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Removal of arsenic from contaminated groundwater by solar-driven membrane distillation

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Solar-driven membrane distillation has the potential of removing arsenic from contaminated groundwater.

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ABSTRACT

Experimental investigations were carried out on removal of arsenic from contaminated groundwater by employing a new flat-sheet cross flow membrane module fitted with a hydrophobic polyvinylidene-fluoride (PVDF) microfiltration membrane. The new design of the solar-driven membrane module in direct contact membrane distillation (DCMD) configuration successfully produced almost 100 per cent arsenic-free water from contaminated groundwater in a largely fouling-free operation while permitting high fluxes under reduced temperature polarization. For a feed flow rate of 0.120 m^3/h, the 0.13 μm PVDF membrane yielded a high flux of 74 kg/(m^2 h) at a feed water temperature of 40 °C and, 95 kg/m^2 h at a feed water temperature of 60 °C. The encouraging results show that the design could be effectively exploited in the vast arsenic-affected rural areas of South-East Asian countries blessed with abundant sunlight particularly during the critical dry season.

1. Introduction

Groundwater contamination by arsenic leachate has now affected millions of people from South-East America to Argentina, Taiwan, China, Nepal, Bangladesh and India. Most of the affected parts belong to the developing countries in South-East Asia where the problem assumes an alarming proportion particularly during the dry seasons (January–June) when groundwater levels fall sharply. Arsenic contamination and its mitigation is a priority area in drinking water quality within the World Health Organization (WHO) and other national and international agencies, and a multitude of studies (Schreiber et al., 2000; Panthi et al., 2006; Pokhrel et al., 2009; Chen et al., 2009; Harvey et al., 2006; Chowdhury et al., 2000; Chakraborti et al., 2003; Bhattacherjee et al., 2005; Acharya, 2002) have been commissioned many of which focus on West Bengal (India) and Bangladesh where the largest affected population lives on the Bengal Delta Basin. While the problem is relatively well known, challenges remain in the widespread implementation of low-cost and effective arsenic removal strategies in such regions. Through extensive studies (Pal et al., 2007a,b; Wickramasinghe et al., 2004; Pagana et al., 2008; Hsieh et al., 2008; Xia et al., 2007; Hering and Elimelech, 1996; Greenleof et al., 2006; Brandhuber and Amy, 2001; Fagarassy et al., 2009; Nguyen et al., 2009) carried out over the last few decades on removal of arsenic from drinking water, adsorption, chemical coagulation–precipitation, ion-exchange and membrane separation have been established as the broad technology options of purification. Though arsenic removal efficiencies of these processes are largely established as shown in the review paper (Shih, 2005) and presented in Table 1. Wide variations are observed in designs, separation results, applicability and viability of the reported membrane-based techniques which are relatively new. Socio-politico-economic conditions (Roy et al., 2008) also vary from country to country and treatment options are not equally available in all the affected countries. Thus permissible maximum contaminant level (MCL) of arsenic in drinking water varies across the affected countries as compiled by Choong et al. (2007) in Table 2. Moreover, in majority of membrane-based separation studies, simulated water instead of actually contaminated groundwater has been used in the backdrop of high sensitivities of membranes to feed water characteristics. Pal et al. (2007a) have shown that for large scale treatment, physico-chemical separation technique is possibly the best for the developing South-East Asian countries. For small-scale treatment, solar-driven membrane distillation (SDMD) could be an ideal technology option as almost 100% arsenic can be separated out from groundwater using the low grade solar energy

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Table 1
Relative removal efficiencies for As(V) by the major existing techniques.

Treatment process	Maximum removal, %
Alum precipitation process	90
Iron precipitation	95
Lime softening process (pH > 10.5)	90
Combined with iron (and manganese) removal	>90
Ion exchange (sulfate 50 ppm)	95
Activated alumina	95
Reverse osmosis, nanofiltration, electrodialysis	>95
Membrane distillation	>99.9%

Table 2
Maximum permissible contaminant level (MCL) of As set by different countries.

Countries/others	Permissible value (μg/L)
WHO/USPEA/European union	10
Germany	10
Australia	7
France	15
India, Bangladesh, Vietnam, Mexico	50
Malaysia	10–50

which is abundant in these affected countries, particularly during the crisis months of the dry season. Fouling which is the major disadvantage of a membrane-based separation process is almost absent here as there is little chance of clogging of the pores of the hydrophobic microfiltration membrane used in MD. Moreover, necessity of high transmembrane pressure of reverse osmosis is redundant in this SDMD. Using microporous membranes as a support for vapor–liquid interfaces at the entrance of the pores, SDMD can operate on the principle on vapor liquid equilibrium as a basis for molecule separation. In MD process, a hot aqueous feed solution is brought in contact with one side of a hydrophobic, microporous membrane. After the evaporation of volatile molecules, to be separated from the feed, at the hot feed side, transport of vapor through dry pores of hydrophobic membranes occurs due to a vapor pressure difference across the membrane, which is the driving force. As membrane material is water repellent, liquid water cannot enter the pores unless a hydrostatic pressure exceeding the liquid entry pressure of water is applied. In the absence of such a pressure differential between the two sides of the membrane, a liquid–vapor interface is formed on either side of the membrane pores and a vapor pressure difference can result between these two interfaces from a temperature difference that has to be maintained. Evaporation can take place on the hot interface producing vapor to be subsequently transported to the other relatively cold side through the pores. Transport of such vapor can take place following Knudsen model, Poiseuille model, transition-Knudsen model or pore diffusion model depending on the magnitude of Knudsen number (K_n) which is defined as the ratio (λ/d) of the mean free path (λ) of the transported molecules and the diameter of the pores (d). When $K_n > 1$, Knudsen model dominates and for $K_n < 0.01$, molecular diffusion model can better explain the transport process. Details of such models can be found in Schofield et al. (1987), Kimura et al. (1987) and Phattaranawik et al. (1998).

Membranes with pore sizes ranging from 0.01 μm to 1 μm should be generally used. MD can be compared with pressure-driven microfiltration, which is characterized by a membrane pore size between 0.05 μm and 2 μm and operating pressure above 2 bars. The main requirements for MD process are that the membrane should not be wetted and only vapor and noncondensable gases should be present within its pores. Such hydrophobic, microporous membranes made of polytetrafluoroethylene (PTFE), polypropylene (PP), polyethylene (PE), and polyvinylidenefluoride (PVDF) are now commercially available.

Though solar-driven membrane distillation (SDMD) could be an ideal technology solution to groundwater arsenic contamination problem relatively little attention has been drawn to this technique and membrane distillation despite being known since the late 1960s mainly remained confined within desalination for the production of ultra pure water from saline water. However, in some recent studies (Macedonio and Drioli, 2008; Qu et al., 2009) experiments have been conducted utilizing laboratory-scale direct contact membrane distillation (DCMD) modules with tubular geometries for arsenic separation. These studies report high removal efficiencies, especially when compared to pressure-driven membrane processes like reverse osmosis (RO) or nanofiltration (NF). Qu et al. (2009) found that the concentration of arsenic in product water could be brought down to 10 μg/L with feed water arsenic concentrations as high as 40 mg/L and 2000 mg/L for As(III) and As(V), respectively. Macedonio and Drioli (2008) reported similar results, although the feed water arsenic concentration was much lower in their studies. Islam (2005) studied arsenic separation by air gap membrane distillation (AGMD) using a small-scale commercial prototype MD module and reports successful treatment of arsenic-contaminated water. However, in the reported investigations, flux still remains low which stands in the way of viability of MD process in arsenic separation and studies on SDMD in arsenic separation are highly inadequate to build up scale up confidence.

The objective of the present work was to study a solar-driven DCMD module using flat plate geometry (Fig. 1) in a cross flow mode for arsenic removal from contaminated groundwater.

2. Materials and methods

2.1. Experimental set up

Fig. 2 shows the solar-driven membrane distillation set up used for carrying out the DCMD tests. The solar-driven membrane distillation set up consisted of four major components – a direct contact membrane distillation (MD) module, a solar energy collector and two thermostatic baths. The system works in two loops, namely the solar loop and the arsenic removal loop.

2.1.1. Solar heating loop

An evacuated glass tube type solar energy collector (Bhaskar Solar, India) was used to heat up the feed (arsenic-contaminated water). The schematic diagram of

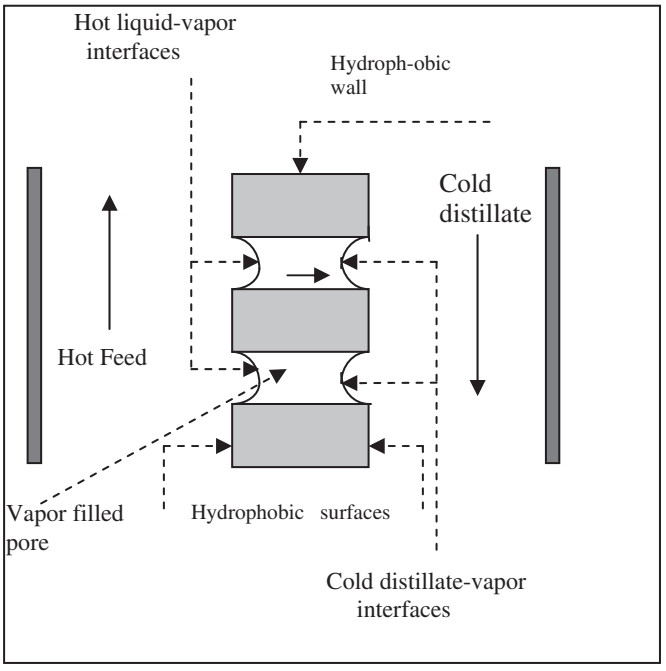

Fig. 1. DCMD configuration.