Engineering Journal of Qatar University, Vol. 1, 1988.

"SOLAR WATER PUMPING — AN ANALYTICAL OVERVIEW"

By

Wafik A. Kamal,
Associate Professor,

Faculty of Engineering,
Qatar University, Doha,
Qatar, Arabian Gulf.

ABSTRACT

Two basic thermodynamic conversion techniques of solar water pumping are recognized. In the first technique, a high internal energy fluid heated in a solar collector is used to power a conventional heat engine which drives a conventional pump. The second technique involves specially designed solar pumps, for example the Boldt, Rao and Michaelis designs. The study reveals that an engine working on the organic Rankine cycle and having an output of a few kilowatts (maximum 20KW) would be most suitable for pumping purposes. It is also concluded that a pumping rate of 2-3 cubic meters per hour is obtainable for every square meter of the flat plate collector area in an engine employing Freon-11 as the working fluid.

1. INTRODUCTION

Developing countries are mostly situated in sunny regions of the world and are in general not self sufficient for their conventional (fossil fuel) energy requirements. Therefore, it is very vital that they should develop their utilization of solar energy.

Solar energy is a free, inexhaustible, omnipresent (no transport or distribution problems) and non-polluting form of energy. In addition to its strategic potential in the production of electricity and its domestic uses in cooking, space heating and air conditioning, some essential agricultural applications can be cited namely, desalination of sea water, irrigation and food preservation by means of refrigeration and drying. However, the intermittance and variability of solar radiation reaching the surface of earth inherently limit useful conversion by requiring either intermediate storage of energy or application to a task where intermittency is acceptable. The pumping of irrigation water is an operation where normally intermittent operation is acceptable.

A review of past efforts to develop solar powered irrigation pumps (1) revealed that successful attempts were made as early as 1850. Nearly seventy years ago, one of the largest (37KW) and most important solar irrigation plants was constructed and installed by Shuman & Boys in Meadi, Egypt in 1913 (2).

In this paper, basic mechanical technique for solar water pumping are critically reviewed and assessed. The Rankine cycle-powered solar pump is then studied in detail and the different design alternatives outlined. Thermal calculations of the cycle are made to find the most suitable working fluid. Finally, a survey of the different designs of such pumps, already in operation, is presented.

2. SURVEY OF TECHNIQUES OF SOLAR PUMPING

In principle, a solar pump is a conversion system comprised of different single converters, which transforms energy in solar radiation to mechanical energy which in turn is used to drive the water pump. As can be seen from Figure (1), solar energy can be converted to mechanical power in a conventional or a specially designed thermodynamic system. Alternatively, solar energy can be converted directly, to electricity which is fed to an electric motor driving the pump. This survey will concentrate, however, on thermodynamic conversion methods.

In the solar-thermal scheme, any solar collector or concentrator is employed to produce a high internal energy or temperature in a fluid. The energy may then be utilised directly in any of the conventional cycles such as Rankine, Stirling or Brayton to produce mechanical energy. The mechanical energy is then used to operate conventional or specially designed pumps. Alternatively, the high internal energy contained within a fluid may be utilized in specially designed systems for water pumping. In the following sections, the thermodynamic conversion processes are briefly discussed.

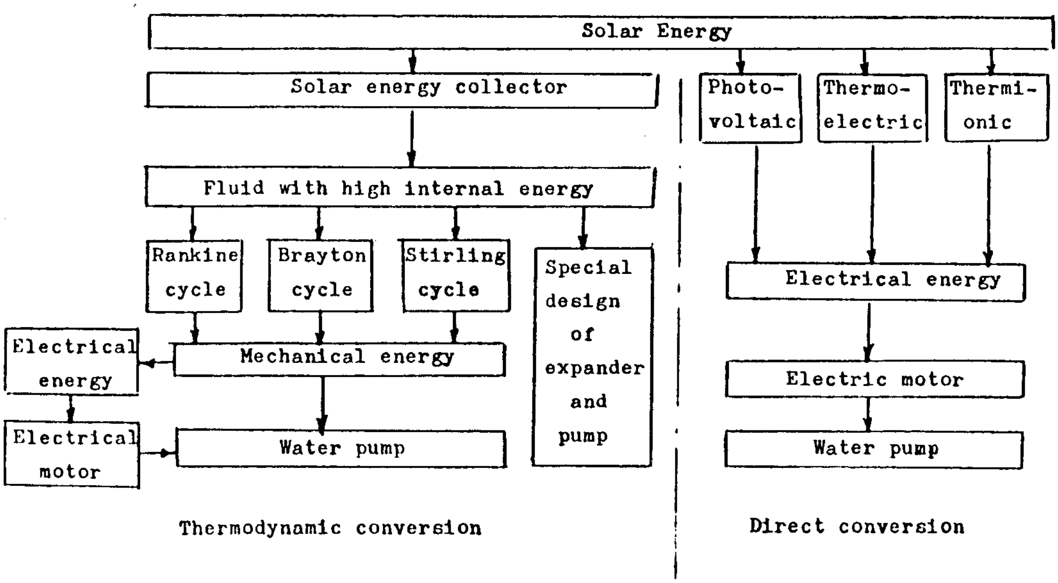

Fig. 1: The Solar Water Pumping Chart.

A — SOLAR PUMPS WORKING ON CONVENTIONAL CYCLES

i The Solar Rankine Cycle

The cycle consists basically of an evaporator, an expander, condenser and a liquid feed pump. Vapour is obtained when a liquid working fluid is heated by solar radiation either directly in the collector or indirectly by exchanging heat with the primary fluid as shown in Figure (2). The vapour expands in a turbine, a reciprocating engine or a rotary displacement engine, to do work. From the engine it flows to the condenser which is either air cooled or is cooled by the pumped water. The condensate is re-injected by the feed pump (usually operated by the solar engine itself) to the evaporator. The solar collector may be a solar pond, a flat plate collector or any two or three-dimensional concentrator.

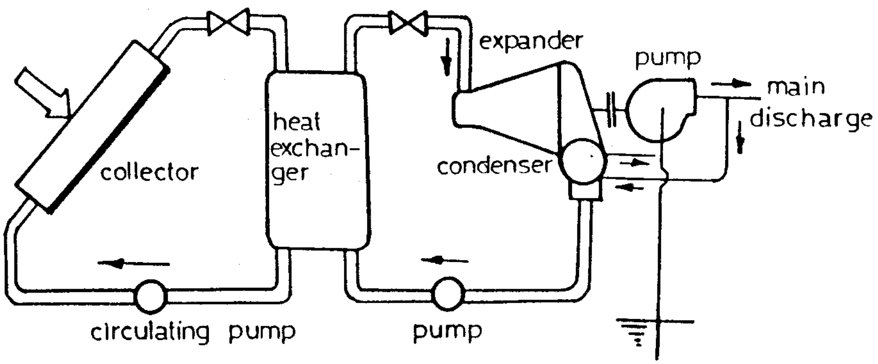

Fig. 2: The Solar Rankine Cycle.

The solar Rankine cycle will be analysed in further detail in the second part of this paper.

ii The Solar Stirling Cycle

Two of the hot-air engines designed to operate on the Stirling cycle have been adapted to use solar energy as their input heat source. These are the Farber engine (4) and the Khana engine (5). The Farber engine is shown schematically in Figure (3). The solar energy is focused on area (A) where air is heated and its expansion pushes the piston (P) down. In the down-stroke of the piston, the displacer (D) moves to the left by the linkage (L). On the up-stroke of the piston, the displacer moves to the right and all the hot air is at the left section of the cylinder (B) and loses heat to the cooling water. The engine has an efficiency of 9% (not including collector efficiency) and develops maximum power at crank speed of 150 rpm. When the solar radiation is concentrated directly within the engine through a quartz window by using a parabolic concentrator a brake efficiency of over 30% can be accomplished (6).

iii The Solar Brayton Cycle

The cycle is shown in Figure (4). Air is drawn from the atmosphere and is compressed in a compressor to a higher pressure. The high pressure is then admitted to the absorber of a high concentration parabolic concentrator.

Then, it expands in a gas turbine producing mechanical work before being exhausted to the atmosphere.

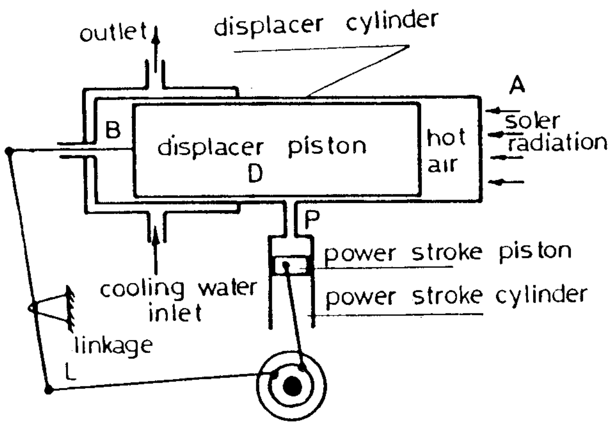

Fig. 3: The Solar Stirling Engine.

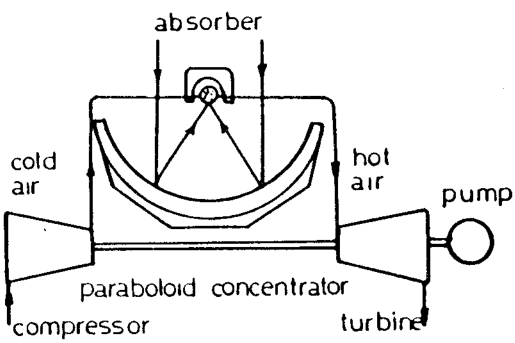

Fig. 4· The Solar Brayton Cycle.

The main disadvantage of hot-air engines, either Stirling or Brayton, is that they require high temperatures for their operation. Therefore, flat plate collectors cannot be used and the engines have to be operated in conjunction with two and preferably three-dimensional solar concentrators. Since there is a practical limit to the size of dish-type concentrators, due to the wind loading and their sun tracking, one may conclude that such systems are for small capacities, lower than 5KW.

B — SPECIAL DESIGNS OF SOLAR PUMPS

In the previous section, different designs of solar engines working on conventional thermodynamics cycles were surveyed. Conventional pumps can be operated by any of these solar engines. In this section, special designs of expanders and pumps that have been developed especially for solar energy as their input source are presented. Basically, they all make use of the fact that the change of phase of any substance (for solid to liquid or from liquid to vapour) upon heating results in a change in its volume. The volume increase at a given pressure may be utilized to displace water to a higher elevation whereas the volume reduction at a lower pressure is used to produce suction of water from a depth.

Three different designs of solar pumps are presented in this section, namely those of Boldt (7), Rao (8) and Michaelis (9). The first two use the change of phase from liquid to vapour while the third uses the change of phase from solid to liquid.

i The Solar Powered Thermopump

Figure (5) shows the basic idea of a thermopump. At the beginning, the pump is filled with water. When heat from a solar collector is supplied to the cylinder, water evaporates, changes volume and pushes down the water level in the cylinder discharging water through the outlet check valve. When the vapour volume increases so that the water level comes below the base of the "U" of the vapour tube, a triggering action takes place which syphons all the vapour from the cylinder into the condenser. As the vapour comes in contact with the mass of cool water in the condenser, it condenses and the pressure decreases sucking fresh water through the inlet check valve and refilling the pump. The intermittent pumping action starts again.

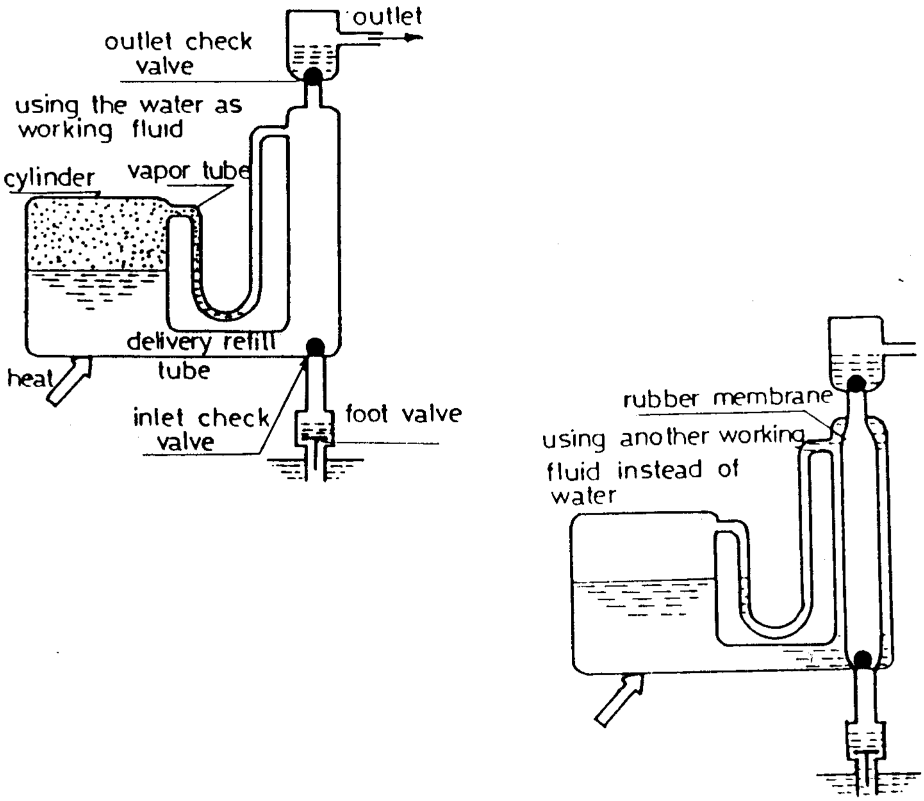

Fig. 5: The Basic Idea of a Thermo-Pump.

If a working medium other than water is used, a collapsible rubber lung is used to separate it from the pumped water, Figure (5)b. Normally a liquid with a low boiling point such as freon, propane or ethyl-alcohol can be used. Figure (6) shows a schematic diagram of a solar powered thermopump designed by Boldt and tested in Tanzania (7). The pump is cheap, reliable and can be produced locally from readily available materials and requires no high standard of accuracy. However, it has a very small capacity and is limited to shallow wells (less than 15m deep).

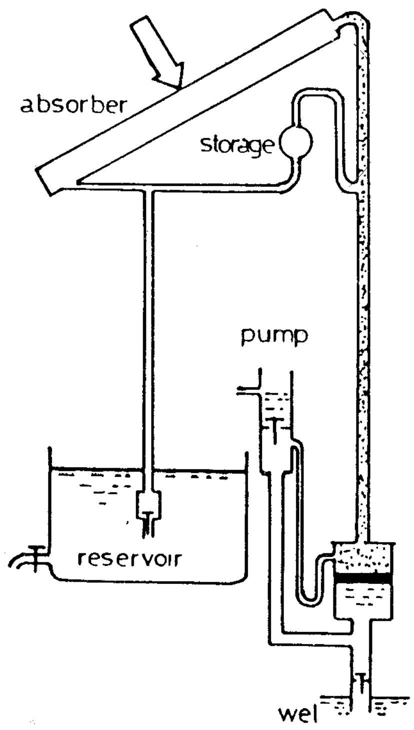

Fig. 6: Principle Diagram of the Solar Powered Thermo-Pump.

ii The Birla Pump

In 1976, Rao & Rao (8) presented the first prototypes of their air-cooled (Figure 7) and water-cooled (Figure 8) solar water pumps having no moving parts except for check valves. The pumps are specifically designed for rural lift irrigation and use an inexpensive mixture of petroleum liquids with a boiling temperature in the range of 35-40°C. In the case of the water-cooled pump, Figure 8, the working fluid drawn into the flat plate collector is vapourized and returned to the flash tank. Vapour from the flash tank is let into one of the water tanks, displacing the water. The displaced water condenses the vapour in the shell side as it goes through the condenser coils. After the first tank is emptied, the vapour is switched over to the second tank. Simultaneously, the vapour in the first tank is condensed by the water being pumped from the second tank. As condensation proceeds, the pressure in the first tank is reduced and water enters through the non-return valve. Thus, as the second tank is emptying the first one is being filled. On reversing the cycle, by manipulation of the valves, the first tank will pump while the second one draws water, and water can be pumped continuously. On the other hand the air-cooled pump, Figure 7, pumps only once in a day thus its pumping capacity is limited by the water tank size.

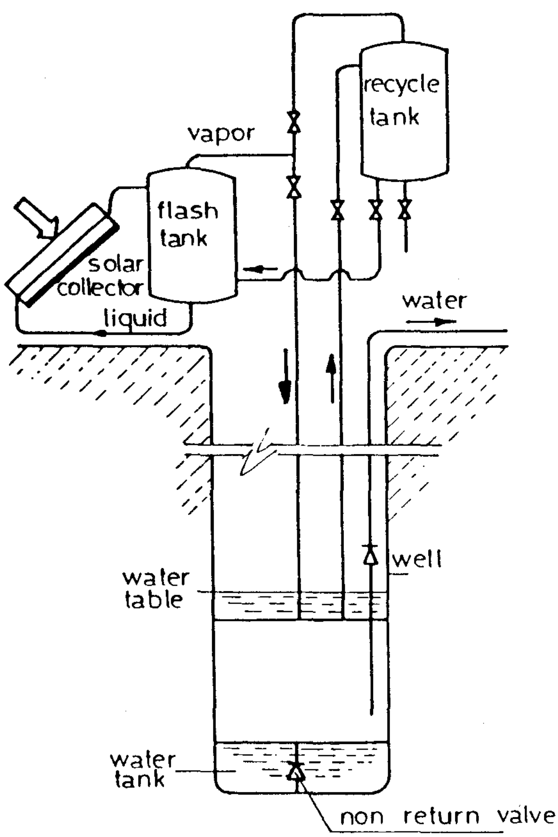

Fig. 7: Air Cooled Birla Pump.

Control of the system of valves is, in general, the major disadvantage of Birla pumps since the proposed electrical control does not meet the requirements of a rural solar pump which should be independent of any external source of power.

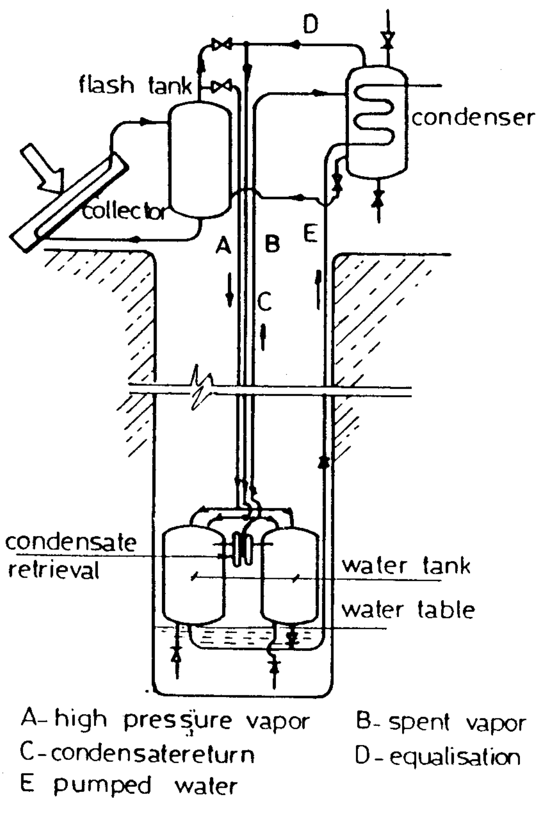

Fig. 8: Water Cooled Birla Pump.

In 1980, Sudhakar et. al. (11) modified Rao's original design to solve the problems of contamination of the pumped water with the working fluid, a problem which limited the types of working fluids to be used and required the occasional make-up of the organic working fluid. Control of valves remains, however, quite sophisticted.

iii A Pump Employing a Thermal Linear Motor

This pump, shown schematically in Figure (9), was first operated in Hannover, West Germany; it gave a discharge of $1m^3/hr$ with a flat plate collector of area $2m^2$ (9). The solar thermal linear motor depends on the increase of volume of wax when changing from solid to liquid. In Figure (9), the two linear motors (5) & (6) each consists of a cylinder inside which wax is put and the cylinder is encased in a jacket through which the alternately hot (80-90^{0}C) and cold (20-30^{0}C) water flows and brings the expansion wax to the point of melting or setting. Therefore, the sliding sealed pistons (7) & (8) are forced out or in again, operating the water pump pistons (9) & (10). The two slide valves (11) & (12) are opened and closed alternately by means of the control linkages (13) & (14). A hand operated pump (15) is needed only for starting.

The pump is relatively cheap and durable but the pumping rate is low and the efficiency is very low.

From the previous survey, it is clear that the efficiency of the conventional cycles (Rankine, Stirling and Brayton) as well as their daily output are higher than those of unconventional designs. The special designs, on the other hand, have the advantages of being cheap, easy to maintain and can be produced locally, which makes them suitable for developing countries. However, since in solar power systems, the cost ratio of the collector to the engine is usually high, the engine must have a high efficiency. Thus, the concept of a simple, cheap engine is not economically viable.

Among pumps operating on conventional cycles, that of the Rankine cycle is recommended for the following reasons:-

i) It has a high efficiency even when operating with the moderate temperatures (80-120^{0}C) attainable by a flat plate collector.

ii) It is highly reliable and durable because of its sealed construction.

iii) It is adaptable for use over a wide power range (1KW to hundred of KWs).

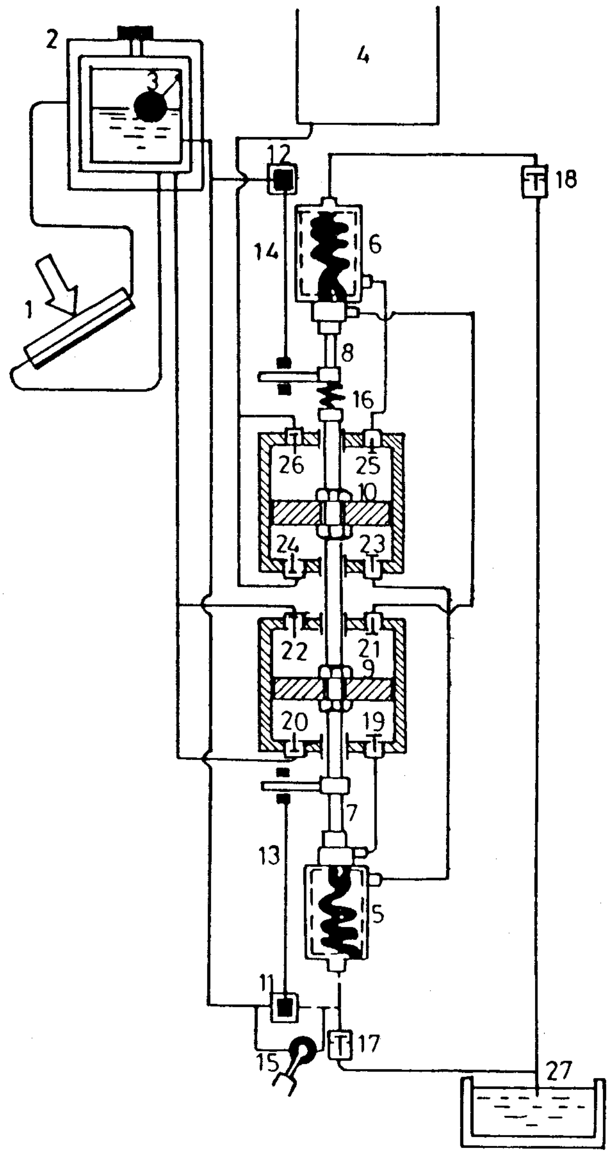

Fig. 9: Solar Thermal Linear Motor Pump.

Part No.	Part Name
1	Flat Plate Collector
2	Insulated Hot Water Storage Tank
3	Ball Valve
4	Elevated Tank
5 & 6	Linear Motors
7 & 8	Working Pistons
9 & 10	Water Pump Pistons
11 & 12	Slide Valves
13 & 14	Control Linkeages
15	Hand-operated Pump for Starting
16	Spring
17 & 18	Non-return Valves at inlet to Linear Motors 5 & 6
19 to 26	8 Valves at entrance & exit of Water Pump Cylinders
27	The Well from which water is pumped

As can be seen from Figure (10), c decreases as the collector temperature increases, while the Rankine cycle efficiency improves. The resultant is that there is an optimum operating boiler temperature (around 100°C for R-11) resulting in the highest overall system efficiency, (14).

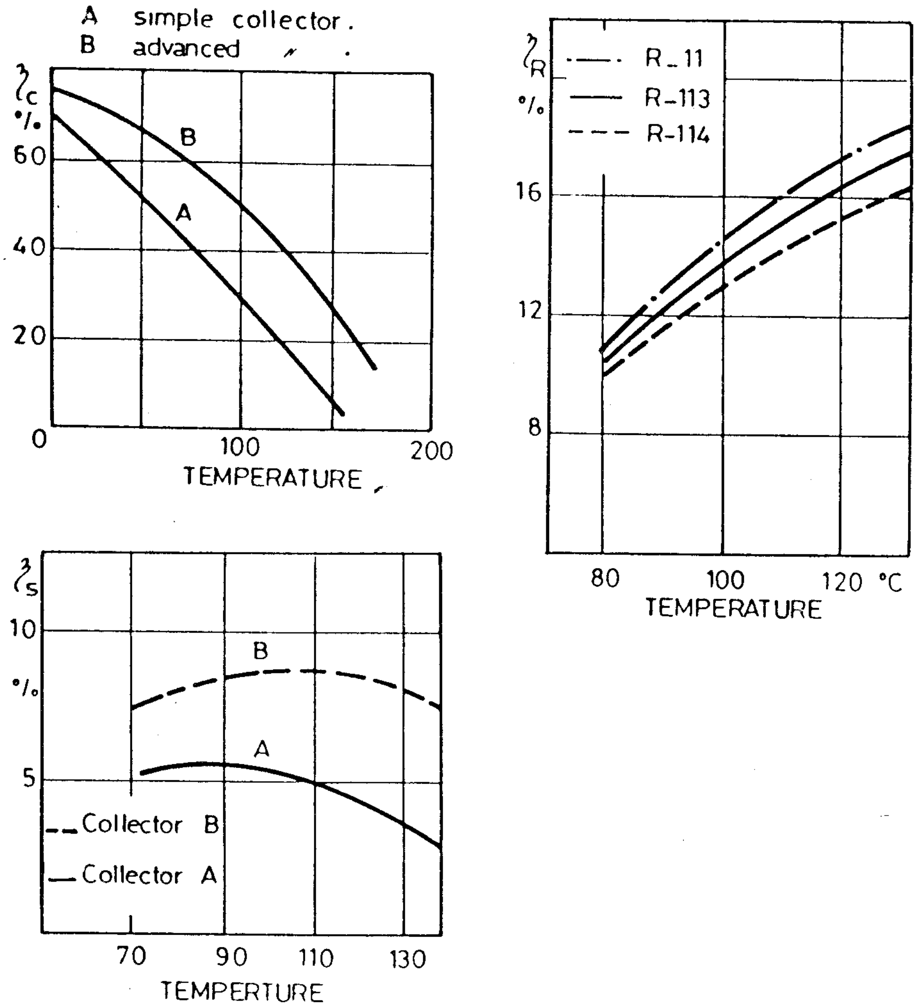

Fig. 10: Variation of Collector Rankine Cycle Engine and System Efficiency with Collector Outlet Temperature (14).

B — THERMAL ANALYSIS OF RANKINE CYCLE

The calculations were performed to estimate the discharge of the pump operated by a Rankine cycle at the time of peak solar radiation intensity per square meter of the collector area, when different types of the working fluid are used. The most suitable fluid is considered to be that giving the highest rate of water pumping (for a fixed lift of 3 meters), the highest cycle thermal efficiency and highest overall plant efficiency.

It is assumed that solar collector leaving temperature and efficiency are 80°C & 43% for a flat plate collector, 200°C and 60% for a parabolic cylindrical concentrator and 450°C and 60% for paraboloid concentrator. The condensing temperature is fixed at 30°C while the incident solar radiation per m^2 is 800 watts. Besides, the following efficiency values are assumed for the different components of the plant:- reciprocating engine 75%, turbine 80% (when expanding steam) and 70% (when expanding refrigerant), water pump 70%, mechanical transmission 95% and heat exchanger 95%. The cycle is represented on the pressure-enthalpy chart for the cases of direct and indirect evaporation in Figure (11).

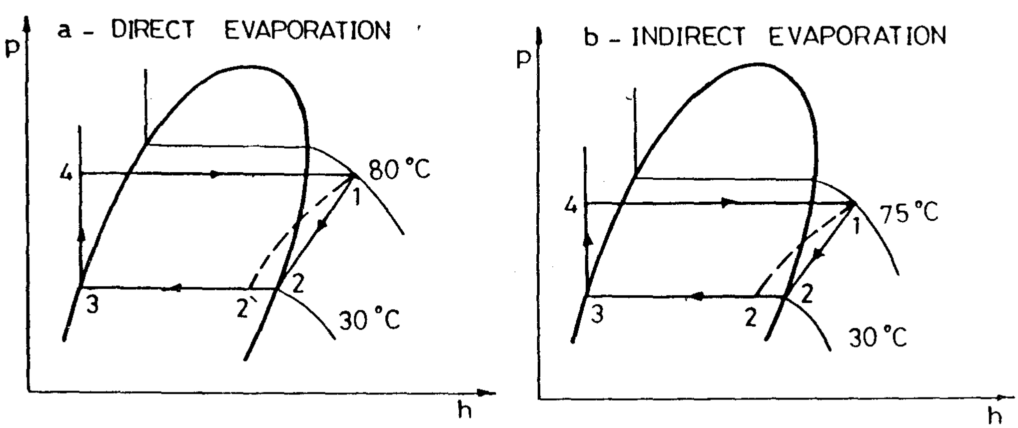

Fig. 11: Pressure Enthalpy Chart for a Simple Rankine Cycle.

Results for the case of indirect evaporation of working fluid using water heated in a flat plate collector are given in Table (1), from which it is clear that Freon-11 is the most suitable organic fluid for the Rankine cycle pumping plant.

Results for a flat collector evaporating Freon-11 directly are compared in Table (2) with those for concentrators of the trough & dish types evaporating water. The clear increase in pumping capacity and efficiency is accompanied by a big increase in cost, which makes use of concentrators viable only for large plants. Due to the scattered nature of deep-well irrigation, several small irrigation pumps rather than a large unit, are generally needed.

Table (1): Effect of type of working fluid on the performance of a Rankine cycle solar pump (indirect evaporation).

Working fluid	Expander	Pump Discharge m^3/hour	Cycle thermal efficiency %	Overall system efficiency %
Freon-11	Turbine	2.262	8.49	2.31
	Rec. Eng.	2.424	9.09	2.47
Freon-12	Turbine	1.970	7.46	2.00
	Rec. Eng.	2.000	8.00	2.17
Freon-22	Turbine	1.860	7.08	1.92
	Rec. Eng.	1.990	7.60	2.06
Freon-113	Turbine	2.178	8.20	2.22
	Rec. Eng.	2.333	8.80	2.38
Freon-114	Turbine	2.149	8.08	2.19
	Rec. Eng.	2.303	8.65	2.35
Butane	Turbine	2.130	8.00	2.17
	Rec. Eng.	2.280	8.56	2.30
Methyl Chloride	Turbine	1.676	6.07	1.74
	Rec. Eng.	1.796	6.50	1.00

*Pump discharge is for 1 m of collector area. Lift = 3 meters Water is the primary fluid.

Table (2): Comparison between the results for cycles using a F.P. Collector, a trough concentrator and a dish concentrator.

Collector/ Concentrator	Working fluid	Pump Discharge m^3/hour	Rankine cycle efficiency %	Overall efficiency %
Flat plate	Freon-11	2.99	10.7	3.0
Parabolo-cylindrical	Water	10.53	27.0	10.8
Paraboloid	Water	11.90	30.4	12.1

C. DIFFERENT DESIGNS OF RANKINE CYCLE SOLAR WATER PUMPS

Several solar pumping installations have been erected in different parts of the world. The six most significant designs are considered here. Table (3), summarises the main characteristics of the six pumping plants, while some main construction details are shown in Figures (12) to (15).

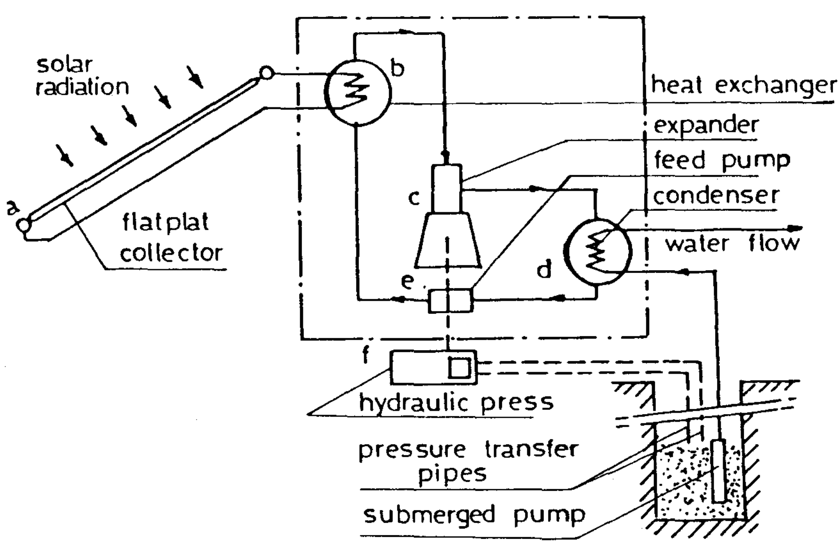

Fig. 12: Schematic Diagram of Sofretes Solar Water Pump.

Table (3): Main characteristics of Rankine cycle pumping stations already in operation

Design by	Power KW	Collector type	Collector area m²	Max. temp. C	Working fluid	Expander	Speed rpm	Construction shown in
SOFRETES (France)	1	F.P.C.	70	90	Butane R-11	2-cyl rec. eng.	200	Fig. 12
	30		1500	90	R-11	Turbine	7400	
N.P.L. (India)	1	F.P.C.	10	90	R-114	Spiral expander	1800	Fig. 13
MBB (Germany)	10	F.P.C.	400	90	R-114	Spiral expander	1500	Fig. 14
NML/BMI (USA)	37	Trough Concnt.	554	150	R-113	Turbine	30000	Fig. 15
MBB + KISR (Kuwait)	100	Dish Concnt.	1000	above 400	Toluene	Turbine	19000	—
ERDA/DSE (USA)	150	Heliost. + central-receiver		above 440	water	Turbine	5400	—

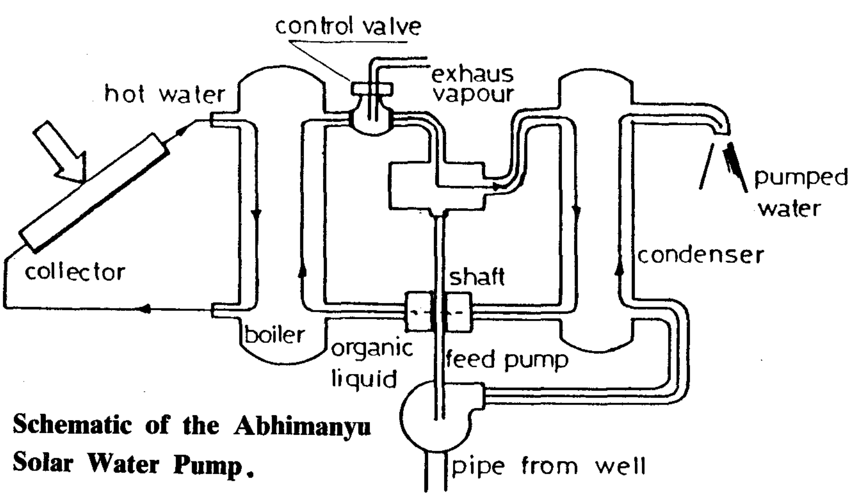

Fig. 13: Schematic of the Abhimanyu Solar Water Pump.

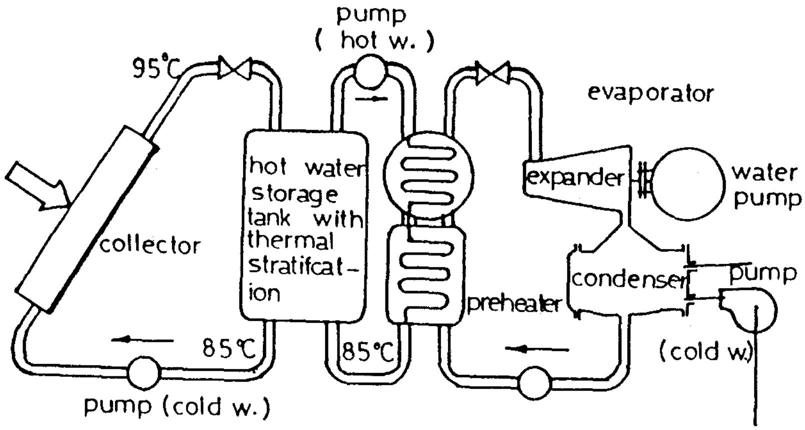

Fig. 14: Schematic of the MBB Solar Water Pump.

4. ECONOMICS & PROSPECTS FOR SOLAR PUMPING

In a study of the technical and economic factors of solar water pumping undertaken as part of UNDP/World Bank Project, Derrik et al (15) argue that it is likely that solar thermodynamic pumping will be more cost-effective in large scale systems rather than in small scale systems. They base their argument on that, as the size of the system is increased the fixed cost proportion of any installation becomes less significant. In addition, development cost for a small system may well be similar to those for a large system. A larger system may also justify the cost of attendance of a local person to maintain and operate the system.

However, the potential of local manufacture of simple small scale thermodynamic systems is an attractive advantage, since it can lead to a reduction in the total fabrication cost, availability of spare parts and reduction of maintenance time as well as being part of the much needed technology transfer. An example of such cooperation is the joint production of the Dornier 1KW solar water pump in Hyderabad together with their Indian partner BHEL (16). The hermitically sealed pump, operated by 32.5m^2 selectively-coated refrigerant-charged collector and a double-acting piston directly coupled to a piston pump is priced at $16,000. It is designed for lifts **up to 40m.**

As part of the UNDP/World Bank Project to examine the economic viability of solar pumping, Kenna et al (17) compared solar pumps, wind pumps, diesel pumps, animal powered pumps and hand pumps for application in irrigation and/or rural water supply.

Their computer models predicted that, at present, solar pumping may be competitive with diesel pumps at static heads of **around 2m.** Solar pumping may have an optimum capacity to suit areas of around 1 hectar for heads in the 2-7m range. Thermodynamic solar pumping is potentially an economically competitive option to solar pumping in the near term, but anticipated reductions in the cost of photovoltaic modules to below $5 per peak watt will result in PV systems costing less than thermosystems. They will make solar even competitive with diesel at lifts upto 7m.

The study by Karmeli et al (18) was addressed to two questions. The first was concerned with finding the least-cost solar system by considering the alternative use of either thermal or water storage. The second involved the determination of areas where solar energy could be economically competitive with conventional sources for pumping installations. In previous economic comparisons it was assumed that conventional energy might be available in the vicinity of a proposed pumping site. Yet, there are many developing countries with large areas of land, plentiful sunshine and which lack conventional power infrastructure. The paper attempts to find the critical distance that a proposed pumping site must be located from a source of electricity or fuel for which the solar option would start to be less expensive. A tentative example — based on 1981 figures for energy cost and inflation rates — showed that solar would be more economical than diesel if a pumping site was located more than 22.5 Km from the nearest source of diesel fuel or more than 63 Km from the electricity grid.

In analysis and evaluation of the 19 KW Willard solar thermal power irrigation system published recently, Fenton et al (19) suggested that extensive R & D work has to be put into large scale solar pumping units before they can be regarded as proven technology. Their system consisted of 1276m^2 trough-type single axis tracking collectors powering a R-113 Rankine cycle heat engine. The engine operated only 560 hrs over 1.5 years operational period, while the collector array operated 74% of the time possible. The reflectivity of the polished aluminium surface of the collector array degraded from 65 to 50%. The heat engine operated 30% of the time possible due to problems with the turbine-gearbox assembly that warranted improvements. Fenton et al concluded that compared to conventional pumping systems, large solar systems similar to the Willard unit cannot be justified in the immediate future.

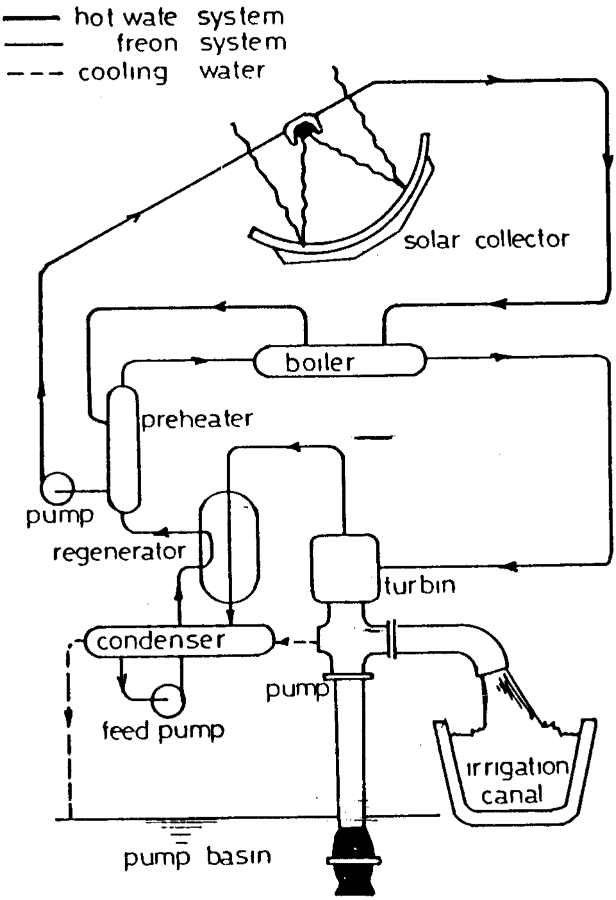

Fig. 15: Schematic of the NML/BMI Solar Irrigation Pump.

5. CONCLUSIONS

Solar energy can be readily used in pumping water for irrigation at relativel igh initial cost and low running cost. Due to the scattered nature of deep well irrigation, several small pumps rather than a large unit are generally needed. This makes it possible to mass produce small solar pumps and therefore reduce the production cost making them competitive with the alternative sources.

REFERENCES

1. **Pytlinski, J.T.:** "Solar Energy Installations for Pumping Irrigation Water". Solar Energy Vol. 21, 1978, pp. 255-262.

2. **Ackerman, A.S.:** "The Utilization of Solar Energy". *Trans. The Society of Engineers, London,* Vol. 103, 1914, pp. 81.

3. **Bahadori, M.N.:** "Solar Water Pumping". *Solar Energy,* Vol. 21, 1978, pp. 307-316.

4. **Farber, E.** and **Prescott, F.:** "Closed-cycle Solar Hot Air Engines" — part 1, a 14 HP engine. *Solar Energy,* Vol. 9, 1965, pp. 170-176.

5. **Khana, M.L.:** "Studies on Hot Air Engines Run With Solar Energy". Paper No. 7/14 presented at *ISES Confr., Melbourne, Australia, 1970.*

6. **Trayser, D.** and **Eibling, J.:** "A 50-Watt Portable Generator for Remote Area Use Employing a Solar Powered Stirling Engine". Presented at *Int. Soc. Energy Conversion Conference, 1966.*

7. **Boldt, J.:** "Solar Powered Water Pump for the Rural Third World". *Laboratory for Energetics Report* RE 78-3, *Technical University of Denmark,* 1966.

8. **Rao, D.P.** and **Rao, K.S.:** "Solar Water Pump for Lift Irrigation"¼Solar Energy, Vol. 18, 1976, pp. 405-411.

9. **Michaelis, F.U.:** "Water Pump Operated by a Solar Thermal Linear Motor". In (*Solar water pumps, technical potentialities*) published by the German Appropriate Technology Exchange (GATE). S1/4, 1978, pp. 62-67.

10. **Maccraken, C.D.:** "The Solar Powered Thermopump". Presented at *Conf. Solar Energy — The Scientific Basis,* Tucson, Arizona, 1955.

11. **Sudhakark, K., Krishna, M., Rao, D.P.** and **Soin, R.:** "Analysis and Simulation of a Solar Water Pump for Lift Irrigation". *Solar Energy,* Vol. 24, 1980, pp. 71-82.

12. **Wood, R.** and **Platt, E.:** "Shallow Solar Pond Powered Irrigation Pumping — A Feasibility Study". *Lawrence Livermore Laboratory Report,* University of California, 1979.

13. **Bhide, V.G.:** "Conversion of Solar into Mechanical or Electrical Energy, Indian Experience". In (*Solar Water Pumps, Technical Potentialities*), published by GATE, S., 1/4, 1978, pp. 35-41.

14. **Ishikawa, S.** and **Watanabe, M.:** "Organic Rankine Cycle Engine Development and its Applications to Solar Energy Utilisation". Presented at *COMPLES Conference, Dhahran,* Saudi Arabia, 1975.

15. **Derrick, A., Kenna, J.** and **Gillet, W.:** "Small Scale Solar Thermodynamic Water Pumping Systems". In *Proceedings of the Solar World Congress,* Perth, edited by S. Szokplay, Pergamon Press, 1983, pp. 1279-1283.

16. **Spiedel, K.** and **Schneller, D.:** "Field Tests of a Solar Powered Thermal Water Pump, Potentiality and Economics in Developing Countries". In *Proceedings of the Solar World Congress,* Perth, edited by S. Szokolay, Pergamon Press, 1983, pp. 2686-2690.

17. **Kenna, J., Wright, D.** and **Fraenkel, P.:** "The Prospects for Solar Water Pumping". In *Proceedings of the Solar World Congress,* edited by S. Szokolay, Pergamon Press, 1983, pp. 2703-2710.

18. **Karmeli, D., Atkinson, J.** and **Todes, M.:** "Economic Feasibility of Solar Pumping". *Solar Energy,* Vol. 27, 1981, pp. 251-260.

19. **Fenton, D., Abernathy, G., Krivokapich, G.** and **Ots, J.:** "Operation and Evaluation of the Willard Solar Thermal Power Irrigation System". *Solar Energy,* Vol. 32, 1984, pp. 765-751.