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Development of low temperature heat engine for water pumping application

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Abstract

This paper presents the description and operation of solar powered heat engine for water pumping operation. The heat engine model has been developed to deliver 2L per stroke and at operating head of 5 meters. The design of the heat engine is based on thermal water pump cycle and uses organic working fluid. Working fluids like acetone and n-pentane were tried during the experimental investigation. The heat engine operates between 30 °C to 100 °C temperature. The major part of this paper reports the design of the heat engine, recognition of problems occurred during the actual operation of the system and finally the material compatibility test. Thermal performance test results have been presented with recommendations for further improvement.

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Keywords: solar thermal pump; working fluid for solar thermal pump; diaphragm compatibility with working fluid, thermal pump.

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1. Introduction

India is one of the solar belt countries and its economy depends on irrigated agriculture. The estimated electricity consumption in the agricultural sector is (18.03%) [1]. Development of a solar pump for irrigation is important and worth investigation.

Several attempts have been made to develop a solar thermal pump. In 1976, D. P. Rao and K. S. Rao developed a solar pump in which they have used n-pentane as working fluid (Boiling point 36 °C at 1 atm). In this project they pressurised the water tank immersed in water table with the vapour of n-pentane and pumped the water [2]. Duffie and Beckmann elaborate the Gila-Bend project in which R-113 used as working fluid. In Gila –Bend project vapours of R-113 are expanded on turbine which was coupled to impeller having functioning to pump the water [3]. In 1986 Kishore et.al developed a solar pump prototype named 'Indo-Swiss experience'. In this prototype piston-cylinder assembly was developed to pump the water. R-11 was used as working fluid. In that system, two cylinders were used, one main cylinder and another hydraulic cylinder. R-11 vapour was actuating main cylinder's piston which was connected to hydraulic cylinder by means of mechanical shaft. This actuation of hydraulic cylinder was pumping water [4]. In year 2001 another solar pump was developed by Wong and Sumathy. Ethyl ether (Boiling Point 34°C at 1 atm) was used as working fluid. In that system compressed air was lifting the water from the water tank immersed in water table. This compression of air was carried out by vaporisation of working fluid by solar energy [5]. During the year 2013 Date et.al developed a solar pump using piston cylinder arrangement and acetone as working fluid (boiling point 56 °C at 1 atm). The energy source was solar pond for that project [6].

The purpose of this research project is to develop a solar thermal pump using diaphragm arrangement. The tests were also performed to select the compatible diaphragm material with the working fluid. The principal of working is similar to that described by Mehdi N. Bahadori for pumps [7] i.e. to evaporate the working fluid having low boiling point with the help of solar thermal principle and provide the energy to lift the water.

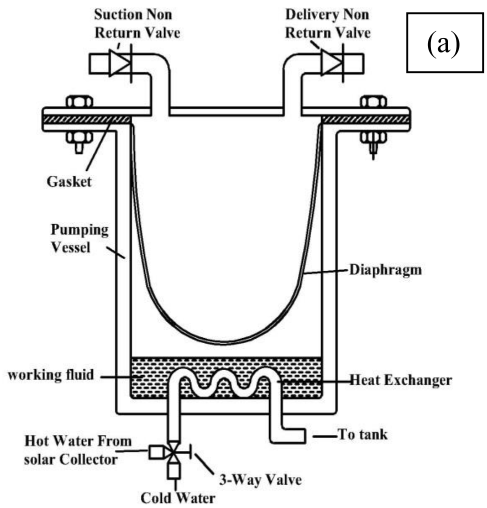
Nomenclature

$\dot{m}h$	Hot water flow rate (Lpm)
m	Mass of water pumped (Kg)
η	Overall Efficiency (%)
H	Total Head developed (meter of water column)
Hs	Static Head (meter of water column)
Hd	Dynamic Head (meter of water column)
Th	Hot water circulation time (second)
ΔT	Difference between inlet hot temperature and outlet hot water temperature (°C)

2. Experimental Design

The system works on the principle of membrane displacement using pressure developed by working fluid. This membrane has to be compatible with the working fluid in terms of chemical inertness and permeability and pressure bearing capacity. The membrane is displaced by phase change of the working fluid on heating and the membrane will displace the water present across the membrane. The general assembly drawing of pumping vessel is shown in the figure 1(a).

In construction of pumping vessel, compatible diaphragm is assembled as shown in figure 1(a) between gasket and flange of pumping vessel and fastened by nut and bolts. Suction NRV (Non return valve) has connected to cover plate at suction side of the vessel. The delivery side NRV delivers the water at pumping stroke. A heat exchanger coil is assembled at the bottom of the pumping vessel. At inlet of the heat exchanger coil three-way valve was connected to switch supply of hot water to cold water or vice-versa. The working fluid with known quantity was filled at the bottom of the pumping vessel. The general assembly drawing of the complete pumping system is shown in figure 1(b).



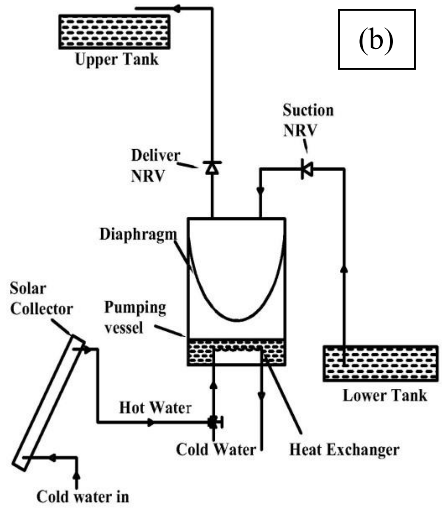


Fig. 1. (a) General Assembly drawing of pumping vessel, (b) System Assembly Drawing.

2.1. Working principle

When the hot water supply is switched on through three-way valve, hot water enters the heat exchanger and heats up the working fluid. When temperature of the working fluid exceeds the saturation temp of the working fluid, it gets vaporized and increases its volume and generates slight positive pressure into the vessel below the membrane. This pressure difference across the diaphragm pushes the water through the delivery non return valve, which is present above the membrane.

At the end of the delivery stroke, the hot water supply to the heat exchanger is turned off and cold water supply is turned on through the three-way valve. This condenses the vapours of the working fluid and creates the negative pressure difference across the membrane. This pressure difference will cause the suction of water through suction-non return valve and portion above the membrane will again get filled up by lower tank water. In this way, system completes one cycle and system gets ready for next cycle.

3. Results and Discussion

1.1. Material compatibility test

Before the actual pumping system was assembled, the material compatibility with working fluid was carried out. Photograph of the material compatibility test setup is shown in the figure 2. The experimental setup uses k-type thermocouples to measure temperature. Hot water bath (below 100°C) is used for heating of working fluid uniformly. The hot bath is heated using heater and stirrer setup.

Figure 3 shows the working fluid chamber and its assembly, this working fluid chamber has flange on the upper side which connects with flange of the gas outlet tube. The membrane material sample has 50 mm diameter and pitch circle diameter of 37.5 mm. The samples may have different thicknesses. Sample tried were of neoprene rubber, Butyl rubber, polyethylene, polyethylene with WVTR additives, Polyethylene with laminated films material. Gas outlet tube was used to visualise bubbles of working fluid that have percolated from the membrane material.

After completing setup, heater was switched on for heating water present in the hot water bath. This water heats up the working fluid present in the working fluid chamber and pressurize the working fluid chamber. If membrane material is permeating the working fluid vapours then gaseous working fluid will pass through gas outlet tube and it would be visualised in the form of bubbles. By measuring the bubbling rate with respect to time, the supervisor can judge the permeability of diaphragm sample. During the conduction of this experiment, a scale has been defined for judging the permeability of the material i.e. Excellent: 0 bubbles/hour (No bubble), Good: 0-5 bubbles/hour, Average: 5-30 bubbles/hour, Bad: Above 30 bubbles/hour. Table 1 and 2 summarize the results of material compatibility test with n-pentane and acetone as working fluid.

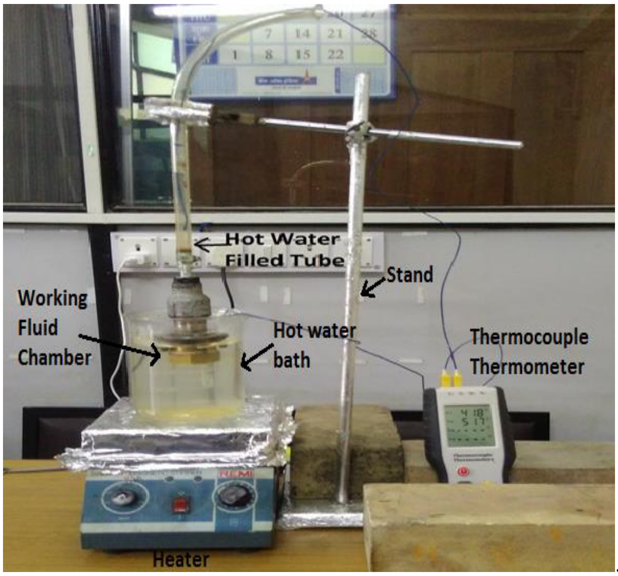


Fig. 2. Set up for material compatibility test

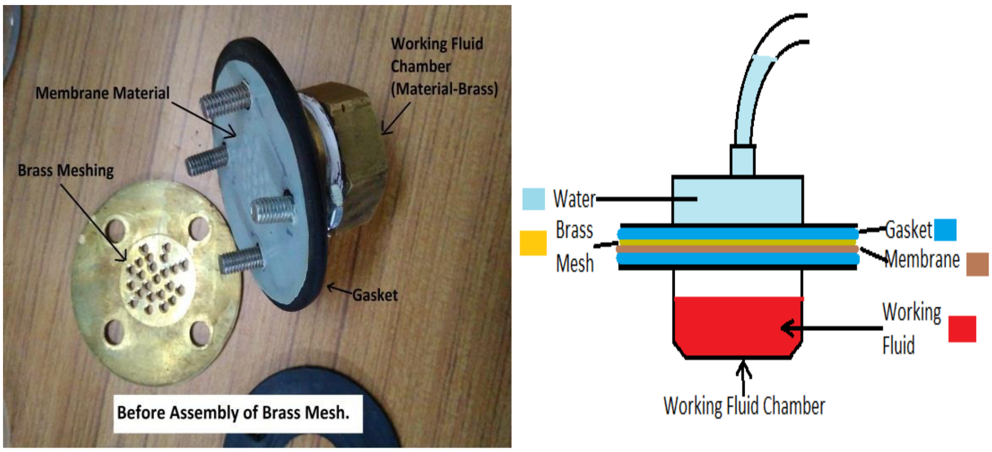


Fig. 3. Assembly of working fluid chamber with membrane and brass mesh

Table1. Compatibility of n-Pentane

Working Fluid	Membrane material	Compatibility
n-Pentane (@53 °C)	Silicon Rubber	Bad
	Nitrile Rubber	Excellent
	Polyethylene	Bad
	Aluminium film laminated Polyethylene	Average
	Butyl Rubber	Bad

Table2.Compatibility of Acetone

Working Fluid	Membrane material	Compatibility
Acetone (@76 °C)	Silicon Rubber	Bad
	Nitrile Rubber	Bad
	Polyethylene	Average
	Aluminium film laminated Polyethylene	Good
	Butyl Rubber	Bad

3.2 Thermal pump testing

Figure 4 shows the actual assembled system. The pumping vessel has inner diameter 135 mm and diameter of 145 mm (Approximately 2 litre volume) and thickness of the vessel is 3.5 mm. Non return valve has flap type configuration and 1/2” BSP threading. Flow control valve has gate type configuration with 1/2” BSP threading. Hot water supply tube has internal diameter 10 mm. First trial was carried out on acetone as a working fluid which has boiling point (56 °C) and diaphragm as polyethylene (thickness 120 micrometre) which has average compatibility with acetone. In this system temperature is measured with temperature sensor (PT 100) and data logged in data logger. While taking trials following readings of particular parameters were noted such as volume of water pumped, pressure at the delivery side, time taken to achieve certain pressure (10 psi-69 kPa-7 m of water head) etc.

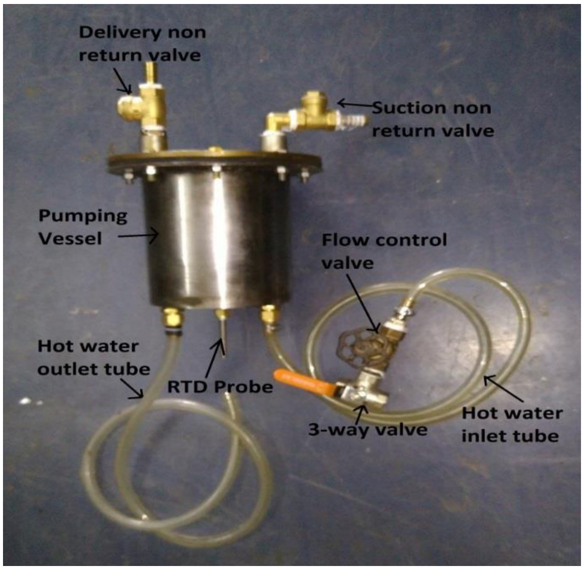


Fig. 4. Actual photograph of the assembled thermal pumping system.

The table 3 below summarizes the results obtained in the present study.

Table3-Results of system using acetone

Sr. No.	Hot water flow rate ($\dot{m}h$) lpm	Total head developed (H) (Hs +Hd) Meters of WC	Hot water circulation time (Th) sec	ΔT °C	Mass of water pumped (m) Kg	Input work kJ	Output work joules	Overall Efficiency (η) %
1	1.0	8.89	154	5.7	1.77	61.15	154.36	0.252
2	1.4	8.89	1371	4.8	1.72	64.13	150.02	0.233
3	1.5	8.89	135	4.6	1.78	64.89	155.23	0.239

4	1.8	8.89	120	4.1	1.70	61.69	148.25	0.240
5	2.0	8.89	98	3.8	1.78	51.88	155.23	0.299
6	2.4	8.89	77	3.2	1.75	42.98	152.61	0.355
7	2.6	8.89	62	3.0	1.80	33.69	156.97	0.466

4. Conclusion

The thermal pump system designed for 5 meter head and capacity of 20 lit/hr with working temp of 85°C was designed, assembled and tested successfully. The system showed efficiency in the range of 0.25-0.5 %. The major cause for the limited efficiency is loss of heat through the membrane which is present at the interface water. The material compatibility test detected compatible membrane material for n-Pentane and Acetone.

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