Feasibility and parametric study of a thermal-energy driven Reverse Osmosis system for Water Treatment in India

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Abstract. Reverse osmosis (RO) is the choice in most cases for its clean and trouble free operation in spite of the use of high-grade electric energy. The challenge with this process is increasing electricity cost and rejection of brine. We have modelled a new system which is capable to run RO module using low-grade thermal energy instead. A steam source drives a cylinder piston arrangement and this kinetic energy is transferred to another cylinder piston through a linkage mechanism. This energy finally is used to pressurize the saline water towards RO membrane. Steam may be generated from Solar or from a biomass boiler as available in rural areas of India. The results found so far are encouraging and indicates product water cost to be around $ 1.5 per m$^3$ by use of small design. Such designs may give a wide range of units capable of producing from few m$^3$ to hundreds of m$^3$ per day.

Keywords: Reverse osmosis, Rankine cycle, Recovery ratio, Gain output ratio, Solar, Biomass

1. Introduction
Ground water quality is a big concern in many countries including India. Rapid urbanization and industrialization at one end has increased contamination level because of waste disposal and population growth at the other end require large amount of fresh water supply. A vast majority of groundwater quality problems present today are caused by contamination and by over-exploitation, or by combination of both. Treatment of brackish ground water is the solution for inland areas which are away from coasts and lack fresh water sources. Due to lack of adequate infrastructure and resources the waste is not properly collected, treated and disposed; leading to accumulation and infiltration causing groundwater contamination. The problem is more severe in and around large cities as also various clusters of industries. In many of these areas groundwater is the only source of drinking water, thus a large population is exposed to risk of consuming contaminated water.

Urbanization in India has increased from 10.84% in 1901 to 28.5% in 2001. According to the Census figure of 2001, the number of class I cities and class II towns was around 900. As per the latest estimate of Central Pollution Control Board, about 29,000 million litre/day of wastewater generated from class-I cities and class-II towns out of which about 45% (about 13000 MLD) is generated from 35 metro-cities alone [1]. The collection system exists for only about 30% of the wastewater through sewer line and treatment capacity exists for about 7000 million litre/day. Thus, there is a large gap between generation, collection and treatment of wastewater [2]. A large part of un-collected, un-treated wastewater finds its way to either nearby surface water body or accumulated in the city itself forming cesspools. A vast majority of groundwater quality problems are caused by contamination, over-exploitation, or combination of the two [3]. Most groundwater quality problems are difficult to detect & hard to resolve [4]. The solutions are usually very expensive, time consuming & not always effective. An alarming picture is beginning to emerge in many parts of our country. Groundwater quality is slowly but surely declining everywhere. Groundwater pollution is intrinsically difficult to detect, since problem may well be concealed below the surface & monitoring is costly, time consuming & somewhat hit-or-miss by nature [5].
This case study is based upon the data presented in the environmental profiles of metropolitan cities and Problem areas identified by Central pollution control board (CPCB) India and their groundwater quality status (CPCB 2007, 2012). We have selected 10 problematic states with different level of contamination as presented in Table 1 and Figure 1 [6].

Calculation of Osmotic pressure is done putting contamination values in classical Van’t Hoff expression [7]

\[ P_{osm} = cRT, \quad c = \sum v_i \alpha_i \frac{n_i}{V} \]

Where \( \frac{n_i}{V} \) is the molar concentration (Kmol/m\(^3\)) of each species, present and \( v_i \) is the number of ions available of each species. \( \alpha_i \) is the osmotic coefficient of each species, which is generally close to unity [8]. State wise ground water salinity level and corresponding osmotic pressure is given in Figure 2.

Table 1. Major salinity and contamination contributing species present in sample water in selected states and locations. All contamination are in ppm (part per million)

| Location / Contamination | TDS  | Ca  | Mg  | Na  | Cl  | S   | N   | Fe  | \( P_{osm} \) |
|--------------------------|------|-----|-----|-----|-----|-----|-----|-----|--------------|
| Rajsthan (Pali)          | 4492 | 140 | 246 | 1200| 1988| 460 | 29  | 3.40|             |
| Tamil Nadu (Vello)       | 3844 | 800 | 820 | 530 | 1400| 140 | 35  | 3.03|             |
| Madhya Pradesh (Gwalior)| 3340 | 240 | 180 | 450 | 890 | 630 | 450 | 2.71|             |
| Himachal Pradesh (Manali)| 2434 | 0  | 160 | 688 | 1076| 667 | 49  | 2.25|             |
| Orissa (Puri)            | 2680 | 380 | 267 | 412 | 826 | 175 | 54  | 1.75|             |
| Gujarat (Vapi)           | 1880 | 372 | 150 | 81  | 393 | 323 | 70  | 1.11|             |
| Uttar Pradesh (Saharanpur)| 1500 | 400 | 78  | 258 | 570 | 27  | 1   | 1.02|             |
| Andhra Pradesh (Hyderabad)| 1550 | 248 | 119 | 477 | 198 | 21  | 450 | 0.99|             |
| Kerala (Cochin)          | 525  | 68  | 15  | 79  | 129 | 27  | 16  | 108 | 0.33         |
| West Bengal (Durgapur)   | 550  | 94  | 37  |     |     |     |     |     | 0.12         |
2. Methodology
A steam-driven system has been designed in which a power piston actuates a water piston via a coupling mechanism, pressurizing saline water through a RO membrane in batches, and achieving high recovery of freshwater [9]. The steam may be generated by solar panels, biomass boilers, or as an industrial byproduct. The mechanism must provide the requisite mechanical advantage to couple the two pistons. The mechanical advantage gained by the crank mechanism is utilized to work against osmotic pressure of saline water. The linkage mechanism is so designed that net drive remains almost steady irrespective of continuously increasing osmotic pressure during compression of saline water. Mechanical advantage leads the process to deliver a high recovery ratio and rejection proportion is only about 30%. A novel mechanism has been designed for low cost, and a steam-jacketed arrangement has been designed for isothermal expansion and improved thermodynamic efficiency. For more details article “A cost-
effective steam-driven RO plant for brackish groundwater, Desalination 385 (2016) 167–177” may be referred. Cross-section view of the system is shown in Figure 3.

3. Results
Considering energy requirements to run prescribed RO system in line with the osmotic pressure a theoretical model has been developed and consumption of steam was evaluated. For the sake of uniformity in comparison of results, the steam pressure at the inlet of lower piston was kept 9 bar throughout the analysis. The results found are presented in Table 2 and Figure 4.
Table 2. Cycle time to complete one batch and corresponding steam consumption at different locations

| Location/State                      | Cycle time (s) | Throughput (L/min) | Output (L/h) | Output (m³/day) | Steam consumption (kg/h) at 9 bar | Specific steam consumption |
|-------------------------------------|----------------|--------------------|--------------|----------------|----------------------------------|---------------------------|
| Rajasthan (Pali)                    | 75             | 2.25               | 135          | 3.24           | 2.17                             | 62.21                     |
| Tamil Nadu (Vellore)                | 65             | 2.6                | 156          | 3.74           | 2.51                             | 62.15                     |
| Madhya Pradesh (Gwalior)            | 59             | 2.86               | 171.6        | 4.12           | 2.76                             | 62.17                     |
| Himachal Pradesh (Manali)           | 98             | 1.73               | 103.8        | 2.49           | 1.35                             | 76.89                     |
| Orissa (Puri)                       | 69             | 2.46               | 147.6        | 3.54           | 1.92                             | 76.88                     |
| Gujarat (Vapi)                      | 55             | 3.08               | 184.8        | 4.44           | 2.4                              | 77.00                     |
| Uttar Pradesh (Saharanpur)          | 54             | 3.15               | 189          | 4.54           | 2.46                             | 76.83                     |
| Andhra Pradesh (Hyderabad)          | 53             | 3.18               | 190.8        | 4.58           | 2.47                             | 77.25                     |
| Kerala (Cochin)                     | 46             | 3.68               | 220.8        | 5.30           | 2.87                             | 76.93                     |
| West Bengal (Durgapur)              | 66             | 2.58               | 154.8        | 3.72           | 1.57                             | 98.60                     |

The results found indicate feasibility and applicability of the proposed steam driven system as a solution to variety of contaminated water throughout the country. Figure 5 presents gain output ratio and quantity of water produced per day. The GOR varies from 60 to 100 and clean water production from 2.5 m³/day to 5.3 m³/day. The hourly requirement of steam varies from 1.5 kg to 3 kg and may be produced using parabolic trough collector and/ or biomass boilers.
4. Conclusion
The present study clearly indicates that there are possibilities to use thermal energy for water treatment by direct coupling of the steam Rankine cycle to a batch-RO system. High gain output ratio confirms less steam consumption per cycle or batch. Modelling suggests that the specific steam consumption is small and gain output ratio reaches up to 100. A wide range of steam driven RO mechanisms may be designed as per the requirement and availability of steam pressure. The required steam may easily be produced using solar collectors, especially in India where solar energy has lot of thermal potential. In cloudy weather or rainy season biomass boilers are the option. The recovery ratio is found above 0.7, irrespective of size of unit due to its kinematic design. A demonstration unit is shortly proposed to be built in India, and experimental results are expected soon. The main features of this proposed thermal-energy driven RO module are low running cost, high recovery ratio and gain output ratio. Here we are doing a case study for providing clean water in different problematic areas in India using this technology. Different designs of the system may be created to fit with input water condition and output requirements. The proposed design here delivers 2.5 m$^3$/day to 5.3 m$^3$/day of clean water with hourly steam consumption of 2.2 kg to 2.7 kg/hr. Expenses incurred are mainly maintenance cost of the unit which is not much.

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