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Experimental Analysis of Process Parameters on Energy Consumption for Nitrate Removal from Water Using VMD

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Abstract—*The need for fresh drinking water is increasing rapidly but on the other hand it is also becoming more limited. Even the ionic contamination of groundwater is increasing alarmingly. In various drinking sources, a number of inorganic ions were found which are in very harmful concentration like nitrate, fluoride, sulphate ion etc. Nitrate comes from numerous natural and man-made sources, including wastewater, agricultural and urban runoff. It becomes very difficult to remove nitrates from water as it is chemically non-reactive in dilute aqueous solutions. To check the problems and counter this, a 0.22 µm hydrophobic membrane made up of poly tetra fluoro ethylene was used in the VMD setup which consisted of a membrane holder assembly and a vacuum pump on the downstream side. In the present study, The effect of process parameters like nitrate concentration, feed side bulk temperature, Permeate flux and feed flow rate on specific energy consumption and nitrate removal from water has been investigated. As a result we found that, the effect of feed concentration and feed flow rate on nitrate rejection were in range of 200 mg/l to 1500 mg/l, and of 97-100 %respectively. The rejection remained almost constant with change in feed flow rate from 1- 2 lpm. The variation in temperature from 40-60º has shown negligible effect on nitrate rejection. The permeate flux has increased from 15-60 kg/m^{2}h with increase in temperature from 40ºC to 60ºC. Similarly, the increase in feed flow rate from 0.75-1.5 lpm has also shown increase in the permeate flux from 40-60 Kg/m^{2}h.*

1. INTRODUCTION

The most important commodity is drinking water 'The elixir of life', which is very scarce in today's world. The need for fresh drinking water is increasing rapidly but on the other hand it is also becoming more limited. Even the ionic contamination of groundwater has been increasing alarmingly. In various drinking sources, a number of inorganic ions were found which are in very harmful concentration like nitrate, fluoride, sulphate ion etc. Nitrate comes from numerous natural and man-made sources, including wastewater, agricultural and urban runoff. It becomes very difficult to remove nitrates from water as it is chemically non reactive in dilute aqueous solutions. Rajasthan is considered as major nitrate affected state in the country [Jain Jyoti, 2014]. Nitrate levels in drinking water have caused a great concern particularly in arid and semiarid climates. Nearly the whole world is suffering from the problem of high nitrates with concentration ranging from 40 to 1200 mg/l. World Health Organisation (WHO) proposed the internationally accepted standards and guidelines, regarding the maximum allowed levels of nitrate as 50 mg/*l* whereas BIS (IS-1050:1991) prescribed value for nitrate in drinking water is 45 mg/*l* [Richardson S. D. (2003), S. Aslan and Turkman (2006)]. In addition, there are some other international agencies who publish exactly similar drinking quality and environmental standards in whole world for the analysis of inorganic anions in drinking water. In order to protect human health from the adverse effects of nitrate, the European Union limits the concentration of nitrate in public drinking water and supplies to a maximum of 50 mg/l (EEC, 1991). On the other hand, the U.S. Environmental Protection Agency (EPA) has established a maximum contaminant level (MCL) in drinking water of 10 mg/L as nitrate–N to protect infants from methemoglobinaemia (Ward et al., 2005).

The main objectives of the work are to study the effect of different process parameters (Feed concentration, feed flow rate and feed temperature) on the permeate flux and specific energy consumption and rejection of nitrate ion from water by Vacuum Membrane Distillation and also to validate the data from existing VMD models.

2. MATERIALS AND METHODS

The 0.22 µm hydrophobic membrane made up of poly tetra fluoro ethylene (Millipore make) was used in the VMD setup which consisted of a membrane holder assembly and a vacuum pump on the downstream side. The feed flow rate was measured with rotameter and temperatures were measured with thermocouples provided in the setup. The analysis of nitrate ion was done by using UV Spectrophotometric method.

3. RESULTS AND DISCUSSION

The effect of process parameters like nitrate concentration, feed side bulk temperature and feed flow rate on specific energy consumption and nitrate removal from water has been investigated. Permeate flux were also measured in all different conditions. The effect of feed concentration and feed flow rate on nitrate rejection is shown in Fig. 1. In the feed concentration range of 200 mg/l to 1500 mg/l, rejection was found in the range of 97-100 %. The rejection remained almost constant with change in feed flow rate from 1- 2 lpm.

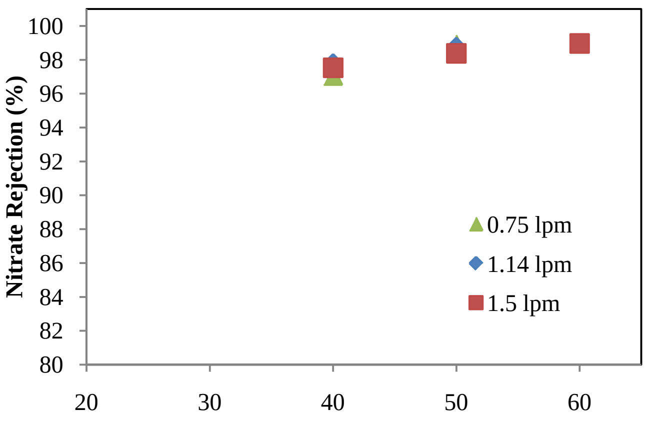

Fig. 1: Effect of nitrate concentration and feed flow rate on nitrate rejection.

As shown in Fig. 2, the variation in temperature from 40-60º has shown negligible effect on nitrate rejection. The effect of feed bulk temperature and feed flow rate on permeate flux are shown in Fig. 3. The permeate flux has increased from 15-60 kg/m^2h with increase in temperature from 40ºC to 60ºC. Similarly, the increase in feed flow rate from 0.75-1.5 lpm has also shown increase in the permeate flux from 40-60 Kg/m^2h.

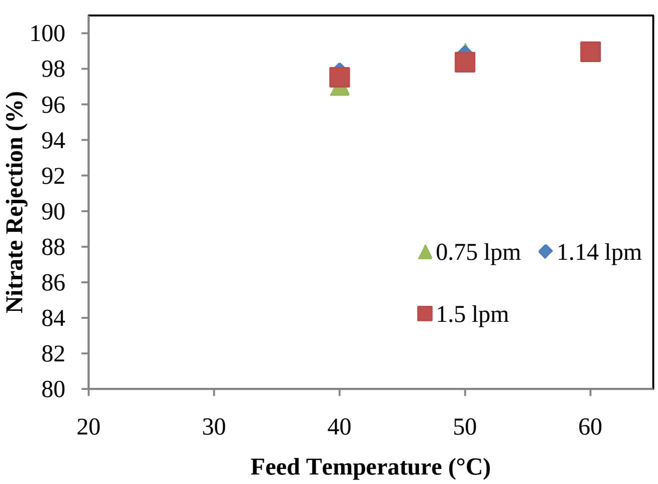

Fig. 2: Effect of feed bulk temperature on nitrate rejection.

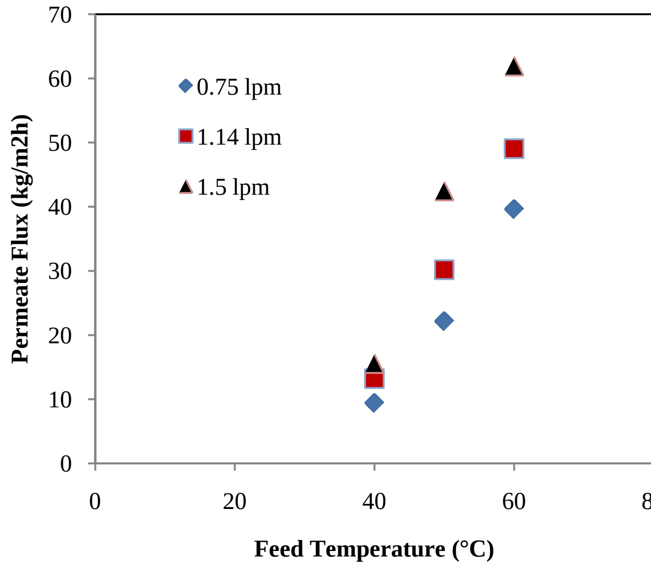

Fig. 3: Effect of Feed flow rate and feed temperature on energy consumption.

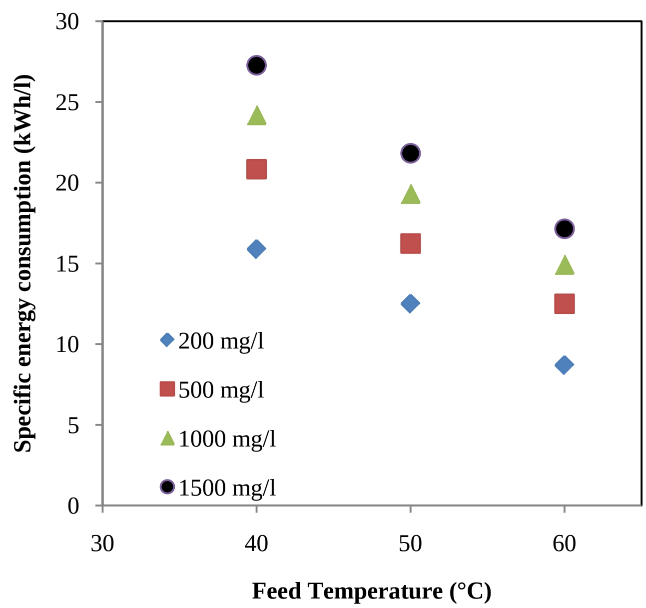

Fig. 4: Effect of feed temperature and nitrate concentration on energy consumption.

The energy consumption for VMD operation is shown in Fig. 4 & 5. The energy consumption has increased from 15 to 27 kWh/l on increase in feed concentration. However, the increase in temperature and feed flow rate shown decrease in energy consumption per liter of permeate collected.

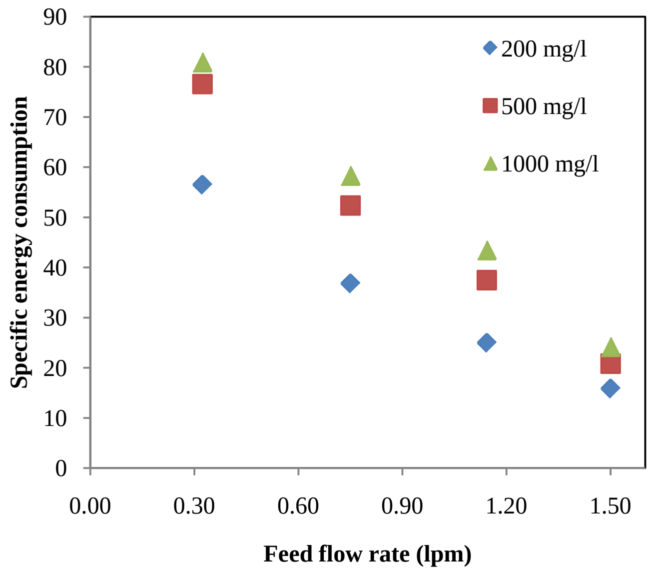

Fig. 5. Effect of feed flow rate on energy consumption.

4. MODEL VALIDATION OF VACUUM MEMBRANE DISTILLATION

4.1 Mass Transfer

The mechanism of mass transfer occurs in two steps, one across the boundary layer in the feed side and other through the membrane pores. The mass transfer through the membrane may occur by the three different mechanisms, Knudsen diffusion, molecular diffusion, viscous (Poiseuille) flow and surface diffusion. When the ratio of pore radius and mean free path is less than 0.05, i.e. (r/λ) < 0.05, Knudsen Diffusion model dominates.

The following assumptions have been considered for the Knudsen diffusion model used:

a) The mass transfer process is governed by the mechanism of Knudsen diffusion and contribution of the Poiseuille flow has been neglected.
b) The formation of thermal boundary layer on the permeate side is considered to be negligible due to the presence of vacuum.
c) The permeate side bulk temperature and membrane side temperature is equal.
d) The process has been studied at steady state conditions.
e) The flow of feed and permeate on the feed and permeate side respectively, is laminar flow, and therefore the heat transfer coefficient calculated corresponds to laminar flow.
f) The vapour pressure of feed on the membrane surface is given by the Henry's law.
g) The values of membrane properties such as pore diameter, porosity and thickness have been assumed correctly mentioned by the manufacturer.

Equations used in calculating model flux are:

$$N = \frac{\varepsilon}{\zeta \delta R T_{fm}} \left[\left\{ \frac{1-y_a}{D_{AB}} + \frac{3}{4d}\sqrt{\frac{2\pi M}{R T_{fm}}} \right\}^{-1} + \frac{r^2 P_{fm} M}{8\eta} \right] \left(P_{fm} - P_{pm}\right) \quad (4.1)$$

$$P_{fm} = x_i \gamma_i P_i^{sat} \quad (4.2)$$

$$\gamma_i = 1 - 0.5\,x - 10x^2 \quad (4.3)$$

Where, ε=Membrane Porosity (%)
ζ=Tortuosity
δ=Membrane Thickness (m)
R=Gas constant=8314 m^3Pa/mol K
T_{fm}=Temperature of feed on membrane surface(K)
D_{AB}=Knudsen Diffusion Coefficient (m^2/s)
d=Pore diameter (m)
M=Molecular weight (Kg)
r=Pore radius (m)
P_{fm}=Pressure on feed side of the membrane (Pa)
P_{pm}=Pressure on the permeate side of the membrane (Pa).

The model validation for permeate flux for VMD setup is shown in Fig. 6.

Table 1: Model validation for permeate flux on VMD.

[Membrane Area: 0.00212m^2, Feed flow rate 0.343 lpm, Feed Temperature: 40° C, Vacuum pressure: 10 kPa.]

Feed Concentration (mg/l)	Model Flux (Kg/m^2h)	Experimental Flux (Kg/m^2h)
200	4.1941	5.43
500	4.1414	5.38
1000	4.0670	5.31
1500	4.0215	5.25

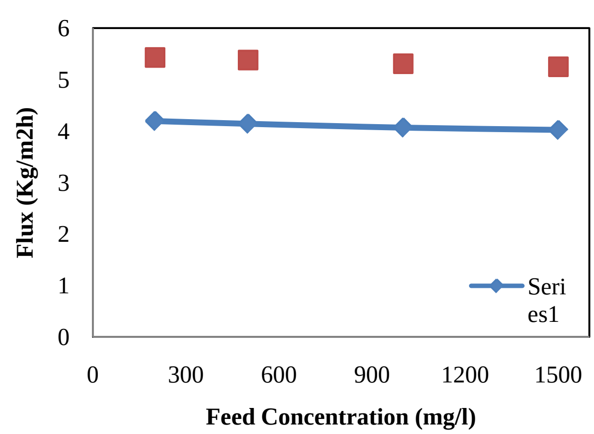

Fig. 6: Model validation for permeate flux in VMD

Table 2: Model validation for permeate flux on VMD

[Membrane Area: 0.00212m^2, Feed flow rate 0.343 lpm, Feed Temperature: 50° C, Vacuum pressure: 10 kPa.]

Feed Concentration (mg/l)	Model Flux (Kg/m^{2}h)	Experimental Flux (Kg/m^{2}h)
200	10.1132	10.87
500	10.0652	10.81
1000	10.0173	10.75
1500	9.9693	10.61

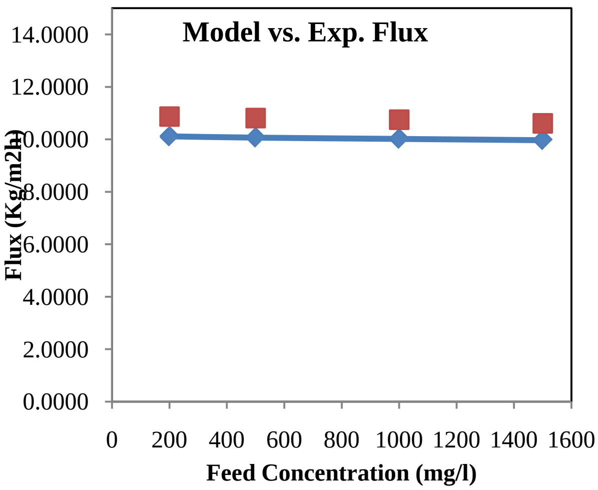

Fig. 7: Model validation for permeate flux in VMD

Table 3: Model validation for permeate flux on VMD

[Membrane Area: 0.00212m^2, Feed flow rate 0.343 lpm, Feed Temperature: 60° C, Vacuum pressure: 10 kPa.]

Feed Concentration (mg/l)	Model Flux (Kg/m^{2}h)	Experimental Flux (Kg/m^{2}h)
200	37.0200	34.03
500	37.0093	33.91
1000	36.9915	33.82
1500	36.9736	33.77

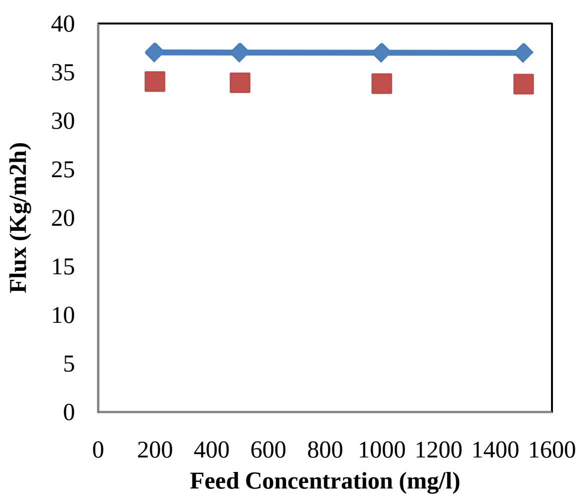

Fig. 8: Model validation for permeate flux in VMD

Model has shown relatively good fitting with data at feed side bulk temperature of 50°C. At temperature lower than 50°C and also at higher than that, larger deviation between model prediction data and experimental data has been obtained.

5. CONCLUSIONS

The following conclusions can be made on the basis of my present work:

When the nitrate concentration in feed was increased from 200 to 1500 mg/*l*, a negligible effect on flux was observed i.e. from 28.13 to 30.02 kg/m^{2}h at constant parameters of feed temperature 50° C, feed velocity 1.343 lpm and an increase in specific energy consumption was observed from 56.52 to 92.31 kWh/*l* at constant parameters of feed temperature 40° C and 0.323 lpm, which may be because of the reduction in activity coefficient of water and nitrate rejection was observed in between 96.39 % and 99.97 %.

When there was an increase in feed flow rate from 0.323 lpm to 1.5 lpm, the permeate flux was also increased from 26.68 to 65.09 kg/m^{2}h at constant feed temperature of 60°C and feed concentration of 200 mg/*l* and a decrease of around 65% in specific energy consumption was observed which may be because of the increase in feed circulation velocity which minimises the thermal boundary layer thickness and maximises the mass transfer coefficient. The nitrate rejection varied from 99.65 % to 99.75%.

With an increase in a feed temperature from 40°C to 60° C, an exponential increase in permeate flux was observed from 3 to 16 Kg/m^{2}h at constant feed flow rate of 0.323 lpm and feed concentration of 500 mg/*l* while from 13 to 62 Kg/m^{2}h at constant feed flow rate of 1.5 lpm and feed concentration of 500 mg/*l* and a decrease in specific energy consumption was observed from 15.87 to 27.27 kWh/*l* at constant feed flow rate of 1.5 lpm and feed side bulk temperature of 40° C. This change is because of the decrease in temperature polarization and due to maximization of mass transfer coefficient across the membrane.

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