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ENHANCEMENT OF SOLAR DESALINATION STILL PRODUCTIVITY USING FLASH EVAPORATION

تحسين إنتاجية التحلية للمقطر الشمسي باستخدام التبخير الوميضى

A.M. El-Zahaby[*], A.A. Kabeel[*], A.I. Bakry[*], S. A. El-agouz[*], and O.M. Hawam[**]

*** Mechanical Power Department, Faculty of Engineering, Tanta University, Egypt**

**** Workers University, Tanta, Egypt**

ملخص البحث

يقدم هذا البحث تحلية المياه بالطاقة الشمسية باستخدام التبخير الوميضى. الهدف الرئيسي من هذه الدراسة هو تحسين أداء المقطر الشمسي التقليدي من خلال تعديل تصميمه باستخدام حوض متدرجا للمياه مع استخدام نظام لرش المياه. تمت هذه التعديلات بهدف زيادة الاستفادة من الطاقة الشمسية لإنتاج المياه المقطره. وتم دراسة تأثير استخدام نظام رش المياه عند سرعات مختلفة، وكذلك عند معدلات مختلفه لتدفق الماء على إنتاجية وكفاءة المقطر الشمسي عمليا. وقد تبين أن إنتاجية وأداء النظام كانت ايجابية إلى حد كبير وتعتمد على كل من معدل تدفق المياه والسرعة الخطية لرش الماء وكذلك زيادة طفيفة مع استخدام مواد مسامية في حوض المقطرة. الإنتاجية اليومية وصلت إلى 6.7 L/m^2.day ومتوسط الكفاءة اليومية وصلت 77.35 %. و الإنتاجية القصوى تحدث عند سرعة 250 rpm

Abstract

A solar desalination system with flashing chamber is experimentally investigated. The main objective of the present study was to improve the performance of a traditional single slope solar still through a design modification using step-wise water basin instead of flat basin and coupling the solar still with a spray water system. These modifications can increase the solar still capability to capture more solar energy. The effect of using the spray system for seawater is investigated experimentally at different spray water velocities, and flow rates on the productivity and efficiency of the solar still. It was found that the productivity and performance of the system were significantly positive dependent on both the mass flow rate of the impure water and the linear speed of the nozzles holder. They increase slightly with the using of a porous medium in basin of the still as a heat storage sink. There is an optimum mass flow corresponding to the holder linear speed with respect to both thermal efficiency and distilled water production. The unit daily productivity reaches 6.7 L/m^2.day and the average daily thermal efficiency reaches 77.35%. The maximum accumulated productivity is obtained at 250 rpm.

Keywords: Solar still; Flash evaporation; Enhancement productivity; Spray system

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E-mail address: **Kabeel6** @yahoo.com, **Bakry100** @yahoo.com, **elagouz2002**@yahoo.com

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1. Introduction

Solar stills have been thoroughly studied and tested for the production of desalinated water using solar energy. Many investigators studied the effect of different factors such as solar radiation, ambient temperature, water depth, and wind velocity, on the performance of the still. For most cases, even under optimized operating conditions, the reported efficiency of the single basin solar still was in the range of 30-45%, with less than 5 L/m^2.day of fresh water production. This low efficiency is mainly due to the complete loss of latent heat of condensation of water vapor on the glass cover of the solar still. Multi-effect solar stills used to improve production of desalinated water but only in small capacities because the condenser is an integral part of the still. The low heat and mass transfer coefficients in this type of stills require operation at relatively high temperatures and thus the use of large, expensive, metallic surfaces for evaporation and condensation. A solar still, with its lower productivity, does not compete with other desalination techniques. However, when the demand of fresh water does not exceed a few cubic meters, the solar still is a viable option. Since the productivity of the solar still increases as the saturation pressure of the water increases, this is determined by the temperature at the brine surface.

Badran and Al-Tahaineh [1] and Tiris et al. [2] integrated a flat plate collector with a single basin solar still. They found that the maximum increase in productivity of potable water was 52%. A flat plate collector with hot water storage tank [3,4] was integrated with solar stills by Voropoulos et al. It was found that the amount of water produced was doubled when the still was operated alone. El-Bahi and Inan [5] tried to improve the efficiency by using solar still with minimum inclination coupled to an outside condenser. The results show that, the solar still yielded a daily output up to 7 L/m^2 and efficiency of 75% during the summer months. They found also that the efficiency of a solar still operated without a condenser is only70% of that with a condenser. Moreover, analysis of a parallel double glass solar still with separate condenser was studied by El-Bahi and Inan [6]. It was found that the variations of solar radiation, ambient temperature, basin water temperature, vapor temperature and other important temperatures at different locations in the solar still are investigated. The efficiency was increased from 48% to more than 70% when the condenser cover was cooled down. In addition of this, Varopoulos, et al [7] designed a hybrid solar desalination and water heating system. It was found also that the drawl of hot water from the storage tank reduces the production of distilled water in a specific pattern. Productivity of potable water increases by 18% when sponge cubes [8] were used in the saline water. A Multi wick single slope solar still was designed by Shukla et al [9] and Tiwari et al. [10]. Nabil Hussain A. Rahim [11] introduces a new techniques developed to improve the efficiency of both evaporating and condensing zones, and concluded that; separating the evaporating and condenser in two different units allows the temperature difference between the evaporating and condenser zone to be controlled independently to a relatively large amounts during the day. Chen Ziqian, et al [12] developed and tested a special desalination unit which utilizes solar or waste energy. He concluded that by the simulation of this unit operating with a solar system under practical weather conditions, the yield rate of the unit is more than two times comparing with that of a conventional single basin type of solar still. Potable water productivity increases by 20%, when a baffles uspended absorber was used by El-Sebaii et al. [13]. A plastic water purifier was designed by Ward [14] and the effect of double glass in the still was studied by Zurigat [15]. It was concluded that the productivity of the double glass regenerative solar still is higher than that for the conventional still by about 20%. For augmenting the evaporation rate of effluent in the flat plate collector, Srithar et al. [16] compared the simulated performance of open flat plate collector with the experimental data. Al-Hayek et al. [17] studied the effect of using different designs sun tracking system with a basin type solar still. A.A.El-Sebaii et al [18] investigated a single basin solar still. by computer simulation under Jeddah weather conditions, he concluded that the PCM becomes more effective at lower masses of basin water during the winter . therefore, it is recommended to integrate storage materials in active and wick-type solar stills to produce fresh water overnight. A sun-tracking system was deployed for enhancing the solar still productivity by Abdallah [19]. A computerized sun-tracking device was used for rotating the solar still with the movement of the sun. A comparison between fixed and sun tracked solar stills showed that the use of sun tracking increased the productivity by about 22%, due to the increase of the overall efficiency by 2%. It can be concluded that the sun tracking is more effective than fixed system and it is capable of enhancing the productivity. Al-Hussaini et al [20]. used vacuum technology. The results show that applying vacuum inside the solar still increases the water productivity by about 100%. El-Sebaii [21] developed a triple basin solar still for enhancing productivity of the solar still, he concluded that the daily productivity of the still increased with an increase of wind speed until a typical velocity. Velmurugan et al. [22] designed amini solar pond integrated with a basin type solar still. The results show that the productivity increases by 58% over that of the ordinary solar still. Al-Hayek and Badran [23], and Tanaka and Nakatake [24] found that the productivity of fresh water by solar distillation depends mainly on the intensity of solar radiation, the sunshine hours and the type of the still.

Very few works have been carried out so far in stepped solar still thereby constant depth trays are used in the basin plate. Abdallah et al. [25] tried to improve the performance of a traditional single slope solar still through three design modifications: by addition of internal reflecting mirrors on all interior sides of still, by using step-wise water basin instead of flat basin, and by coupling the solar still with a sun tracking system. The inclusion of internal mirrors improved the system thermal performance up to 30%, while step-wise basin enhanced the performance up to 180% and finally the coupling of the step-wise basin with sun tracking system gave the highest thermal performance with an average of 380%. A stepped still with two different depth of trays is presented by Velmurugan et al. [26]. The basin plate contains twenty-five trays with 10 mm depth and twenty-five trays with 5 mm depth. Experiments are carried out using integrating small fins in basin plate and adding sponges in the trays to improve the productivity. Theoretical and experimental as well as economic analyses are made for fin type, sponge type, and combination of fin and sponge type stepped solar still. The results show that, when the fin and sponge type stepped solar still issued, the average daily water production has been found to be 80% higher than the ordinary single basin solar still.

The objective of the present study was to improve the performance of a traditional single slope solar still through some of design modifications using step-wise water basin instead of flat basin and coupling the solar still with a spray water system. These modifications can increase the solar still capability to capture more solar energy. The effect of using the spray system on the productivity and efficiency of solar still.

is investigated experimentally at different spray water velocities, and flow rates

2. Experimental Setup

The solar desalination system under study sprays impure water with a defined different flow rates is schematically shown in figure (1). This system includes stepped basin still with 10 steps; which represents the absorber with area of 1.0 m^2 (1.54×0.65 m^2). Higher side and the two similar sides are constructed from 2 mm blackboard coated iron while the casing is constructed from 0.8 mm galvanized steel. The stepped-bed and the two sidewalls of the still are insulated with 30 mm glass wool (thermal conductivity of 0.036 W/m K) while the front wall was normal to the bed and is made of glass like the cover. The lower side of the still is made of a plastic sheet 3 mm thickness in an aluminum frame. The main condenser is the still body cover, which made of 3 mm plastic sheet thickness (1.54×1.06 m^2) in an aluminum frame. There is a secondary condenser which constructed from 0.8 mm galvanized steel (1.3×0.1×0.4 m^3) and 9 copper tubes 6.35 mm in diameter. The system includes two loops. The main loop is used for injecting impure water in the flash chamber (evaporation area). It consists of water supply tank, water flow meter (orifice meter), controlling valves, and 3 sprayers. These sprayers could be modified to provide a variety of profiles but only one set is used during all experiments. The exit diameter of the spray nozzles is about 1.25-mm. Special mechanism for moving the sprayer's holder in a reciprocating linear motion is designed and constructed. The mechanism converts the rotary motion of 0.37 kW electric motor to a reciprocating linear motion with the required speed. Figure 1.b shows a photo of the designed solar still coupled with the electrical motor. The second loop is used to condense, collect and measure the flashed vapor. The entire test facility was constructed of iron tubes 12.5 mm in diameter, stainless steel tube 12.5 mm in diameter, copper tubes 6.35 mm in diameter and rubber tubes. The test loop is designed to work with a flow range of 0 to 16 L/hr, and an electric motor speed range 0 to 350 rpm which is corresponding to the reciprocating speed 0 to 0.0237 m/s as shown in table 1. Impure water is continually sprayed at a defined constant flow rate through the nozzles to form falling scattered small drops on the heated stepped basin (absorber). Because of the flash evaporation and mass exchange between impure water and air, the vapor condenses mainly on the inner cover surface and secondarily (partially) in the condenser unit, turning into fresh water. The remaining impure water is drawn continually by gravity.

Table 1 shows corresponding motor speed to the reciprocating speed

rpm	100	150	200	250	300	350
Cm/s	0.628	0.977	1.313	1.625	2	2.364

3. Instrumentation

The temperatures at different points in the system are measured by T-type thermocouples, 0.5 mm diameter. There are twelve thermocouples located at the base of the still, two thermocouples on the inner cover surface (condenser) and other two thermocouples on the outer cover surface. All the thermocouples were calibrated in hot water bath with the aid of a standard thermometer. Through a multi-point switch, the thermocouples are connected to a digital thermometer type BK precision 922 of an accuracy ±0.1 °C. With a standard T-type thermocouple, the BK precision 922 is capable of temperature measurements in the range of –20 °C to +1370 °C. Finally, the solar radiation is measured by using of both TD 208 b-solar meter and a silicon cell pyranometer model 3120 of an accuracy ±1 W/m^2. Moreover, the wind speed was measured by a digital turbofan (TFA) of an accuracy ±0.1 m/s. The productivity is measured by graduated vessel 1000 mL plus or minus 10 mL.

4. Experimental Procedure

The experimental tests of this work were conducted at Tanta University, Egypt during the period from April 2008, to July 2008. Each experiment is conducted in one day, during which the following measurements have been recorded:

- Basin (absorber) local and mean temperatures.
- Outer and inner plastic cover temperatures.
- Productivity .
- Total solar radiation intensity on a horizontal plane.
- Ambient air temperature and wind speed.

The experimental data are collected at regular intervals of one hour, starting from about 9 a.m. up to the sunset.

5. Comparison with Published Work

The comparison of the productivity of stills and solar intensity between the present work, and Abdallah et al. [25] as well as Velmurugan et al. [26] is shown in Figure 2. The productivity of the present still is higher than that of the Abdallah et al. [25] and Velmurugan et al. [26]. Figure. 2a shows that the overall trend of the yield for both stills is consistent with the daily collection. The average productivity for the present work still is nearly 30.5% higher than that of the Abdallah et al. [25] while it is 55% higher than that of the Velmurugan et al. [26]. The solar intensity for the present still is lower than that of the Abdallah et al. [25] still at around 15:00 h and then it is nearly the same while the solar intensity for the Velmurugan et al. [26] is lower than that of the present work as shown in Figure 2b.

Table 2 Collected distilled water of the present work which used step-wise basin with spray system, Abdallah et al. [25], which used step-wise basin with sun tracking system and Velmurugan et al [26], which used still with fins from 10 to 17 hr .

Cases	Productivity, L/day/m^2	Gain (%)
Present work Day (15/6/2008)	5.536	-
Abdallah et al. [27] Day (3/6/2006)	4.243	30.5
Velmurugan et al. [28] Day (29/9/2006)	3.605	55

6. Results and Discussion

Results for different experiments are given in graphical form in order to simplify the discussion. The experimental results of the present work are divided into three cases.

The first case concerns with the effect of speed variation at constant flow rate of the impure water (3.635 L/hr) on the system performance. The experiments are carried out during the period from 3/4/2008 to 13/4/2008. Figure 3 shows the variation of base temperature and inner cover temperature with time during the day time. From this figure it can be seen that: the base and consequently, cover temperature increases with time starting from sunshine hour, reaches its maximum value around the noon time and then decreases gradually. The differences in the base temperature and consequently, the cover temperature for the different speeds reaches its maximum value (about 10°C) around 12 o'clock.

Figure 4 shows the variation of both solar radiation and ambient air temperatures along the day. It can be seen that both solar and so ambient air temperature increases up to 12 hr, and then decreases gradually.

Figure 5 illustrates the hourly and accumulated productivities for various speeds. As shown in the figure, both the hourly and accumulated productivities increase with the increase of speed. Accumulated productivity reaches about 2 to 3 times of the traditional type at the same time of the year (water depth 3 cm).

The variation of both daily productivity and the average daily efficiency with speed are shown in Figure 6. It is clear that the productivity and consequently, average daily efficiency increases with speed to a certain amount. The hourly and daily efficiencies may be calculated from the following equation,

$$\eta_h = \frac{M_w \, L_{w \cdot av}}{3600 A_b H} \qquad (1)$$

$$\eta_d = \frac{1}{n}\sum_{i}^{n} \eta_h)_i \times 100 \qquad (2)$$

Where M_w is the hourly productivity (kg/hr), $L_{w.av}$ is the hourly average of the latent heat of vaporization of water (J/kg), A_b is the basin area (1.0 m^2), H is the incident solar radiation on the horizontal surface (W/m^2) and n is the number of desalination hours.

The second case deals with the influence of the impure water flow rate on the performance of the system for different constant motor speeds. It is carried out during the period from 29/05/2008 to 25/07/2008. Figures. 7 and 8 indicate the variation of base temperature and inner cover temperature with time at different values of water flow rates and motor speeds. From these figures it is clear that both base and inner cover temperatures have the same trend. They reached the maximum value at about 13 o clock. A converge of the two values for both base and cover temperatures at the same time is observed. Therefore, the water production rate increases with the increase of the temperature difference between the water and glass.

Figure 9 illustrates the accumulated productivity for five groups, each one for five different flow rates at the same motor speed. As shown in the figure, at 100, 150, 200 and 300 rpm motor speed, the optimum flow rate is 3.635 L/hr and the corresponding accumulated productivities are 5.881, 6.051, 6.162, 5.812 L/m^2.day respectively while at 250 rpm the optimum flow rate is 4 L/hr and corresponding accumulated productivity is 6.655 L/m^2.day. It is noticed that the accumulated productivity reaches about 2.5 times of the traditional type at the same time of the year. The accumulated productivity increases up to flow rate 3.635 L/h at 100, 150, 200 and 300 rpm and it increases up to 4 L/h at 250 rpm and then decreases gradually. Based on the above results, it can be said that applying speed of about 250 rpm and water flow rate about 3.635 L/hr in a solar still enhances the daily productivity by nearly 33.76% approximately. In general, the accumulative productivity is the highest at a discharge of 3.635 L/hr and the maximum accumulated productivity is obtained at 250 rpm.

Figure 10 shows the effected of the solar radiation for the still with various water flow rate at different speed. From this figure it is clear that the solar radiation has the same trend at different speed and days; they reached the maximum value about 13 o clock and difference between them is small.

The third case concerns the influence of porous medium on the productivity of the system. The porous medium is achieved through using one layer black gravel of nominal diameter 5-10 mm which is put on the absorber base. Figure 11 represents a comparison between the base temperature with and with out porous medium. Figures 12- 14 show the same comparison for the inner cover temperature, the hourly productivity and the accumulated productivity. It is clear that a very small effect of the porous medium on the performance is obtained. Figures 15 and 16 illustrate the solar intensity and the air temperature.

7. Conclusion

An extensive experimental investigations on a stepped solar still augmented with porous medium using flash evaporation was carried out. The work is concerned with the variation of the speed of the nozzle's holder ranging between .013 and .0237 m/s, feed flow rate ranging between 2.124 and 9.333 L/hr and augmented porous medium (black gravel 5-10 mm). The results show that:

- Increasing the speed, leads to an increase in the flashing vapor (productivity) to a certain amount.
- In the investigated limits, there is an optimum value of the flow rate, it is about 4 L/hr.
- The maximum accumulated productivity is obtained at 250 rpm.
- The adding of porous medium results in a slight increase of the still productivity.
- The maximum reached productivity is 6.7 L/m^2.day with a thermal efficiency of 77.35%. Such productivity represents 2 to 3 times of the traditional type in the same time of the year.

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Nomenclature

A_b	Base area, m^2
H	Hourly solar intensity, W/m^2
$L_{w,av}$	Latent heat of water at average base temperature, kJ/kg
M_w	Hourly productivity, mL/h
n	Number of sunshine hours, h
η_d	Average daily efficiency
η_h	Hourly efficiency

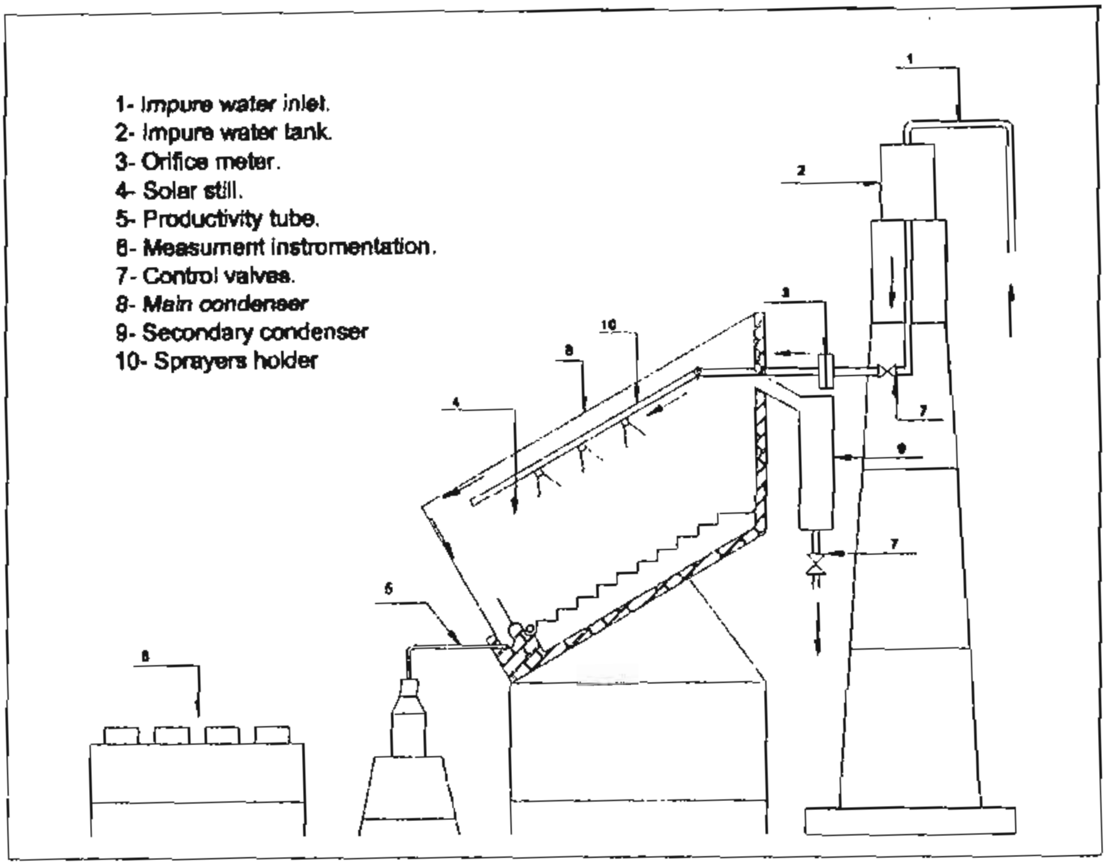


Figure 1.a Schematic diagram of the setup

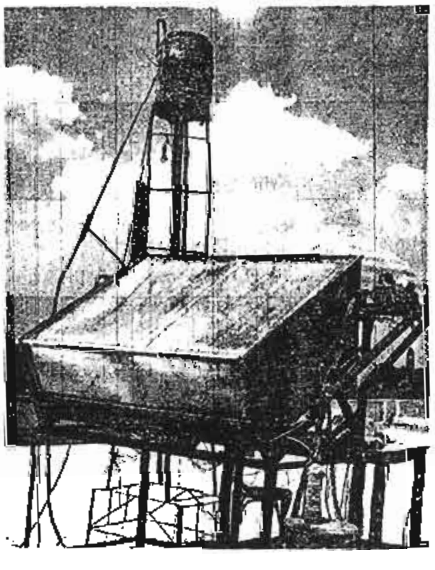
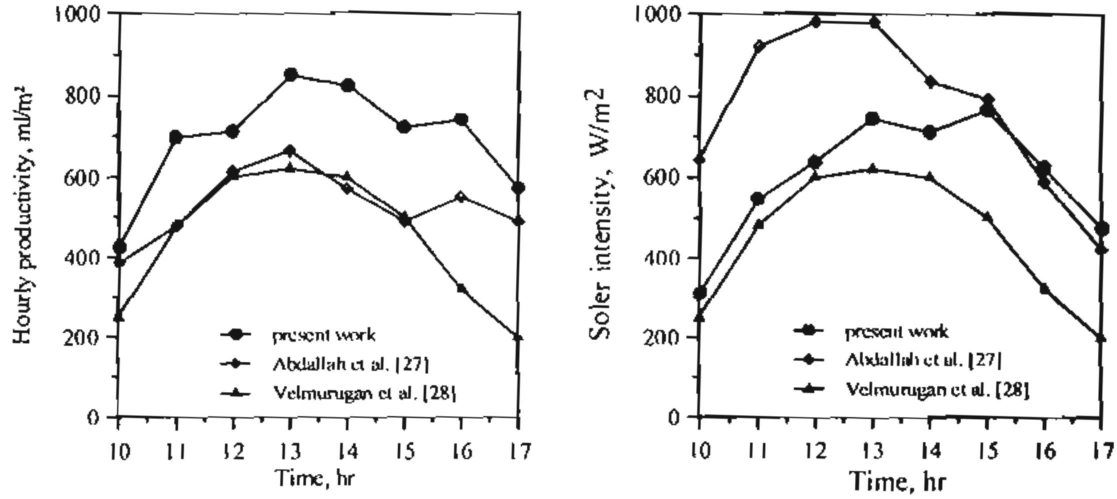


Figure 1.b Shows a photo of the designed solar still coupled with the electrical motor.



a) b)

Figure 2 Comparison between the present work Abdallah et al. [25] and Velmurugan et al. [26] for productivity and solar intensity

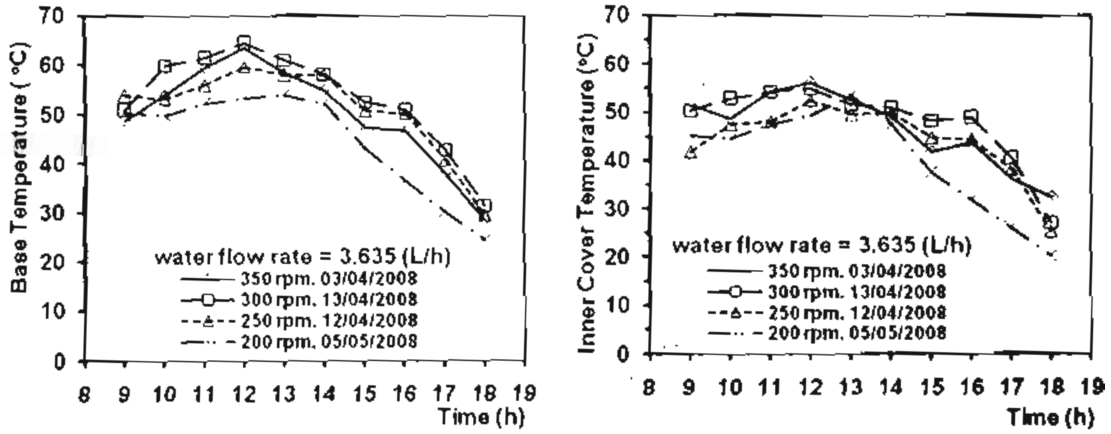


Figure 3 Variation of base and inner cover temperatures along the day time with different motor speeds

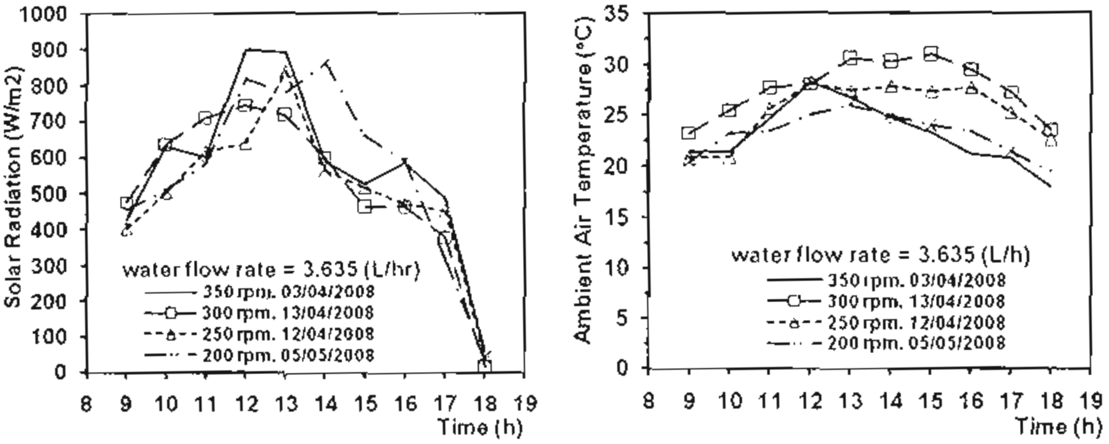


Figure 4 Variation of solar radiation and measured air temperature along the day for the different days (motor speeds)

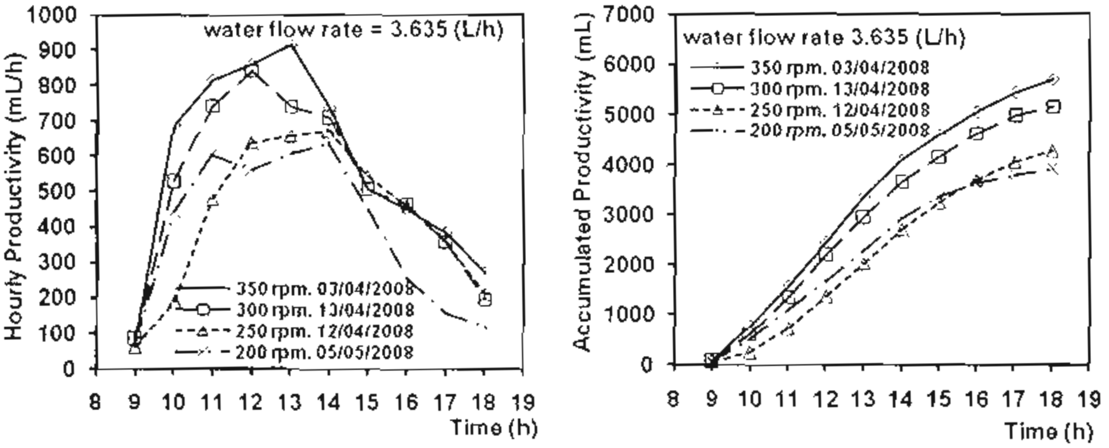


Figure 5 Hourly and accumulated productivity along the day with different motor speeds

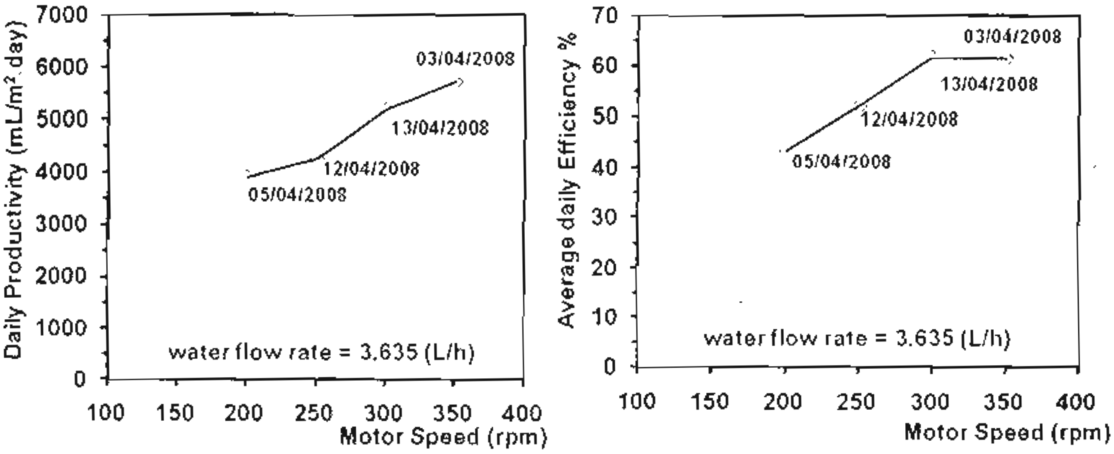


Figure 6 Variation of the daily productivity and still average efficiency with motor speeds

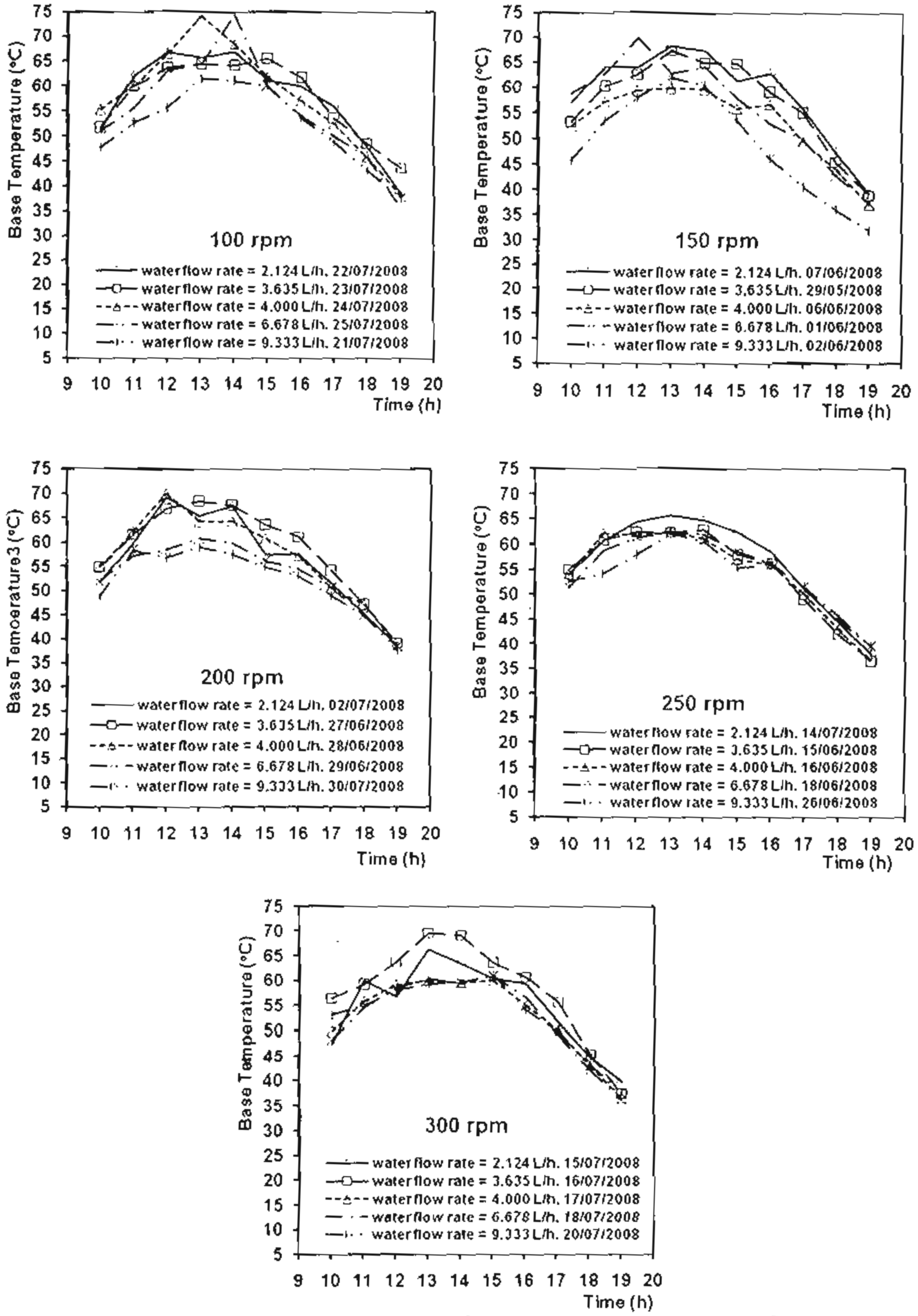


Figure 7 Variation of the basin temperature for the still with various water flow rates at different speeds.

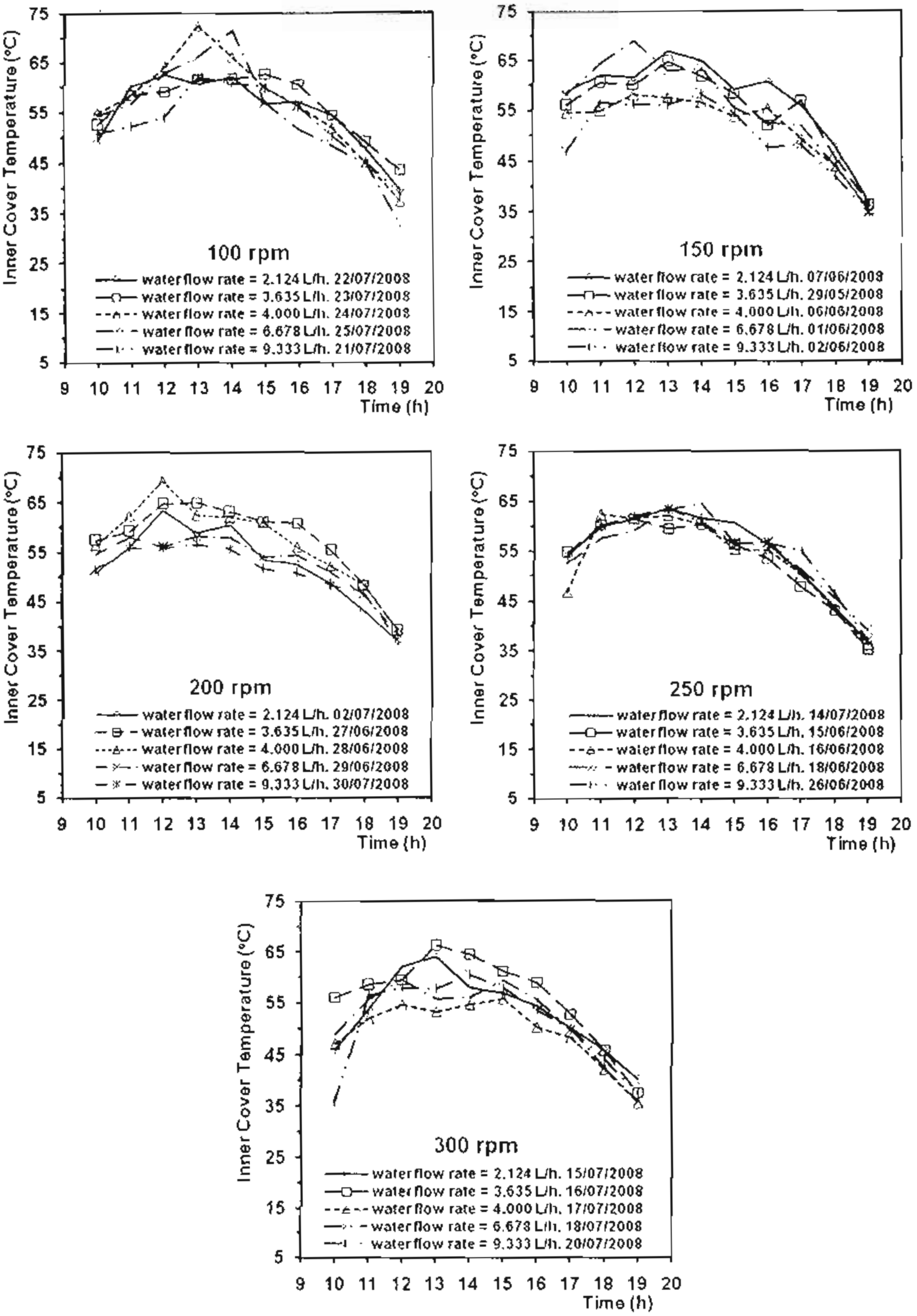


Figure 8 Variation of the inner cover temperature for the still with various water flow rates at different speeds.

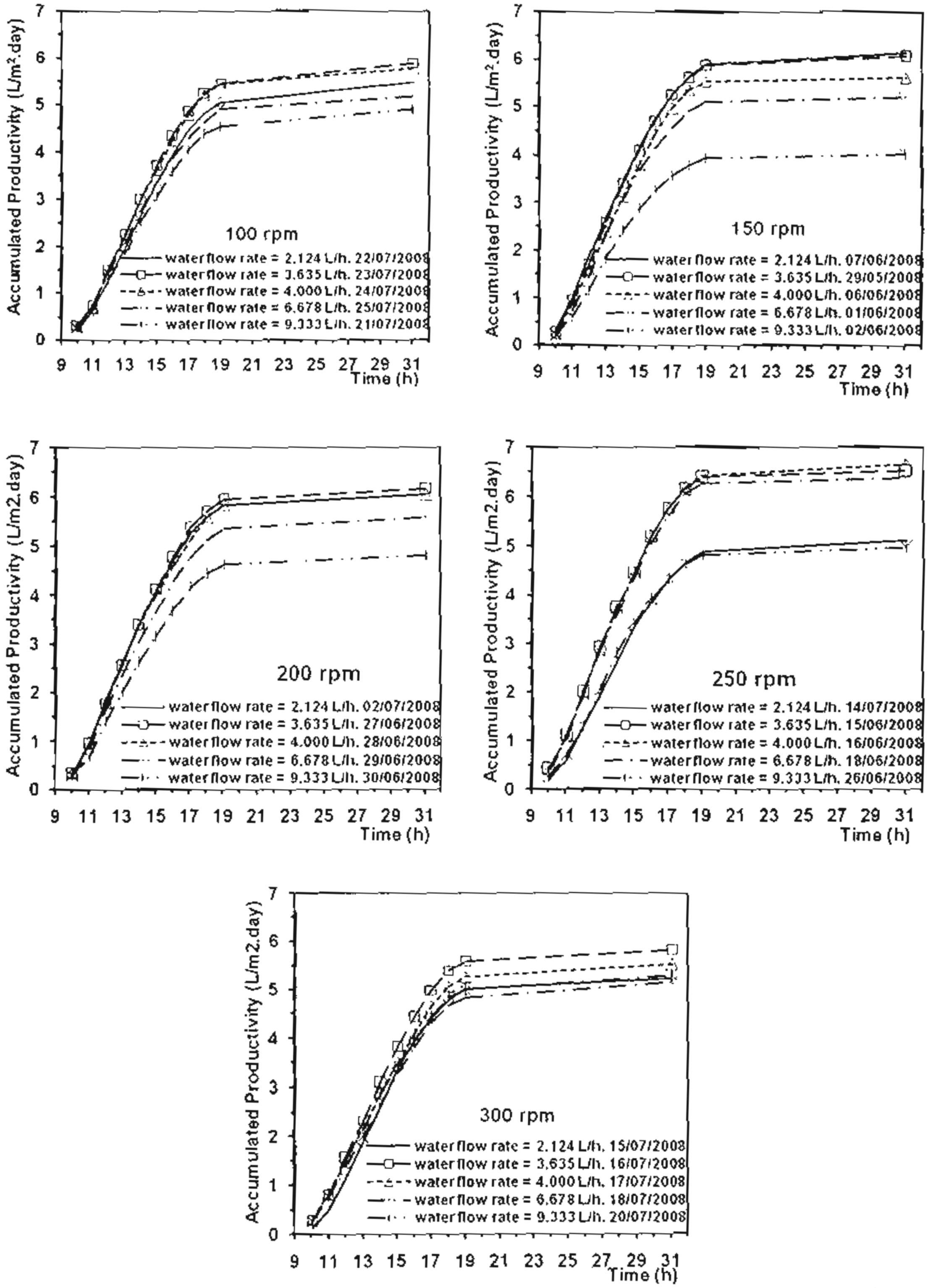


Figure 9 Variation of the accumulated productivity for the still with various water flow rates at different speeds.

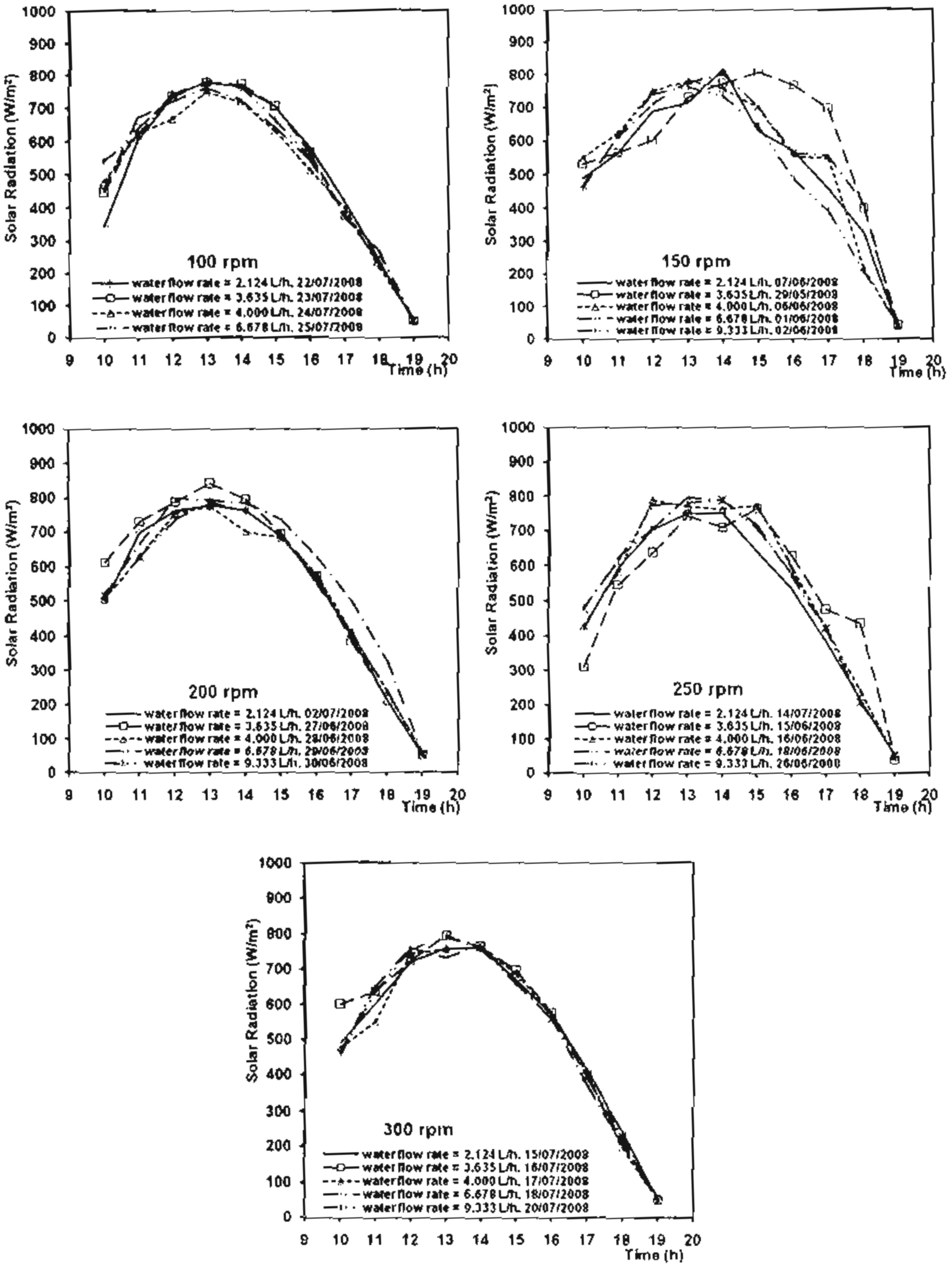
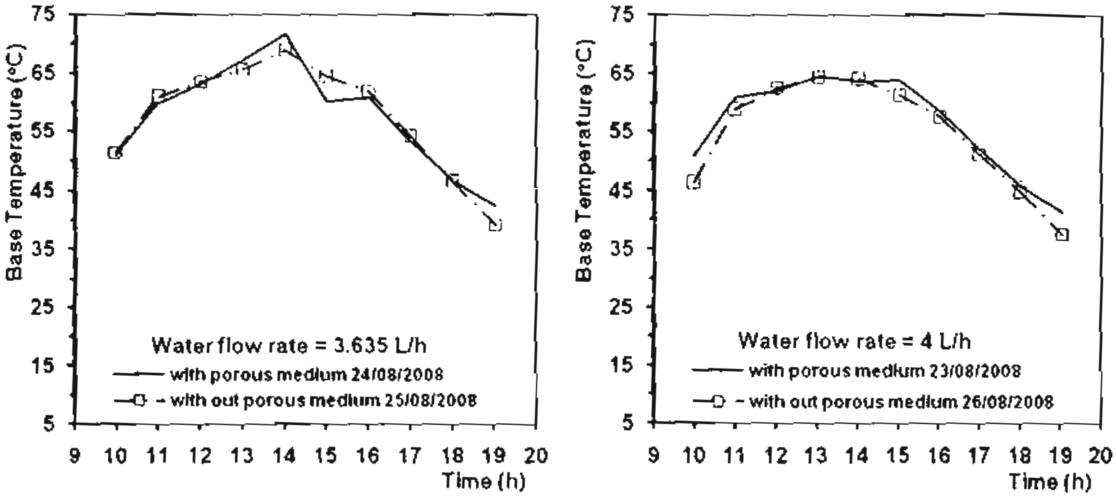
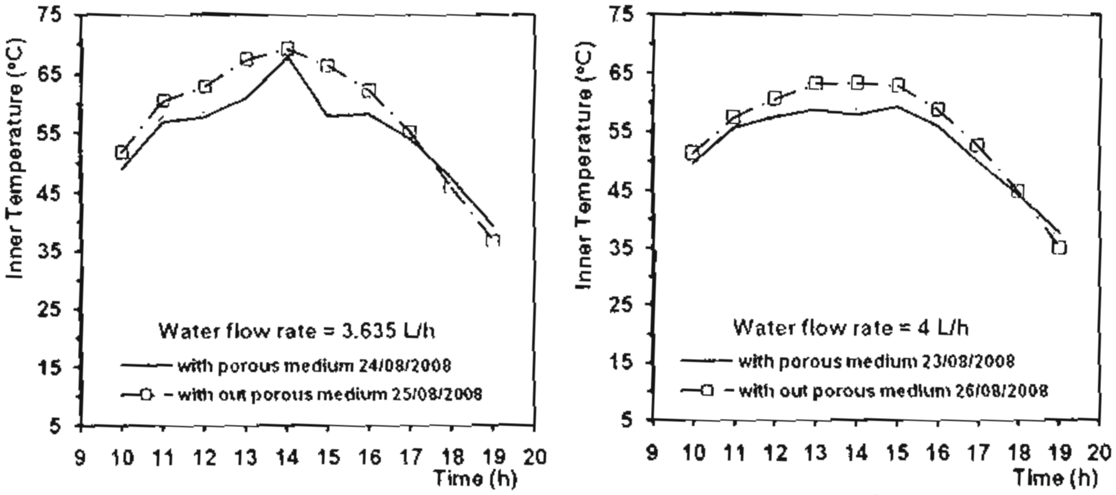


Figure 10 Variation of the solar radiation for the still with various water flow rates at different speeds.



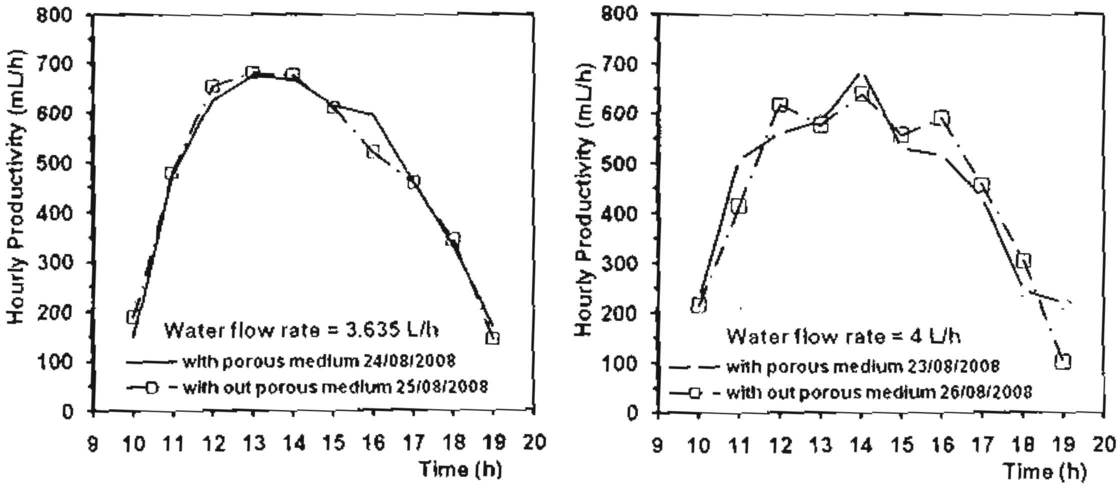
a) b)

Figure. 11 Variation of the base temperature with time at 250 rpm



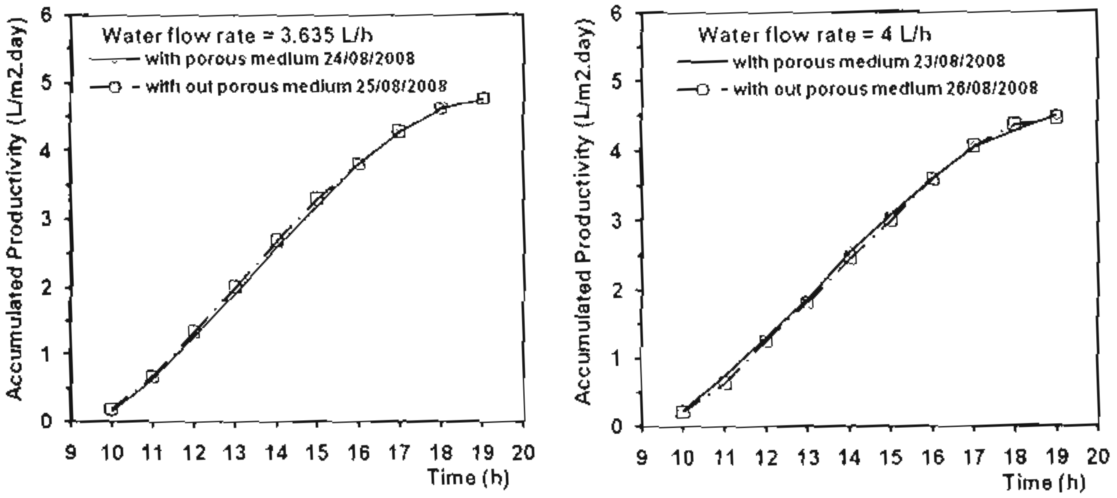
a) b)

Figure 12 Variation of the inner cover temperatures with time at 250 rpm



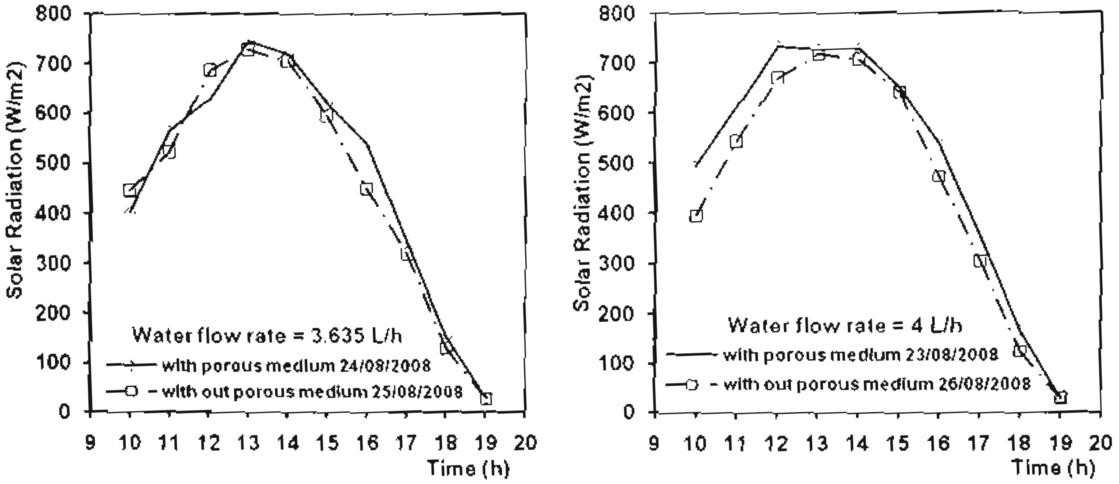
a) b)

Figure 13 Variation of the hourly productivity with time at 250 rpm



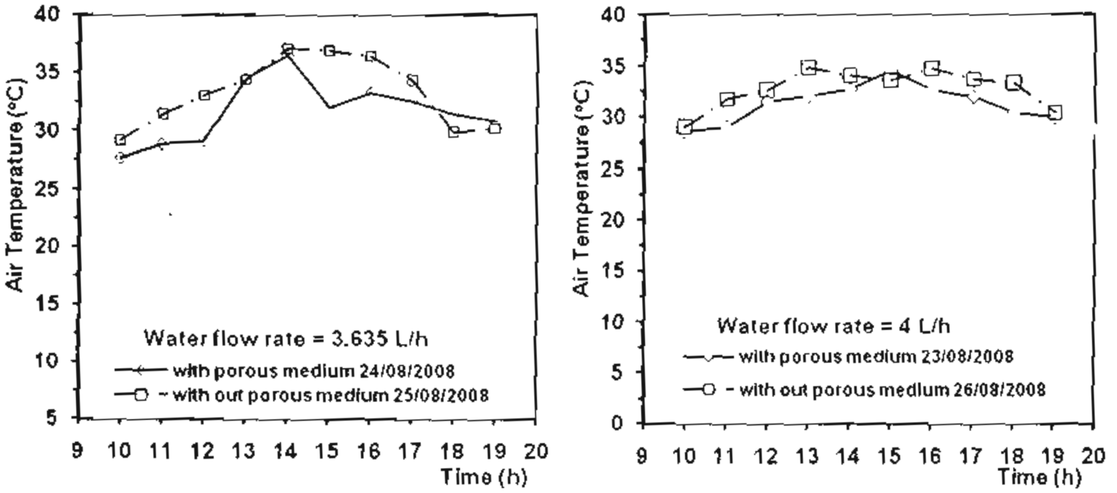
a) b)

Figure 14 Variation of the accumulated productivity with time at 250 rpm



a) b)

Figure 15 Variation of the solar radiation with time at 250 rpm



a) b)

Figure 16 Variation of the air temperature with time at 250 rpm