Water purification of arsenic-contaminated drinking water via air gap membrane distillation (AGMD)

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Abstract

Arsenic contamination in shallow tubewell water is a serious health issue in Bangladesh and other Southeast Asian countries. Rural and remote areas in these locations continue to face tremendous challenges in providing access to affordable and safe arsenic-free drinking water. In recent years, intensive efforts have been undertaken to identify appropriate technologies for arsenic removal. This study examines one approach by investigating the application of suitable membrane technologies, specifically air gap membrane distillation (AGMD), as a promising method for small-scale, low cost deployment. The objective of this study was to test an AGMD commercial prototype (nominal capacity of 2 L/hr) with three different feedstocks: plain water and arsenic-spiked tap water. Results show that the tested AGMD prototype is capable of achieving high separation efficiency, as all product water samples showed arsenic levels below accepted limits even for initial concentrations over 300 µg/L. Parametric studies with focus on variation of coolant temperature illustrate the possibility of integrating AGMD in various thermal systems.

Keywords: arsenic removal; air gap membrane distillation (AGMD); internal heat recovery; MD performance

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1. Introduction

Bangladesh is a densely populated country with over 80% of the population living in rural areas. Like several developing Southeast Asian countries, Bangladeshi drinking water is contaminated with arsenic, and the country faces immeasurable health consequences as a result [1]. According to Tan et al. [2] 2010), 20% of deaths in Bangladesh can be attributed to arsenic poisoning due to various diseases including lung, skin, and bladder and kidney cancers. Moreover, researchers estimate that around half of the nation's 154 million people have been seriously exposed to arsenic contaminated drinking water [2]. The groundwater of 50 districts out of a total of 64 districts contained arsenic higher than the country standard for shallow tubewell drinking water (50 µg/L), and in around 60 districts surface water was contaminated with arsenic levels higher than WHO recommendations (10 µg/L) [3]. Uddin et al. [4] reports that the range of arsenic concentration in ground water of Bangladesh is between 0.25 µg/L to 1600 µg/L. One of the key challenges towards overcoming this problem is the development and implementation of technologies that meet several tough demands: technically sound, robust in operation, cost effective, and environmentally compatible. Several technologies have been tried for removal of high arsenic concentration arsenic from tubewell drinking water. The commonly used conventional methods employ adsorption processes – coagulation and ion exchange [4]. Incorporating such processes is viable economically only at a large scale in centralized water treatment plants, requiring heavy capital outlays and skilled staff in addition to the necessary distribution systems and their maintenance. Also conventional methods are most effective on As(V), whereas As(III) is more prevalent in groundwater [4]. Therefore alternatives are needed for distributed deployment and operation in small communities.

Reverse osmosis (RO), a widespread membrane technology for a broad range of capacities, exhibits very good to excellent separation efficiencies and has potential as a water treatment technology in this context. However drawbacks like formation of polarization film, fouling, high electricity consumption and brine disposal are limiting factors [5]. Several experimental results showed that reverse osmosis (RO) is an effective method for separation of arsenic up to 90%; however RO failed to remove arsenic concentration to safe levels when arsenic concentration is very high in the ground-water [6]. Membrane distillation (MD) has also been considered as an alternative technology for arsenic removal. In short MD is a thermal water purification process involving a hydrophobic, microporous membrane. Hot feed is kept on one side of the membrane, and a vapor pressure difference is established across the membrane via cooling on the opposite side. Water evaporates from the feed, passes through the membrane, and condenses; all non-volatile components are retained in the liquid phase, thus ensuring extremely high separation efficiency and high product water purity. Pangarkar and Sane [7] mention MD's advantages over other technologies like low-grade energy utilization, low pressure and cost, and possibility to integrate MD with combined electricity, heat, cooling, and other energy services (i.e. polygeneration). Qu et al. [8] experimentally investigated direct contact membrane distillation (DCMD) for arsenic removal; DCMD was found to have a higher removal efficiency rate (above 99.95%) than RO and also exhibited the ability to treat high-concentration arsenic solutions. Manna et al. [1] and Pal and Manna [9] achieved 100% As separation efficiency in a laboratory-scale DCMD unit supplied with heat from an evacuated tube solar collector. Small scale vacuum membrane distillation (VMD) was tested for arsenic contaminated water at low feed temperatures [10], and excellent separation efficiency was demonstrated.

Air gap membrane distillation (AGMD) has also been proposed as a promising approach that combines the excellent separation characteristics of DCMD and VMD with lower specific thermal energy consumption [11]. Islam [12] studied arsenic removal by AGMD using a small-scale commercial prototype module and reported successful treatment of arsenic-contaminated well water in Bangladesh. Kullab and Martin [13] investigated AGMD for flue gas condensate treatment in biomass-fired boilers; here product water in pilot-scale trials exhibited As levels less than 1μg/L, despite high contamination levels of a number of components in the feedstock. Recently Khan et al. [14] proposed a biogas integrated system with AGMD in Bangladesh for pure water and clean energy provision, and Kumar et al. [15] has presented a solar hot water system with integrated AGMD for water purification.

The above studies indicate that AGMD is a promising technology for producing arsenic-free drinking water, however further research is required to firmly quantify actual performance in terms of separation efficiency and thermal energy consumption for near-commercial modules. Such data is necessary for the design of integrated small-scale polygeneration systems featuring MD. The present investigation addresses this issue via an experimental investigation of a household AGMD water purifier prototype (2 L/hr nominal capacity) supplied by HVR Water Purification AB, Stockholm (subsidiary of Scarab Development AB). A parametric variation of coolant-side inlet temperature was conducted for plain and As-spiked tap water, and the resulting yield and thermal energy consumption were determined.

2. Methodology

2.1. AGMD experimental setup

Fig. 1 shows a schematic of the AGMD system. Two immersion heaters (combined rate of 4.5 kW) provide temperature control to feedwater contained in a 24 liter tank. A small circulation pump and bypass valve allow the hot-side flow rate to be controlled, and a rotameter is employed to measure flowrate. Once-through tap water is used as a heat sink, which can be heat exchanged with an external source to raise the inlet coolant temperature to the desired level. Here a second rotameter with built in control valve measures cold water flowrate in the cooling channel. Product water is measured with a graduated cylinder and stopwatch, typically during a 30-minute period of steady operation. To measure the feed and cold temperatures, thermocouples were installed at the inlets and outlets of the module and were connected to a data logger (Keithley 2701 DMM with a 7706 card). Experimental errors are as follows: temperature, +/- 2.0 ^{o}C; flow rate, +/- 0.1L/min; and yield, +/- 0.02 L/hr.

The AGMD module consists of a 2.4 cm separation between two vertical condensation plates, behind which are located serpentine cooling channels. A polypropylene cassette with membranes attached to either side is placed between the condensation surfaces (cassette dimensions 42 cm wide by 24 cm high, total membrane area 0.19 m^2). This arrangement provides for an initial gap of 9 mm on each side, although the actual gap size is reduced by bulging of the membranes during operation. The feedstock is introduced at the bottom of the cassette and flows out from the top, as seen in Fig. 1 (b). The membrane material is PTFE (polytetrafluoroethylene, supplied by Gore) with a porosity of 80% and thickness of 0.2 mm.

2.2. Experimental procedure

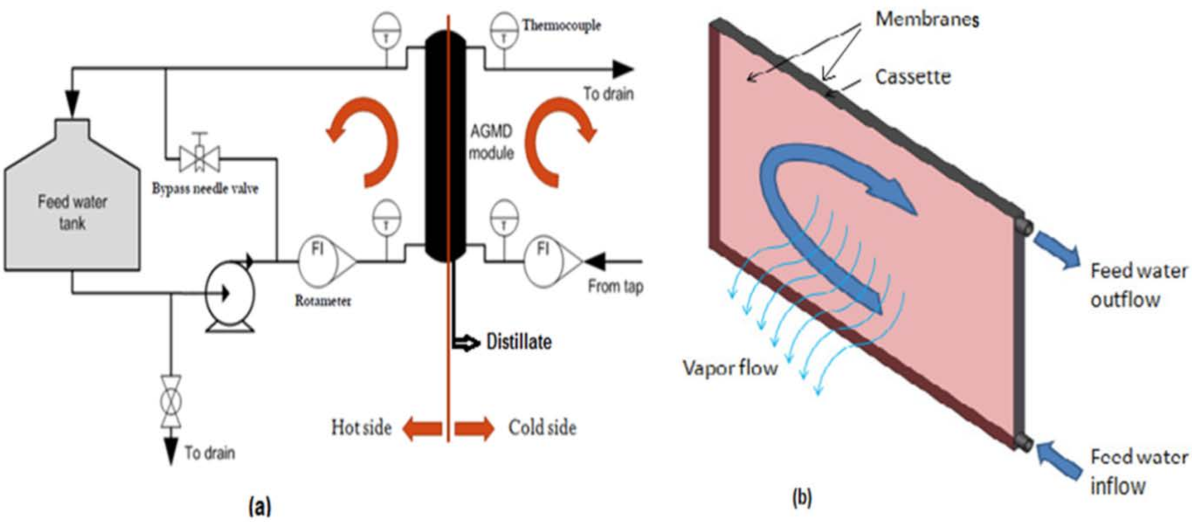

Fig. 1 - (a) MD bench scale unit setup at KTH (b) Membrane Cassette (MD)

The AGMD experiments consist of analyzing the performance of the system under different operating conditions, namely cold-side temperature levels. The operating conditions on the cold side included a flow rate of 1.9 L/min and a range of coolant inlet temperatures: 15^oC, 30^oC, 45^oC, 55^oC, and 70^oC. On the hot side, the temperature was kept constant at about 80^0C, with a constant feed flow of 3.8 L/min.

3. Results

3.1. Parametric study

The performance of the AGMD prototype is evaluated by analyzing pure water flow rates and specific thermal energy requirements (kWh/m^3) as a function of feed and coolant temperature difference. As mentioned previously, experiments were performed for high and low temperature differences across the membrane for tap water and arsenic-spiked water. A feedstock-to-coolant temperature difference ΔT is defined for reference purposes:

$$\Delta T = T_{fi} - T_{ci} \tag{1}$$

where T_{fi} and T_{ci} are the inlet temperatures of the feed and coolant, respectively. Fig. 2 shows the effect of this temperature difference on permeate flux at constant feed flow and coolant flow rate (the temperature difference is based on inlet conditions). The results show the increase of permeate flux with increase in temperature difference, an expected observation owing to the higher driving forces in this scenario. A small but significant flux is measured at a very low temperature difference, corresponding to a coolant temperature of around 70^oC, which has implications for heat recovery on the cold side (see next section). Overall the performance of the AGMD commercial prototype is within expectations, although the permeate flux has been reported to be much higher in DCMD and VMD (2-6 times increase, respectively) [16, 17].

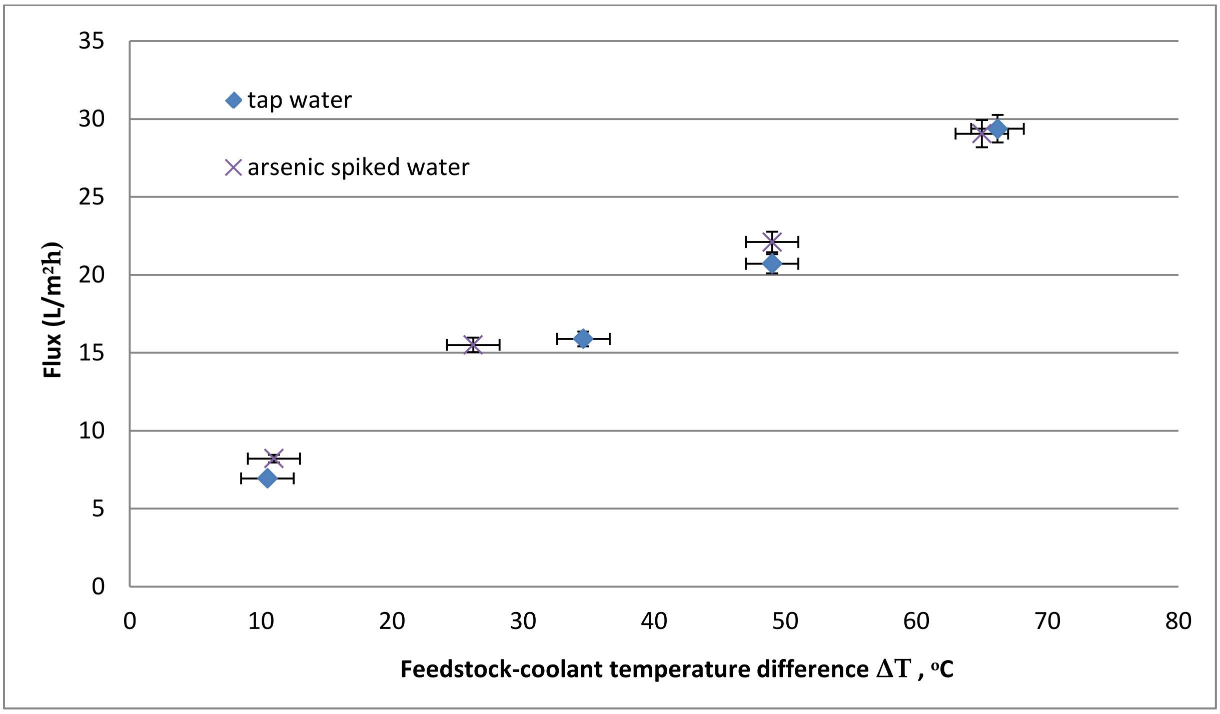

Fig. 2 - Product water flux as a function of temperature difference across the membrane (feed water flow 3.8 L/min, coolant flow 1.9 L/min, feedwater inlet temperature ca 80^{o}C, coolant inlet temperature varying)

Internal heat recovery can be achieved by AGMD since the modules allow the latent heat of vaporization to be transferred to the coolant channel via the distillate. The specific thermal energy consumption has been estimated in two ways:

Enthalpy drop across the hot side,

$$Q_1 = \dot{m}_h c_{ph}(T_{hi} - T_{ho})/\dot{m}_p \qquad (2)$$

Net enthalpy change,

$$Q_2 = \left[\dot{m}_h c_{ph}(T_{hi} - T_{ho}) - \dot{m}_c c_{pc}(T_{co} - T_{ci})\right]/\dot{m}_p \qquad (3)$$

where $\dot{m}$ is the mass flow rate and c_p is the specific heat for cold (subscript *c*), hot (subscript *h*), and product water streams (subscript *p*); subscripts *i* and *o* denote inlet and outlet, respectively. Fig. 3 shows this data as a function of feedstock-to-coolant temperature difference. Specific thermal energy consumption as defined by Q_1shows a weak correlation to temperature, especially when considering the high level of uncertainty in propagated errors.

The slight increase at higher ΔT is attributed mainly to the fact that the enthalpy drop across the hot feedstock side rises at a faster rate than the concomitant augmentation in product water yield (Fig. 2). The opposite trend can be seen in the specific thermal energy consumption as defined by Q_2, i.e. as the feedstock-coolant temperature difference is raised, the rate of increase in product water yield dominates over the difference in net feedstock and coolant enthalpy change. Moreover heat recovery is enhanced with higher driving forces, which is reflected in a reduction of Q_2 at higher feedstock-coolant temperature differences.

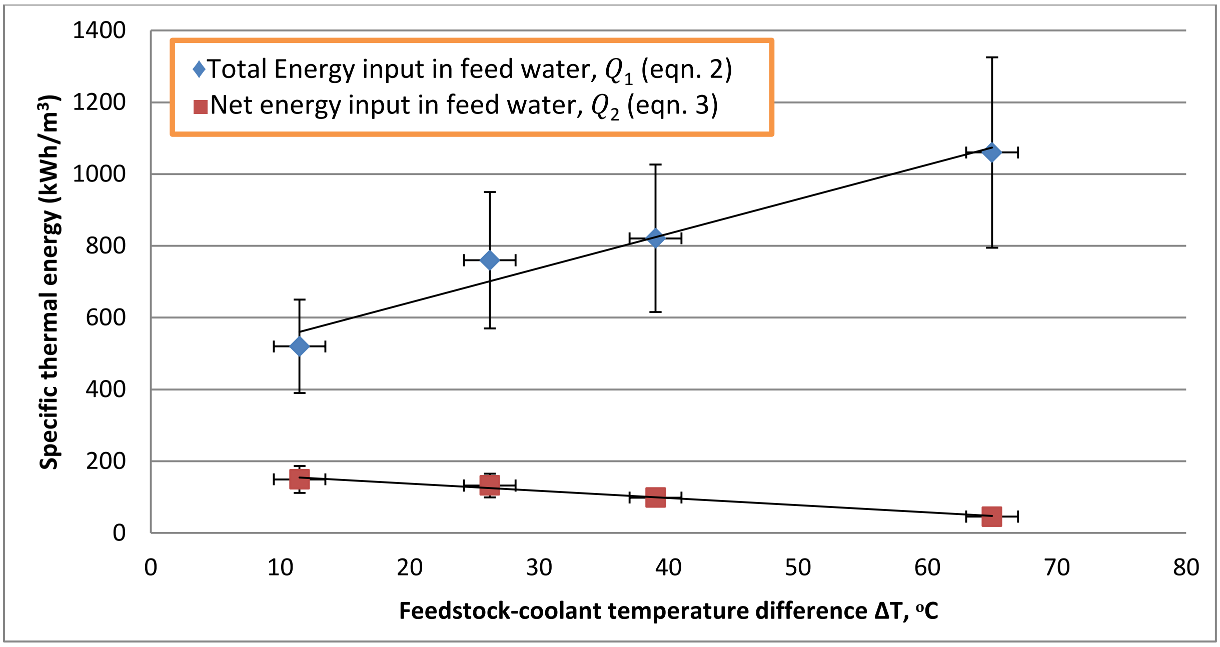

Fig. 3 - Specific thermal energy consumption for AGMD module (feed water flow 3.8 L/min, coolant flow 1.9 L/min, feedwater temperature ca 80^{o}C, coolant temperature varying)

3.2. Water quality analysis of arsenic-spiked tap water

For the tests presented in section 3.1, the conductivity of plain and arsenic-spiked tap water is about 250 µS/cm. Values of product water conductivity fluctuated on average between 0.6 and 1.5 µS/cm, indicating a very high purity level. Table 1 contains the water analysis of arsenic spiked tap water and product water (analyses conducted by Activation Laboratories Ltd, Ontario, Canada). The results are very promising in terms of arsenic concentration in the distillate, which was at extremely low levels.

Table 1 - Water quality analysis for arsenic-spiked tap water

Parameter	Unit	Concentration in arsenic spiked feed water	Concentration in distillate
As	µg/L	300	<0.03
Ca^{2+}	mg/L	50	<0.7
Mg^{2+}	mg/L	12.5	<0.02
Na^{+}	mg/L	100	<0.17
K^{+}	mg/L	5	<0.03
Conductivity	µS/cm	250	0.6-1.5

4. Conclusions

Air Gap Membrane Distillation has been demonstrated as a viable technology for arsenic removal with realistic feedstocks. Yields are maximized by increasing the temperature difference between feedstock and coolant, yet there is scope to utilize high coolant temperatures to achieve low specific thermal energy consumption and thus enhance heat recovery. Temperature levels on the hot side (at about 80^{o}C) are amenable to thermal integration with a variety of appropriate sources - biomass-derived waste heat, solar thermal, etc. Moreover cold side temperatures can be increased to fairly high amounts (up to 70^{o}C) while exhibiting reasonable yields, opening up further possibilities for thermal integration. Considering the socio-economic situation of rural areas in Bangladesh, AGMD seems difficult to be applied alone due to high capital cost and energy consumption. Therefore, an integrated system could be one of feasible and viable alternative to solve the safe and arsenic free drinking water. The future aim is to develop and commercialize a simple low-cost polygeneration system with an integrated biogas digester, gas engine, and AGMD unit, and activities are already underway.

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