



## Solar-driven flash vaporization membrane distillation for arsenic removal from groundwater: Experimental investigation and analysis of performance parameters



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### ARTICLE INFO

#### Article history:

Received 27 July 2015

Received in revised form 16 October 2015

Accepted 17 October 2015

Available online 10 November 2015

#### Keywords:

Flash vaporization membrane distillation

Cross flow module

Solar energy

Arsenic removal

Performance parameter

### ABSTRACT

Experimental studies on removal of arsenic from contaminated groundwater were investigated using solar energy for phase change in a new flash vaporization membrane distillation (FVMD) module. The module was fitted with the composite flat-sheet polytetrafluoroethylene (PTFE) membrane. The highest flux (52.94 kg/m<sup>2</sup> h) with more than 99% arsenic rejection was achieved with this cross-flow FVMD module working in the direct contact membrane distillation (DCMD) configuration. In order to evaluate the performance of solar-driven membrane distillation process, it has been analyzed the variation of the flux and the arsenic rejection with the feed and distillate temperatures, the distillate flow rate, the arsenic concentration in the feed, and the operating hours. The study also shows the effects of the performance parameters of the FVMD module and the solar collector with feed temperature. Arsenic removal efficiency and flux at enhanced temperature of around 70 °C almost remained constant with the arsenic concentration variation and after 40 h of operation, whereas the significant effect on flux was noticed during variation of the distillate flow rate, the feed and distillate temperatures. The present investigation helps one to arrive at a better system configuration that can be effectively implemented in the arsenic affected areas.

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### 1. Introduction

Arsenic contamination in groundwater is a major threat to the people living especially in Bengal delta plain of Bangladesh and West Bengal (India), where reported arsenic concentration (upto 1000 ppb) is much above the WHO (World Health Organization) permissible limit (10 ppb in drinking water) [1]. Because of a serious consequence of arsenic carcinogenicity and genotoxicity, WHO forcefully reduced the Maximum Contaminant Level (MCL) of arsenic in drinking water to 10 µg/L from 50 µg/L in 1993. Over the last few decades, various treatment options like chemical precipitation [2], coagulation/flocculation [3,4], adsorption [5,6], ion exchange [7], and membrane technology, like nanofiltration (NF) [8,9], reverse osmosis (RO) [10,11], and membrane distillation (MD) [1,12–14] have been established for arsenic removal from contaminated water. Removal efficiency of different processes as reported in the literature [10,12] is less than 95% for first four

methods; and more than 95% for reverse osmosis, nanofiltration, and electro dialysis whereas it is greater than 99% by membrane distillation [1,12–20].

Membrane distillation (MD) is a relatively recent development and is a thermally driven non-isothermal process in which water vapor diffuses through a micro-porous hydrophobic membrane due to a vapor pressure driving force provided by temperature difference across the membrane. The diffusing vapor then condenses at the permeate membrane interface. Major benefits of MD when compared with nanofiltration, reverse osmosis and electro dialysis are: (a) low operating temperature (30–90 °C) that enable to use low grade energy, such as solar and geothermal energy, and industrial waste heat; (b) low operating pressure (close to atmospheric pressure) increases process safety and decreases equipment cost; (c) the possibility of membrane fouling is much less; (d) chemical pretreatment of feed water is not required; (e) no expert maintenance is required; (f) more than 99% rejection of non-volatile solutes.

The main limitations of MD process are: (a) the main limitation of MD process arises from the hydrophobic nature of the membrane. Pores of the hydrophobic membrane are wetted by the feed above a given pressure, which is called the liquid entry

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**Symbols**

$A_s$	solar collector area ( $\text{m}^2$ )
$c_p$	fluid specific heat ( $\text{J kg}^{-1} \text{K}^{-1}$ )
$\Delta H_v$	heat of vaporization of water ( $\text{J kg}^{-1}$ )
$I_s$	global solar irradiation ( $\text{W m}^{-2}$ )
$m_c$	mass flow rate of feed through the collector $m_c$ ( $\text{kg s}^{-1}$ )
$m_h$	mass flow rate of feed through the membrane module $m_h$ ( $\text{kg s}^{-1}$ )
$N$	water flux ( $\text{kg m}^{-2} \text{s}^{-1}$ )
$p_{im}^o$	interfacial vapor pressure of pure water $p_{im}^o$ (Pa)
$Q$	heat flux ( $\text{W m}^{-2}$ )
$T_{ci}$	feed temperature at the solar collector inlet (K)
$T_{co}$	feed temperature at the solar collector outlet (K)
$T_{fi}$	feed temperature at the module inlet (K)
$T_{fo}$	feed temperature at the module outlet (K)

## Greek

$\eta$  solar collector efficiency

## Subscripts

f	feed
i	feed or permeate
m	membrane
p	permeate
mv	membrane pores related to water vapor

pressure (LEP) [19]. (b) The presence of organic solute in aqueous solution reduces the LEP value. If the concentration of the organic solute increases, the LEP decreases rapidly that results spontaneous wetting of the membrane occurs. Therefore, MD can only be applied to a narrow range of concentrations [20]. (c) To prevent

wetting of the hydrophobic microporous membrane, the process solutions must be aqueous and sufficiently dilute [19,20]. (d) More than 99% solute rejection of volatile solute is not possible if the feed aqueous solution contains volatile components other than water because the volatile components along with water vapor pass through non-selective hydrophobic membrane.

Though MD can be a potential option for arsenic removal from contaminated water to meet the maximum contaminant level of 10 ppb as set by WHO, only in a very few lab scale investigations [1,12–14] have been performed for arsenic removal from arsenic contaminated water. Qu et al. [13] achieved a permeate flux of  $20.90 \text{ kg/m}^2 \text{ h}$  at  $70^\circ\text{C}$  and adjusted pH of 5.0 using self-made poly(vinylidene fluoride) (PVDF) capillary membranes by direct contact membrane distillation (DCMD). Macedonio and Drioli [12] recorded a still lower distillate flux at maximum temperature of  $35^\circ\text{C}$  taking the synthetic aqueous feed of arsenic(V) and arsenic(III) of various pH (pH at around 5, 7, and 9) using a hollow fiber polypropylene DCMD membrane module. Criscuoli et al. [1] recorded maximum flux  $12.4 \text{ kg/m}^2 \text{ h}$  at low temperature  $40^\circ\text{C}$  and fixed vacuum pressure 10 mbar carrying out on a commercial flat membrane module using polypropylene and PVDF membranes by vacuum membrane distillation (VMD). In the above three MD experimental investigations [1,12,13], the common observations are: (a) the feed was synthetic aqueous arsenic solution and heated by thermostat; and (b) the flux resulted is low. Reported studies on a stand-alone solar-driven membrane distillation in the literature [15–18,21] have usually involved in desalination. In the most recent study [14], potentiality of solar-driven DCMD has been demonstrated in producing more than 99 percent arsenic-free water from arsenic contaminated groundwater with reasonably high flux ( $52.94 \text{ kg/m}^2 \text{ h}$ ). The study [14] has mainly focused on the modeling and the validation of the developed model through experimental investigations. But analysis of the performance parameters, and effects of some major operating variables (such as the feed and distillate temperatures, the distillate flow rate, the

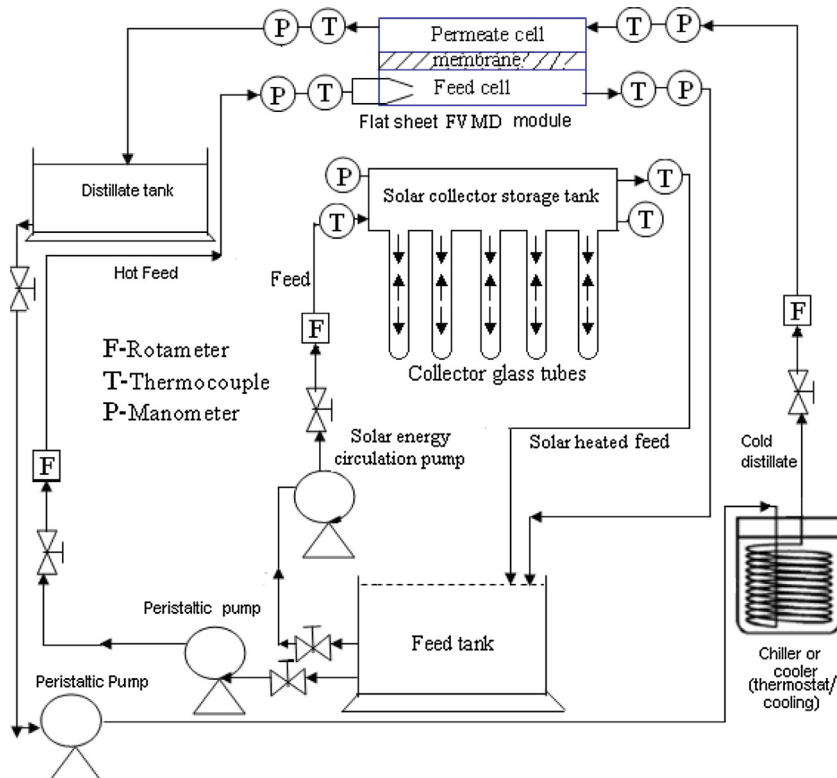


Fig. 1. Flow diagram of experimental set up for solar-driven FVMD process [14].

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