Development of a model for spray evaporation based on droplet analysis

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HIGHLIGHTS

• A rigorous mathematical model for spray evaporation has been developed.
• Developed model is validated against 14 experimental data sets from literature sources.
• Spray evaporator enhances evaporation and improves the thermal efficiency of multi-stage flash distillation plants.
• Developed model allows quick calculation of brine temperature without the need for computational iterations.

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ABSTRACT

Extreme flash evaporation occurs when superheated liquid is sprayed into a low pressure zone. This method has high potential to improve the performance of thermally-driven desalination plants. To enable a more in-depth understanding on flash evaporation of a superheated feed water spray, a theoretical model has been developed with key considerations given to droplet motion and droplet size distribution. The model has been validated against 14 experimental data sets from literature sources to within 12% discrepancy. This model is capable of accurately predicting the water productivity and thermal efficiency of existing spray evaporator under specific operating conditions. Employing this model, the effect of several design parameters on system performance was investigated. Key results revealed that smaller droplet enabled faster evaporation process while higher initial droplet velocity promoted water productivity. Thermal utilization marginally changes with the degree of superheat, which renders a quick design calculation of the brine temperature without the need for iterations.

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1. Introduction

Water scarcity is one of the most pervasive problems throughout the world. In 2030, world water demand is estimated to be 6890 billion m³, yet natural water cycle can only supply 60% [1]. Desalination is one of the most promising technologies to address the water deficit [2]. Driven by the development of desalination technology and increasing of water demand, world desalination market is growing rapidly. In 2012, world desalination capacity reached around 70.8 million m³/day, and yearly growth rate of desalination capacity was 55% [3].

Currently, membrane based reverse osmosis (RO) desalination is dominating the desalination market. RO uses semi-permeable membranes to separate potable water from salty water. It is characterized by low energy consumption and smaller plant footprint. With recent progress made in membrane science, RO has gained popularity and accounts for >60% of global desalination capacity [4]. But RO is not suitable for feed water with high salinity, because higher operating pressure is required to overcome the increased osmotic pressure, resulting in the use of massive amount of energy. At times, the osmotic pressure of feed water can even exceed the operation pressure of RO [5], making the separation process infeasible. In seawater desalination application, RO is typically designed for a recovery ratio (the ratio of distilled water flowrate to feed water flowrate) lower than 50%, which corresponds to a maximal salinity of 0.07 kg/kg in the system [6]. For the treatment of high salinity water, traditional thermal desalination technologies remain indispensable. Thermal desalination separates water from salt by evaporation, and its performance is not affected by feed water condition [7]. Thus, it is highly suitable for regions with harsh water quality, e.g. the Gulf region. Another appealing feature of thermal desalination is its ability to utilize low-cost thermal energy sources, such as solar thermal energy, geothermal energy and industrial waste heat. Multi-effect distillation (MED) and multi-stage flash distillation (MSF) are two major thermal desalination technologies, accounting for >90% of thermal desalination market. MSF operates at top brine temperature of 90–120 °C and the operating stage spans 20 to 40 [8]; MED normal operates at top brine temperature of 55–75 °C under operating stage spanning 8 to 16 [9]. Such low operating temperature makes
possible the utilization of various renewable energy sources and industry waste heat. In recent years, several novel configurations have been proposed to improve the thermal utilization of desalination plants and increase production rate [10–14]. Efforts have also been reported on thermal desalination systems employing renewable energy sources [15–19]. However, both MED and MSF are energy intensive processes, with typical energy consumption spanning 250 to 330 kJ/kg-water [20]. In addition, their initial cost is high because a large area is required for the necessary heat transfer to take place. They are also prone to scaling and fouling problems. Therefore, new fundamental research to translational development is required to make thermal desalination technology more competitive and appealing in water treatment.

Spray evaporation is one of the promising methods to address the problems of thermal desalination technology. In the spray evaporator, extreme flash evaporation occurs when superheated liquid is injected into a low pressure zone. The heat and mass transfer process is much more severe than pool boiling in MSF process [21]. Besides, the employment of metallic heat transfer surfaces is unnecessary, leading to smaller fouling and scaling problems and lower initial cost. Further, spray evaporation employs relatively small temperature differences as the heat sources, which enables better utilization of renewable energy. By replacing the flash chambers with spray evaporators, the performance of MSF plants can be markedly improved. Higher production rate and thermal efficiency can be achieved due to enhanced heat and mass transfer.

One pilot plant has been constructed and operated in Egypt, and recorded performance data has demonstrated all the technical merits mentioned for spray evaporation [22]. Several experimental studies have also been carried out on flash evaporation to evaluate its thermal performance [21,23], enhance evaporation rate [24] and investigate the effect of design and operating parameters (direction of injection [25–28]; initial liquid temperature, spray velocity, and degree of superheat [29–31]; nozzle geometry and nozzle size [32,33]). All these studies offer only general conclusions at system level, and little or no information is available on the droplet heat and mass transfer process due to the infeasibility of experimental investigation. But such information is essential for the design and optimization of spray evaporator. The development of an in-depth theoretical spray evaporation model is necessary. Thus far, to the best of our knowledge, few models can be found in the literature. Hwang, T. H. et al. [34] analyzed the evaporation process of a single droplet in low pressure systems theoretically. In his model, he considered heat conduction in the liquid and heat convection between the liquid and the vapor. The evaporation mass flux on the droplet surface was calculated using kinetic theory. In another model developed by Muthumayagam et al. [35], conduction thermal resistance inside the droplet was neglected and the evaporation mass flow rate on the droplet surface was derived using vapor diffusion theory. In these two models, constant velocities were assumed for the droplet, and the effects of gravity, buoyancy and drag force were neglected. Another limitation is that both models investigated the performance of a single droplet only. In physical reality, spray contains droplets with varying diameters [36–38]. Due to these simplifications, these models provided only qualitative conclusions and their value-add to designers are limited.

This paper intends to make key contributions through a spray evaporation model processing better predictive capability. A comprehensive model that considers droplet motion and droplet diameter distribution is developed. The evaporation rate of a single droplet is first predicted and analyzed. The motion of droplets due to gravity, drag force and buoyancy is considered while the variation of droplet diameter is depicted using a droplet diameter distribution function. The model is validated with experimental data acquired from literature [24,25,32,33]. Based on the model, the effects of key design parameters on thermal efficiency and evaporation rate of spray evaporator are estimated and discussed.

2. Mathematical model

The schematic of the spray evaporator is shown in Fig. 1. Superheated water is injected to the depressurized chamber via a nozzle. Water ejects from the nozzle as solid jet first and then breaks up into large amounts of small droplets. Subsequently, part of the water in the droplet surface flashes into vapor and the rest portion with lower degree of superheat is drained off at the bottom of the chamber. Vapor is then directed to the condenser to sustain the low pressure in the chamber. When the system reaches steady state, all the produced vapor condenses in the condenser. Therefore, both vapor pressure and
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