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Mathematical modeling of a low temperature low approach direct cooling tower for the provision of high temperature chilled water for conditioning of building spaces

Mehdi Nasrabadi*, Donal P. Finn

School of Mechanical and Materials Engineering, University College Dublin, Dublin, Ireland

HIGHLIGHTS

- Article presents a mathematical model of an open direct contact cooling tower.
- The tower optimised for producing low temperature water for building cooling systems.
- The proposed model has ability to integrate to building energy simulation.
- Cooling tower coefficient used in the model is based on an experimental correlation.

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ABSTRACT

Recent interest in cooling towers, as a means of producing chilled water in conjunction with radiant systems for cooling in buildings, has prompted interest in evaporative cooling in temperate maritime climates. For such climates, evaporative cooling has the potential to offer an alternative approach to refrigeration-based air-conditioning systems for producing chilled water, where conventional refrigeration-based systems can, for certain buildings, be considered to be an over engineered solution and where passive cooling is insufficient to offset cooling loads. The thermal efficiency of evaporative cooling systems is a key performance indicator, as a measure of the degree to which the system has succeeded in exploiting the cooling potential of the ambient air. The feasibility of this concept depends largely however, on minimizing the approach water temperatures within an appropriate cooling tower, at acceptable levels of energy performance. Previous experimental work for a full scale evaporative cooling system has shown that it is possible to produce cooling water with low approach temperatures (1–3 K), at the higher temperatures required in radiant and displacement cooling systems (14–18 °C), with varying levels of annual availability for different temperate climate locations. The current paper is concerned with the development of a mathematical model which describes the behavior of such a low temperature low approach direct evaporative cooling tower. The mathematical model is evaluated against experimental data reported for a number of open tower configurations, subject to different water temperature and ambient boundary conditions. It is shown that the discrepancies between the calculated and experimental tower outlet temperatures are to within ±0.29 °C for a low temperature cooling water process (14–18 °C), subject to temperate climate ambient conditions and ±0.57 °C for a high temperature cooling water process (24–30 °C), subject to continental climate ambient conditions. Considering the associated tower cooling loads, predicted results were found to be within a 6.93% root-mean-square difference compared to experimental data. Furthermore, the influence of different cooling tower coefficients on water outlet temperature and heat rejection of tower is investigated.

1. Introduction

Evaporative cooling using cooling tower systems has the potential to offer an efficient approach for producing high temperature chilled water in the range 14–16 °C, particularly in temperate climates, where conventional mechanical air-conditioning systems are for certain buildings, considered to be an over engineered

* Corresponding author.
E-mail addresses: m.nasrabadi@gmail.com, mehdi.nasrabadi@ucdconnect.ie (M. Nasrabadi).

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solution and where passive cooling is insufficient to offset cooling loads [1–3]. Costelloe and Finn report that evaporative cooling systems for producing chilled water are most effectively utilised for sensible cooling when integrated with either a chilled floor or ceiling system, due to the higher cooling water temperatures (16–18 °C) that can be used with these systems [4]. For office buildings located in temperature climates, where design cooling loads lie between 50 and 100 W m^{-2}, the use of hydronic radiant cooling systems such as chilled ceilings, panels or floors offer an alternative approach to fan coil mechanical refrigeration cooling [5]. Harvey notes that passive chilled ceilings can provide cooling up to 11 W m^{-2} per degree temperature difference between the panel surface temperature and the mean room temperature, whereas chilled floors can provide up to 6 W m^{-2} per degree temperature difference. Bergsten examined, for northern European locations (50°N), the use of active chilled beams with constant air volume flow in conjunction with an open evaporative cooling tower [3]. This analysis was undertaken using building simulation of an office building, where the total cooling load was between 40 and 70 W m^{-2} and the temperature difference between the chilled water and the ambient wet bulb temperature (primary approach temperature) varied from 3 to 5 °C. For these conditions, an overall seasonal COP of 7.0 was achieved, while maintaining an operative indoor temperature of less than 27 °C [3].

Considering the cooling tower system, tower design can be categorised according to different criteria such as the air transport system (natural draught, fan draught or induced draft), air movement systems within the tower (counter flow, cross flow) and the design of heat exchanger surface (open, closed and hybrid) [6]. In building energy applications, both open and closed tower designs are frequently used for heat rejection in air-conditioning systems. In open (direct) cooling towers, the water is cooled by direct contact with the ambient air, whereas in closed (indirect) cooling towers, there is no contact between the chilled water and the surrounding air, instead the water passes through a heat exchanger within the tower [7]. Direct cooling tower design is suggested for non-uniform loads and cooler climate conditions, whereas indirect cooling towers are recommended for warmer climate conditions and more uniform load conditions [7]. Costelloe and Finn [4] designed and built a full scale evaporative cooling system as shown in Fig. 1. Its features include; an open direct contact counter flow cooling tower, a primary and secondary chilled water circuit separated by an intermediate heat exchanger and a secondary side variable system load. Experimental studies demonstrated that for climatic conditions typical of Dublin, Ireland, the system was capable of delivering cooling water to within a 1 K primary approach temperature and a 2 K secondary approach temperature of the ambient wet bulb temperature [8]. The boundary conditions that distinguish the operation of this cooling tower from other heat rejection towers include a low heat rejection range, typically less than 21 °C and a low approach to the ambient wet bulb temperature (to within 1 K). In order to achieve this, a number of unique features were incorporated into the design of the tower including a low L/G ratio (L/G < 1.0) due to the relatively high air flow rates and a relatively high surface area to volume ratio [7,8]. Experimental correlations for estimating the cooling tower coefficient or the Merkel (Me) number for the cooling tower were published, where it was reported that the average uncertainty associated with the correlation coefficient was to within ±5%, based on the uncertainty of the experimental data [7]. The performance of this system for different water flow rate was investigated and system COPs of between 6 and 16 were reported, which is better than the average COP for centrifugal chillers operating under similar boundary conditions [4].

The role of the Merkel number is assessing cooling tower performance has been examined by a number of researchers including: Costelloe and Finn [7], Khan and Zubair [9], Bernier [10] and Kuehn et al. [11]. Apart from the design of the cooling tower, the Merkel number is strongly influenced by the water to air (L/G) flow ratio, as well as the inlet water temperature and the ambient air conditions [7,10]. Using experimental data extracted from extensive testing of the open cooling tower shown in Fig. 1, Costelloe and Finn [7] report that for a low temperature heat rejection tower (20–14 °C), the Merkel number is different than other correlations reported in the literature, which were analysed at higher water rejection temperatures (35–30 °C) [10,11]. These differences reflect both the design and operational issues associated with the low temperature, low approach tower. Moreover, the Merkel number difference is most marked at low L/G ratios, when a higher air flow rate is utilised.

To date, little assessment has been carried out that considers the integration of a low temperature low approach direct cooling tower for the provision of high temperature chilled water for the

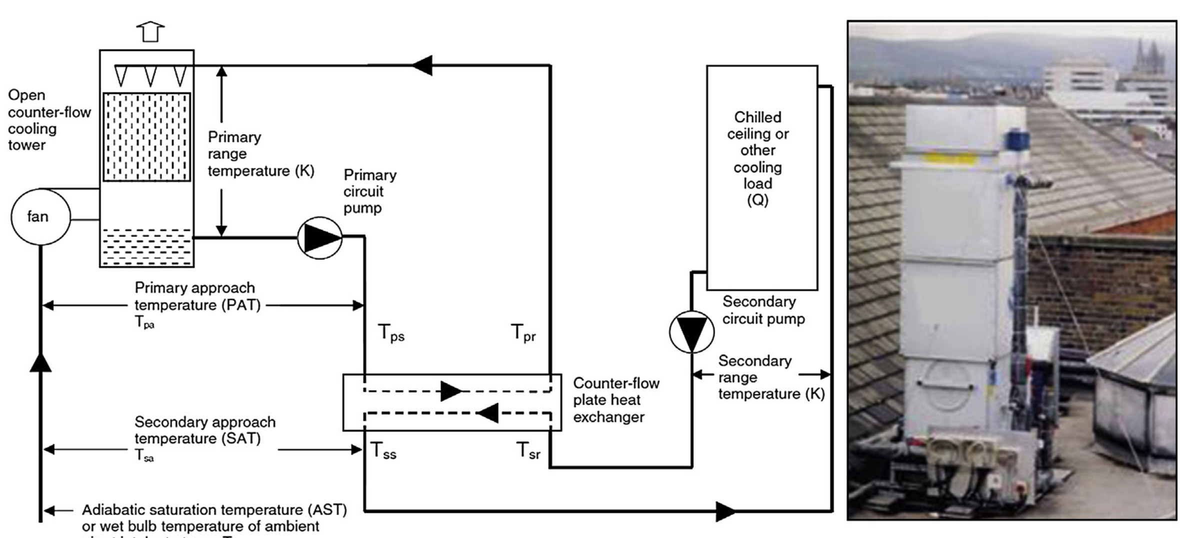

Fig. 1. Schematic of an indirect evaporative cooling system and the associated cooling tower [4].