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# Parallel and series multistage air gap membrane distillation

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ABSTRACT

The performance of multistage air gap membrane distillation (MS-AGMD) system is experimentally investigated. The effects of feed temperature and flow rate, coolant temperature and flow rate, air gap width, and feed concentration on the system performance are studied. Parallel and series flow stage connections for the feed stream and coolant stream are tested. Energy analysis is performed for the MS-AGMD and compared with the single stage system. Parallel stage connection shows better performance than series connections in terms of permeate flux and energy consumption. The distillate volume of MS-AGMD module is measured to be 2.6 and 3 times the distillate volume of single stage AGMD module, for series and parallel stage connections; respectively. However, the specific energy consumption of multistage system is only 1.5 times the single stage system. The gain output ratio of the parallel stage MS-AGMD system is higher than the series stage MS-AGMD system, and it reached 0.6 for parallel MS-AGMD system and 0.45 for the series MS-AGMD system, at 90 °C.

## 1. Introduction

Shortage of fresh water is a major challenge facing modern societies. To overcome the shortage of fresh water, the world today depends on desalination of seawater and brackish water [1]. Water and energy are critical, mutually dependent resources (water-energy nexus) [2]. Water is required to generate energy. Thermoelectric cooling, hydropower, energy mineral extraction and mining, fuel production, and emission controls all rely on large amounts of water. On the other hand, water supply also requires energy use. A large amount of energy is needed to extract, convey, treat, and deliver fresh water. Membrane distillation (MD) is one of the promising techniques for water desalination and treatment. It is a thermally driven membrane separation process that uses a micro-porous hydrophobic membrane to separate water vapor from the feed solution (e.g. seawater). The vapor pressure difference between the two sides of membrane is the driving force of permeation in the MD process [3–5]; which is a direct function of temperature difference across the membrane. The permeated vapor through the membrane is then condensed and collected as distillate. MD process has been utilized for many applications like water desalination [6–9], treatment of waste water [10], and even the treatment of radioactive waste [11,12]. The four widely known configurations of MD are Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD), and Vacuum Membrane Distillation (VMD). The design of the feed side of all these MD configurations is the same, however, the design of the cold side of the membrane and the way in which the permeated flux is collected are different for each configuration [13].

Air gap membrane distillation (AGMD) process is one of the common MD configurations [13,14]. In AGMD there is a direct contact between hot feed stream and membrane surface. On the other side of the membrane, a stagnant air gap exists between the hydrophobic membrane cold surface and a condensation cold surface. The vapor permeates across the membrane pores and diffuses across the air gap to condense on the condensation plate surface. The advantage of the air gap is to reduce the conduction heat loss through the membrane, however the air gap reduces the permeate flux, which is considered a disadvantage of AGMD [15–18]. The performance of AGMD system is greatly affected by several operating factors which includes feed temperature, feed flow rate and the air gap depth. The influence of coolant temperature on the performance of AGMD unit is relatively low, while the effect of coolant flow rate is negligible [17–20].

Main limitations facing industrialization of the MD systems include high energy consumption, the absence of perfect design of module (membrane cell), the hydrophobic membranes which are designed specifically for MD applications, and the relatively low productivity. Thus, new designs of multistage membrane distillation (MS-MD) systems are needed for industrial applications. The multistage vacuum membrane distillation (MS-VMD) module has been successfully commercialized, and accomplished higher heat recovery as compared to the single MD units [21,22]. A multi-effect air gap membrane distillation (ME-AGMD) module for water treatment is developed by Pangarkar and Deshmukh [23]. They developed a mathematical model of a single stage AGMD system for four-stage ME-AGMD system, and presented the

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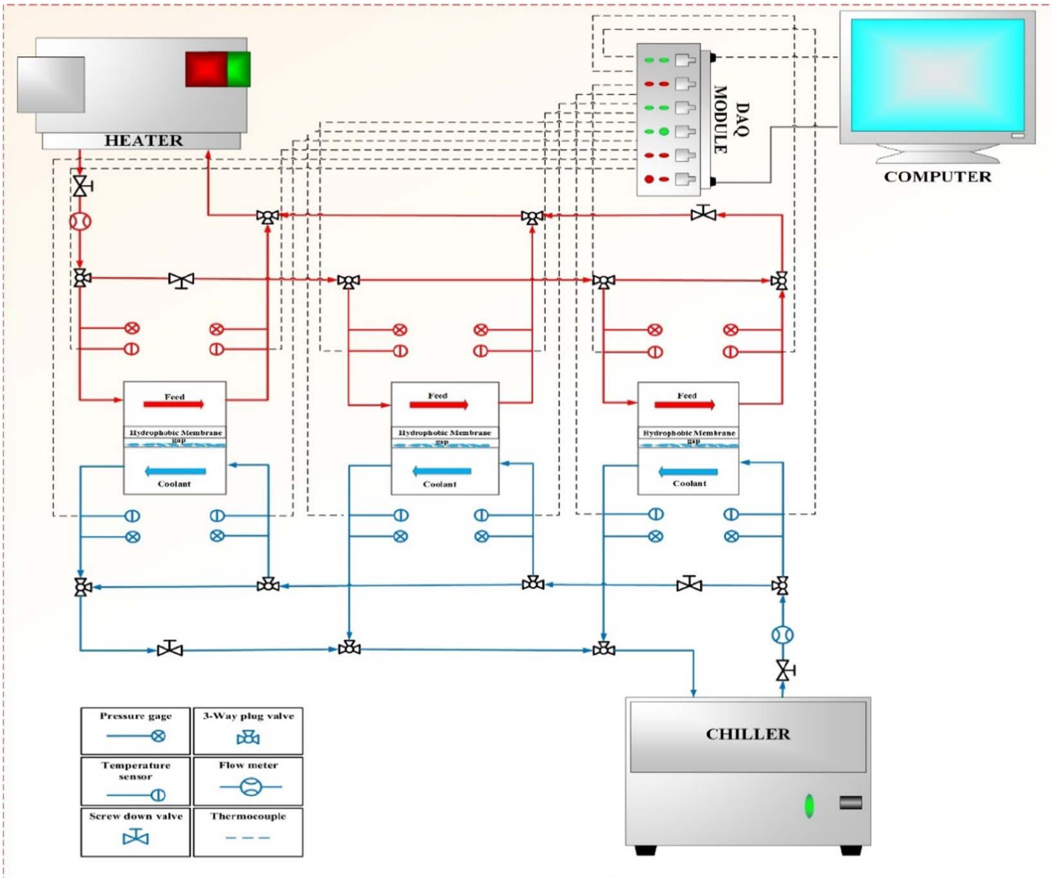


**Fig. 1.** Schematic diagram of multistage MD system (parallel stage connection).

performance of the single and multi-effect AGMD systems at various operating conditions. They reported that the flux of ME-AGMD module is about 3.2–3.6 times the flux of single stage AGMD module and the efficiency of the ME-AGMD system is higher than efficiency of the single effect AGMD system. Geng et al. [24] investigated a multi-stage (4-stage) air gap MD system for reverse osmosis brine gaining a higher water recovery. They used a one-stage air gap MD system with brine rejected from a reverse osmosis unit as feed. They reported that the maximum value of the gained output ratio and the permeate flux could reach 7.1 and 6.8 $kg/m^2 \cdot h$; respectively.

Lawal and e. Khalifa [25] performed a parametric study of double staged AGMD system at different operating parameters. They tested an air gap membrane distillation unit with double-sided cooling channel. The multi staging the MD system is essential for efficient energy usage, and high system productivity. Lee and Kim [26] Simulated a multi stage vacuum membrane distillation (MS-VMD) system by using a one-dimensional in-house code with heat and mass transfer equations and momentum and energy balance equations. They used different arrangements for the system (series, parallel, and mixed). They evaluated the water product cost by considering the maintenance cost, capital cost, operation cost, and spares cost. They analyzed the membrane wetting problem, the productivity, and the water product cost in order to find the best arrangement. They reported that the mixed MS-VMD system with 20 stages has the less water product cost ($1.16/$m^3$), less maximum trans-membrane pressure difference (93.8 kPa), and highest productivity (3.79 $m^3$/day). In addition, they mentioned that using the waste heat source with MS-VMD system can reduce the water product cost from $1.16/$m^3$ to $0.52/$m^3$.

Lee et al. [27] introduced an integrated pressure-retarded osmosis (PRO) with multi-stage vacuum MD system, using a recycling flow scheme (MVDM-R) for highly concentrated brine and to produce the fresh water continuously. They used the concentrated brine that is produced from the system to generate the power in the pressure-retarded osmosis system. At constant feed flow rate, the permeate flux increases when the recycling flow decreasing. At constant hydraulic pressure difference and using the river water as a feed water with 0.5 kg/min flow rate, the maximum power density of 9.7 $W/m^2$ is achieved. Kim et al. [28] described a solar multi-stage vacuum membrane distillation system. The system consists of temperature modulating (TM) scheme to measure the variation of the feed seawater temperature, a unit to recover the energy from the water vapor to the seawater, and hydrophobic fibers membrane module. They used a mathematical model to study the system for different numbers of heat recovery units. Their results showed that the total productivity for the system with 10 energy recovery units and 24-stages is about 3.37 $m^3$/day, and it is about 34% more than the system with one energy recovery unit. For a Vacuum Membrane Distillation system without solar-thermal unit, when the number of heat recovery units increasing from 1 to 10, the overall specific thermal energy consumption (OSTEC) decreases by 20%. The overall specific thermal energy consumption for the system without the solar thermal unit is 28%–36% higher than the solar-thermal system. Lienhard et al. [29] evaluated the performance of a multi-stage vacuum membrane distillation (MS-VMD) system which is thermo-dynamically comparable to a multi-stage flash (MSF) for water desalination. They reported that increasing the boiling point elevation (BPE) of the feed water at high salinities resulted in higher heating requirements, lower GOR values, and lower fluxes. When the feed salinity increases the separation least heat increases faster than the specific energy consumption for the system. By using different feed concentrations, and reasonable membrane areas, the MS-VMD systems will be as efficient as the multi-stage flash system.

In the present work, the performance of the multistage air gap MD