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A cost-effective steam-driven RO plant for brackish groundwater

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HIGHLIGHTS

- Design study of a steam Rankine cycle with isothermal expansion coupled to batch-RO
- New compact coupling arrangement for cost-effective construction
- Detailed heat transfer and cost calculations
- GOR of 69–162 is obtainable, with specific thermal energy consumption of 4–6 kWh/m^3
- Total water cost 71 Indian Rupees/m^3 for a biomass-powered plant of 7 m^3/day output.

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ABSTRACT

Desalination is a costly means of providing freshwater. Most desalination plants use either reverse osmosis (RO) or thermal distillation. Both processes have drawbacks: RO is efficient but uses expensive electrical energy; thermal distillation is inefficient but uses less expensive thermal energy. This work aims to provide an efficient RO plant that uses thermal energy. A steam-Rankine cycle has been designed to drive mechanically a batch-RO system that achieves high recovery, without the high energy penalty typically incurred in a continuous-RO system. The steam may be generated by solar panels, biomass boilers, or as an industrial by-product. A novel mechanical arrangement has been designed for low cost, and a steam-jacketed arrangement has been designed for isothermal expansion and improved thermodynamic efficiency. Based on detailed heat transfer and cost calculations, a gain output ratio of 69–162 is predicted, enabling water to be treated at a cost of 71 Indian Rupees/m^3 at small scale. Costs will reduce with scale-up. Plants may be designed for a wide range of outputs, from 5 m^3/day, up to commercial versions producing 300 m^3/day of clean water from brackish groundwater.

Symbol	Unit	Description
A_{mem}	m^2	Area of RO membrane
c	kmol/m^3	Molar concentration
Cc	INR	Capital cost (Indian Rupees)
C_{pf}	kJ/kg K	Specific heat of water
C_{pg}	kJ/kg K	Specific heat of steam
d_p	m	Diameter of power piston
d_w	m	Diameter of water piston
E	kJ	Energy
F_{g12}		Grey body factor
h	W/m^2 K	Convective heat transfer coefficient
i		Interest rate
INR		Indian Rupee
L_p	m	Length of power stroke
L_w	m	Length of water stroke
MA		Mechanical advantage
n	years	Life span of machine

(*continued*)

Symbol	Unit	Description
P_{net}	bar	Net driving pressure
P_{osmf}	bar	Osmotic pressure of feed water
Q	litres/s	Flow rate of treated water
q_{in}	kJ	Energy input
q_{out}	kJ	Energy output
R	INR	Repayment instalment
R_p	m	Length of power side crank
R_w	m	Length of water side crank
s	m/s Pa	Permeability
T_c	°C	Condenser temperature
T_h	°C	Input steam temperature
V	m^3	Volume
X_p	m	Movement of power piston from cylinder end
X_w	m	Movement of water piston from cylinder end
σ	W/m^2 K^4	Stefan–Boltzmann constant
ε_1		Emissivity of wall
ε_2		Emissivity of steam
α_p	degree	Crank angle of power side crank from horizontal
α_w	degree	Crank angle of water side crank from horizontal

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(*continued*)

Symbol	Unit	Description
η		Efficiency
in.		Inch
GOR		Gain output ratio
RO		Reverse osmosis
ppm		Part per million

1. Introduction

Availability of usable water has emerged as one of the most crucial problems throughout the globe in recent times. Desalination using reverse osmosis or distillation is a potential solution, but economic and environmental constraints limit the use of such technologies [1]. In developing and underdeveloped countries, the situation is especially severe, as there is usually a pressing need for clean water. But high operating costs and energy demands typically rule out desalination [2]. A sustainable and non-polluting solution to energy and water shortages could only be provided by renewable energy systems [3].

In India, availability of water is reducing steadily as population grows. It is estimated that by 2020 India will become a water-stressed nation. Groundwater is the major source of water in the country, with 85% of the population dependent on it. While the urban water supply predominately uses surface and ground water, nearly 70% of drinking water requirements in rural India are met by ground water. The quality of ground water is variable and fails to meet the drinking water requirements in many areas. Frequently it is brackish or contaminated with excess fluoride, arsenic, iron, or microorganisms. In order to augment the available and accessible water, it is necessary to implement suitable treatment technologies to render such contaminated water potable [3].

Prompted by the growing crisis, a technology mission on Winning, Augmentation and Renovation (WAR) for water has been initiated

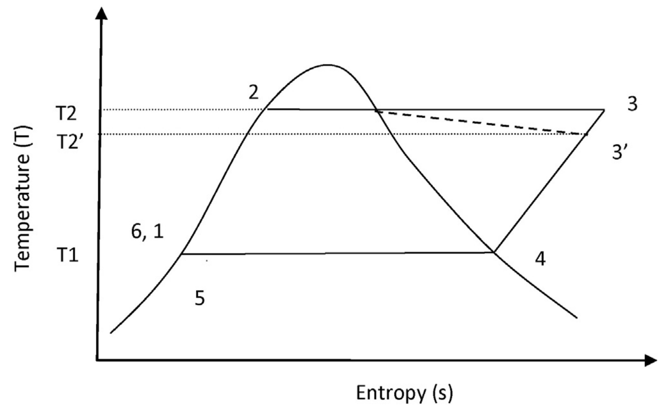

Fig. 2. *T*–s diagram of for the concept of the isothermal Rankine cycle.

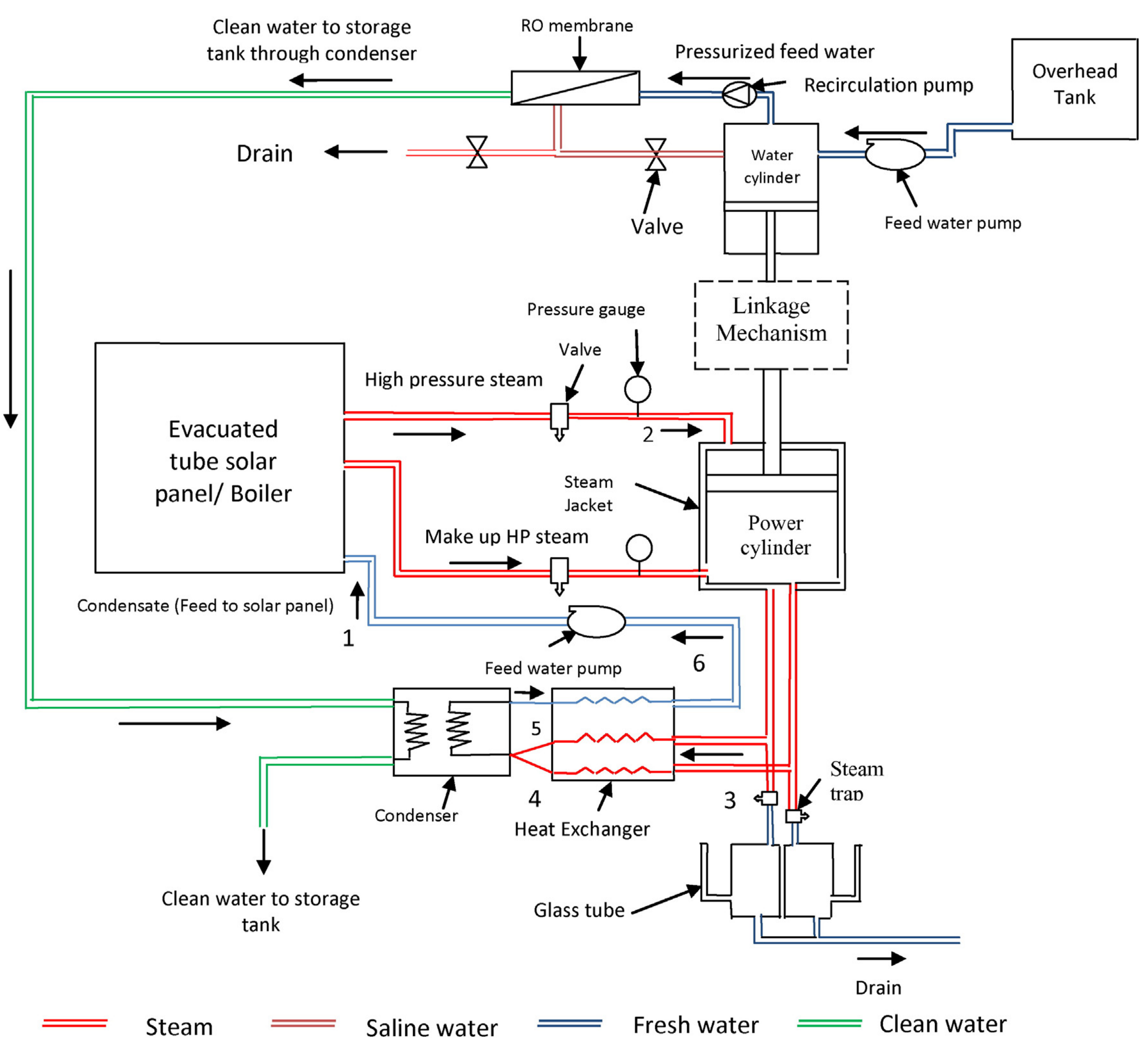

Fig. 1. Schematic view of the proposed steam-driven RO desalination plant with steam raised in a solar or biomass boiler.