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Comparative Study of Pumping Performance of Fluidyne Pump with Ejector and Centrifugal Solar Pumping Systems

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ABSTRACT

Fluidyne pump is a promising type of solar pumping system because of the absence of moving parts and low maintenance and primary cost. One of its defects is the small flow rate and efficiency. This paper presents a mathematical analysis of its governing equations to identify its key controlling parameters. These parameters were found to be the gas-to-liquid volume ratio, a temperature factor, and a pressure factor. These factors were found to be proportional to the system's efficiency and flow rate. Comparing the fluidyne pump with different solar pumping systems shows that every system is suitable for specific operating conditions. Ejector solar thermal refrigerant system is suitable for high flow rate, low pressure, and large size applications, while centrifugal pump/ PV system is preferred for medium head, medium flow rate, and medium installation cost. The Fuidyne pump is suitable for low head, low flow rate, and low-cost applications.

1. Introduction

Solar energy is considered the main source of life as applied in the studies by Yahya *et al.,* [1] and Huzir *et al.,* [2], and renewable energy as applied in the study by Samsudin *et al.,* [3]. The application of solar energy conversion is applied in many fields of life. The two main uses of solar energy are the electricity conversion of the solar radiation as can be found in the studies by Liang *et al.,* [4] and Bakri *et al.,* [5] or the thermal conversion as can be found in the studies Hassan *et al.,* [6] and Rebhi *et al.,* [7]. Many solar conversion systems for agricultural applications were investigated. Greenhouse power supply using PV was investigated by Choong *et al.,* [8]. Water pumping (or other liquids) is one of the most important applications in agriculture and industrial activities. It is one of the earliest considered applications for renewable energy. A solar thermal irrigation station had been built in Egypt, back in 1913 by Frank Shouman, with 27 m^3/min flow rate and about 40 kW output powers [9]. Solar pumping can be classified from of the perspective of pumping techniques, into two groups; mechanical and non-mechanical systems, as shown in Figure 1. For the mechanical

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systems, energy recovered from solar thermal radiation or solar light is converted and producing mechanical work. Mechanical work drives a centrifugal or positive displacement pump. In case of PV, it is converted into electricity and then mechanical work through an electric drive. For non-mechanical systems several techniques have been developed.

They integrate both the driving unit with the pumping unit. They include verity of techniques ranging from pressure differential techniques such as bellows and diaphragm techniques, ejector pumping to Fluidyne pumping technique. The latter is using Stirling engine approach, yet it has liquid piston instead of conventional metallic piston.

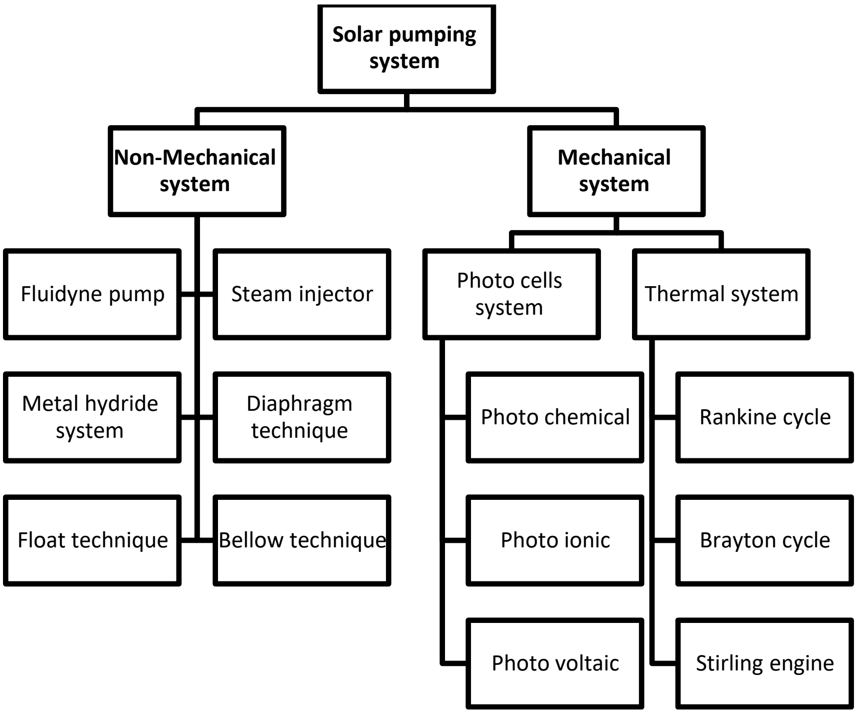


Fig. 1. Solar thermal pumping systems classification

Regarding the comparison between the mechanical and non-mechanical solar thermal pumping systems, Table 1 shows the flow ranges and operational requirements of the two categories.

Table 1
Advantages and disadvantages of mechanical and non-mechanical systems

Item	Mechanical Solar Pumping Techniques	Non-Mechanical Solar Pumping Techniques
Output flow rates	High – medium	Medium - low
Installation cost	High	Low
Maintenance cost	High	Low
Moving parts	High	Low / non
Total efficiency	High – medium	Medium - low

Mechanical applications had the largest portion of solar pumping applications, especially photovoltaic panels, due to their acceptable efficiency compared to non-mechanical systems. This research aims to expand the scope of non-mechanical systems due to their many advantages, but their low efficiency remains the most obvious disadvantage. Therefore, the research deals with one of the non-mechanical systems, fluidyne, with the aim of raising its efficiency through research into the basic factors affecting its performance due to an acceptable efficiency. And comparing its performance and conditions with the existing technologies of the solar pumping.

2. Fluidyne Pumping System

FP is a Stirling-type engine as described in the previous studies [10,11]. It works with a gas and the working pistons are liquid. It has the advantage of exerting work with low-quality heat. This means that it can work with waste heat from industrial processes or thermal energy collected from solar collectors. Defects of the FP pump lie in its low flow rate and pressure rise as indicated by Stammers [11], however, it is still applicable in agricultural and industrial fields as revealed by West [12]. It was developed first by C. West in 1971 [9]. The operating idea is the same as a Stirling cycle as described by Wang *et al.,* [10] and Stammers [11], that works with two isochoric processes and two isothermal processes, as shown in Figure 2. The difference in the gas temperature in the hot and cold sides creates expansion pressure waves that create a reciprocating effect on the liquid surface that produces work.

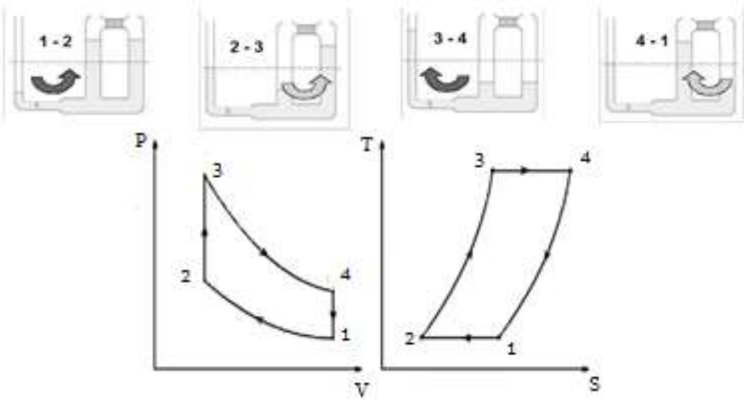


Fig. 2. P-V and T-S diagram of FP engine [10]

Harwell and Metal Box Company developed large-capacity FP model having a flow rate of 28.3 LPM, for 500-cm head as shown in Figure 3 [13].

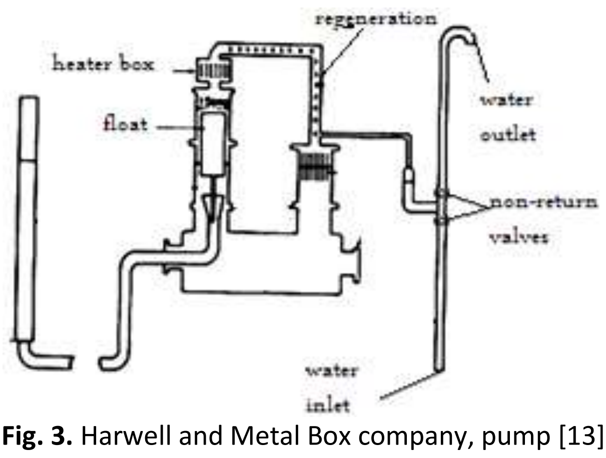


Fig. 3. Harwell and Metal Box company, pump [13]

Table 2 shows the enhancement achieved for the basic design over 1971-1981. As shown in the table, the flow rate reached 158.3 LPH and the head reached 3300 cm for the highest efficiency of 4.7% from 1800 and 0.35% for the head and efficiency respectively in 1971 based on the design of West [14].

Table 2
Performance variation of the FP through 1970-1981

System (year)	Flow rate [LPM]	Head (h) – [cm]	η %
West [14]	6.3	1800	0.35
Goldberg *et al.,* [15]	0.73	100	0.08
Mosby [9]	0.37	40	0.15
Reader and Lewis [16]	......	....	0.03
Bell [17]	1.9	1200	0.18
Pandey and West [18]	29	3300	4.7

During the 1990s, interest in research on the pump declined due to the low flow rate, efficiency, and head, compared with other pumping methods. With the development of methods for using and storing solar thermal energy systems, interest in the FP has returned again, as mentioned by Der Minassians [19]. A free-unloaded Fluidyne engine built and tested by Mason and Stevens [20] using a Fresnel lens. They found the ratio between the positive and negative work per cycle is 12%. Obodoako and Everbach [21] built and tested a new F.P., as shown in Figure 4; the pump has 4-Hz frequency and 25 cm amplitude, and has 5 watts output with 3.5% efficiency.

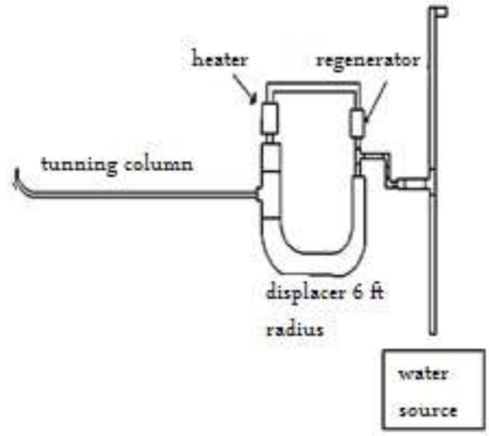


Fig. 4. F.P. model [21]

Two phase models of FP engine built and tested in 2022 by the study of Huang *et al.,* [22] using working liquids like acetone, methanol, and chloroform. It shows that the FP performance increases with increasing the temperature difference between hot and cold tubes for different fluids.

2.1 Mathematical Formulation

The main conservation equations of the mass, momentum and energy for both the hot and cold sides have been solved by Wang *et al.,* [10]. The assumptions proposed for these derivations include using the same diameter for all the tubes, initial pressure is equal in both cold and hot sides of the gas section. Megahed [23] reviewed and analysed the main equations to convolute the main independent parameters that affecting the flow rate and efficiency of the FP.

Considering the dimensions shown in Figure 5, the governing equations of the FP are as follows as described in previous studies [9,12]

$$\frac{T_2 - T_1}{T_2 + T_1} = \frac{\rho_w * V_g}{P_o * A_d}\left[\frac{0.5 * g * L_d}{2H + L_d} + \frac{8\pi\mu_w}{(A_o * \rho_w)^2}\left(\frac{2H + L_d}{L_d}\right) b\right] \quad (1)$$

where "μ_w" is absolute viscosity for working liquid [pas. s], "ρ_w" is the working liquid density [kg/m^3], "A_d" is the displacer cross section area, "L_D" is the displaced horizontal length (m), and "b" is the loading factor.

The frequency of the FP in the (ω_{un}) unloading case is

$$\omega_{un} = \sqrt{\frac{2g}{2H+L_d}} \tag{2}$$

For the loading (ω_l) case, the frequency is expressed as [9]

$$\omega_l = \sqrt{\frac{L_o\, \rho_w v_g}{P_o A_o}} \tag{3}$$

It was found that the loading state does not affect the frequency as indicated in the study by Wang *et al.,* [10]. To simply expressing the large number of factors existing in the governing equations non-dimensional geometrical factor (d_i) and temperature factor (T_i) were suggested as

$$d_i = \frac{L_d}{2H+L_d} \quad \text{and} \quad T_i = \frac{T_2 - T_1}{T_2 + T_1}$$

where "T_1, T_2" are the hot, and cold area temperature of gas areas, while "L_d" is the displacer horizontal length (m), "A_o, L_o" is the output tube cross area and length, respectively, and "H" is the height of working liquid, and output columns.

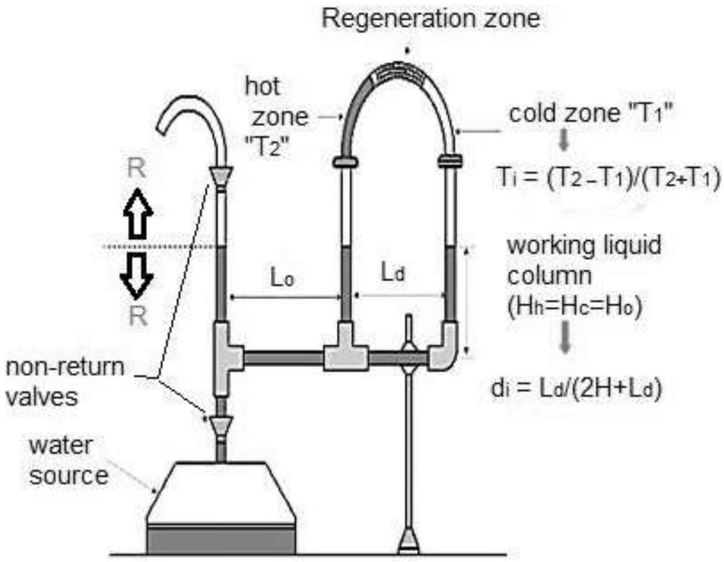


Fig. 5. FP design/operating parameters

The pump load equals ($\rho_o\, Q^o\, g\, h$), where "P_o" is the output pressure, Q^o is the volumetric flow rate, "g" is the gravitational acceleration. By introducing the load coefficient b, the pump load can be expressed as a function of the pump load coefficient **b** and working frequency. This can take the following from as described in the study by Wang *et al.,* [10]

$$\text{Pump Load} = 0.5b(\omega_p R)^2, \text{ then } b = \frac{\text{Load}}{(0.5\, (\omega_p R)2}$$

As $Q^o = \frac{2RA_o}{\text{period time}} = \frac{\omega_{p\,R\,A_o}}{\pi}$, then $\omega_p R = \frac{\pi\,\mathbf{Q^o}}{A_o}$

So, b is expressed as

$$b = \frac{\rho_o\, g\, h}{0.5\mathbf{Q^o}\,(\pi/A_o)^2} \tag{4}$$

Where "R" is the amplitude, and "A_o" is the output section area.

2.1.1 Flow rate

To calculate the flow rate from the FP, Eq. (4) and Eq. (1) are considered and manipulated as follows

$$\frac{T_2 - T_1}{T_2 + T_1} = \frac{\rho_w * V_g}{P_o * A_d}\left[\frac{0.5*g*L_d}{2H+L_d} + \frac{8\pi\mu_w}{(A_o*\rho_w)^2}\left(\frac{2H+L_d}{L_d}\right) * \left(\frac{\rho_o\,\mathbf{Q^o}gh}{0.5\left(\frac{\pi\mathbf{Q^o}}{A_o}\right)^2}\right)\right] \tag{5}$$

Then,

$$\frac{T_2 - T_1}{T_2 + T_1} * \left(\frac{P_o*A_d}{V_g}\right) = 0.5\rho_w * g\left(\frac{L_d}{2H+L_d}\right) + \frac{8\mu_w}{\rho_w}\left(\frac{2H+L_d}{L_d}\right) * \left(\frac{\rho_o gh}{0.5\,\pi\mathbf{Q^o}}\right) \tag{6}$$

By separating the flow rate in the L.H.S., it will be expressed as

$$\mathbf{Q^o} = \frac{\left(\frac{32}{d_i * d_i \pi}\right)\left(\frac{\mu_w}{\rho_w}\right)*h*\left(\frac{\rho_o}{\rho_w}\right)}{\left[\left[2\left(\frac{P_o}{\rho_w * g}\right)*\left(\frac{A_d}{V_g}\right)*\left(\frac{T_i}{d_i}\right)\right]-1\right]} \tag{7}$$

This can be expressed as

$$\mathbf{Q^o} = \frac{(\mathbf{10.19/d_i^2})*\boldsymbol{\gamma_w}*\left(\frac{\mathbf{V_g}}{\mathbf{V_w}}\right)*\left(\frac{\boldsymbol{\rho_o}}{\boldsymbol{\rho_w}}\right)}{\mathbf{2\ Ti}\left(\frac{\mathbf{P_o}}{\boldsymbol{\rho_w}*\mathbf{g}*\mathbf{L_d}}\right)-\left(\frac{\mathbf{V_g}}{\mathbf{V_w}}\right)} * \mathbf{h} \tag{8}$$

Where "V_g" is the working gas volume (m^3), "V_w" is the working liquid volume (m^3), and "γ_w" is Kinematic viscosity of working liquid [m^2/s].

2.1.2 Output length (L_o)

The value of Lo can be deduced from Eq. (3) as follows

$$L_o = (P_o*A_o) / (\rho_w*V_g*\boldsymbol{\omega_p}^{\mathbf{2}}) \tag{9}$$

Considering that $\omega^2 = 2g/L_w$, the value of Lo can be expressed as

$$L_o = 0.05\ (P_o/\rho_w)(L_w/L_g)(D_o/D_g)^2 \tag{10}$$

2.1.3 Efficiency

Considering that Q_{in} is the input power and the pump demand as the output work, the pump efficiency is

$$\eta = \frac{(\rho_o * g * \gamma_w) * \left(\frac{10.19}{d_i^{\,2}}\right) * \left(\frac{V_g}{V_w}\right) * \left(\frac{\rho_o}{\rho_w}\right) * h^2}{Q_{in}\left[\left[2\,Ti\left(\frac{P_o}{L_d * g * \rho_w}\right)\right] - \left(\frac{V_g}{V_w}\right)\right]} \tag{11}$$

3. Mathematical Study Results

The independent non-dimensional parameters which affect the output flow rate and efficiency are: (T_i), (V_g / V_w), and ($\frac{P_o}{\rho_w * g * L_d}$). According to Eq. (11), the value of $\left[\left[2\,Ti\left(\frac{P_o}{\rho_w * g * L_d}\right)\right] - \left(\frac{V_g}{V_w}\right)\right]$, is the value that controls the flow rate, and the efficiency. The smaller the difference, the greater the value of the flow rate and efficiency.

Also, the difference must be larger than zero, to avoid negative work. Input energy "Q_{in}" is an important parameter, which defines the FP efficiency. It is cleared that "T_i" depends on Q_{in}/V_g. For which T2 depends on the heat input, and T_1 depends on the cold sink cooled by the discharged water. Figure 6 shows the effect of volume ratio ($V_g \backslash V_w$) on the volumetric flow rate- in the non-dimension formula, dividing by gas volume and frequency (Q^o/V_g*f*60)- and shows that: the higher the ratio, the higher the flow rate of FP. Figure 7 and Figure 8 respectively show the effect of Ti and $V_g \backslash V_w$ on the efficiency. It is cleared, shown in Figure 9, that efficiency increases as (T_i), and $V_g \backslash V_w$ increases, but limited by the mathematical relations as shown in Eq. (8), and Eq. (11).

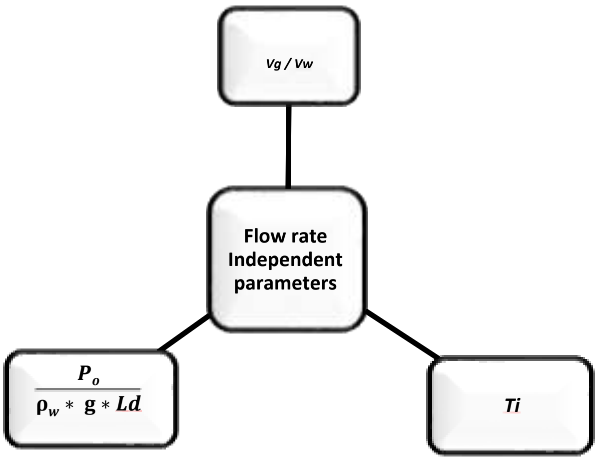


Fig. 6. FP. independent parameters [20]

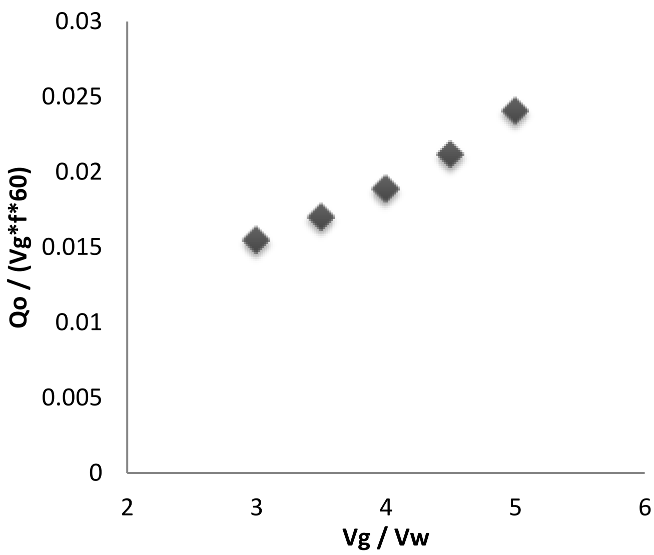


Fig. 7. Flow rate at different (V_g / V_w)

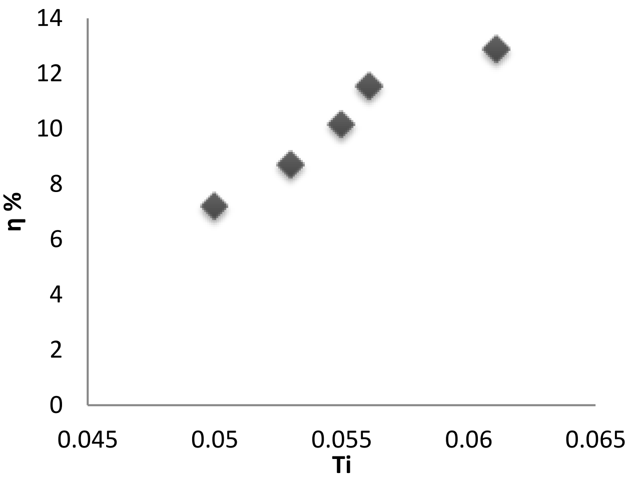


Fig. 8. Effect of temperature parameter T_i on η

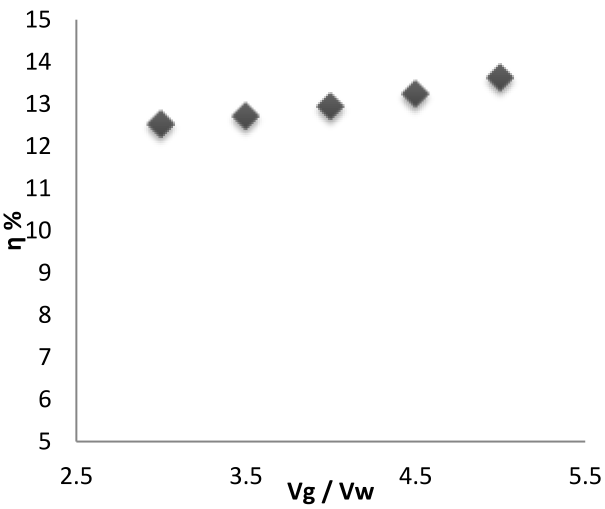


Fig. 9. Effect of (V_g/V_w) on the efficiency [20]

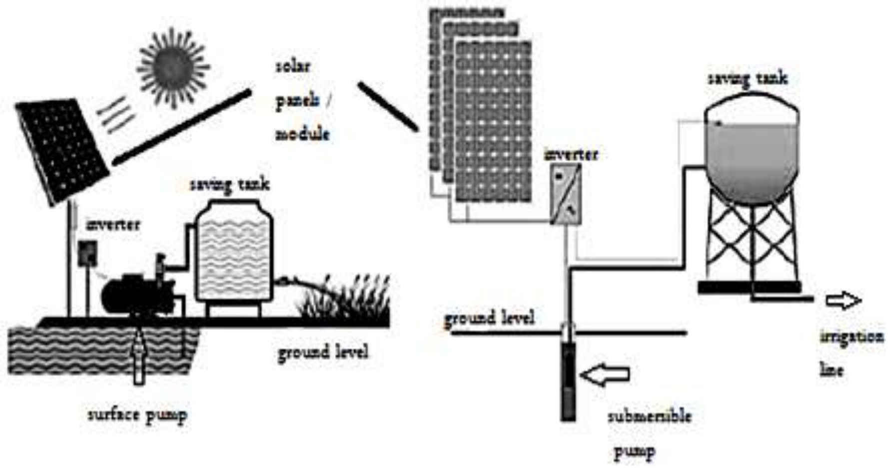
4. Alternative Solar Pumping Systems

Two types of the mechanical and non-mechanical solar pumping systems have been selected to provide an assessment for the FP in comparison with the other solar pumping techniques. These include centrifugal/PV and Ejector/Thermal solar/ refrigerant systems. In the following section a quick brief on the system systems is presented.

4.1 Centrifugal/P.V. Solar Pumping System

Centrifugal /P.V. solar irrigation systems – pumping in general- became one of the most growing solar system applications, and expected to grow from 5% in 2022 to 33% in 2050 for Egypt market, as RCREEE report 2020 has noted [24]. This will represent an increase in investments from 1,079 million $ in 2022 to be 7,121 million $ in 2050. So, it still represents good alternative to the traditional irrigation (pumping in general) systems.

Figure 10 shows the P.V. components: P.V. panels – centrifugal pump – electrical motor (A.C. or D.C.) – inverters – cables – controllers – accessories (valves – elbows – tubes – tanks).



(a) (b)

Fig. 10. Main components of P.V. solar pumping system, (a) surface source, (b) deep source

4.2 Ejector Solar Pumping System

Ejector system uses heated refrigerant to have a vapor that creates vacuum, when it flows through the ejector pump. The vacuum draws water. Accordingly, the pumped water is mixed with the un-dissolved refrigerant. Therefore, the system includes a separation tank to collect the refrigerant back to be recirculated. This is also important to avoid any pollution to the pumped water. However, this cause minor loses refrigerant, such that the refrigerant needs to be compensates. The system has an advantage of large flow rate (407 m^3/hour) at 7 m head as described in the previous study [24].

Steam Injector can be used as a solar non-mechanical pumping system. It has the advantages of no moving parts and low cost. Bennigoton and King in the study by Der Minassians [19], designed and implemented a station in 1976. It suffers from low efficiency, which is less than 1%. Other system was designed and tested by Paul A. Dellenback as described in the studies of Mason and Stevens [20] and Clements *et al.,* [25], as shown in Figure 11.

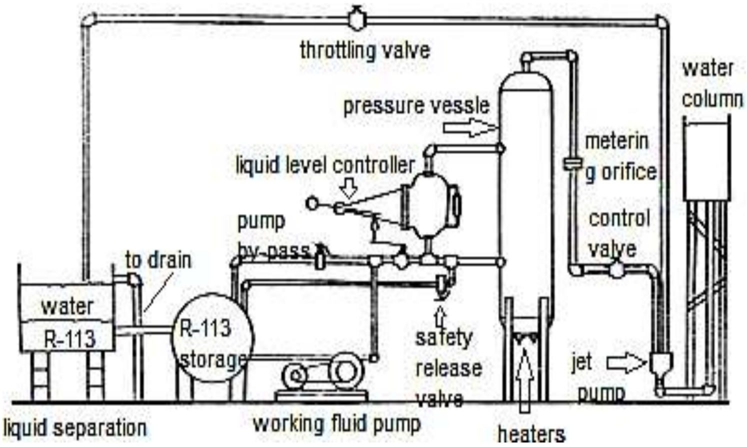


Fig. 11. Solar thermal jet pumping for irrigation [17]

5. General Comparison

Table 3 shows the advantages and disadvantages of FP and, P.V. centrifugal, solar pumping systems from the prospective of installation simplicity, operation, and maintenance.

Table 3
General comparison between F.P., P.V., and ejector solar pumping systems

System	Advantages	Disadvantages
Fluidyne pump	(i) Simple installation (ii) Simple operation (iii) Low installation and maintenance cost (iv) Minimum moving parts	(i) Low total head (ii) Low flow rate (iii) Low efficiency
Centrifugal P.V. system	(i) High flow rate (ii) Can designed and installed for different heads and different applications (iii) Acceptable efficiency	(i) High installation and maintenance cost (ii) System became more complex for large size (iii) More moving parts, so, needing spare parts and maintenance
Ejector – R-113 system	(i) High flow rate (ii) Suitable for large size applications	(i) High system complexity (ii) More controller parts and loops (iii) High installation and maintenance cost (iv) The system needs separation between water and working gas, that makes water pollution

In order to find out the economic viability of the FP in comparison with other solar water pumping system, the PV/Centrifugal pump is selected as a base for comparison since it is currently the most spread system for solar water pumping. According to Abou-Khodier and Mahmoud [24], the average cost for a solar PV water pumping system the average cost of complete water pumping system including the PV system as well as the electric pump per kW is 1750-2000 US$ in 2017. Considering the recent reduction in the system cost, this cost has been dropped to 1500 US$ per kW or even less as described by West [12]. Also, the comparison includes the R-113 ejector pump system which designed and tested as an irrigation station working by solar heaters [18]. Table 4 shows the comparison between the pumping cost between one meter cube of water, when it is being pumped using P.V. solar pumping system and that when the FP is used, using the best price estimates. Comparison between the cost per m^3 for water using Solar PV, R-113 ejector, and FP systems.

Table 4
Performance comparison between F.P., and P.V. solar pumping systems

Item		P.V. pumping system [9]	Fluidyne system	Ejector system [17]
Pumping parameters	Head (m)	≤ 10 m	≤ 7m	≤ 8m
	Flow rate (m^3/h)	12	6	180
	Pumping system Efficiency (including Motor, panels and inverters)*	15:20 %	≤ 7 %	≤ 30%
Components cost (E.P.)	solar panels Inverters	17500	- -	--
	cables	1000	--	1000
	Accessories & Control	1750	200	2500
	solar heater	--	4000	4000
	Valves and Metal tubes	200	500	3500
	Tanks	--	--	3500
	Electrical motor and Centrifugal pump	2500	--	1500
	Installation cost	1500	750	3000
Total CAPEX		24450	5450	18850
Annual OPEX (not including Labor Cost)		1000	800	1500
Annual amortized CAPEX		1,553.2	519.4	12,566.67
Total Annual cost including CAPEX and OPEX		2,553	1,020	14,067
Annual pumped flow (m^3)**		21,600	8640	388800
Cost per 1 m^3 pumped (EG pound)		0.12	0.22	0.08***

*Efficiency includes motor, panels, inverters, and battery (if there) and chargers, while efficiency for Fluidyne include the output work to input power, while ejector system includes efficiency of solar heaters and pressure vessel.
**Daily operating system assumed 6 hours, and 20 years for system life.
***Doesn't include the cost of R-113.

6. Conclusions

Stirling engine efficiency at the corresponding T_i represents a theoretical upper limit for the FP efficiency. This makes the effectives of the regenerator of important impact on the efficiency of the Fluidyne pump. Higher efficiency needs gas to liquid volume ratio greater than unity. Also, the materials of both the hot and cold tube should be of high thermal conductivity to ensure the most efficient thermal energy transfer to the working fluid. Displacer ratio (d_i) is preferred to be less than or equal to 0.5. Increase the heat added per specific volume of the pump increases the pump flow rate and efficiency. By comparing Fluidyne solar pump with other solar pumping systems including centrifugal/PV and Ejector/thermal solar/ refrigerant it has been found that Fluidyne solar pump is preferred for low flow rate and low head working conditions. Furthermore, it enjoys simplicity and low cost compared with the other systems.

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