A Novel Effluent Evaporation System for Industrial Applications

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Abstract

This paper presents the design, working principle, and field performance data of a novel effluent/brine evaporation system developed and commercialised by Quadsun solar solutions, India. The developed evaporator aims to address the challenges with existing evaporation technologies to reduce the land area requirement and heat consumption for brine evaporation while minimising the system operational cost. The developed evaporator system works on a data-driven control strategy where the effect of constraints on the evaporation rate is non-linear, and the objective function is set to minimise the electricity consumption of the system. The optimisation of the evaporation rate in the system control volume is achieved by variation of a) mass flow rate of brine, b) wind speed over the evaporation surface and c) contact area between brine and air. The system performance results are presented for an installed site located in Northern India for a testing period of 64 days. The results are further compared with a solar pond evaporation system using an analytical model. The result shows that the proposed evaporator has an average specific evaporation rate (SER) of 0.48 L/(h·m^2), which is 3.8 times higher compared to SER for the solar pond for the same meteorological conditions. Furthermore, the compactness of the proposed evaporator design results in significant land savings compared to the pond evaporation system.

Keywords: Evaporation, quadsun, brine management, solar pond, solar evaporation.

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1. INTRODUCTION

"Industrial effluent" is the wastewater generated by various industries as an undesirable by-product. The old practices to get rid of the effluent such as draining of effluent into natural water bodies, and deep injection into the ground has posed a severe threat to the ecosystem. The consequences of these unsustainable practices are severely reflected in a water-stressed country such as India. The major sources of water pollution are concentrated among highly water-intensive industries such as leather, textile, chemical, mining, steel, sugar, and paper industry (Murthy and Dasgupta, 1985). It is estimated that only 40 % of the industrial effluent is treated from these industries and rest 60 % of untreated effluents ended into the ecosystem (Rajaram and Das. 2008). The problem can be realized on a larger scale in certain regions such as Tiruppur (Tamil Nadu) and Kanpur (Uttar Pradesh) with a strong presence of the textile and leather industry. These regions are affected by wastewater to an extent that resulted in the drinking of groundwater and soil cultivation nearly impossible (Furn, 2004). The effect of untreated water has enabled the infusion of toxic elements such as Lead, Mercury, and Zinc in the domestic water supply.

Global research organisations and national governments put a lot of efforts to develop sustainable solutions to curb this problem. Solar heating and cooling program of IEA initiated task 62 in the year 2018 with a focus on the use of sustainable energy sources such as solar energy for industrial wastewater treatment (IEA SHC task 62, 2018). Realizing the severity of the problem, the government of India in the year 2015 issued a draft notification on the amendment of rules on standards for effluent from the textile industry. The amendment proposed to install zero liquid discharge (ZLD) systems in all textile processing units (Grönwall and Jonsson, 2017). ZLD is based on the reduce-reuse-recycle principle, which recycles the wastewater by chemical treatment and therefore allows the reuse of treated water (Lee et al., 2007). In a ZLD system achieved using reverse osmosis (R.O), wastewater is passed thru R.O membranes at high pressure. The permeate is recycled as input water, whereas R.O rejects (brine effluents) undergoes reject management cycles using mechanical evaporation and crystallization where salt is recovered from the brine effluents (Grönwall and Jonsson, 2017b).

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The R.O reject can be also be transported to the common effluent treatment plants set up by the local pollution control bodies or industrial clusters.

Achieving ZLD is an energy-intensive process and most of the energy is consumed in the electrical and thermal form. Thermal energy is usually consumed in the form of steam during evaporation in reject management systems which can employ a multi-effect evaporator, falling film evaporator, evaporation by spraying, etc. Reject management (evaporation and crystallization) can cost almost 50 % of the total ZLD cost. Moreover, the high operational cost forced the industries to bypass these systems to protect their profits and resulted in the use of unsustainable practices such as drainage of wastewater in rivers. However, strong enforcement by the state pollution control agencies results in closure of various industrial units due to the non-adherence to the treatment standards. This enforcement attracted a lot of interest to develop a cost-effective brine effluent management system to lower down the capital and operational cost (Narayanan, 2015). Therefore, this paper presents a novel wastewater evaporator for R.O rejects, developed and patented by Quadsun solar solutions in India (Quadsun, 2020). The design of the evaporator is intended to address the major challenge faced with existing evaporation techniques such as high temperature and pressure requirements, high electricity consumption, and high operational costs. The developed evaporator can be used in combination with solar heat, which can further lower down the operational costs. The working methodology of the evaporator is presented along with various integration schemes. Moreover, the field performance of the evaporator from one of the installed sites is also presented and compared with a solar pond evaporation system. The next section presents the overview of various technologies used for evaporation, followed by the proposed system description. Lastly, field performance, conclusions, and uncertainties are presented.

2. LITERATURE REVIEW

Most of the evaporation techniques used in the industries consist of:

- Thermal evaporation system: Multi-effect evaporator (MEE), multi-stage flash (MSF) evaporator, and falling film evaporator.
- Mechanical evaporation system: Mechanical vapor recompression, evaporation ponds with sprinklers.
- Solar pond.

Currently, MEE is widely popular in industries having an in-house effluent treatment plant. MEE is used in combination with a crystallizer or agitated thin film dryers to dry out the salt from the brine. These systems required steam input at a temperature above 120 ^{o}C and 3 bar pressure (Nafey, 2006). The vapor from one stage of the evaporator is used as a heat source for the subsequent stage (called effects) and this results in the better utilisation of input steam. The number of effects is an optimisation between an increase in capital cost and energy savings due to the additional effect. The overall operational cost of MEE can range from 50-300 Rs/kL (0.5-3.5 €/kL) of evaporated brine, depending on the number of effects and type of fuel used to generate the steam.

Evaporation ponds are characterized as a wide-open area exposed to solar irradiation and filled with brine water which is to be evaporated. These ponds are easy to construct and operate with minimal mechanical and operator inputs. These ponds are widely used in arid and semi-arid regions as the meteorological conditions are favorable for evaporation. The evaporation rate using this method is dependent on the local weather conditions and can vary from 1-6 mm/day from a solar pond having a surface area of 1 m^2. The major concern with this method is the low evaporation rate and large area requirement. Furthermore, the failure of the protective lining in these ponds can results in the seepage of brine into the ground, which poses a severe threat to groundwater.

A number of studies are available which deals with evaporation enhancement of solar ponds using solar thermal collectors. Sampathakar et. al (2001) tested an evaporation system consist of solar flat plate collectors (FPC) and brine sprinkler system. The FPC is used to increase the brine temperature by 3 ^{o}C and nozzles of various diameters are used to sprinkle brine on the evaporation pond. The rate of evaporation observed from the system is 14 mm/(day.m^2), which was 2-3 times more than the natural evaporation system. However, the author realized the problem with drifting of the sprinkled brine into the air during the experimentation. In another similar study by Reilly (2009), a solar evaporation pond of 20,000 m^2 surface area was integrated with a 100 m^2 FPC system and long-term performance was monitored for Melbourne climatic conditions. Results show a mean evaporation enhancement ratio (EER) of 1.52 compared to the natural evaporation. Philip et. al (2013) presented a solar and wind-aided cross flow evaporator for RO reject management, as an alternative to conventional evaporator systems. In the proposed arrangement, the brine drips from an elevated tank on a vertical hanging cloth. The wind flow across the cloth results in mass and energy transfer and cause brine evaporation. The author reported a strong increase (13 folds) in the evaporation rate compared to conventional ponds. However, no information on the operational cost and durability of clothes under high brine concentration is provided. Guitierrez et. al (1993) studied the effect of floating aluminium fins in various orientations to analyse the increased evaporation area due to the fins. The experiments carried on small-scale prototype results in 20 % more evaporation using perpendicular fin arrangement compared to the natural evaporation. Kannan and Rao (2000) carried a detailed experimental parametric study to analyse the effect of various parameters such as air temperature, wind velocity, salt bath temperature, and salt concentration on the evaporation rate. The results are compared with the Sherwood and Pigford model to verify the effect of controlling parameters. The author concluded a good match in experimental and predicted results derived from the model. Moreover, brine input temperature was identified as the strongest influencing parameter to increase the evaporation. Based on the literature survey, the following controllable parameters were used in the developed evaporator to increase the evaporation rate:

- Increase in the brine temperature.
- Increase in wind speed on the evaporating surface
- Increase in the contact area between brine and air.

The proposed evaporator in this paper makes use of the above 3 parameters, along with a stringent control strategy for optimizing the thermal mass of brine and wind speed over the evaporating surface to maximise the evaporation rate and minimising the required energy input. The control of these parameters results in a significant increase in the evaporation rate which further results in lower operational costs.

3 SYSTEM DESCRIPTION

3.1 Working principle

The working principle of the developed evaporator is based on maintaining a certain set of conditions in the evaporator control volume predicted and optimised by a data-driven control strategy. The control unit of the evaporator plays a central role to optimise the system operation. The input to the control unit is provided by measurements of meteorological and energy parameters as defined in Table 1. The control unit uses these parameters to calculate the evaporation rate using artificial neural network (ANN) trained with experimental data. Using ANN model, several sets of simulation runs are carried over a wide range of control parameters such as the mass flow rate of brine, wind speed, and injection velocity.

Tab. 1: Parameters used for the evaporator control system

Parameter type	Control parameter	Instrument
Controllable input parameters	Mass of feed brine	Variable speed pump and controller
	Wind speed on the evaporator surface	Variable-speed fan and controller
	Contact area b/w air and water surface	Injection velocity and spray angle
Meteorological parameters	Ambient temperature	Temperature sensor
	Relative humidity at the inlet of the evaporator	Hygrometer
	Relative humidity at the outlet of the evaporator	
	Wind speed	Anemometer
	Global horizontal irradiation	Pyranometer

Energy parameters	Solar collector efficiency	Controller (only in case of the solar hybrid evaporator)
	Energy in the storage tank	Temperature sensor and level sensor
	Brine concentration	Digital TDS meter

As the aim is to reduce the operational electricity consumption, the model with a minimum value of specific fan power consumption (kWh/m^3) is selected. The output of the control system is a new set of input parameter values that are communicated to the interface devices to vary mass flow rate, wind speed, and injection velocity of effluent. The framework for the evaporation control system is shown in Figure 1. The evaporator also has various safety features and a remote management system to identify and resolve any issue during the operational period to ensure system reliability.

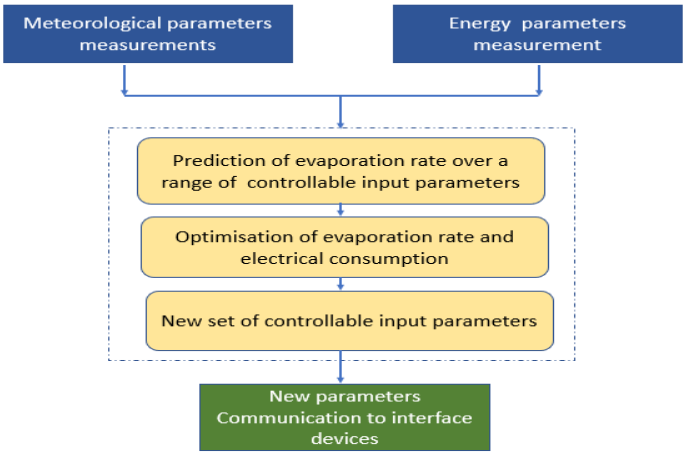

Fig. 1: Framework of the evaporator control system

3.2. System components

The evaporator can be seen as a stacked version of the solar pond, where several evaporating surfaces (pans) are placed on top of each other, resulting in significant footprint savings. An evaporation unit is a combination of various sub-modules (pan, fan, and injection sub-modules) integrated and working in synchronization with the control system. The schematic of the evaporator with various components is shown in Figure 2.

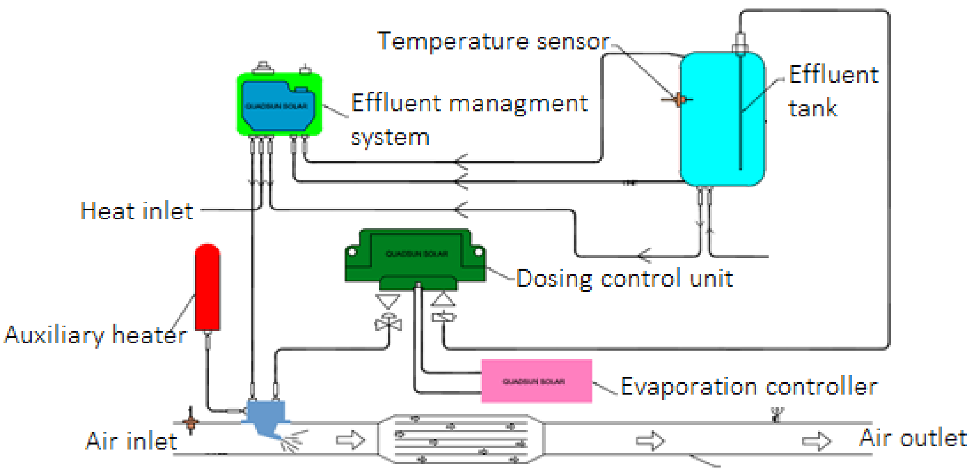

Fig. 2: Schematic of the developed evaporator

A carefully designed pattern on the surface of the pan allows the uniform spreading of the sprinkled brine and also increase the contact area between brine and air stream. The gap between the pan surfaces is optimised to maximise the surface wind speed while preventing the drifting of brine into the air stream. The fan and injection sub-modules work in conjunction with the evaporator controller to assure a set of input data conditions governed by the control algorithm. The evaporator has a peak capacity of 2500 litres per day (LPD) under defined climatic conditions of input brine temperature > 40 ºC, ambient temperature >20 ºC, relative humidity < 70 %). The capacity of the evaporator is optimised to assure the scalability of the unit for larger installations while minimising the installation time and logistic issues. The key design specifications of the evaporator are shown in Table 2 and the exploded view of the various components is shown in Figure 3.

Tab. 2: Design specification of the evaporator

Unit capacity	2500	LPD
Hours of operation	20	Hours/day
Input brine TDS range	0 - 300000	mg/L
Brine temperature range	20- 90	ºC
Electricity consumption	25-35	kWh/day
Thermal energy requirement	160-180	kWh/day
Footprint area	4	m^2

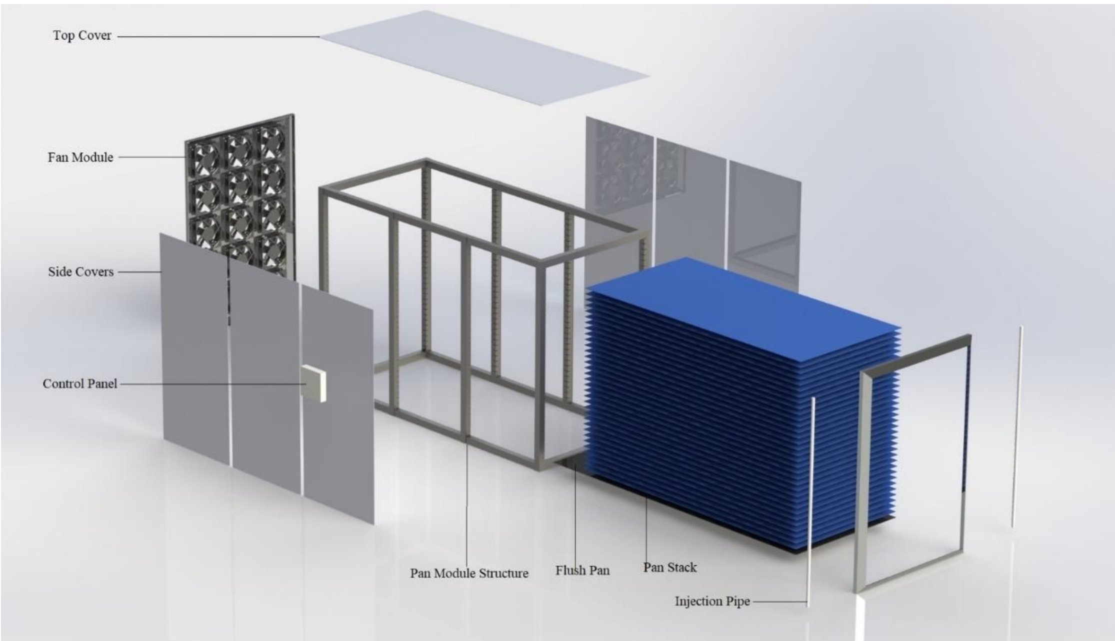

Fig 3: Exploded view of the evaporator

To achieve a higher evaporation capacity, several modules are integrated with a parallel arrangement. The system is designed to evaporate a wide variety of R.O reject (brine) with TDS up to 300,000 mg/L.

3.3. Integration

The brine to be evaporated is stored in an insulated storage tank. The brine in the tank can be heated using multiple sources such as solar thermal collectors, condensate return from the boiler system, or waste heat from various processes. The maximum allowable storage temperature is 95 ºC due to material constraints in the evaporator. The working cycle of the evaporator is as below :

- Brine is sprinkled on pan modules by an injection system to create a thin layer of fluid over the pan surface area. The quantity and frequency of the injection are decided by the control system.

- The thin layer of hot brine is evaporated by the air flowing over the pan surface. The wind speed over the surface is varied by the control module.
- The injection process continues as per the design control strategy until the flush cycle is triggered.
- The flush cycle drains the high TDS brine from the pan into another holding tank.
- This loop is continued until a drying cycle is triggered, and the brine injection on the pans in stopped.
- The drying cycle results in salt precipitation over the entire pan surface.
- Once the salt is formed on the pans, a semi-automatic scrapping process recovers the salt to start with the next cycle.

The higher wind speed on the evaporator surface along with control of injection brine quantity and contact area results in optimum conditions to achieve a high evaporation rate. The evaporator unit can also be used as a "concentrator" without the requirement for salt precipitation. This arrangement is of particular interest while retrofitting the evaporator unit in the existing brine management system to lower down the operational cost. The intended purpose of the evaporator in this configuration is to increase the concentration of the input brine and therefore reducing its volume, before feeding it to the existing MEE or MVR system. This results in lower operational costs due to fewer operating hours of the existing evaporation system. The working cycle in this configuration is similar to "salt precipitation" configuration except that the drying cycle is bypassed. The framework for both integration schemes is shown in Figure 4.

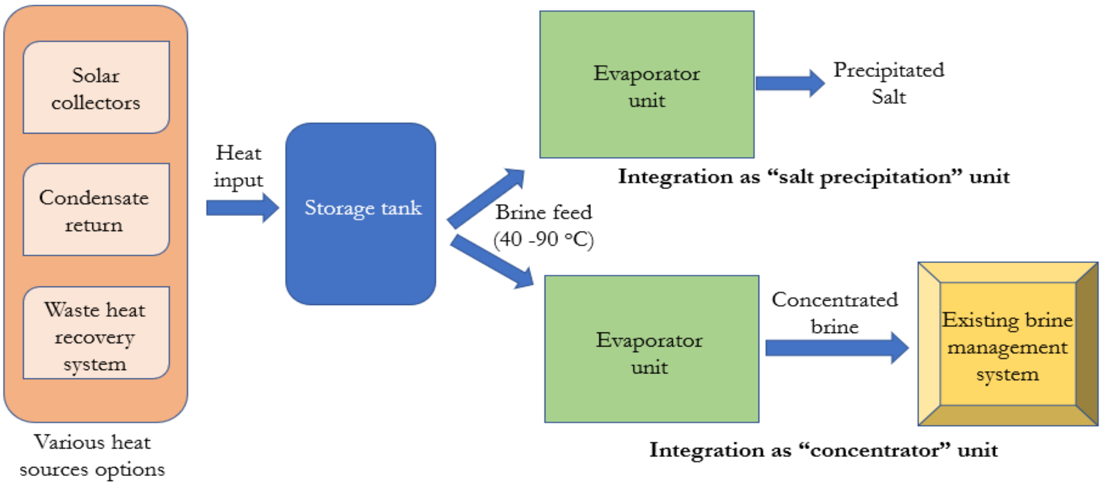

Fig. 4: Various integration schemes for proposed evaporator

3.4 Analytical model for pond evaporation

In this paper, the performance of the proposed evaporator is compared with a solar pond evaporation system. Standard Penman equation (Penman, 1948) is used to determine water evaporation from open water sources. However, to determine the evaporation rate from salt solutions, the standard Penman equation was modified to account for the reduced vapour pressure of the saltwater mixture. For this study, an analytical model based on modified Penman's equation is used to calculate the evaporation rate for solar ponds (Akridge, 2008), as expressed in Equation 1.

$$\lambda E = \frac{\Delta}{(\Delta+\gamma)} R_n + \frac{\gamma}{(\Delta+\gamma)} f(u)(e_s - e) \qquad \text{(eq. 1)}$$

Where, E is the evaporation rate from salt solution (mm/day), λ is the latent heat of vaporization (MJ/kg), Δ is the gradient of the vapour pressure-temperature curve (kPa °C^{-1}), γ is the psychometric constant (kPa °C^{-1}), R_n is the net solar radiation (MJ m^{-2} day^{-1}), $f(u)$ is a function of wind speed and e_s and e are the saturation vapour pressure of water and ambient vapour pressure (kPa), respectively. The latent heat of vaporization λ is a function of temperature and is expresses using Equation 2.

$$\lambda = 2.501 - 0.002361 * T \qquad \text{(eq. 2)}$$

where T is ambient temperature (°C). The saturation vapour pressure e_s is modified by introducing a factor a_w to reflect the reduction in saturation vapour pressure when salts are dissolved, and shown in Equation 3.

$$e_s = 0.6108 * a_w * e^{\frac{17.27*T}{237.3+T}} \qquad \text{(eq. 3)}$$

a_w is the activity coefficient of water as per Equation 4.

$$a_w = -0.0011m^2 - 0.0319m + 1 \qquad \text{(eq. 4)}$$

Where m is the concentration of brine expressed as molarity. The gradient of saturation vapour pressure-temperature function Δ is calculated as per Equation 5

$$\Delta = \frac{4098e_s}{(237.3+T)^2} \qquad \text{(eq. 5)}$$

The psychometric constant γ is calculated as per Equation 6.

$$\gamma = 0.000655 * 101.3 * \left(\frac{293-0.0065z}{293}\right)^{5.26} \qquad \text{(eq. 6)}$$

where z is the altitude above sea level (m). The vapour pressure e can be obtained from the relative humidity H_r (%) using Equation 7.

$$e = \frac{H_r e_s}{100} \qquad \text{(eq. 7)}$$

For an exposed evaporation surface, the wind function f(u) is obtained using Equation 8.

$$\text{f(u)} = 6.43(1 + 0.536U_2) \qquad \text{(eq. 8)}$$

where U_2 is the wind speed (m/s). Akridge validated the model by comparing the results of the modified Penman equation by comparing the evaporation rate from salt ponds in Chinese and Mexican climatic conditions (William, 2002; Chiang,1976)

3.5 Key performance indicators

The KPIs in this study are defined to evaluate evaporator performance and to establish a comparison with pond evaporation. The following KPIs are used in this paper for results and discussions on system modus operandi. Specific evaporation rate (SER): This represents the volume of water evaporated per unit evaporation surface area in one hour, shown in Equation 9.

$$SER = \frac{v}{A_e \cdot N} \qquad \text{(eq. 9)}$$

Where, $v, A_e, and\ N$ represents volume of water evaporated (litres), evaporation surface area in (m^2), and the number of operational hours respectively. It is important to realise the potential land savings benefits of the proposed evaporator system compared to pond evaporation. To account for this, a footprint area specific evaporation rate (SER_{fp}) is used, and calculated using Equation 10.

$$SER_{fp} = \frac{v}{A_{fp} \cdot N} \qquad \text{(eq. 10)}$$

Where, A_{fp} represents the footprint area of the evaporation system.

4. PERFORMANCE RESULTS

The product was commercialized in the year 2018 and is currently installed in various industries across India. Performance data from one of the installed site is presented in this section, and results are compared with the pond evaporation system. The installed site is located in Gurugram, Haryana (28.25° N, 76.96° E), which is classified as a humid subtropical climatic zone. The installed system is used to evaporate the brine from the effluent treatment plant having a TDS concentration of 100000 mg/L. The evaporator unit consists of 40 pans with a total evaporation surface area of 60 m^2. The footprint area of the installed system is 4 m^2. In the tested arrangement, the brine feed to the evaporator is given at ambient water temperature without any external heating provision. The exclusion of the heating source is chosen to have a fair comparison with the pond evaporation system. The measured parameters along with a list of instruments are given in Table 3. The data logging interval for all parameters in 1 minute. The irradiation for the test site is obtained from weather data station located 10 km from the test site.

Tab. 3: List of measurement parameters and instrument details

S.No	Parameter	Instrument	Model No	Range	Resolution	Accuracy	Logging time
1	Temperatures (Ambient/Brine)	Temperature sensor	PT100	(-200 to 800 ºC)	0.001 ºC	0.015	1 minute
2	Wind speed	Anemometer	HTC AVM 07	0.8 to 30 m/s	0.01 m/s	±2 %	1 minute
3	Relative humidity	Hygrometer	RHT10	0 to 100 %	0.1% RH	±3 %	1 minute
4	Global horizontal irradiation	Extracted from a calibrated weather station					1 minute

Testing is performed for 64 days from April to June 2019. The testing setup is shown in Figure 5. The average ambient temperature, wind speed, and R.H value for the tested period are 30.4 ºC, 1.4 m/s, and 43.2 % respectively, and the daily variation for these parameters is shown in Figure 6.

Fig. 5: Overview of the testing setup

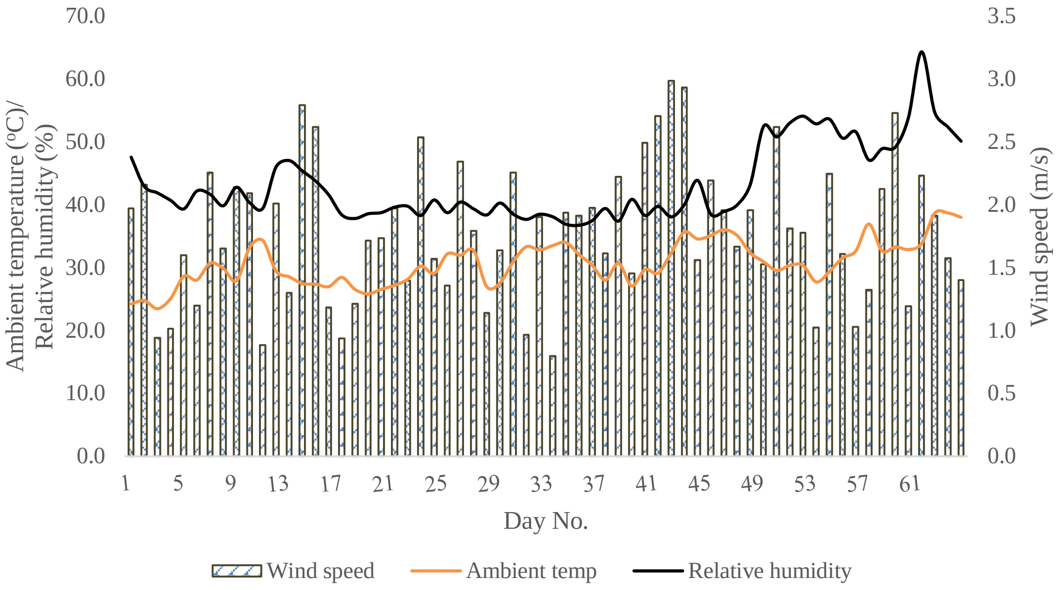

Fig. 6: Daily variation in meteorological parameter

Measurements show that the total quantity of brine evaporated during the testing period is 35.9 m^3, with total system operational hours of 1233. The analysis shows that the hourly average evaporation rate is 29.1 L/h, SER is 0.48 L/(h·m^2), and SER_{fp} is 7.29 L/(h·m^2). The variation in evaporated brine quantity per day is shown in Figure 7.

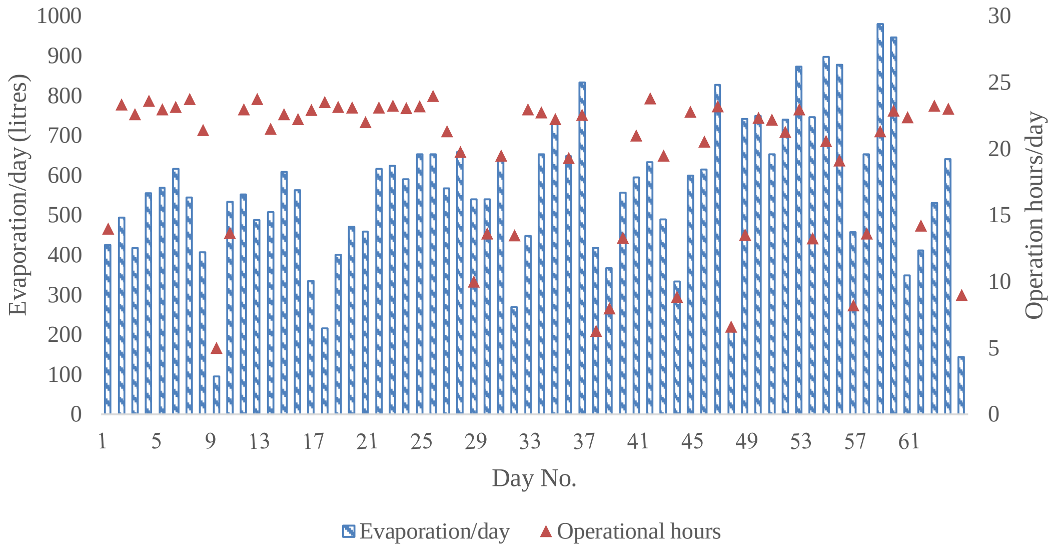

Fig. 7: Variation of evaporation quantity per day

The results show a strong effect of relative humidity and ambient temperature on the evaporation rate as shown in Figure 8. As expected, SER is higher at high ambient temperature and lower relative humidity conditions. However, the evaporation rate is dependent on a complex interplay of meteorological parameters and operating condition, and justify the higher evaporation rate for some point despite low ambient temperature and higher relative humidity conditions.

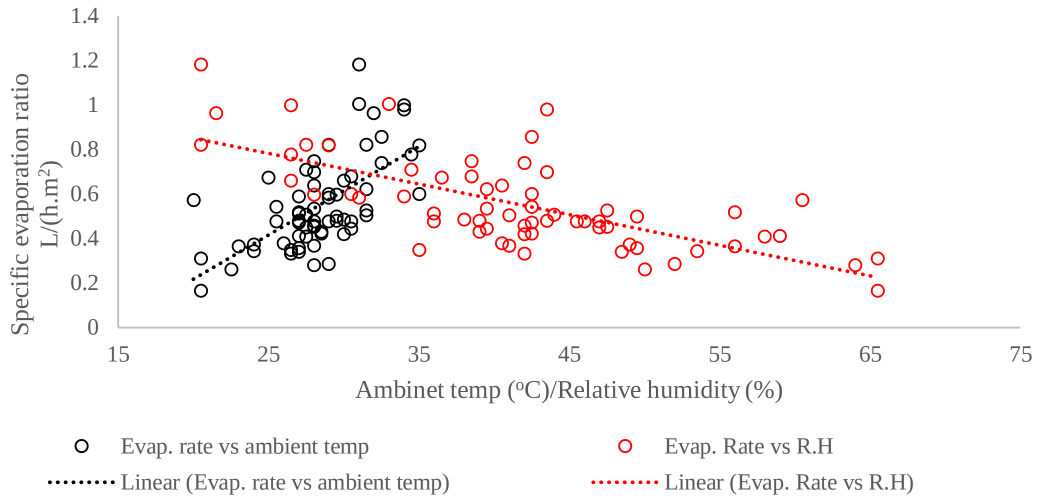

Fig. 8: Effect of R.H and ambient temperature on Specific evaporation ratio

In the proposed evaporation system, electricity is consumed by fans, water pumps, and electronic components of the control system. The average electricity consumption of fans and the water pump is measured at 19.2 kWh/m^3. The operational cost of evaporation with the proposed system is 0.15 Rs/L (1.7 €/m^3) calculated at an electricity price of 8 Rs./kWh (91 €/MWh), and Rs. to € conversion rate of 0.0113.

The performance results are compared with a hypothetical evaporation pond using an analytical model as explained in sub-section 3.4. Pond surface area is assumed at 60 m^2, which is equal to the total evaporation surface area in the proposed evaporator. The footprint area for the pond is assumed the same as its surface area i.e. 60 m^2. R.H data used in the analytical model is derived from a separate hygrometer installed in an open area to avoid uncertainties due to the localised humidity zone near Quadsun evaporator. The irradiation data is obtained from ground-based weather stations near the test site. The average daily GHI for the testing period 6.7 kWh/m^2 and the daily variation in GHI is shown in Figure 9.

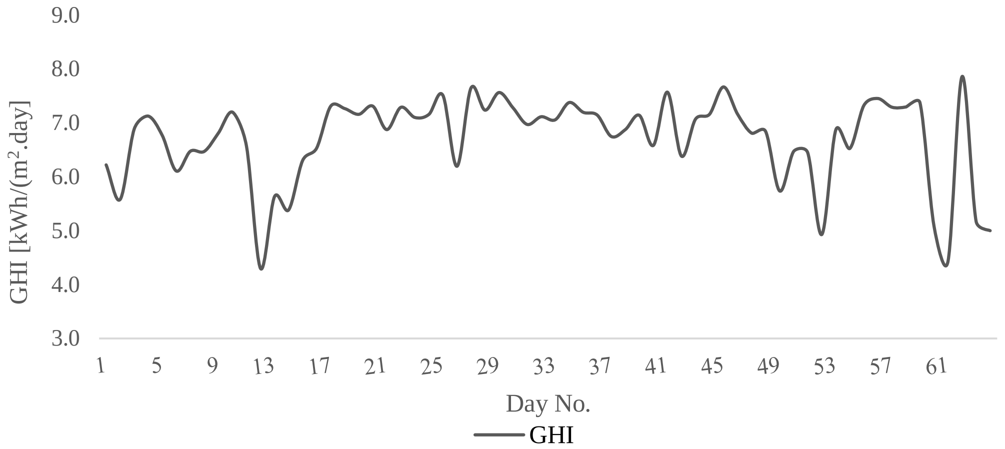

Fig. 9: Daily variation in global horizontal irradiation during the testing period

The pond model predicts the average evaporation of 3.1 L/(day·m^2), with a peak value of 4.5 L/(day·m^2). The model results match well with measurements from a real pond detailed in Sampathakar et. al (2001). The simulation results show a total evaporation of 9.4 m^3 evaluated for the same operational hours as QS evaporator (1233 hours). The hourly average evaporation rate for 60 m^2 pond surface area is calculated at 7.6 L/h, with SER and SER$_{fp}$ of 0.12 L/(h·m^2). The results show that the proposed evaporator has a 3.8 times higher SER compared to the pond evaporator. Furthermore, the designed evaporator can be imagined as a stacked version of pond evaporator, which leads to significant land savings for end-users. Analysis reveals that SER$_{fp}$ for QS evaporator is 57 times higher compared to the pond evaporator. This is because the proposed evaporator requires nearly 4 m^2 footprint area for 60 m^2 evaporation surface area. The comparison of cumulative evaporation and SER is shown in Figure 10.

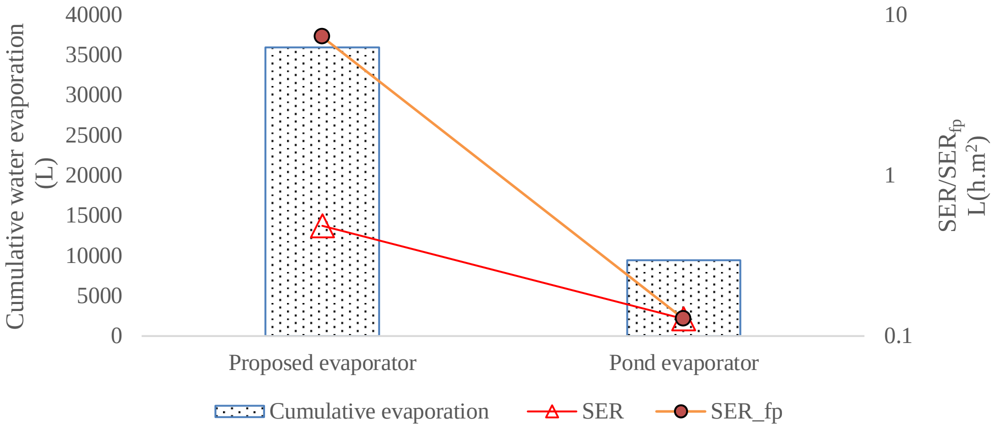

Fig. 10: Comparison of total evaporation and specific evaporation ratio

5 LIMITATIONS

The data analysis is detailed in approach however limited to only one climatic context. System performance will have significant seasonal variation, and thus needs evaluation. The data for rainy days is omitted from the analysis. To have a fair comparison, the operational hours of the pond evaporation is considered equal to the proposed evaporator. In reality, the pond system will evaporate for 24 hours daily as there are no mechanical/electrical components involved. During rainy seasons, rainwater can accumulate in these ponds and most industries have no provision of covering these ponds. This can have a negative impact on evaporation however, this effect is not considered in this study. Future work can include a detailed economic analysis along with land savings potential.

6 DISCUSSION

An evaporator unit is developed, and the field-testing results for the Northern Indian climatic context is presented. The developed evaporator aims to address the challenges of existing evaporation systems by minimizing the operational cost, land area requirement, heat, and electricity consumption of the system. The stringent control strategy is based on data-driven optimisation which keeps the system electricity consumption to a minimum while maximizing the evaporation rate. The testing data over 64 days is presented, which results in an average evaporation rate of 0.48 L/(h·m^2). The system has a footprint area of 4 m^2 and evaporates about 36 m^3 of brine in 64 days with total operational hours of 1233. The operational cost of evaporation is evaluated at 0.15 Rs./L, which is about 4 times less than the conventional brine management systems. A comparison with the pond evaporation system reveals significant improvement in the evaporation rate with the proposed evaporator design. The SER for the proposed evaporator is 3.8x higher achieved at 15x less footprint area. The evaporator holds tremendous potential and can be integrated with solar heat and PV to provide a complete sustainable solution to industries.

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