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Full Length Research Paper

An experimental study of the solar Jack pump

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An experimental study of the performance characteristics of a water jack pump powered by solar energy at the Department of Mechanical Engineering Workshop of the KNUST, Kumasi has been conducted. The 0.062 m plunger diameter, 0.16 m stroke, lift pump recorded an average hourly discharge of 0.546 m^3/h and an overall efficiency of 1.2% at a head of 5.6 m. The Volumetric efficiency of the system, η_v was 98%. The array efficiency of the solar panel was η_p 11%. The water pump system usually started between 9h00-10h00 a.m. with an average start-up and cut off threshold irradiation of 350 W/m^2 and operated for about 6 hours daily. Although the efficiency was small, the fulfillment of a daily discharge of 3.3 m^3/d was enough to supply 73 persons per day in Kumasi, Ghana, with 45 litres minimum standpipe water demand per capita per day.

Keywords: Solar energy, Solar powered pump, Pump discharge, Solar panel, Array power

INTRODUCTION

Solar energy technologies have become very important in the world energy market. Analysis of a solar technology depends on the availability of reliable solar energy conversion devices. The use of solar energy for water pumping to improve the living conditions of the population in rural areas in the tropical environmental condition of abundant solar radiation is well known (e.g. Bahadori, 1978; Shama and Singh, 1980; Hamza and Taha,1995; Wong and Sumathy, 2001; Mahkamov and Orda, 2005; Ramos and Ramos, 2009)

The jack pump is common in oil drilling but the use of the solar jack pump for a stand-alone domestic water supply system is rare. Most homes in the city, urban and peri-urban areas have their own stand-alone water supply systems in addition to the municipal water supply, which is often beset with irregular supply in developing countries. The cause of water cuts or insufficient supply by municipal water supply companies is usually attributed to electricity power outages. Therefore, most homes have their own stand-alone water supply systems in the form of wells or bore holes which use submersible centrifugal pumps or lift pumps driven by stand-alone generators or municipal electricity supply. In this article, we propose an innovation to use the traditional jack pump driven by solar energy as a stand-alone water supply system. As access

NOMENCLATURE

D = Diameter of plunger; g = Acceleration due to gravity; H = Head; L = Stroke; Pi = Solar power input; Po = Array; power input to the system;Pw = Useful power output of the system or water power; Q = Volumetric flow rate; QH = Average hourly discharge for a day; QD = Average daily discharge; Qp = Actual pump capacity; QT = Theoretical pump capacity; ηv = Volumetric efficiency; ηp = Array efficiency; ηo = Overall efficiency; ρ = Density of water

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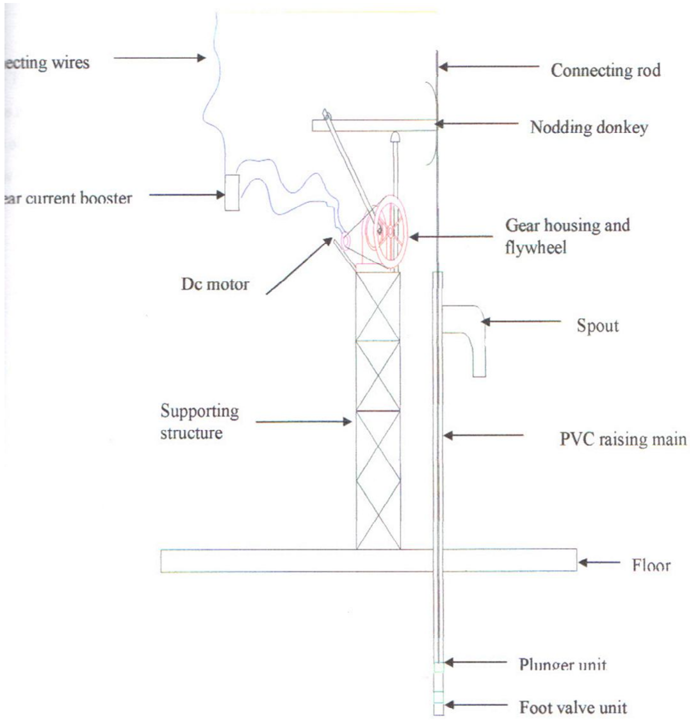

Figure 1. A schematic of the Jack pump installed near the SEAL, KNUST, Kumasi.

Figure 2. **A picture of the Jack pump**

to energy services for rural and peri-urban populations in Africa is increasingly difficult, the use of solar energy to power the jack pump will serve as an alternative to improve security of energy supply in peri-urban and rural areas. Meanwhile, electricity generation by the solar panels and their efficient use would reduce the environmental impacts of energy services by providing clean and sustainable solutions such as reduction of greenhouse gas. Solar energy is suitable for small-scale water pumping in remote areas for drinking water and for irrigation. Solar powered water pumping is encouraged and promoted in Sudan by Hamza and Taha (1995) and Omer (2001).

The objective of this study is to conduct a characteristic study of the solar water pumping system used for domestic water supply. This is to demonstrate an effective use of the solar energy in stand-alone water supply systems. The Jack pump was first assembled and tested (Figures 1 and 2) at the Mechanical Engineering Workshop of the College of Engineering, Kwame

Figure 3. Photograph of the set up to measure voltage and current of motor and the flow rate simultaneously, showing: A-Camera recording flow meter, B- Camera recording Ammeter and Voltmeter and C- the computer.

Nkrumah University of Science and Technology (KNUST), Kumasi. The measurements to determine the characteristics of the pump involve solar Insolation (W/m^2), solar panel power (VI) and pump discharge. The photograph of the set-up devised to measure the panel voltage and current as well as the pump flow rate, simultaneously is shown in Figure 3. The measurement innovation involves computer and digital camera simultaneous monitoring of the discharge Q, Current I, and Voltage V, as well as computations of the array power, water power, volumetric efficiency and overall efficiency of the solar water supply system.

Furthermore, the study involves feasibility of coupling rain water harvested, stored underground and lifted overhead with a pumping machine that utilizes solar energy resource. The overhead stored water flows by gravity through water conduits such as PVC pipes and taps into the house just as municipal water supply in the home. The case study of the solar Jack pump water supply system at the Mechanical Engineering Workshop of the College of Engineering, KNUST was used to supply water to the six-seater water closet lavatory at the Workshop.

Operation of the solar jack pump

The solar Jack pumping system (Figure 1) consists of solar panels which power a d.c. motor via connecting wires. Using V-belt pulleys, the motor drives a flywheel which is a part of a mechanical driving unit that converts the rotational motion of the motor into a reciprocating motion of a connecting rod that is attached to the nodding donkey (Figure 2). This connecting rod is attached at the other end to the plunger of the lower pump assembly. When the plunger is reciprocated in its cylinder in combination with a foot valve unit, it creates a partial vacuum thereby drawing water into the chamber through the foot valve and eventually lifting the water to a greater height through its poppet valve and cage. In the KNUST Mechanical Engineering Workshop, the entire pumping system (apart from the lower pump assembly) is raised to a height of about 3 m above ground to simulate lifting water from a deep well or the underground water reservoir (Dzokoto, 2000; Amakiri, 2007) . The water level was 1.5 m below ground level and the suction end of the pipe was 1 m below the water surface in the underground storage tank. The solar panels were placed about 0.9 m above the pump. Thus the height of the solar panels above ground was 3.9 m. The two mono-crystalline type solar panels are each of length 100 cm and breadth 50 cm making a total area of 1 m^2.

Material and methods

The measuring equipment included: Ammeter, voltmeter, pyranometer, digital cameras, laptop size computer and flow meter. The procedure involved connecting the ammeter and voltmeter in series and parallel respectively

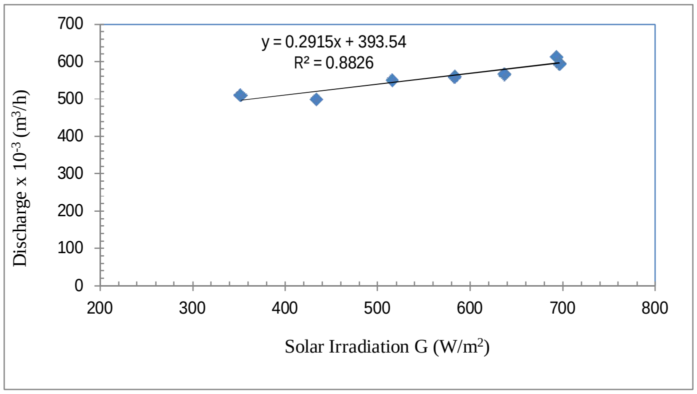

Figure 4. Graph of discharge per hour against hourly irradiation on 07/4/2007

(see Figure 3). One digital camera (A) captured the readings on the flow meter while a second camera (B) recorded the readings of both the ammeter and voltmeter. All images were fed directly into the computer (C) and saved. The use of digital camera was necessitated due to the location of the flow meter, which was fixed in its position and was about 0.5 m from the other meters. Also, the digital cameras were valuable in obtaining data from the three meters that were recording continually changing quantities, which needed to be read simultaneously for long periods of time in usually very hot weather conditions. With the set-up, data was easily collected simultaneously by the combination of the cameras and computer.

Data acquisition, analysis and results

The average hourly solar irradiation measured at the Solar Energy Applications Laboratory (SEAL) at KNUST from 9h00 a.m. to 16h00 p.m. was used for the analysis for two different days, 24th March 2007 and 7th April 2007. The system worked for about 6 hours a day from about 10h00 a.m. when the pump usually made full swings up to 16h00 p.m. when it usually slowed down lifting. The corresponding solar radiation range recorded during the experiment was 400 W/m^2 at 10h00 through a peak of about 700 W/m^2 at 12h00 and to 400 W/m^2 at about 16h00. The system actually kick-started oscillating with a solar radiation of about 350 W/m^2 between 9h00 and 10h00.

Pump capacity

The pump discharge per stroke was measured with a flow meter. The discharge for 5 strokes was taken and the average recorded as the actual pump capacity Q_p per stroke. Thus, the average actual pump capacity Q_p obtained was 0.000476 m^{3}per stroke.

Pump hourly discharge

The pump was timed for one hour while it discharged to obtain the relation between the hourly average irradiation and the pump discharge per hour as shown in Figure 4. The average hourly discharge Q_H was studied over one day between start-up, after sunrise and cut-off solar radiation on 24th March and 7th April, 2007. The average hourly discharge obtained during the experiment on 24/3/2007 was 0.539 m^3/h while for the operation on 7/4/2007, the hourly average discharge was 0.556 m^3/h. Therefore, the overall hourly discharge for the two days is Q_H = 0.546 m^3/h.

Pump system efficiency

The irradiation values for the days of the experiment were derived from the databank of the solar radiation measurements at the SEAL (about seven meters away from the system solar panels) and computed as solar power input P_i. The Head of the pump was H = 5.6 m, measured from the water level in the underground reservoir to the overhead tank. The power available to lift the water referred to as useful power output of the system or water power was recorded as $P_{w,}$ which was derived as $P_w = \rho gQH$ where, ρ is density of water and g is acceleration due to gravity.

The array efficiency is obtained as $\eta_P = \frac{P_o}{Pi}$, which is the ratio of the power output from the array to the solar power input to the array. Power output from the panel, P_o is assumed to be the same as input power to the motor. By measuring the voltage (V) and current (I) of the motor

Table 1a. Pump data obtained for 24/03/07 between 10h00 and 12h00

Time (hrs)	Volume pumped (m^3)	Flow rate, Q x 10^{-4} (m^3/s)	Current, I (A)	Voltage, V (V)	Power from array $P_o = VI$ (W)	Useful power $P_w = \rho gQH$ (W)
10:00-10:05	0.030	1.000	3.5	18.18	63.63	5.494
10:10	0.036	1.200	3.5	18.05	63.18	6.592
10:15	0.036	1.200	3.0	17.95	53.85	6.592
10:20	0.040	1.333	3.1	18.17	56.33	7.323
10:25	0.047	1.567	4.1	18.59	76.22	8.608
10:30	0.050	1.667	4.0	18.20	72.80	9.158
10:35	0.051	1.700	4.3	18.77	80.71	9.339
10:40	0.055	1.833	4.3	18.15	78.05	10.07
10:45	0.041	1.367	4.5	19.91	86.36	7.510
10:50	0.043	1.433	3.7	19.88	73.56	7.872
10:55	0.041	1.367	3.7	19.00	70.30	7.510
11:00	0.050	1.667	3.6	18.88	67.97	9.158
11:05	0.044	1.467	3.7	19.16	70.89	8.059
11:10	0.047	1.567	3.6	18.17	65.42	8.608
11:15	0.045	1.500	3.9	18.31	71.41	8.240
11:20	0.044	1.467	3.7	18.04	66.75	8.059
11:25	0.040	1.333	3.4	19.17	65.18	7.323
11:30	0.047	1.567	3.5	17.22	60.27	8.608
11:35	0.045	1.500	4.1	17.00	69.70	8.240
11:40	0.042	1.400	4.5	18.00	81.00	7.691
11:45	0.044	1.467	4.7	18.16	85.07	8.059
11:50	0.043	1.433	4.1	18.06	74.05	7.872
11:55	0.049	1.633	4.1	18.01	73.84	8.971
12:00	0.044	1.467	4.0	18.17	72.68	8.059

the power output from the panel was obtained as $P_o = VI$.

Volumetric efficiency

The Volumetric efficiency of the system, η_v is obtained as the ratio of actual pump capacity Q_p to the theoretical pump capacity Q_T. The average pump capacity obtained is 0.000475 m^3. The theoretical pump capacity is obtained as $Q_T = 1/4\pi D^2 L$ where, D is the pipe inner diameter (plunger diameter) and measured as D=0.062 m and L is the Stroke obtained as L= 0.16 m. Thus the theoretical capacity is Q_T = 0.00048305 m^3 and the volumetric efficiency η_v is found as 0.000475/0.00048305= 0.98. The high volumetric efficiency is expected as the leather seals which were new and effective kept the pump leakages through its glands at minimal level.

Array efficiency

The Efficiency of the array, η_p was found as ratio of power output from the array, P_o to the solar power input to the array, P_i. The surface area of the two panels was 1 m^2. The solar power was obtained by multiplying the irradiation values in W/m^2 by the panel surface area. On 27/3/2007, the solar power observed from 10h00 to 11h00 was 663 kW and from 11h00 to 12h00 it was 834 kW. On 7/4/2007, the solar power obtained from 10h00 to 11h00 was 693 kW and from 11h00 to 12h00 it was 515 kW. Since the irradiation values were in hourly averages, hourly array power Pi was used to determined the average array efficiency, $\eta_{p,}$ (see Table 1a and b). Therefore, on 24/3/2007 the array efficiency, P_o/P_i is (70.25/663) + (71.36/834) which equals 0.096. On 7/4/2007, the average P_o/P_i (70.48/693 + 68.82/515) obtained is 0.114. The array efficiency η_p was obtained as average efficiency over the two days that is 0.11 or 11%.

Overall efficiency

The Overall efficiency, η_o was found as the ratio of the useful system power to the Power input to the system P_w/P_o. The average hourly irradiation and pump hourly discharge values were used for the computation. The overall efficiency was found from Table 1 a & b as average of the P_w/P_o =0.0109 on 27/3/2007 and P_w/P_o = 0.0135 on 7/4/2007. The overall efficiency was therefore η_o= 0.0122 or 1.2%.

Mechanical efficiency

The electric motor power given to the mechanical driving unit including the flywheel and connecting rod is more than the power available at the plunger to lift the water.

Table 1b. Pump data obtained for 07/04/07 between 10h00 and 12h00

Time (hrs)	Volume pumped (m^3)	Flow rate, Q x 10^{-4} (m^3/s)	Current, I (A)	Voltage, V (V)	Power from array P_o = VI (W)	Useful power, P_w = ρgQH (W)
10:00-10:05	0.041	1.370	3.0	18.11	54.33	7.508
10:10	0.040	1.330	4.1	18.74	76.83	7.324
10:15	0.048	1.600	4.1	18.80	77.08	8.790
10:20	0.040	1.330	4.5	18.11	81.50	7.324
10:25	0.055	1.830	4.0	18.95	75.80	10.072
10:30	0.058	1.930	4.3	18.07	77.70	10.621
10:35	0.035	1.170	4.1	17.11	70.15	6.409
10:40	0.050	1.670	3.5	18.95	66.32	9.156
10:45	0.051	1.700	3.3	18.95	62.53	9.339
10:50	0.044	1.470	3.7	18.75	69.38	8.057
10:55	0.047	1.570	3.5	18.77	65.70	8.607
11:00	0.042	1.400	3.8	18.00	68.40	7.691
11:05	0.040	1.330	3.4	18.00	61.20	7.325
11:10	0.033	1.100	3.5	18.00	63.00	6.043
11:15	0.035	1.170	3.5	18.11	63.39	6.409
11:20	0.042	1.400	3.5	19.05	66.68	7.691
11:25	0.038	1.270	3.9	18.75	73.12	6.959
11:30	0.038	1.270	3.3	18.66	61.58	6.959
11:35	0.045	1.500	3.5	18.91	66.19	8.240
11:40	0.049	1.630	3.4	18.93	64.36	8.973
11:45	0.048	1.600	3.6	18.91	68.08	8.790
11:50	0.041	1.370	3.5	18.89	66.12	7.508
11:55	0.045	1.500	3.9	18.91	73.75	8.240
12:00	0.050	1.670	3.3	18.90	62.37	9.156

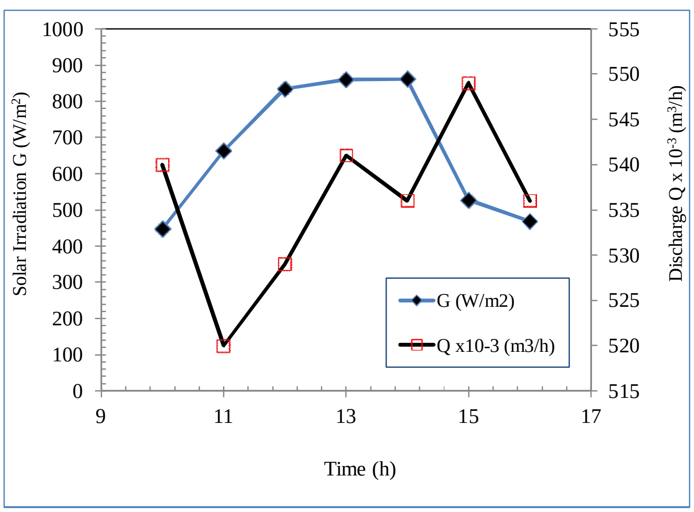

Figure 5. Graphs of solar irradiation and pump discharge against time on 24/3/2007

The mechanical efficiency η_m can be estimated as the overall efficiency divided by the product of the array and volumetric efficiency. Thus $\eta_m = \eta_o/(\eta_p \times \eta_v)$ and is found as 0.012/ (0.11 x 0.98) = 0.11 or 11%.

DISCUSSIONS

The capacity of the solar jack pump is determined as 0.000745 m^3 per stroke while the hourly discharge is 0.546m^3/h. The pump starts work at a threshold radiation of about 350 W/m^2 and attains full swings at 400 W/m^2 which occurs around 10h00 and cut-off around 16h00 making about 6 hours a day. Hence the average daily discharge H_D = 3.3 m^3, i.e. (0.546 m^3/h x 6 h). Comparing this system with the solar-powered thermal water pump developed by Wong and Sumathy (2001), which delivered 1.4 m^3 per day at a head of 6 m and at an efficiency of 0.42%, the solar jack pump has a higher

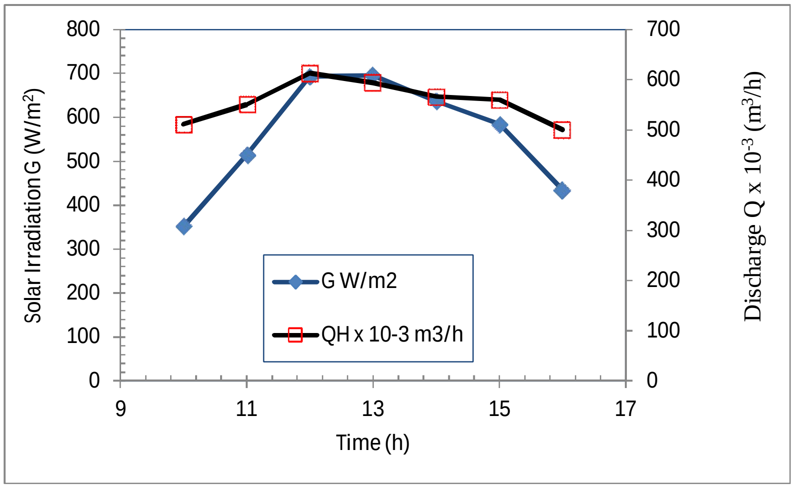

Figure 6. Graphs of solar irradiation and pump discharge against time on 07/04/2007

discharge of 3.3 m^3 per day at 6 m head and at 1.2% efficiency. Furthermore, the solar jack pump has a better discharge than the solar thermal diaphragm pump developed by Shama and Singh (1980), which gives a discharge of 2.8 ℓ/min or 0.168 m^3/h at a head of 6 m. The solar jack pump can be compared to the Solar thermal water pumping system of Mahkamov and Orda (2005) which delivers 0.2-1 m^3/h at a head of 1.5–5 m with an air-steam mixture as the working fluid.

Meanwhile, the solar radiation data from the SEAL shows that the system is highly sensitive to spells of cloudiness, which is rampant in Kumasi (Sunnu et al., 2008). Thus, modifications such as using a linear current booster, which increases discharge by about 43% and efficiency by 27%, as shown by Dzokoto (2000), in combination with a larger motor, would increase the discharge and the overall efficiency of the pump.

By plotting a graph of hourly discharge against hourly irradiation for 7/4/2007, it is shown in Figure 4 that there is a positive correlation with correlation coefficient of about 0.88 between both variables. As expected, the discharge increases with the solar irradiation. A linear relation between discharge Q (x 10^{-3} m^3/h) and irradiation G (W/m^2) is $Q = 0.2915G+393.54$. From the equation, one can estimate expected hourly discharge for a given hourly irradiation.

Figure 5 and Figure 6 show the graphs of the solar irradiation and pump discharge against time in hours for 24/3/2007 and 7/4/2007 respectively. Generally, the discharge and solar irradiation curves increase from 10h00 to a peak at about 12h00 and then decrease to about 16h00 for the two days except for the operation on 24/3/2007, which shows an unexpected increase of discharge at the start of operation at 10h00 and at 15h00. The overall efficiency of 1.2% and the mechanical efficiency of 11% imply that there is room for improvement. There is the need for further optimization to improve the mechanical efficiency and the overall efficiency

If the WHO standard water usage per capita per day for Kumasi in Ghana was 45 litres 45 litres (Aklaku, 2002), then the 3.3 m^3 daily delivery of the solar jack pump would suffice 8- person household with the underground stored rainwater supply for 9 days or 73 persons per day. This compares with the case study by the Ramos (2009) who considered a small village composed of 10 families with a daily consumption of 100 ℓ each, a well with a depth of 100 m, a reservoir at 10 m above ground level, an autonomy of 6 days, and a PV, producing a pump power of 154 W, at an array power of 195 Watt peak (Wp) and at a water cost of 1.07 €/m^3. They showed that the stand-alone system was a good alternative to extending the electric grid or having a diesel generator connected to the pump.

Case study

The case study of the solar jack pump water supply system at the workshop of the Department of Mechanical Engineering, KNUST, is analyzed as a demonstration of an efficient use of the solar energy resource. The uniqueness of the system involves harvesting rainwater from the workshop and laboratory rooftop then carried through pipes to the underground concrete water tank. Rainwater in suburbs of Kumasi has good properties. Results of water quality analysis of rainwater showed that all physico-chemical parameters fell within the WHO guidelines for drinking water quality (Awuah and Anipa, 2002). The water from the 80 m^3 underground water storage tank is lifted by the solar Jack Pump to an overhead storage tank. The water is then supplied through PVC pipes to the cisterns at the six-seater toilet of the College of Engineering laboratories and

Workshops, KNUST, Kumasi. The workshop is opened between 8h00 and 17h00. The pump stops pumping about 1 hour to the end of work on each day. The water left in the overhead tank after pump stoppage each day is enough for use by the staff in the workshop until end of work on the day. Furthermore, the overhead tank holds enough water to be used by the staff for about 2 hours before the start of pumping in the morning between 9h30 and 10h00. There was no water shortage during the period of the solar pump usage. Meanwhile, there were times of over pumping and the pump has to be stopped by switching off the solar PV power input.

CONCLUSION

An experimental study of the performance characteristics of the solar jack pump at the SEAL KNUST Kumasi has been conducted. The 0.062 m piston diameter water lift pump recorded a stroke L equal to 0.16 m, the actual capacity measured was 0.000475 m^3 per stroke, the average hourly discharge was 0.546 m^3/h, while the average daily discharge recorded 3.276 m^3/d and the overall efficiency was 1.2%. The water supply jack pump system usually started between 9h00 and 10h00 with an average start up and cut off threshold irradiation of 350 W/m^2 and operated for about 6 hours daily on average. Although the efficiency was small, the pump could discharge 3.3 m^3 per day which was enough to supply an 8-person household for 9 days or 73 persons per day in Kumasi, Ghana.

The studies also suggested that the system could be used as a household water supply unit with appropriate modifications. However, as an alternative for use as a backup system in urban areas, in the light of recent energy crisis, the solar jack pump could be a most viable economically in the nearest future.

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