ISSN: 1994-7801
Journal of Iraqi Desert Studies
Special Issue of 1st Scientific Conference
Vol.2, No.2, 2010

EFFECT OF THE SHAPE SURFACE OF ABSORBER PLATE ON PERFORMANCE OF BUILT-IN-STORAGE SOLAR WATER HEATER

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Keyword: Solar energy, Storage solar collector, Absorber plate.

Received: 15/12/2009 **Accepted:2/7/2010**

Abstract:

An experimental and numerical study was carried out on a storage solar collectors to verify its suitability for domestic use. These storage collectors can be used as storage water tanks to replace the ordinary cubical or cylindrical tank commonly used in Iraqi houses. The paper includes study the effect of the shape surface of absorber plate on performance of storage solar collector by construction of three-box type, built –in-storage water heaters with three different shape of front absorber plat, flat, wavy, and zigzag shapes. Experiments were conducted in summer and autumn seasons, and the results were comprable to the theortical calculation.

The results indicated clearly that the storage collector can be used for providing hot water for domestic uses, the zigzag storage collector was the best to obtain a high temperature than the other two designs, also the finite difference model proved to be useful for prediction of water tempeatures under variable operating conditions.

تأثير شكل الصفيحة الماصة على اداء المجمع الشمسي الخازن الصندوقي

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الكلمات المفتاحية: الطاقة الشمسية، المجمع الشمسي الخازن، الصفيحة الماصة.

تاريخ الاستلام: 2009/12/15 **تاريخ القبول: 2010/7/2**

المستخلص:

يتضمن البحث دراسة عملية ونظرية لمجمع شمسي خازن وتحقيق ملاءمته للاستخدامات المنزلية. ويمكن استخدام هذا المجمع كخزان ماء بدلا من الخزانات المعتادة المكعبة أو الأسطوانية الشكل المستخدمة في البيوت العراقية. يتضمن البحث الحالي دراسة تأثير شكل الصفيحة الماصة على اداء المجمع الشمسي الخازن ببناء ثلاثة مجمعات شمسية ذوات اشكال صفيحة ماصة مختلفة مستوية وموجية ومتعرجة الشكل واجريت التجارب في فصل السيف والخريف وقورنت النتائج العملية مع النتائج النظرية.

بينت النتائج امكانية استخدام المجمع لتجهيز الماء الساخن للاستخدامات المنزلية، وسجل المجمع الشمسي ذو الصفيحة الماصة المتعرجة نوعين(ZIGZAG) اعلى درجة حرارة للماء الساخن من الشكلين الاخرين، وتطابقت النتائج النظرية التي تم الحصول عليها باستخدام طرقة الفروقات المحددة مع النتائج العملية لمختلف الظروف.

Notation:

Symbol	*Description*	*Units*
A_a	**Irradiated face of collector**	m^2
C_W	**Specific heat of water**	$J/kg.^oC$
C_c	**Specific heat of metal of tank**	$J/kg.^oC$
F_d	**Fouling factor**	**-**
F_{sh}	**Shading factor**	**-**
h	**Convection heat transfer coefficent**	$W/m^2.^oC$
I_T	**Total solar radiation on a tilted surface**	W/m^2
m_c	**Mass of the empty collector**	*kg*
$\dot{m}_{fw}$	**Mass flowrate of water**	*kg/s*
m_w	**Mass of water inside the collector**	*kg*
T_a	**Temperature of the ambient air**	^oC
T_P	**Temperature of the absorber plate**	^oC
T_{wo}	**Outlet temperature of load water from collector**	^oC
T_{wi}	**Inlet temperature of load water from collector**	^oC
T_{cf}	**Final temperature of the metal of tank**	^oC
T_{ci}	**Initial temperature of the metal of tank**	^oC
U_L	**Collector over all coefficient**	$W/m^2.K$
T_{wsf}	**Final temperature of the water inside tank**	^oC
T_{wsi}	**Initial temperature of the water inside tank**	^oC
$T_{sunrise}$	**Temperature of water inside tank at the sunrise time**	^oC
U_L	**Collector over all coefficient**	$W/m^2.K$
η_c	**Collector efficiency**	**-**
$\tau_g \alpha_p$	**Transmittance – absorbtance product**	**-**
$\Delta\tau$	**Change in the period time**	**sec**

1. Introduction:

Solar domestic hot water systems are probably, to date, the most frequently used devices which utilize solar energy. All the classical solar water heater systems contain two main components; the collector and the storage tank (Duffie and Beckman, 1991).

A compact solar water heater, incorporating the storage tank and collector in a single unit is an attractive alternative to the conventional solar water heating system. The elimination of the storage tank reduces the cost of the solar water heating system and should improve performance Garge (Rani,1982).

The built-in-storage water heater possesses several advantages over other types. First, it has higher efficiency during the daytime owing to the fact that primarily there are no heat losses during the circulation of water. Second, the superior contact of water with the absorber plate results in better heat transfer in comparison with poor bond conductance, as is the case in the thermosyphon and forced circulation type flat plate solar water heaters. Also, it is of low cost and easily manufactured from common materials without the need for high technology. This storage collector can be used as a water tank to replace the ordinary cubical or cylindrical tank commonly used in Iraqi houses.

Experimental and theoretical investigations on such systems have been carried out by a large numbers of investigators to study a large nubmers of design and operation parametrs. (Sokolov and Vaxman,1983),(Vaxman and Sokolov, 1985) analyzed analytically and experimentally the design of an integral compact solar water heater. In the proposed system the collector and the water tank are built into one unit with water flow caused by thermsyphonic force. Two geometries of the system were investigated. The results showed that the efficency of such system were larger than conventional systems. Also, the experimental results were in agreement with theoretical predictions. Marzouq [5] studied the combined collection–storeage solar heating by a gravel bed. The performance tests were carried out at Basrah (Latitude 30.3 ^{o}N) in Iraq. The experiments were conducted in winter and summer conditions, and the results were comprable to the theortical calculations. The theoritcal predictions were based on a simple finite difference model. The year-round performance tests showed that the mean temperature of water reached 50 to 73 ^{o}C in winter and 60 to 72 ^{o}C in summer at 3:00 p.m. The performance of a prism shaped storage solar collector with a right triangular cross sectional area was investigated numerically by (Farhan,2002). The ANSYS software was used for this purpose .The performance parameters such as temperature, velocity distribution, mean tank temperature, total stored energy and the best location of the inlet and outlet water flows were investigated systematically. The results of this study show good agreement with the theoretical results available in the literature.

(Alawi,2004) studied numerically and experimentally the performance of a prism shaped storage solar collector with right-triangular cross sectional area in Baghdad. The experimental study showed that the mean temperature of the tank reached 34 ^{o}C at February when the initial temperature was 16 ^{o}C. The theoretical result of this study were said to be in agreement with the experimental results.

From reconsideration this literature review, we find the effect of the surface shape wasn't studied, therfore, the purpose of this paper, is to study the performance of built-in-storage heaters for different three types of shape surface, and various modes of operation.

2.Describtion of the experimental apparatus:

The construction of a "built-in-storage" heater involves a rectangular box-like structure with the top face painted black and enclosed behind a single sheet of glass. The back surface and sides are properly insulated and the entire assembly is tilted at a suitable inclination and oriented due south. This work involved the construction of three-box type, built –in-storage water heaters with three different shape of front absorber plat, flat, wavy, and zigzag shapes as shown in (Fig.-1). A galvanized steel sheet of 2 mm thickness painted with ordinary blackboard paint was used as the absorber plate. The dimensions were (1 * 1 m), resulting in an absorber area of one m^2. The storage tanks were constructing by bending and welding of the steel sheets, which formed the top, bottom, and sides. The each of three storage tanks was wrap with 5 cm of fiber glass wool insulation on all sides and bottom and housed in an outer woody box. The assembly of each heater was mounted on a steel stand to face south at an angle 45^o to the horizontal. This inclination is nearly 10^o above, the local latitude of 34^o N for Hawija (Iraq), where the experimental tests were carried out, to provide mean maximum collection of solar energy incident on the collector during the winter months (Duffie, and Beckman, 1991. The capacity of each tank was 80 liter. Ordinary window glass of 4 mm thickness was used as the top transparent cover for tilted surface facing the sun. The distance between the absorber plate and the bottom surface of the glass was kept at 45 mm, which is within the recommended value for solar collectors (Buchberg and Edwards, 1976). According to these workers, such a distance was supposed to provide a good insulating gap for the conduction-convection heat transfer from the hot absorber plate to the cooler glass cover. The glass cover edges were sealed with silicon tape to prevent the leakage of the hot air from the gap between the absorbing surface and the glass cover. The refractive index and extinction coefficient of window glass were taken as 1.526 and 0.02 respectively (Whillier,1977).

All construction work was performed at the technical institute of Hawija, Iraq (34 N^o, 44 E^o).

The hourly temperature of heated water was measured, using thermistor probes, at 7 point along the length and breadth of each heater as shown in the (Fig-2). Two separate thermistors were used to measure the inlet and outlet temperatures of the storage water. In addition, the temperature of absorber plate measured by two additional thermistors and one to measure the glass temperature. Calibration of the thermistor was carried out by gradually varying the temperature and recording the corresponding resistance change. A bath of boiling water and a bowl of crushed ice were taken as the two limits of measurement. Calibration of thermistor was carried out against a standard mercury thermometer Data obtained regarding the temperature variation and the corresponding resistances are shown in (Fig. -3).

Davis Vantage Pro with weather station package used to collect weather data. The standard version of the weather station package contains a rain collector, temperature sensor, humidity sensor, solar radiation sensor, ultra-violet (UV) sensor and anemometer. Temperature and humidity sensors were mounted in a passive radiation shield to minimize the impact of solar radiation on sensor readings. In our study, solar radiation and wind speed data were taken from this station.

3. The Experimental procedure:

The collectors were tested under steady state conditions in which the solar intensity, wind speed, and the ambient temperature were considered constant for a period of time. Also, the inlet and outlet temperature difference and hence the useful energy delivered do not change appreciably during such a period (Duffie and Beckman, 1991).

At the onset of each experiment the collector was filled with fresh water, the glass cover was cleaned thoroughly,

Fig.-1: Three types of storage solar collector .

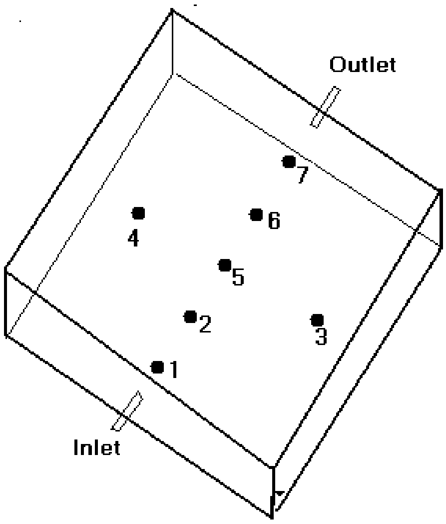

Fig.-2: Positions of thermostat inside the storage solar collector

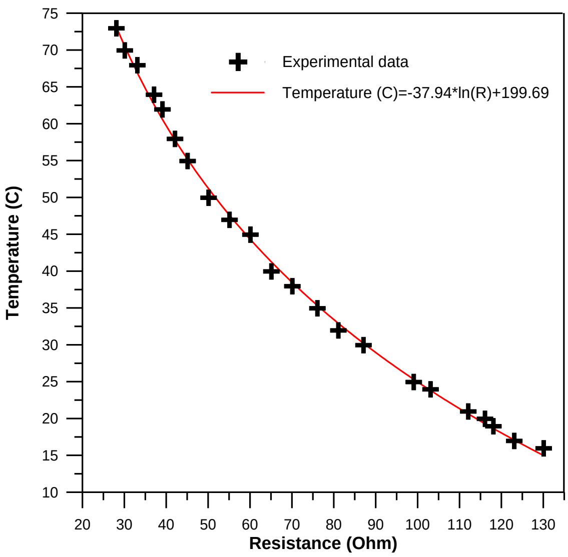

Fig.-3: The calibration curve of the thermistors.

thermistors were checked, and the system faced south. The measuring instruments were switched on. Each test starts at sunrise and ends at sunset for the day of experimentation. The data recorded at the end of each hour included the various temperatures storage, glass cover, absorber plate and the tank inlet and outlet as well as the flow rate of the withdrawn hot water during the test run for each load pattern. The test run was repeated with and without for each load pattern. Some experiments were carried out with a load condition.

The load was connected to the storage collector in such a way that the cold inlet water entered at the bottom of collector and the hot water outlet was taken from the top of collector. A valve at the inlet of the collector regulated the mass flow rate of load water. The load mass flow rate was measured by timing the water collected in a graduated vessel of 1 liters capacity. The temperature of the inlet and outlet of the load water were record at the same time as the other data. A few experiments were conducted by imposing a large load in a short period. Load water, which 12-liter was withdrawn quickly from the collector at a period of approximately 5 minutes. In this, the average temperature of water withdrawn from the collector and the temperature of mains water entering the collector were recorded.

A few experiments were conducted by imposing a load on the system. In this case, the average temperature of water withdrawn from the tank and the temperature of mains water entering the tank were recorded in addition to the other measurements. A few experiments were conducted by imposing a load on the system. In this case, the average temperature of water withdrawn from the tank and the temperature of mains water entering the tank were recorded in addition to the other measurements.

4. Mathematical model:

A lumped parameter thermal balance on a storage solar collector, which is irradiated on one surface by solar energy as:

(Rate of heat absorber by surface absorber) + (rate of heat carried by water inter the collector) = (rate of heat absorbed by water) + (rate of heat absorber by metal of tank) + (rate of heat carried by water leaving the collector) + (heat lost from the collector) [5].

Mathematically,

$$I_T(\tau_g \alpha_p)e \times F_{Sh} \times F_d \times A_a + \dot{m}_{fw} \times C_W \times T_{wi} = m_w \times C_W \times \left(\frac{dT_w}{dt}\right) + m_c \times C_C \times \left(\frac{dT_C}{dt}\right) + \dot{m}_{fw} \times C_W \times T_{wo} + U_L \times A_a(T_p - T_a) \quad \text{…. (1)}$$

We can re-write eq. (1) using the finite difference method as below:

$$I_T(\tau_g \alpha_p)e \times F_{Sh} \times F_d \times A_a + \dot{m}_{fw} \times C_W \times T_{wi} = m_w \times C_w \times \left(\frac{\Delta T_w}{\Delta t}\right) + m_c \times C_C \times \left(\frac{\Delta T_C}{\Delta t}\right) + \dot{m}_{fw} \times C_W \times T_{wo} + U_L \times A_a(T_p - T_a) \quad \text{…. (2)}$$

In other form:

$$I_T(\tau_g \alpha_p)e \times F_{sh} \times F_d \times A_a = J = \dot{m}_{fw} \times C_w(T_{wo} - T_{wi}) + m_w \times C_w(T_{swf} - T_{swi}) \times 1/\Delta\tau + m_c \times C_C(T_{CF} - T_{Ci}) \times 1/\Delta\tau + U_L \times A_a(T_p - Ta) \quad \text{…(3)}$$

Simplfiction eq.(3) we find the outlet temperature of load water from collector as :

$$T_{wo} = T_{wi} + \frac{J}{\dot{m}_{fw}.C_w} - \frac{m_w}{\dot{m}_{fw}.\Delta\tau}(T_{swf} - T_{swi}) - \frac{m_c.C_c}{\dot{m}_{fw}.C_w.\Delta\tau}(T_{CF} - T_{Ci}) - \frac{U_L.A_a}{\dot{m}_{fw}.C_w}(T_p - T_a) \quad \text{…(4)}$$

A program using Fortran-90 language which, used to formulate the eq.(4) and evaluate the Outlet temperature of load water from collector.

For no load condition, we can use the following equation to estimate the temperature of water inside tank (Duffie and Beckman, 1991):

$$T_w^+ = T_a + \frac{(\tau_g \alpha_p)_e I_t}{U_L} - \left[\frac{(\tau_g \alpha_p)_e I_t}{U_L} - (T_w - T_a)\right] e^{\left[-\frac{A_a U_L t}{(MC)_e}\right]} \quad \ldots(5)$$

Eq.(5) was solved by trial and error method using a simple program achieved for this purpose.

5. Performance of the collector:

The maximum useful efficiency (MUE) was used in this paper to determine the efficiency of storage solar collector. Specifically [10],

$$\mu = KF_E \eta_o - \frac{F_E U_L (\bar{T} - \bar{T}_a)}{\bar{I}} \quad \ldots. (6)$$

In eq. (1), T is the temperature of water in the storage, T_a is the ambient temperature and I is the irradiance on the aperture plane of the collector. η_o is the optical efficiency and U_L the heat loss coefficient of the collector storage unit. K is the incidence angle modifier and F_E is an enthalpy retrieval defined as:

$$F_E = \frac{M_W C_W}{M_W C_W + M_C C_C} \quad \ldots. (7)$$

Where M_W and C_W are, respectively, the mass and the heat capacity of the water and M_C and C_C are the respective mass and heat capacity of the material from which the collector-storage unit is fabricated. Most important of all, the bars indicate time average over the daily heating period, from sunrise until the time the water reaches its maximum daily temperature typically about 8 h. That is to say, we use *daily average*, rather than instantaneous, values of the variables in Eq. (1). The bar over K indicates a daily energy average, which is fairly constant on a monthly basis. MUE is defined as:

$$\mu = \frac{M_W C_W (T_{\max} - T_{sunrise})}{A_a \int I(t)dt} \quad \ldots(8)$$

where A_a is the collector aperture area, and the integral is taken over the time from sunrise until the water reaches its maximum temperature.

6. Results and discussions:

The main purpose of a storage solar collector is the conversion of solar energy into thermal energy, many parameters was studied as below:

1. Parametric storage temperatures:

The mean storage temperature is an important parameter. It is defined as a mass weighted average temperature, which is calculated as:

$$T_{av} = \frac{\sum_{i=1}^{n} M_i * T_i}{M_{total}} \quad \ldots (9)$$

(Fig.-4) shows the variation of mean storage temperature during a typical clear summer day. It is observed that the mean storage temperature increased with time, the mean storage temperature reaches its maximum value and then decreases after 4 p.m. This is because the net energy absorbed becomes just lower than the heat losses, which means that the useful energy transferred to the water is insufficient to cause any further increase in the mean storage temperature.

The maximum temperature was recorded for the zigzag storage collector with a front area of 1.414 m^2. The minimum temperature recorded for the flat storage collector with the front area of 1 m^2. The maximum value of mean storage temperature was 63 ^oC for this particular day in the zigzag storage collector. This trend is typical of solar water heating systems (Garg and Rani,1982), (Sokolov and Vaxman,1983),(Vaxman and Sokolov,1985),(Farhan,2002),(Alawi,2004)

The maximum value of the mean storage temperature of the collector and the time of its occurrence is different for the autumn days as can be observed experimentally from (Fig.-5).

The maximum value depends on the solar radiation intensity, the prevailing weather conditions, the starting inlet temperature and the heat losses, which are different during the days. The maximum value was 45 ^{o}C for this particular autumn day, occurred at 3 p.m., and then decreased in the late afternoon. This agrees with experimental results of most designs of solar storage collectors (Garg and Rani,1982), (Sokolov and Vaxman,1983), (Vaxman & Sokolov,1985),(Marzoq,1987) The agreement between the numerical predictions and the experimental data is good as shown in (fig.-6), especially in the first half of the day.

2. Effect of loading:

In order to show the effect of loading conditions on the system performance, some experiments were carried out with hot water withdrawal from the collector during

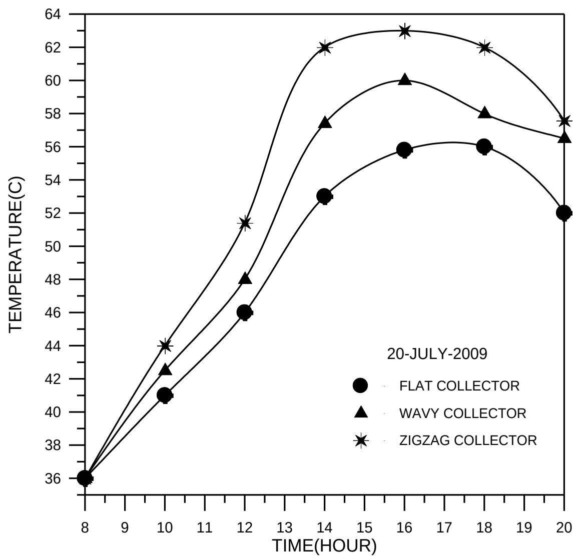

Fig.-4:The variation of mean storage temperature summer day.

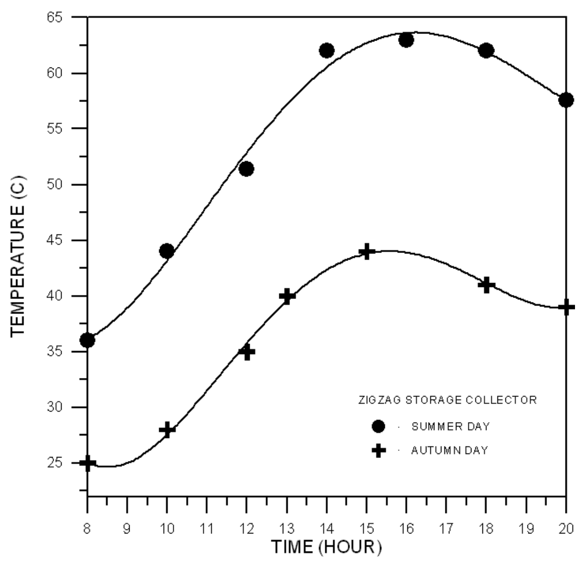

Fig.-5:The variation of mean storage temperature of the zigzag collector through the autumn and summer seasons.

the operating period in October and July 2009. The hot water withdrawn was taking continuously and intermittently. This was done by permitting cold mains water to enter the collector at its bottom, and the hot water was withdrawn from the top of the collector. The mass flow rate and temperature of the water were both measured. (Fig.-7) show the variation of system temperatures for a clear day with continuous load condition. The mass flow rate was 0.2 liter/min where the total hot water removed during the whole working period was 96 and 168 liters in winter and summer seasons respectively. (Fig.-7) shows the variation of inlet, outlet and mean storage temperature during autumn day. It is observed that the outlet temperatures are increasing throughout the period between 8 a.m. and 1 p.m., which indicates that the useful energy (q_u) is higher than that carried out by the load water. After 1 p.m., these temperatures start decreasing because the value of useful energy becomes lower than the energy carried out by the load water. The numerical data showed a higher value than experimental result but the agreement between the numerical and experimental data is acceptable as shown in (Fig.-8).

Fig.-9 shows the variation of system temperature for a clear day with intermittent load conditions on a autumn day. This load condition was imposed by withdrawing hot water from the storage at the end of each hour. The amount of water withdrawal was 10.5 liter/hour, starting at 6 a.m. and ending at 6 p.m. The total hot water withdrawal during the day would be 126 liters. Temperature behavior is similar to the continuous load conditions of (Fig.-6). The temperature difference between the outlet and inlet temperature is higher than the continuous load conditions, and the zigzag collector have the greatest difference between the other designs.

3. Efficiency of storage collector:

From the result of the previous section, the zigzag storage collector was the best to obtain a high temperature than the other two designs. The daily value of MUE of this type are, then plotted against $\frac{T_{avg} - T_{amb}}{I}$ as shown in fig.(10), the equation of this curve as below:

$$MUE = 0.673 - 9.8147\left(\frac{T_{av} - T_{amb}}{I_T}\right) \quad \ldots(10)$$

In comparison eq.(10) with eq.(6), we find that $-F_E U_L = -9.8147$, the value of F_E can be calculated from eq. (7) and equal to 0.96, that mean the heat transfer losses coefficient U_L equal to 10.22 W/m^2.K, this value is high and to enhancement the performance of the collector, reduction of this value is very necessary.

7. Conclusions and recommendations for the future work:

1. The performance of the zigzag flat plate collector was best than the wavy and flat plate collector.
2. The maximum value of temperature difference across the zigzag collector with 80 liters storage was 27 ^oC in summer and 20 ^oC in autumn during clear sky and no load conditions. With continuous loading test for zigzag flat plate collector the maximum temperature difference between the outlet and inlet temperature is 14 ^oC at 12 p.m. and 10 ^oC at the end of the day.
3. Studying water motion inside the collector experimentally by using the heliography techniques.
4. Experimental analysis of performance for parallel, series, and parallel-series connection of a bank of storage collectors.

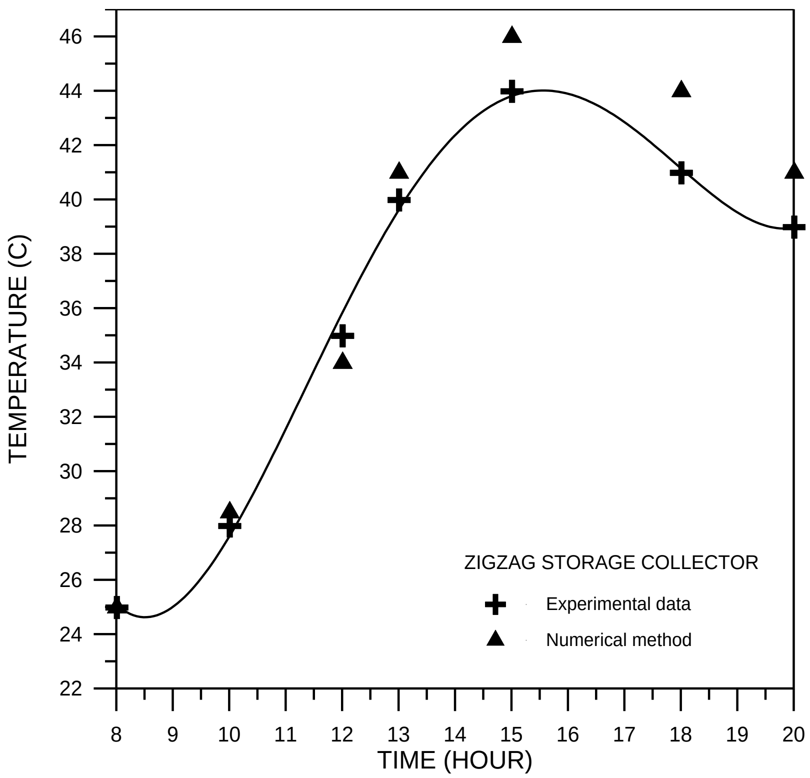

Fig.-6: The variation of mean storage temperature of the zigzag collector in autumn day.

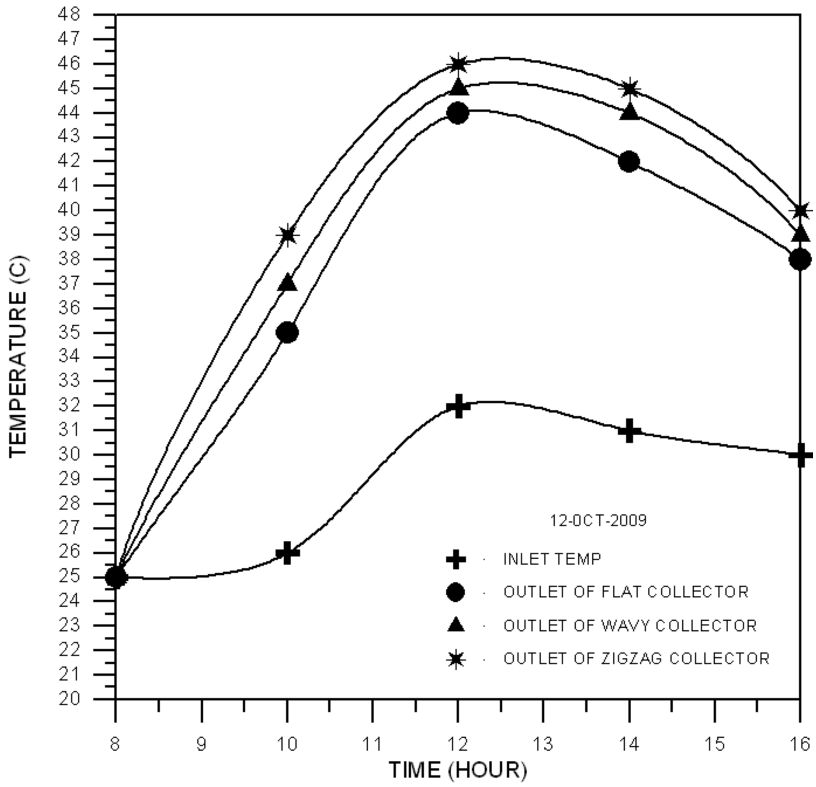

Fig.-7:Variation of system temperatures of storage collector with continuous load in autumn day.

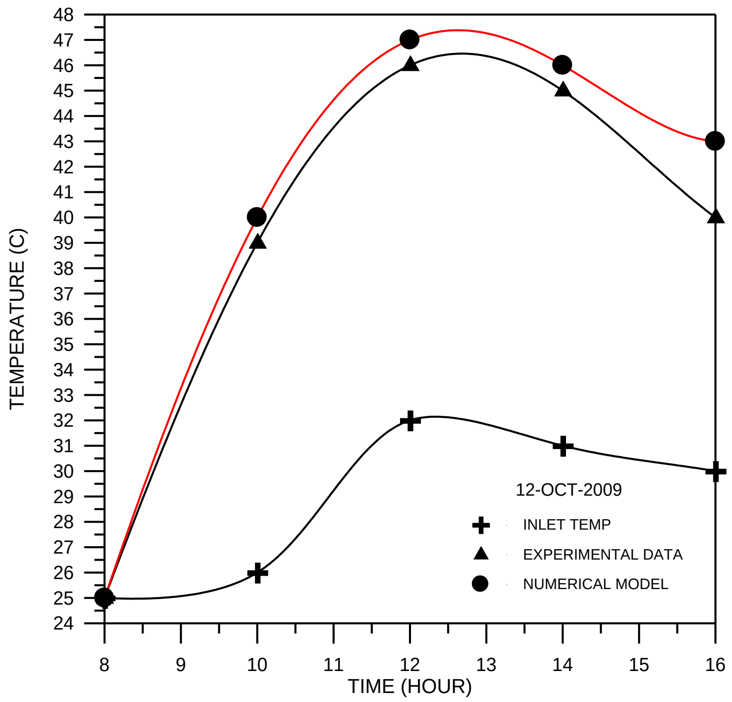

Fig.-8: Comparison of experimental and numerical outlet temperature of zigzag collector with continuous load.

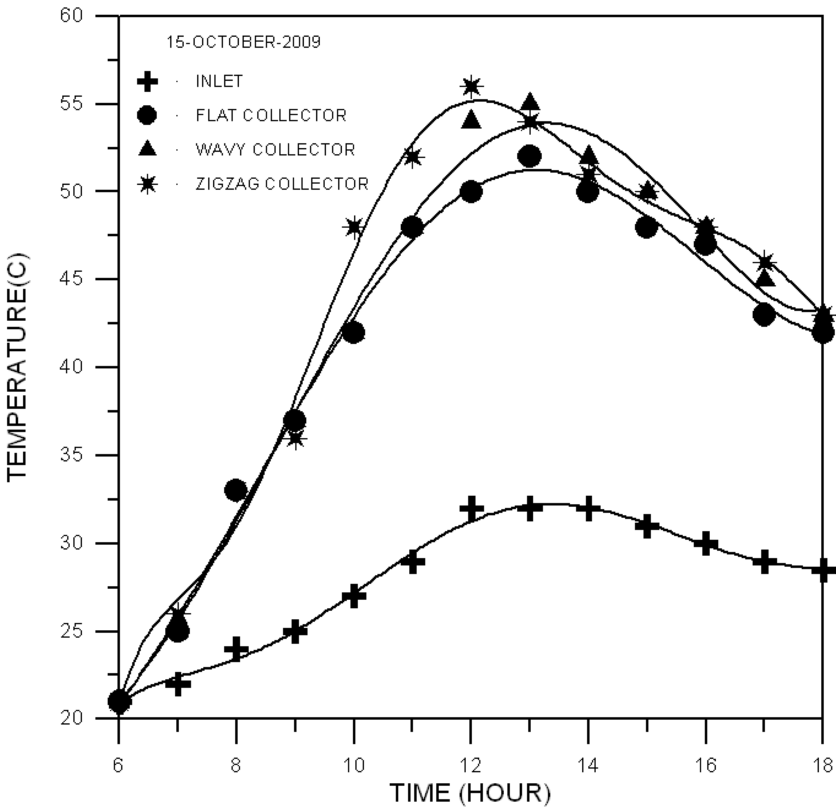

Fig.-9;Variation of system temperatures of storage collector with intermittent load in autumn day

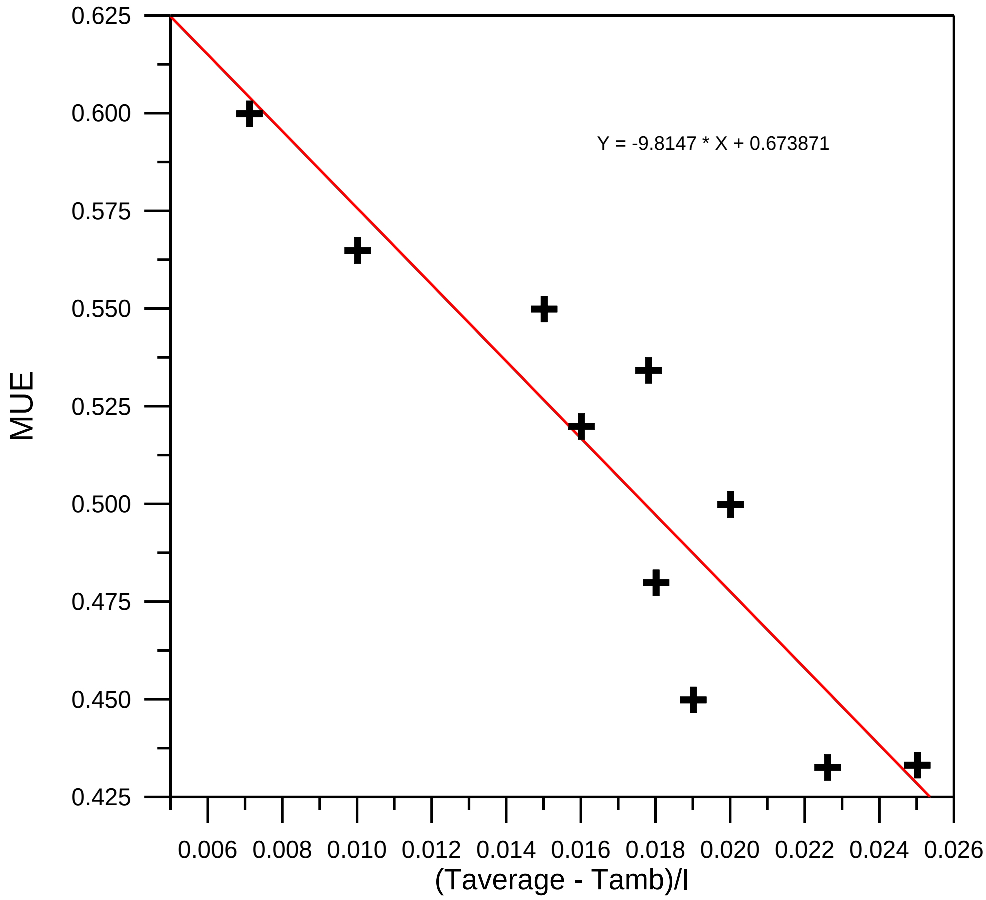

Fig.-10: MUE graph for the zigzag storage collector under study.

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