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Simulation of a cross flow wind aided evaporator

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HIGHLIGHTS

- A novel solar and wind aided cross flow evaporator is numerically simulated.
- The performance of the tower was quantified under different operating conditions.
- The Number of Transfer Units was identified at different equipment configurations.
- Evaporation rates were high at high inlet water temperature and low air relative humidity.
- Numerical simulation enabled both rating and design of wind aided evaporators.

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ABSTRACT

At present, mechanical evaporators are being used by the textile and dyeing units in Tirupur, South India, to further concentrate the discharge from Reverse Osmosis (RO) units. A large amount of wood is burnt as fuel, leading to air pollution and destruction of the natural habitat. To circumvent this problem, the evaporation of water in a cross flow tower configuration has been experimentally studied recently [L. Philip, Reddy, K. S., B. Kumar, B. S. Murty, A. Kannan, Performance evaluation of a solar and wind aided cross-flow evaporator for RO reject management, Desalination 317 (2013) 1–10]. A rigorous mathematical modeling and process simulation approach is now demonstrated for performance analysis and design of wind aided evaporators. Experimental conditions involving different packing configurations including sticks sourced from natural vegetation were simulated. The simulation predictions were fitted to the experimental results and the Number of Transfer Units (*NTU*) was identified. Under conditions of low relative humidity and high water inlet temperature, significant evaporation rates could be achieved. In drier places, the proposed concept offers considerable promise. Numerical simulation enables quick design and performance evaluation of wind aided evaporation schemes that may be incorporated in different industries facing RO reject management problems.

1. Introduction

The effluents from the textile and dyeing industries are sent to Common Effluent Treatment Plants (CETP) in compliance with the pollution control board norms. These industries have to manage their effluent treatments by adhering to the zero liquid discharge (ZLD) policy stipulated by these agencies. In a CETP, the effluents pass through different treatment stages and finally get treated by the Reverse Osmosis (RO) process. As simply letting off the RO rejects would be in violation of the ZLD stipulation, they are further concentrated in mechanical evaporators in the textile and dyeing industries of Tirupur, Tamil Nadu. Moreover letting out the RO reject with high total dissolved solid concentration (TDS) is detrimental to soil as well as surface and groundwater quality. The aim of the evaporation is to concentrate the RO reject to such an extent that the solids may be recovered by chilling and crystallization. However, the mechanical evaporators have several drawbacks such as the large annual consumption of firewood leading to the destruction of natural habitat, high cost of operation, scale formation and frequent shutdowns for maintenance. The textile and dyeing industries in Tirupur contribute to a major portion of the knitwear market segment and many of them are export oriented units. These industries provide employment to several hundred thousand workers and any shutdown of the plants due to the violation of the pollution control norms causes socio-economic problems. In this context, the idea of cross flow wind aided evaporators was proposed as an environmentally friendly alternative to the mechanical evaporators and the results from an experimental prototype was demonstrated [1]. There is an urgent

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need to develop a predictive simulation capability for the wind aided evaporation concept in order to address various issues related to operation and design. Numerical simulation of the wind aided evaporator will enable the rapid implementation of the concept in different industries facing RO reject management problems, and hence forms the focus of the present work.

In this work, the wind aided evaporator is simulated in house based on the mathematical model developed from first principles by Kloppers and Kroger [2] and numerical simulation methodology proposed by Nahavandi and Serico [3]. The numerical simulation scheme developed in the present work was first validated with different literature case studies under both design and rating modes. The experimental data collected from the wind aided evaporator developed by our group are compared with the numerical simulation predictions in order to identify the tower performance characteristic. The utility of the numerical simulation tool to predict the wind aided evaporator's performance under various operating conditions such as (i) water inflow temperature, (ii) packing internals and (iv) changing ambient air conditions is demonstrated. Further, the internal performance of the wind aided evaporator is mapped and evaporator requirements for different operating scenarios are illustrated.

2. Background and scope

The wind aided evaporator is a packed tower contactor, conceptually similar to that of a cross-flow cooling tower. Even though, the former emphasizes on water evaporation and the latter attaches importance to the cooled exit water temperature, the governing model equations are quite similar. Bourouni et al. [4] observed that cross flow cooling towers forms a sizeable fraction (32%) of the total towers operated in Tunisia. These authors also pointed out to the relative lack of attention given to cross flow cooling towers. Shakeri et al. [5] attributed difficulty in analysis for the lesser prevalence of the cross-flow configuration in different applications when compared to counter current configurations.

The design methodologies for cross flow contactors range from early hand calculation methods [6] to more involved numerical simulations [2–4]. Earlier design methods for cooling towers involved approximations and some of them were based on the expression of the saturated air enthalpy–temperature relation [7–10]. Inyazumi and Kageyama [11] developed a graphical method for calculating the enthalpy driving force in the cross-flow cooling tower.

The Merkel's method, which was applicable for counter-current towers, was extended to cross-flow configurations by Zivi and Brand [8]. Kelly [12] applied the method proposed by Zivi and Brand [8] along with laboratory data to produce graphical solutions for estimating the performance of cooling towers. This method is used in industries to test the performance characteristics of cooling towers. Halasz [13,14] developed a general non-dimensional mathematical model to rate different types of evaporative cooling devices operating under steady state. In this approach, the water flow rate is assumed to be a constant and the air-enthalpy saturation function is simplified by a linear relationship. The Halasz's approach has been also adopted by other researchers in recent times [15,16].

Nahavandi and Serico [3] were among the early investigators to solve the simultaneous heat and mass transfer equations numerically for cooling towers using an intuitive methodology. These equations were derived from material and energy balances as well as interphase heat and mass transfer. Their methodology was quite rigorous and did not make any simplifying assumptions either with respect to the saturation enthalpy–temperature relationship or to the water flow rate decrease due to evaporation losses. A mathematical model was developed from first principles for the cross flow cooling towers by Kloppers and Kroger [2] and involved a set of partial differential equations. These described the variation of humidity and enthalpy of air along the traverse direction and mass flow rate and temperature of water along the axial direction. Kloppers and Kroger [2] termed their approach as Poppe method after Poppe and Rogener [17]. They also compared their model predictions with the Merkel's and e-*NTU* methods [18] for different case studies.

Prasad [19] discussed ways by which the upgradation of fill material in cross flow cooling towers may be made in an economical manner using a simplified numerical simulation model. They ignored evaporation losses in their simulation. Hajidavalloo et al. [20] determined the performance of the cooling tower operating under variable wet bulb temperature conditions. They concluded that an increase in the wet bulb temperature at a constant dry bulb temperature decreased the tower performance by reducing the range, approach and evaporation rates.

Different applications involving cross flow configurations have been discussed in literature as reviewed below. RO reject volume reduction using a wind aided intensified evaporation (WAIV) has been reported by Gilron et al. [21]. They wetted either non-woven geo-textiles or woven netting with the salt solution and dried these materials through evaporation. Higher rates of evaporation in the fabrics were achieved in comparison to pan evaporation. However, they cautioned of lowered evaporation efficiency when the configuration was changed from isolated evaporation surfaces to those formed by an array of fabrics. In addition to the cooling of water in different process industries and steam power plants [19], other related applications of cross flow towers include cooling of water from geothermal sources to make them fit for irrigation [4,15] and evaporative cooling in greenhouses [16].

Gradierwerk (graduation tower) is a type of outdoor inhalatorium found in certain health resorts in Germany, Poland and other European countries [22,23]. It comprised of thick layers of brushwood. The local mineral water, concentrated in sodium chloride, was pumped to the top of the wooden structure from where it slowly dripped through the brushwood. Natural wind blowing across this structure caused a small portion of the water to evaporate, thereby further concentrating the mineral water. The graduation towers were traditionally used in Poland for salt production. Even though the Gradierwerks have been in existence for a long time in Europe, they have never been used as an alternative for mechanical evaporators for industrial waste management, to the best of authors' knowledge. Hence, it was felt that the above type of cross-flow arrangement with evaporation enabled by wind may be attempted for concentrating the RO reject [1]. To the best of our knowledge, this is the first application of cross flow evaporators to concentrate CETP rejects. An experimental arrangement of the solar and wind aided cross flow evaporator was fabricated and the evaporation rates were monitored under different operating conditions [1]. This experimental arrangement is discussed in the next section. The scope of the present work is to simulate the wind aided evaporator and understand its performance under different conditions of air and water inlet temperatures, air inlet relative humidity and packing configurations. A predictive capability validated with field experimental data is essential to enable conservative design and/or performance rating of wind aided cross flow evaporators under differing weather conditions or packing type and configuration. The extent of packing deterioration after a period of operation may be quantified by the use of process simulation. The objectives of the present study are listed as follows:

a. Develop an in house numerical simulation capability for simulating the cross flow wind aided evaporator.
b. Validate the numerical simulations by comparing the simulation results with earlier published results.
c. Numerically simulate the wind aided cross flow evaporator operating under various conditions. The effects of wind humidity, wind temperature, water temperature, type of packing and depth of packing are investigated.
d. Identify the tower performance characteristic termed as Number of Transfer Units (*NTU*) using the experimental data obtained from the prototype wind aided cross flow evaporator developed by Philip et al. [1].