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Experimental Investigation Of An Evacuated-Tube Solar Water Collector With Serpentine Through-Flow Pipe

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Abstract:

The present work deals with experimental study of an evacuated-tube (all-in-glass) solar collector. The collector consists of 5 evacuated tubes filled with ordinary engine oil. An additional stainless steel pipe is integrated with the tubes to carry the working fluid (water). The steel pipe (through-flow pipe) is bent 5 times to form 5 U-shape turns. Each U-turn is immersed in a single evacuated tube. Oil acts as the heat transfer medium between tube inner surface and the stainless steel pipe outer surface. Experiments are carried out for several values of water mass flow rate and under various meteorological conditions (irradiance, ambient temperature). Results show that the collector exhibits high conversion efficiency and fast response to the affecting parameters (water inlet temperature changes, clouding, replacement of oil) compared to conventional flat-plate collectors. However, the limited number of tubes and the small diameter of the stainless steel pipe combined with its large length (14 m) caused some fluctuations in the water flow rate at the pipe exit. To enhance the performance of the system and make it suitable for higher loads (e.g. for producing superheated steam) the number of evacuated tubes should be increased and the stainless steel pipe diameter is increased and its length decreased.

Keywords: Evacuated-tubes solar collector, all-in-glass collector, serpentine solar collector.

دراسة تجريبية لمجمع شمسي مائي ذو الأنابيب المفرغة ومزود بأنبوب ناقل من النوع الملتوي

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الخلاصة:

يتناول البحث الحالي دراسة تجريبية لمجمع شمسي ذو الأنابيب المفرغة. يتكون المجمع من خمسة أنابيب مملوءة بزيت المحركات. كما يحتوي المجمع على أنبوب ناقل للمائع الشغال (الماء) يخترق تجاويف الأنابيب المفرغة الخمسة.

ولكي يتم ذلك تم لي الأنبوب الناقل في خمس مناطق وعلى مسافات متساوية للحصول على خمس التواءات بشكل حرف U بحيث يدخل كل جزء ملتوي في واحد من الأنابيب المفرغة الخمسة.

يعمل الزيت داخل تجاويف الأنابيب كوسيط لانتقال الحرارة بين السطح الداخلي للأنبوب المفرغ والسطح الخارجي للأنبوب الناقل.

تم إجراء التجارب لقيم مختلفة من معدل جريان الماء وفي ظروف جوية مختلفة. وقد بينت النتائج كفاءة تحويل عالية للمجمع واستجابة سريعة لظروف التشغيل المختلفة والتي تشمل درجة حرارة الدخول للماء أو وجود الغيوم أو استبدال الزيت، مقارنة مع الأنواع التقليدية من المجمعات الشمسية المسطحة.

ولكن نظرا لمحدودية عدد الأنابيب المفرغة والقطر الصغير للأنبوب الناقل مقرونا بطوله الكبير البالغ 14 مترا فقد عانت المنظومة من تذبذب في معدل الجريان الخارج من الأنبوب الناقل. ولذلك ومن اجل تحسين أداء المجمع وجعله مناسبا لأحمال حرارية أعلى قد تمكن من استعماله مولدا للبخار فيجب زيادة عدد الأنابيب المفرغة وزيادة قطر الأنبوب الناقل وتقليل طوله.

1. Introduction:

The crucial point in designing any solar collector is to allow maximum possible amount of solar radiation to reach the absorber part of the collector, and concurrently, reducing thermal losses from the absorber to the minimum. Evacuated-Tube Solar Collector (ETSC) offers feasible solution to this problem. An evacuated tube is composed of two coaxial glass tubes forming an annulus **(Figure. 1).** The space between the two tubes is evacuated to eliminate convective losses. The outer tube is the transparent cover while the inner tube is the absorber which is coated from outside (vacuum side) with a selective paint to maximize solar absorptance. One end of the evacuated tube is closed while the other is left open. The solar collector usually incorporates several evacuated tubes forming a parallel array.

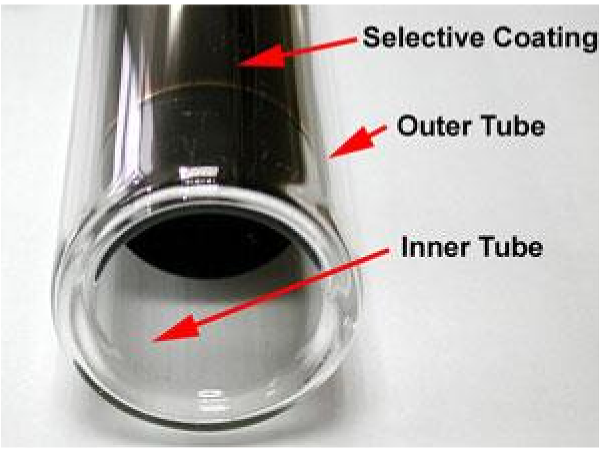


Fig .(1) An evacuated tube shown from its open end.

Heat can be extracted from the tubes by a variety of ways. The simplest way is achieved by the direct connection of the tubes to the storage unit. The working fluid can be either a liquid or a gas. When water is used as the working fluid, it is directly circulated between the tank and tube cavity via natural circulation. The temperature range in this type is limited by water boiling point. However, air or other gases may also be used as working fluids which necessitates the use of an appropriate fan or blower to circulate the fluid.

The first systematic study on an ETSC was done by Eberlein (1976) [1]. He analyzed thermal performance of an ETSC employing air as the working fluid. The solar collector studied by Eberlein consisted of an array of several evacuated tubes. Air is introduced in the middle way between top and bottom of each tube using additional concentric delivery conduit. It circulates in the annular space between the delivery conduit and the absorbing tube to collect solar thermal energy. This analytical study proposed several mathematical models useful in the design of air ETSCs but it was not validated by experimental tests.

A detailed numerical study on the natural circulation inside the evacuated tube cavity was done by Gaa F.O. et. al. (1998)[2]. A numerical model of the inclined open thermosyphon has been developed using a finite difference algorithm to solve the vorticity vector potential form of the Navier-Stokes equations. The study was experimentally verified using laser doppler anemometry to measure the velocity profile at the tube exit.

Bae C.H. et. al. (2006)[3] experimentally studied a concentric evacuated tube solar collector with axially grooved heat pipe. The collector was designed, constructed, and tested at transient conditions to study its performance for different cooling water mass flow rates as well as different inlet cooling water temperatures. The experimental results showed that the mass flow rate has a significant effect on the collector efficiency. Subsequently, long term thermal performance of system can be predicted by giving an annual solar fraction of about 73% for all the hot water system of a house of four people in summer.

A system similar to that studied by Eberlein was adopted by Kim J.T. et. al. (2007)[4] who conducted a numerical investigation of all-glass vacuum tubes with coaxial fluid conduits. Water (instead of air) is heated as it flows through the coaxial fluid conduit inserted in each tube. The space between the exterior of the fluid conduit and the glass tube inner surface is filled with antifreeze solution to facilitate the heat transfer between them. The study proposed one dimensional model that is validated by experimental data.

Zhang X.R. and Yamaguchi H. (2008)[5] experimentally studied a different design of the working fluid pipe used to extract energy from the evacuated tube. They used a U-shape stainless steel pipe equipped with especially designed fin. One U-shape pipe with a fin is inserted in each evacuated tube. Supercritical CO_2 is circulated in the U-shape pipe as the working fluid. The study shows the potential of using CO_2 in power generation via evacuated-tube solar collector array.

Budihardjo I. and Morrison G.L. (2009)[6] studied The performance of water-in-glass evacuated tube solar water heaters using experimental measurements of optical and heat loss characteristics and a simulation model of the thermosyphon circulation in single-ended tubes. The performance of water-in-glass evacuated tube solar collector systems are compared with flat plate solar collectors in a range of locations. The performance of a typical 30 tube evacuated tube array was found to be lower than a typical 2 panel flat plate array for domestic water heating in Sydney.

To obtain higher temperatures, other fluids with higher boiling temperatures my be used either as working fluids or as intermediate media between the inner surface of the tube and the main working fluid. In such a case, another pipe (through-flow pipe) must be inserted inside each glass tube to circulate the main working fluid. The through-flow pipe is surrounded by the fluid of the higher boiling temperature.

Despite the numerous researches found in the literature that tackled various the evacuated-through-flow pipe configurations, many points are still not fully studied and documented. One of such points of increasing interest is the use of evacuated-tube solar collectors as steam generators. To achieve this that, efficient heat transfer between the tube cavity and the through-flow pipe must be ensured. A feasible solution to that is by filling the tube cavity with a liquid whose boiling temperature is far above that of water. This method is adopted in the present work where engine oil (boiling temperature > 350^{o}C) is used as the heat transfer medium filling the tube cavity.

2. Experimental rig and test procedure:

The experimental rig consists of five evacuated glass tubes manufactured by Shentai company (China) **(Figures. 2 to 4).** The specifications of the single tube is given in (**Table 1).** Each tube is filled with appropriate quantity of engine oil (about 2.5 L of 20W50 oil). The oil receives and collects the solar radiation penetrating the two walls of the evacuated tubes causing a rapid increase in its temperature. To convey the heat accumulated in oil, a locally manufactured stainless steel pipe (through-flow pipe) is inserted in the tube cavity so that the oil surrounds it. A single long steel pipe (14 m) is shared by the five evacuated tubes. The pipe is bent at 5 equally spaced locations to form 5 U-shape turns. Each turn is inserted in one tube. The steel pipe, thus, takes a serpentine shape going from tube to tube sharing the five tubes with the same water stream. This configuration resembles a serpentine flat-plate collector without an absorber plate.

Water acting as working fluid is circulated inside the steel pipe by means of external pump. The pump is equipped with a regulation valve to control the amount of mass flow rate out of the pump. After adjusting the regulation valve the water mass flow rate is measured manually by measuring the time required to collect a specified amount of water in a graduated glass container. Pumping water in the steel pipe is necessary to maintain the flow of water through this long and small diameter pipe. Such a pipe exhibits high frictional losses which sometimes temporarily blocks the flow in the steel pipe (even with the pump being on) causing a fluctuation in the water mass flow rate. This intermittence in flow rate appears more clearly at higher temperatures when evaporation commences at some locations along the pipe. Sudden formation of bubbles inside the small diameter pipe (13 mm ID) considerably increases the frictional losses and causes a back pressure adverse to the pump head.

Cold oil is filled in the cavities of the five evacuated tubes at the start of the testing period (early morning hours). The period required for manually filling the five tubes (about 15 minutes) causes a rapid increase in oil temperature ($\Delta T=20^{o}C$) before starting the circulation of water in the stainless steel pipe. This rapid increase in temperature is expected since the convection losses from the oil is almost negligible and the oil quantity is relatively small (about 2.5 L per tube). Any amount of solar radiation penetrating the double-glazed tube is totally converted to an increase in oil temperature.

Test are carried out for about 4 to 5 hours around the solar noon. The data are collected at an interval of 15 minutes. At each interval the water inlet and outlet temperatures are measured along with the oil temperatures at the first and last tubes. Solar radiation intensity (irradiance) and the ambient temperature are also measured and registered at each time interval. The water mass flow rate is kept constant all over the whole test period. The test are repeated for other values of mass flow rate on other testing days.

Fig .(2) The evacuated-tube solar collector under study.

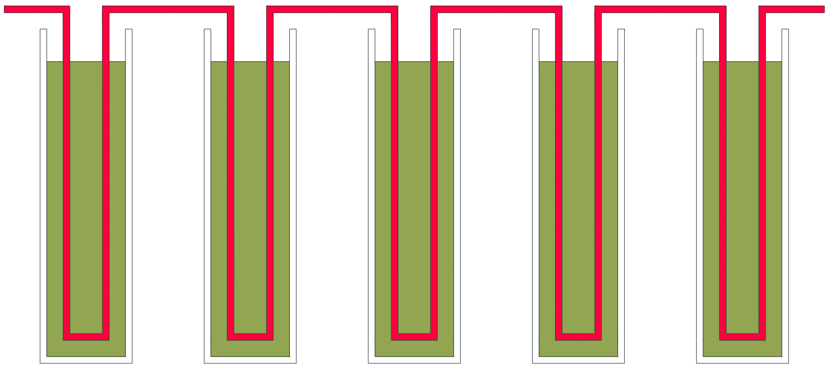
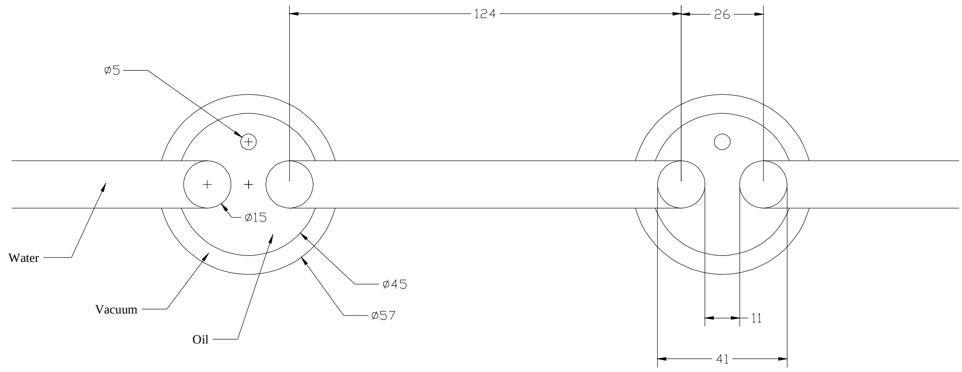


Fig .(3) Schematic view illustrating the steel pipe (red) immersed in the oil (green).



All dimensions in millimeters

Fig .(4) Cross-sectional top view illustrating two evacuated tubes.

(Table 1) System Specifications

Part		Dimension
Evacuated Tube	Total length	1.8 m
	Inside diameter	4.5 cm
	Outside diameter	5.7 cm
Steel pipe	Total length	14 m
	Penetration depth	1.4 m
	Inside diameter	1.3 cm
	Outside diameter	1.5 cm

3. Results and discussion:

Several tests were performed at several days using different water mass flow rate on each day. Applying small mass flow rate produced larger difference between inlet and outlet temperatures for both water and oil as can be seen by comparing (**Figure. 5**) with (**Figure .8**). Using large mass flow rates is necessary to overcome the frictional losses inside the through flow steel pipe. Fig. 5 shows that oil inlet temperature (oil temperature in the first tube) is high in the first reading and rapidly decreases in the subsequent time intervals. Leaving the oil inside the tube cavity without circulating water in the steel pipe even for a short period rapidly increases oil temperature. Once water circulates in the steel pipe the oil temperature rapidly decreases because oil delivers its heat to the water. The oil temperature ceases to decrease after 11:15 a.m. where the difference between oil inlet and outlet temperatures remains approximately constant till the end of test. This means that the incident solar energy is employed in raising water temperature rather than oil. Oil in such case acts as a constant temperature heat transfer medium. This fact is true for higher values of mass flow rate, although the system in such a case requires more time to attain stability (not equilibrium) as can be seen from **Figures. (5 - 8)**.

It can also be seen from Figs. 7 and 8 that the larger mass flow rate considerably decreases the temperature difference between the first and last tubes and both temperatures are above the exit water temperature. While the small value of the mass flow rate makes the water exit temperature lie between the oil inlet and exit temperatures.

In all conditions, the collector under consideration was not able to produce superheated steam. Attaining high exit water temperature or steam is highly dependent on decreasing water mass flow rate. However, working in low mass flow rate region produced unstable operation due to the fluctuations in the exit mass flow rate. This fluctuations and the temporary blockings in the steel pipe are results of high frictional losses in a small diameter and long through flow pipe. Using higher mass flow rates although overcomes the losses in one hand, it decreases the water outlet temperature on the other hand which in turn necessitate the increase in collector interception area.

Therefore the efficient steam generation via an evacuated solar collector requires using a relatively short through-flow steel pipe with moderate diameter to exclude the blocking and fluctuation problems. To achieve a more steady flow of water and/or steam the collector interception area should be increased to enable employing higher mass flow rates. The relation between the collector geometry and the minimum mass flow rate necessary for a steady operation requires more future investigations.

4. Conclusions and suggestions for future work:

Experiments were carried out on a proposed design of an evacuated-tube solar collector to find out its applicability to produce high temperature water or steam. It was found that using long and small diameter through-flow pipe results in many operation problems caused by high frictional losses inside the pipe. To overcome the problems a collector with larger area and higher mass flow rate should be employed. It was also found that engine oil is an efficient medium for heat transfer between the evacuated tube inner surface and the through-flow pipe outer surface. However other fluids may also be used in place of oil like anti-freeze solutions or fluids with suspended nano-particles. The effects of changing the collector geometry (pipe length and diameter) on the minimum mass flow rate necessary to overcome friction and produce steam requires further future investigations.

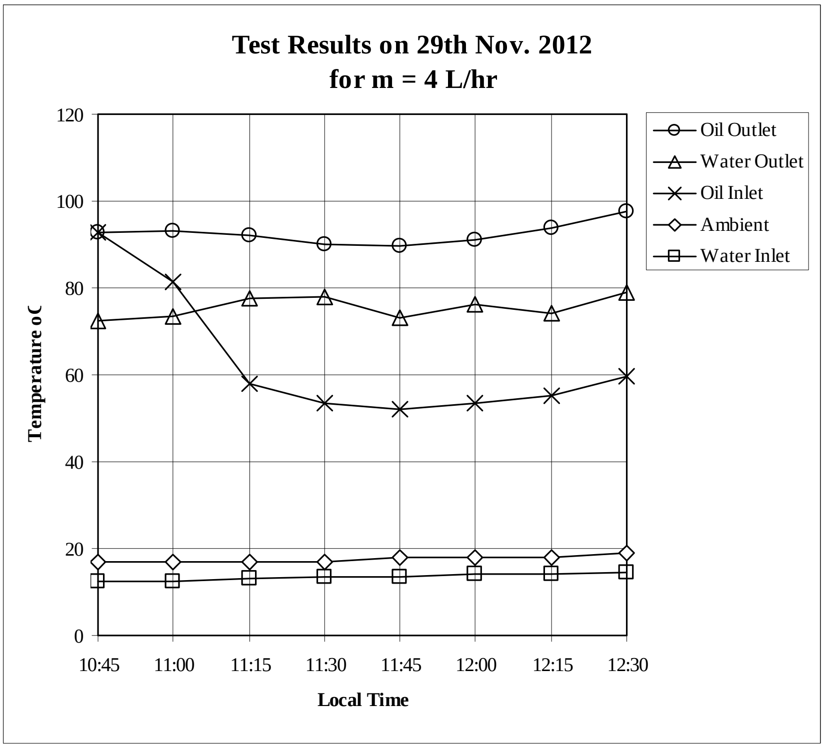


Fig .(5) Variation of oil an water temperatures for a mass flow rate of 4 L/hr.

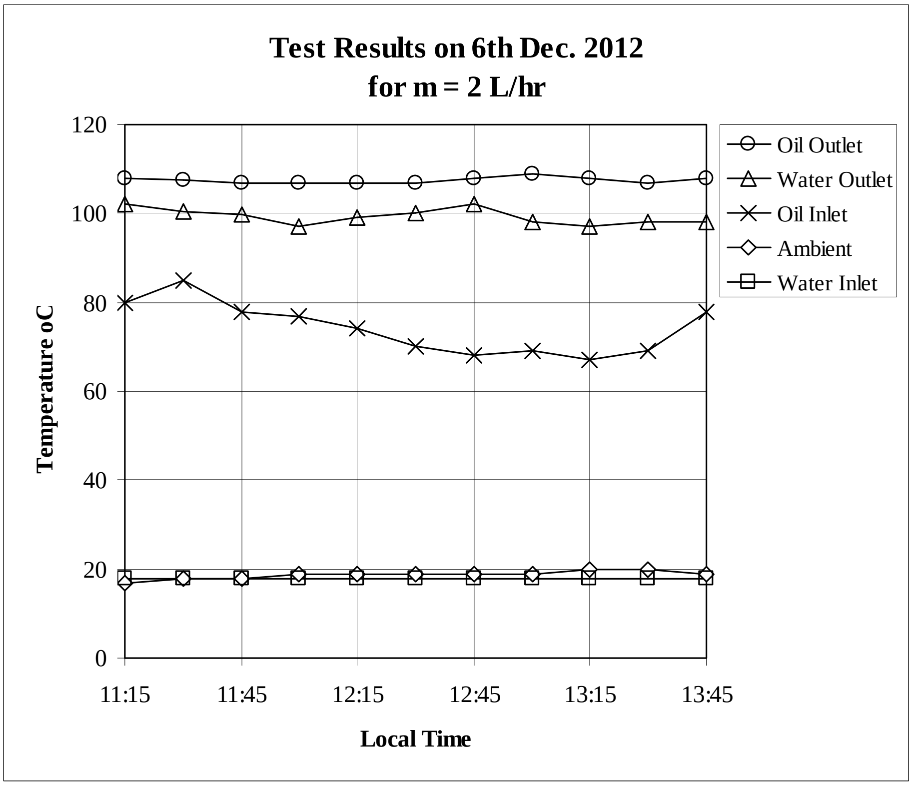


Fig .(6) Variation of oil an water temperatures for a mass flow rate of 2 L/hr.

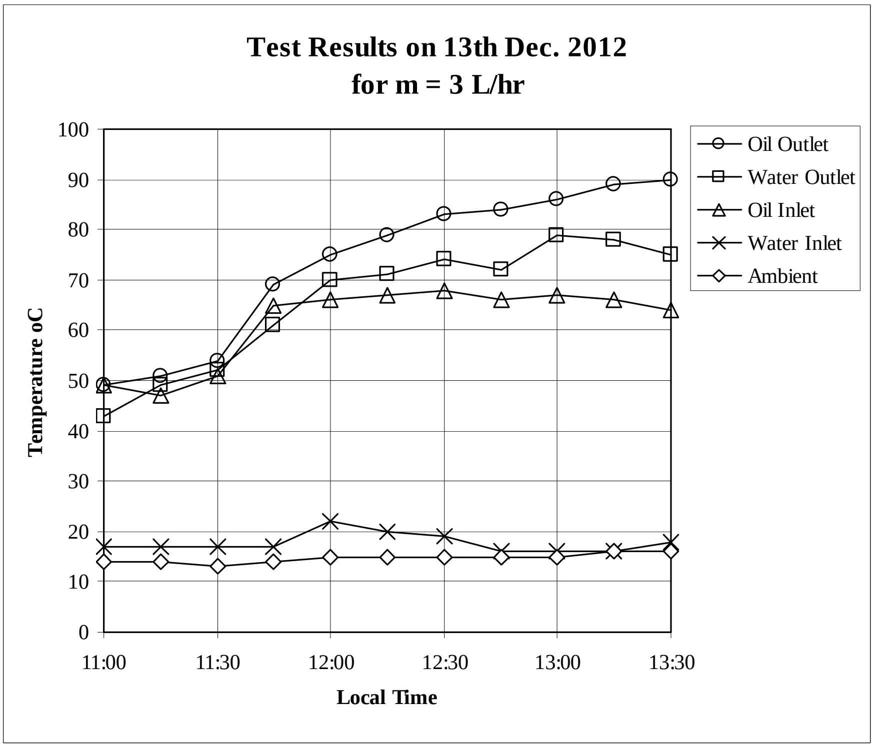


Fig .(7) Variation of oil an water temperatures for a mass flow rate of 3 L/hr.

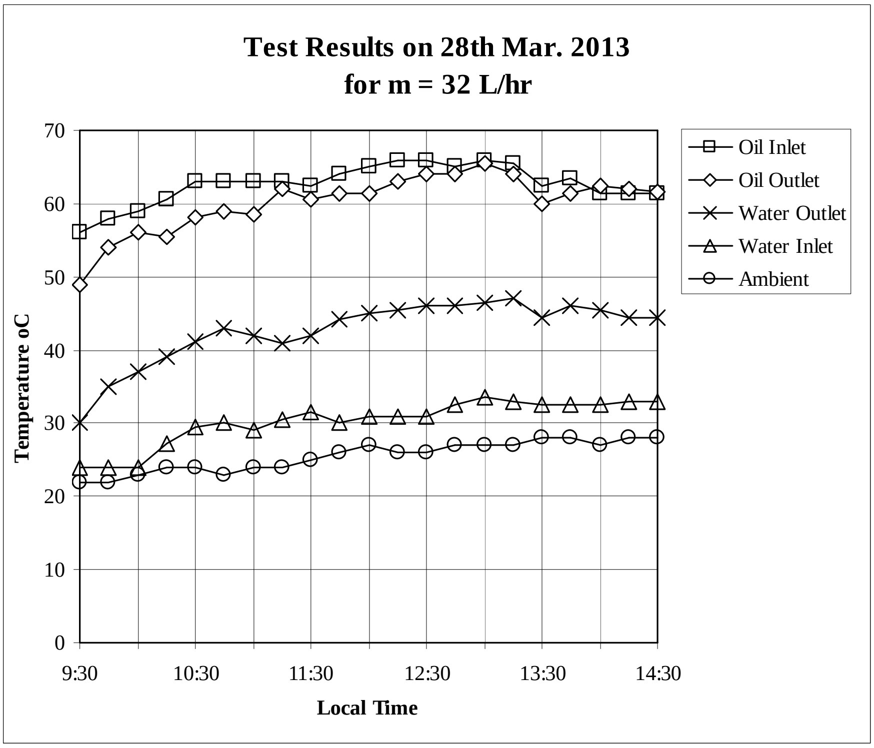


Fig .(8) Variation of oil an water temperatures for a mass flow rate of 32 L/hr.

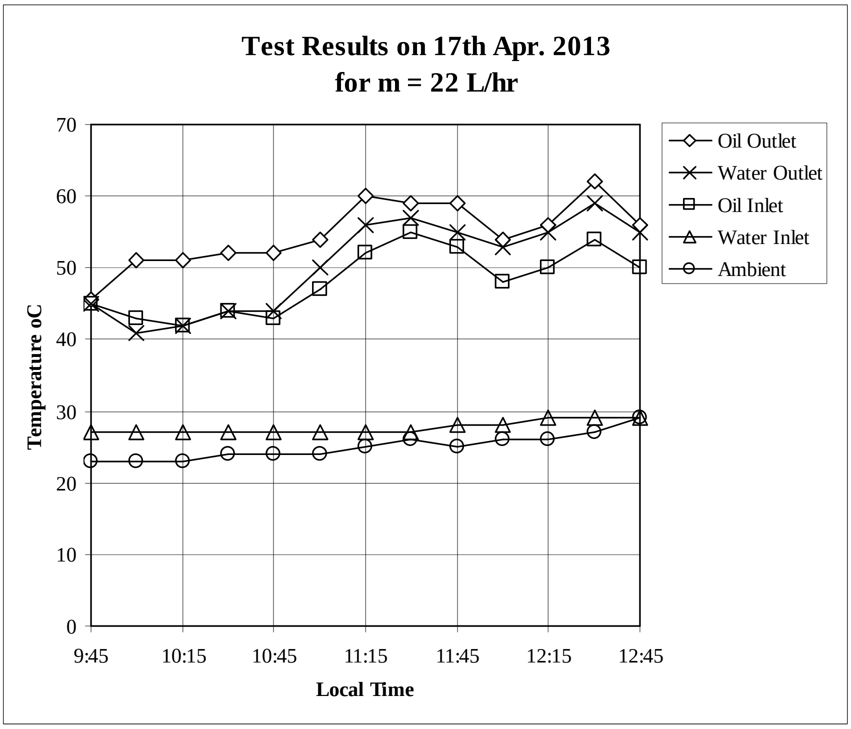


Fig .(9) Variation of oil an water temperatures for a mass flow rate of 22 L/hr.

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