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Adaptable wind/solar powered hybrid system for household wastewater treatment

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ABSTRACT

Sustainable and cost-effective water treatment systems are critical elements to developing nations. In India, the human population is escalating while the water availability is lagging behind. An adaptable, affordable, and sustainable wastewater treatment system powered by wind/solar energy is proposed based on proven theory and technology. A household in India is singled out to illustrate the workings of the proposed system, where the wastewater is recirculated through a hybrid of water purifiers powered by solar/wind energy. The system demonstrated here is specifically designed for small-scale applications, i.e., for a single household. The solar still has been divided into four stages. Partial vacuum is created inside the still so as to obtain boiling point temperatures of 70 °C, 67 °C, 62 °C and 50 °C in the four stages. Dhanbad, India 23.79°N, 86.43°E, with an average solar intensity of 850 W/m^2 for 6 h a day, has been used for this study. A lumped parameter mathematical model was developed for this study. With an aperture area of 2.5 m^2, the total amount of water distilled is found to be 43.3 kg/day. The system proposed is more efficient than existing systems as it is able to achieve efficiencies as high as 53%. The effect of wind speed on distillate output yield has also been discussed.

Introduction

With modernization, urbanization and industrialization, the human race is advancing at one front and sacrificing at the other. The population is rising and the potable sources of water are diminishing. Global climate change and speedy growth in population have many cities under water threat [1,2]. With a few exceptions, water has always been a natural resource that mankind has taken for granted. The worldwide supply is not distributed evenly around the planet, nor is water equally available at all times throughout the year. Strategic reuse has gained importance over the last three decades as demand for water increased dramatically [3]. Reuse of wastewater for domestic and agricultural purposes has been executed to boost water usage efficiency since historical times. Initially, the emphasis was on reuse for agricultural and non-potable purposes but, with innovative advancements in technology, the domain for reused water has widened [4]. Conventional wastewater treatment processes are acceptable for non-potable water reuse applications (e.g. turfgrass, landscape, and agricultural irrigation) that do not require the wastewater to be treated to drinkable standards. Treatment of raw water from lakes, rivers, or wells is required in order to meet drinkability criteria. To do so, it requires work, and thus energy, which is yet another issue in rural areas. Access to modern energy is a social and economic priority to the rural population because of its direct socio-economic and environmental benefits. People living in these communities also face financial problems. With this in mind, this work aims to design a self-sustainable stand-alone water treatment system. There is already an immense amount of research ongoing in the field of applications of renewable sources of energy in an off-grid community [5]. Kulworawanichpong et al. [6] suggested a design for a stand-alone solar photovoltaic system for a rural Tanzanian household. The application of the system presented here, which is driven by renewable sources of energy, is primarily for an off-grid community. The design philosophy is to use solar energy as a primary source, and wind energy as a secondary source, to power the water purification system.

Most filtration techniques like reverse osmosis (RO) require the water to be pumped at high pressures, thus requiring a pump. Supplying power to the pump is another challenge in rural areas. Moreover, filtration techniques have a limitation of the minimum molecular size particles they can remove from water. With distillation, almost 99% of the particles can be removed, leaving only the

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Nomenclature

A	aperture area (m^2)
AC	annual cost (Rs)
AMC	annual maintenance cost (Rs)
C	cost (Rs)
C_p	specific heat (J/kg K)
C_T	collector thickness (m)
C_{um}	cost of unit mass of water (Rs/kg)
d	diameter of pipe (m)
e_T	edge insulation thickness (m)
f	capital recovery factor
f_l	frictional loss coefficient
F	sinking fund factor
F_R	heat Removal Factor
GRP	glass reinforced polymer
h_{ci}	convective heat transfer coefficient (W/m^2K)
h_{ewi}	evaporative heat transfer coefficient (W/m^2K)
h_{fg}	latent heat (J/kg)
H_i	inlet head of cold water in solar collector
H_0	outlet head of water from solar collector
I	solar intensity (W/m^2)
k_i	thermal conductivity of insulation (W/m K)
K	minor loss coefficient in Heat Exchanger
L_c	length of piping of solar collector
L_H	length of piping of Heat Exchanger
L_T	insulation thickness of flat plate collector (m)
$m_{c,i}$	mass of water condensed in the i^{th} stage (kg/s)
m_{ei}	mass of water condensed in the i^{th} stage (kg/s)
m_{si}	mass of water in ith stage (kg)
M	maintenance cost (percentage of annual cost)
M_Y	annual distillate yield (kg)
N	number of years of operation
p	partial vapor pressure (Pa)
P	collector perimeter (m)
Δp	pressure difference
Q_h	heat absorbed from solar water heater (W)
Q_L	heat leaked (W)
Q_u	useful Energy Gain (W)
r	inflation rate
Rs	Indian currency
S	savage value (Rs)
U_B	heat transfer coefficient for bottom losses
U_E	heat transfer coefficient for edge losses
U_T	heat transfer coefficient for top losses
V_w	wind speed (m/s)
T_{ci}	condensing surface temperature (°C)
T_{in}	Inlet temperature of water (°C)
T_{si}	water bed temperature in ith stage (°C)
ΔT	temperature difference (°C)
K	minor loss coefficient in solar collector
η	collector efficiency of top stage (%)
ρ	density of water (kg/m^3)
η_c	flat plate collector efficiency
η_o	overall distill efficiency

Subscripts

c	solar collector
h	heat exchanger
i	inlet
s	still
TC	total cost (Rs)

organic particles which have a boiling point less than water. To accommodate this, a carbon filter can be used in conjunction with the distillation system. The proposed system uses distillation to purify wastewater. Advancements in solar thermal energy technologies are continuing to drive down investment costs, increase ease of arrangement, and optimize direct coupling with other process systems. The system presented here is simple, reliable, affordable, sustainable, and effective.

Status of water consumption in an Indian household

People in some parts of India have adjusted their habits based on the supply such that they do not feel that more water is needed. This, in turn, creates hygiene and sanitation problems, resulting in several health consequences. The effects of consuming water of substandard quality cause a myriad of health issues. In many Indian cities, the supply is very erratic, in addition to the inferior quality of the water. Thus, there is dire need of a system that meets the daily requirements of water adequately. Fig. 1 shows the average consumption of water in liters per capita per day (LPCD) in major Indian cities [7]. Five major Indian cities have been chosen to conduct this study. In this paper, we design our system as per the average water consumption in these cities. The Indian government [8] has reported that approximately 60% of households in major Indian cities are water-deficient. The same report shows that 72% of those people are from lower income families. The average water consumption is approximately 91 LPCD. Fig. 2 depicts the distribution of water in a typical Indian household. Approximately 50% of the total water consumption is for bathing and toilet activities. 25% consumption is for house cleaning and washing clothes. The remaining 25% needs to meet the basic requirements for human consumption.

History of water purification techniques

Purifying water for reuse has been practiced for years [9,10]. Some of the traditional treatment methods are:

- Filtration through winnowing sieve
- Filtration through cloth
- Filtration through clay vessels
- Clarification and filtration through plant material
- Jampeng stone filtration method

However, these methods are not reliable as each of them has its own limitations. The sieve cannot filter the fine suspended particles in the water. Cloth filters water only to a small extent. Pores

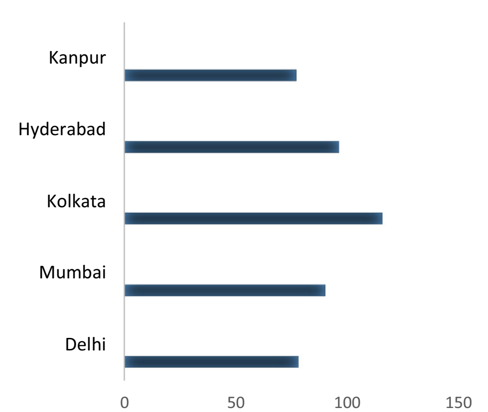

Fig. 1. Water consumption per capita per day (in liters) in distinctive Indian cities.