system that is currently 7.2 MW). The cooling water return temperature is already high (at 52.1 °C).

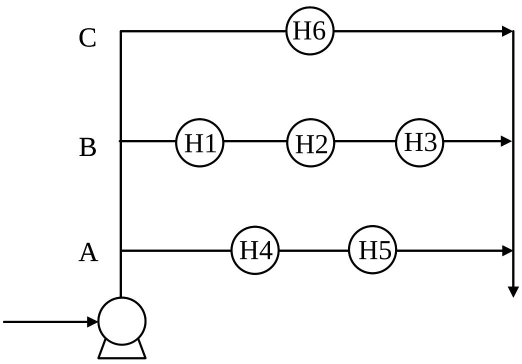

Figure 1: Case Study: Existing Network

4.1 Procedure

Our aim is to identify how the new cooler should be installed within the existing system and what the specification for the new unit should be (cooling water flow, inlet and outlet temperatures and allowable pressure drop). We undertake this by identifying the options for locating the new unit. Then for each option we undertake thermo-hydraulic simulation assuming that the unit adds the specified load to the cooling water and covering a range of K values for the new unit. We then examine the changes that occur to the existing system and list the options (location and K value) that have "acceptable consequences". Using this information the engineer can consider the overall cost implications for the listed options. The simulation for the chosen option provides cooling water flow and inlet temperature. The K value can be converted to "targeted" pressure drop for the design. The first factor that controls the positioning of the new cooler is its geographical location. It is to be positioned in the plant area currently served by branch B (that already accommodates three exchangers).

A common way of installing a new exchanger is to construct a totally new branch. So, this scheme is analysed first. If the new unit is to be installed in the existing branch then the better scheme would be to position it after exchanger H3 for this minimises the changes to the inlet temperatures of the existing coolers. This scheme is examined next. Finally, the installation of a new unit in series with the existing ones leads to increase in the flow resistance of the branch. So, the option of installing the new unit is parallel with the last of the existing coolers is the final scheme examined.

4.2 Scheme 1: Installation in a parallel branch

The results of the simulation of the first scheme are presented in Table 1. We observe that the performance of each of the existing coolers deteriorates significantly. Affect upon cooling tower load and cooling water temperatures.

Table 1: Disturbances to Hot Stream Outlet Temperatures: Scheme 1

Loss factor, K	Increase to process outlet temperature (°C)					
	H1	H2	H3	H4	H5	H6
200	6.2	8.8	8.8	2.5	7	4.2
500	5.2	7.6	7.8	2.1	6	3.5
1000	4.2	6.4	6.7	1.7	5	2.8

Table 2: Changes to Cooling Tower Conditions: Scheme 1

Loss factor, K	CT Load (MW)	CW Feed Temperature (°C)	CW Return Temperature (°C)
200	6.78	31.5	45.5
500	6.99	31.9	46.5
1000	7.19	32.2	47.5

We observe that the load on the cooling tower actually falls. The decline in performance of the existing coolers actually exceeds the additional load placed on the system.

4.3 Scheme 2. Installation at end of existing branch

The results for this scheme are given in Tables 3 and 4. We observe that the disturbances in this scheme are very much lower (in most cases the hot outlet temperatures increase by less than one degree). Eighty percent of the load extracted through the new cooler is removed in the cooling tower. The performance of this scheme is insensitive to the exchanger K value.

Table 3: Disturbances to Hot Stream Outlet Temperatures: Scheme 2

Loss factor, K	Increase to process outlet temperature (°C)					
	H1	H2	H3	H4	H5	H6
200	1	0.9	0.8	0.8	0.7	0.9
500	1.1	1	0.9	0.8	0.7	0.9
1000	1.2	1.1	1	0.8	0.6	0.9

Table 4: Changes to Cooling Tower Conditions: Scheme 2

Loss factor, K	CT Load (MW)	CW Feed Temperature (°C)	CW Return Temperature (°C)
200	7.99	35	55.4
500	7.98	35	55.3
1000	7.97	35	55.3

4.4 Scheme 3. Installation parallel to last exchanger in existing branch

The results for the simulation of the final scheme are presented in Tables 5 and 6. Here we observe that the performance of H3 is (as could be expected) affected quite significantly. The performances of the coolers in the other branches are also affected to a higher extent than observed with scheme 2.

Table 5: Disturbances to Hot Stream Outlet Temperatures: Scheme 3.

Loss factor, K	Increase to process outlet temperature (°C)					
	H1	H2	H3	H4	H5	H6
200	0.9	0	4.9	1.9	1.8	2.3
500	0.9	0	4.2	1.9	1.8	2.3
1000	1	0	3.5	1.9	1.8	2.3

Table 6: Changes to Cooling Tower Conditions: Scheme 3

Loss factor, K	CT Load (MW)	CW Feed Temperature (°C)	CW Return Temperature (°C)
200	7.71	36.4	55.7
500	7.74	36.4	55.8
1000	7.76	36.5	55.9

For this particular case study the installation of a new cooler on a new branch to the system would have quite severe (and probably unacceptable) consequences. Rather than increase the load on the cooling tower by 1 MW it would result in a reduction of around 1.4 MW. The best solution would be to place the new cooler at the end of Branch B.

Conclusions

A procedure for specifying the design conditions for coolers that are to be installed into an existing cooling water network has been developed. This procedure involves thermo-hydraulic simulation of the cooling water network. This simulation includes consideration of pump performance and cooling tower performance. By means of a case study we have confirmed the conclusion made by Tavares et al. (2010) that arbitrarily installing new coolers on new parallel branches is not good practice.

References

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