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Dynamic modelling of induced draft cooling towers with parallel heat exchangers, pumps and cooling water network

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ABSTRACT

In the process industries, cooling capacity is an important enabler for the facility to manufacture on specification product. The cooling water network is an important part of the over-all cooling system of the facility. In this paper a cooling water circuit consisting of 3 cooling towers in parallel, 2 cooling water pumps in parallel, and 11 heat exchangers in parallel, is modelled. The model developed is based on first principles and captures the dynamic, non-linear nature of the plant. The modelled plant is further complicated by continuous, as well as Boolean process variables, giving the model a hybrid nature. Energy consumption is included in the model as it is a very important parameter for plant operation. The model is fitted to real industry data by using a particle swarm optimisation approach. The model is suitable to be used for optimisation and control purposes.

1. Introduction

Optimisation and process control studies of Cooling Water (CW) networks in the process industries are not common in the literature. One reason for this is the relative scarcity of dynamic models of such systems. Dynamic, first principles modelling is done in this paper with the aim of using the resulting model in process control and optimisation studies.

Dynamic modelling has lately been applied by Muller and Craig [1] to cooling water networks with the view to optimise and control the entire process. In [1] a dual circuit cooling water network was modelled including power consumption, with high-level models for the cooling towers, and the plant exchangers. What distinguishes this paper from [1] is that a single circuit network is modelled with detailed heat and mass balance modelling of the internals of the 3 cooling towers, as well as individual models for the plant heat exchangers, and network hydraulics. In addition, in this paper variable speed drives are added to the modelling of the cooling tower fans and the CW pumps. For the purpose of optimisation, more detailed modelling of the process enables better root cause understanding of process conditions, and enables greater increases in efficiency in areas such as water loss and power consumption in the cooling water circuit. Another optimisation area enabled by deeper levels of modelling, is the ratio between the flow rates to the different parts of the plant as served by the different heat exchangers. For the purposes of control, more detailed modelling will add robustness to the closed loop system by decreasing the difference between the actual plant and the controller plant model during both steady-state and dynamic transient conditions, as well as add degrees of freedom to be used by the controller.

A cooling water system is mathematically complex due to the interaction between the thermodynamics and hydraulics [2,3]. Mathematical modelling of a cooling water network has been done by various researchers. Neural network modelling of a cooling water circuit for a petro-chemical facility was done by Malinowski et al. [4]. Multiple authors have done static hydraulic and static thermal modelling (see e.g. [2]).

Power consumption efficiency optimisation is an important strategic focus area in the process industry. The power requirements for cooling water networks have been calculated in [1,5]. It is also included in the modelling done in this paper.

The cooling water network modelled in this paper is inherently non-linear, as well as hybrid, since the pumps and cooling tower fans can be in a running state, or can be off. This gives the state of the equipment a Boolean nature. The system therefore has a combination of continuous process state variables, as well as Boolean state variables. This has an effect on the power consumption modelling of the network, as well as the ultimate aim of control and optimisation. In order to optimise and control a hybrid non-linear system, tech-

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niques from the realm of Mixed Integer Non-linear Programming (MINLP) need to be used [6].

2. Process description

The cooling water circuit modelled in this paper is graphically depicted in Fig. 1. The cooling capacity is supplied by 3 Cooling Towers (CTs) in parallel. Cooling Water Return (CWR) is sprayed into each cooling tower at the top of the tower. At the bottom of the towers, the cooling water falls into a common Cooling Tower Basin (CTB). Airflow through the cooling towers is induced by induction motor driven fans at the top of the cooling towers.

Each tower is designed for a maximum cooling water flow rate of 8700 m^3/h, a heat duty of 101 MW, cooling water return temperature of 45 °C, and a supply temperature of 35 °C. The wet bulb temperature is designed to be 31 °C. Evaporative losses from the cooling tower are designed to be 1.83% of the total cooling tower flow.

The cooling tower fans are 9.1 m in diameter, and rotate at a design speed of 120.1 rpm. The design power consumption of each fan is 137 kW.

Each pump is designed for an operating flow rate of 3850 m^3/h and an operating discharge pressure of 5.3 barg. Each pump was designed to run at an operating point of 740 rpm at which it consumes 811 kW. However, pumps on the actual plant consume more power than this design power operating point.

133 parallel cooling water heat exchangers are fed with cooling water by the cooling towers and the pumps. Most of the heat exchangers are used to cool down process hydro-carbon streams with the cooling water coming from the cooling water pumps. However, 73% of all the cooling water flows through the 10 biggest heat exchangers, and 27% flows through the remaining 123 smaller exchangers. After having passed through the 133 heat exchangers, the cooling water flows back to the cooling towers, completing the cooling water circuit. The 123 smaller exchangers were combined into a single 11th exchanger (see Section 5) for modelling purposes.

In the real plant this paper is based on, each heat exchanger has a hand valve upstream of it. In the model developed here, this hand valve is modelled as a control valve for simulation purposes and motiving future advanced control strategies.

3. Model derivation

In this section the modelling work done is documented, with references to the literature, for each sub area of the model. Dynamic models for the major process unit operations (cooling towers, pumps, valves and heat exchangers) are derived separately, and the equations are developed to link the different operations. Model variables and parameters used are given in Tables 1–4 .

3.1. Cooling tower modelling

The cooling tower model has been constructed with the following initial assumptions:

1. The cooling tower operates under adiabatic thermodynamic conditions.
2. The water and air streams are divided into 10 sections in the vertical dimension (see Fig. 2). The water flow changes vertically between sections throughout the tower due to evaporation.
3. The density and specific heat of the water and dry air are constant across the height of the cooling tower, since the change in temperatures are relatively small.
4. The fill packing is uniformly wet and in thermal equilibrium. with the aqueous phase, and covers all 10 sections in the vertical dimension of the tower.
5. Water waste due to drifting is negligible. As per design this is 0.02% of the water flow through the tower. It is assumed zero for the purposes of this paper.
6. There is no meaningful delay between the tower, the pumps and the heat exchangers.

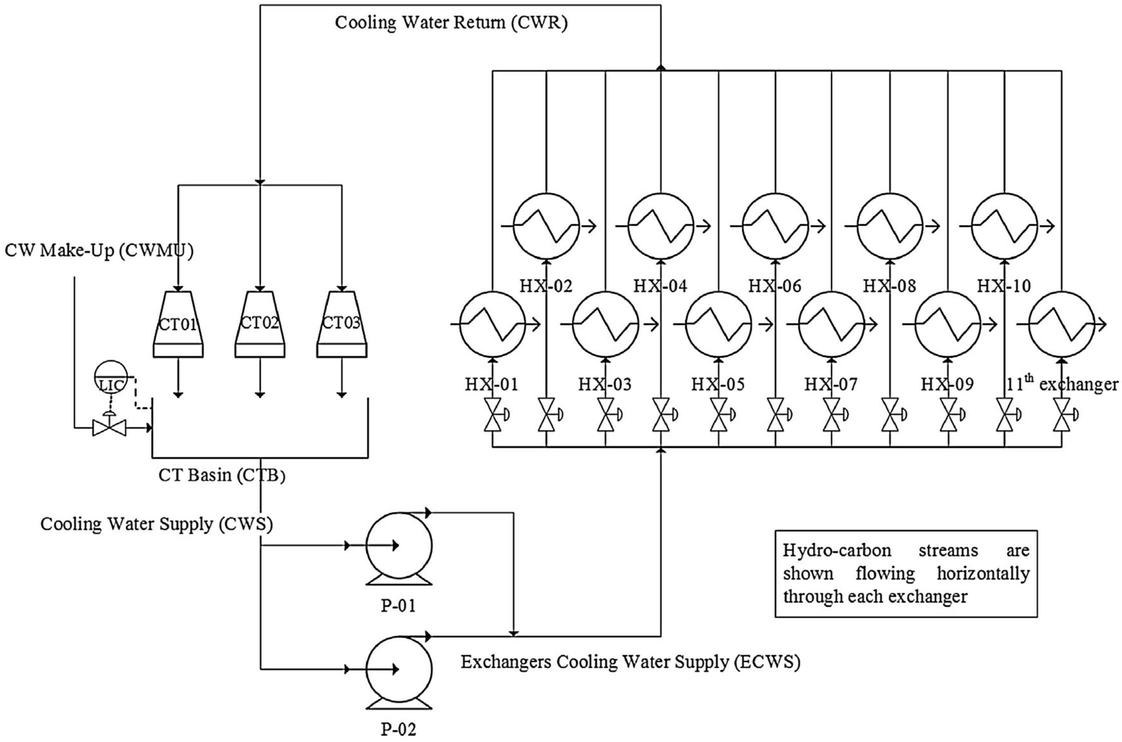

Fig. 1. The cooling network and associated equipment.