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Experimental study on low temperature desalination by flash evaporation in a novel compact chamber design

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ABSTRACT

The production of potable water in dry areas nowadays is mainly done by the desalination of seawater. State of the art desalination plants usually are built with high production capacities and consume a lot of electrical energy or energy from primary resources such as oil. This causes difficulties in rural areas, where no infrastructure is available neither for the plants' energy supply nor the distribution of the produced potable water. To address this need, small, self-sustaining and locally operated desalination plants came into the focus of research. In this work, a novel flash evaporator design is proposed which can be driven either by solar power or by low temperature waste heat. It offers low operation costs as well as easy maintenance. The results of an experimental setup operated with water at a feed flow rate of up to 1600 l/h are presented. It is shown that the proof of concept regarding efficient evaporation as well as efficient gas-liquid separation is provided successfully. The experimental evaporation yield counts for 98% of the vapor content that is expected from the vapor pressure curve of water. Neither measurements of the electrical conductivity of the gained condensate, nor the analysis of the vapor flow by optical methods show significant droplet entrainment, so there are no concerns regarding the purity of the produced condensate for the use as drinking water.

1. Introduction

Almost a quarter of the worldwide installed desalination capacity is provided by systems with Multi Stage Flash evaporation (MSF). In terms of quantity, MSF is therefore the second most important process after Reverse Osmosis (RO) [1]. Especially in the Middle East and the North African region (MENA), where energy supply is based on oil deposits, thermal desalination processes such as MSF strongly predominate [2]. MSF technology is used in large-scale plants with capacities of up to 90,000 m^3/d. The specific energy requirement of MSF plants is comparatively high, since in addition to the electrical energy requirement of 2.5–4 kWh/m^3, a thermal energy requirement of 7.5–12 kWh/m^3 must also be covered [3]. Thus, MSF plants are characterized by large space requirements and high investment and operation costs. Apart from the high energy demand, other environmental aspects need to be taken into account: large-scale seawater desalination plants show severe environmental impacts, mainly associated with the construction and operation of marine intake systems and the disposal of concentrated brines [4]. As highlighted in several studies, the use of renewable energy such as solar thermal energy is expected to play an important role in the future production of potable water by means of desalination in the MENA region [5,6]. Addressing the sustainability of large-scale desalination plants, there are several approaches discussed in literature which deal with seawater desalination by the use of concentrated solar power coupled with a MSF or RO process [7,8].

On the other hand, in rural areas, there is a need for smaller decentralized desalination plants which preferably are based on solar power utilization and allow for cheap and easy to handle water supply. Amongst others, Al-Kharabsheh et al. discuss a simple desalination process that uses low-grade solar heat [9]. Vacuum conditions in the condenser are provided by making use of geodetic height differences between the condenser and the water tanks. Thereby, the use of a conventional vacuum pump is avoided, and the need for auxiliary power is reduced to a minimum. They report a double yield of potable water if compared to a simple flat-basin solar still. Another approach to obtain passively created vacuum conditions for solar flash desalination is investigated with both experimental and simulation studies by Abutayeh et al. [10]. Muthanayagam et al. [11] describe another experimental approach for seawater desalination via flash evaporation. They suggest using seawater from different depths and thus different

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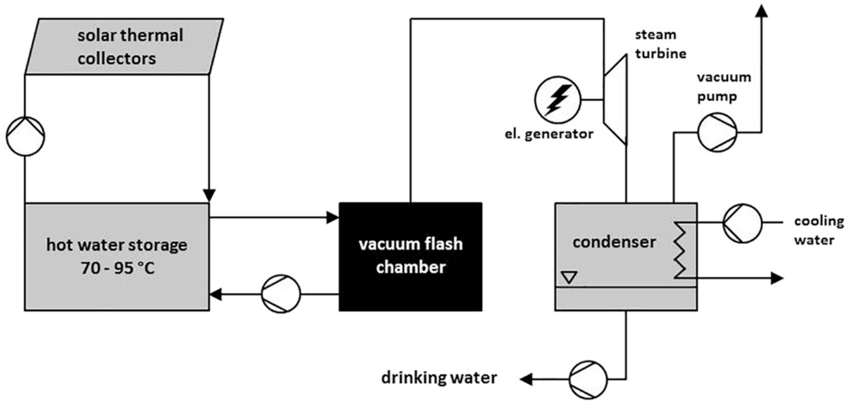

Fig. 1. Schematic flow diagram of a multi-effect solar desalination plant as proposed in [15].

temperatures for feed and cooling water, respectively. Feed water enters the evaporator at a temperature of 26–32 °C and is nebulized by a swirl nozzle. Entrainment of droplets with the steam flow is prevented by using a demister unit. The temperature of the cooling water is given with 6–12 °C, which corresponds to seawater temperatures in high ocean depths. Experimental results at vaporization pressures of 13–24 hPa are reported to show satisfying agreement with a theoretical model. Muthanayagam et al. also report that they did not find a relation between the rate of condensation and the salt content of the feed water. Hence, many of their experiments were conducted with groundwater [12]. The influence of the direction of feed water injection on flash spray desalination was analyzed by Ikegami et al. [13]. They found a vertical, upward jet injection method with a tubular shaped nozzle to be suitable for compact and efficient spray flash desalination systems. Mutair et al. further analyzed the influencing parameters on flash evaporation from a superheated water jet when a nozzle is used [14].

The background of our work is a desalination process which is described in detail by Witt [15]. A schematic drawing of the complete desalination process is depicted in Fig. 1. This multi-effect process offers the supply of drinking water as well as of electrical energy. Hot water with a temperature of 70–95 °C is prepared in solar thermal collectors or by using low temperature waste heat. A high temperature water tank is used for thermal energy storage, e.g. if the production of potable water is needed during night or days with poor solar radiation. Vacuum steam is produced from the hot water by flash evaporation and afterwards expanded in a steam turbine. Additionally, the electrical energy produced by a generator can be used as auxiliary power to drive process components, but also for external applications. In a final step, all remaining vapor is being condensed with cold sea water, and the condensate is used to prepare drinking water. If the electricity gained from the steam turbine can be used for power supply of the desalination plant, this process can be conducted entirely self-sustaining, which presents great potential especially in rural areas.

In our study, a newly developed, both space and cost saving flash geometry is experimentally investigated. It uses standard process engineering components to achieve an efficient thermal desalination with no need to add pressure loss causing demisters. As, in contrast to standard evaporator geometries, there is no generally accepted engineering guideline available that describes how to design and dimension a flash evaporator, an extensive literature study on different flash chamber geometries was conducted.

Most of the flash evaporation concepts mentioned above share the fact that nozzles, f.e. swirl nozzles or tubular shaped nozzles, are used to inject the superheated water into a flash chamber and thereby make the evaporation process faster and more efficient. However, the application of a nozzle could present two major disadvantages if it comes to the flash evaporation of saline water: Firstly, nozzles with small diameters tend to plugging if crude seawater is used which would lead to either high maintenance effort or pretreatment of saline water. Secondly, spraying the liquid could cause the formation of tiny droplets of saline water which are carried along into the condenser by the vapor flow. Not only for vacuum spray evaporation, but also in circulatory and stationary flash evaporation, brine entrainment is reported to be an issue. In a simple flash chamber with a tubular feed inlet, Zhang et al. observed strong steam-carrying effects especially when the inlet superheat increased [16]. This could not only lead to contamination of the condensate, i.e. the drinking water, but in addition cause damage on the steam turbine blades of multi-effect desalination plants. Therefore, the use of a demister unit is required to separate the droplets from the steam. A demister on the other hand leads to pressure loss and for this reason decreases the work gained in the turbine and thus the output of electrical energy.

A quite similar problem occurs in a very different technological area: in geothermic power generation, turbines are reported to fail because of droplet entrainment and mineral carriage with the steam. To ensure that only dry and clean steam enters the turbine, special geometries of liquid-vapor separators are used, which show separation efficiencies of 99.9% or even higher [17]. One type commonly used is a vertical cyclone separator with top or bottom outlet [18]. For these types of separators, which operate at high steam throughputs, the effectiveness of droplet separation is strongly influenced by the inlet flow velocity: for low velocities, poor separation is observed. Increasing the velocity increases the effectiveness of separation and thus leads to smaller equipment sizes, but, at high input velocities, a breakdown point is reached. As of this moment, the wetness of the output flow increases significantly when further increasing the input velocity [19].

In the current work, a flash chamber design is implemented and experimentally analyzed that combines both the function of a flash evaporator as well as of a vertical gas-liquid separator with low pressure drop into one process component. It is designed in a way that allows for easy and cheap maintenance and low investment costs. In the presented experimental study, hot water is produced with electrical power instead of solar energy for experimental reasons. Furthermore, the condenser is replaced by a liquid ring vacuum pump to establish and adjust the investigated vacuum pressures.

2. Experimental setup and procedure

An experimental setup was designed that allows investigations on the kinetics of flash evaporation of water. In principle, there are two functions to be fulfilled by the evaporator: complete evaporation in terms of thermodynamic equilibrium conditions, and phase separation between the gas and the liquid phase. We suggest a novel design that combines both of these two functions into one single component. Hence, the main question to be addressed is whether any formation of droplets can be observed during the flash process, and, if so, how the