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"A SUGGESTED SOLAR HEATER SYSTEM OF RAPID HEATING RESPONSE USING FLAT-PLATE SOLAR COLLECTOR"

BY

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ABSTRACT

This paper presents the main components and theory of operation of a new solar heater system using a doubly metallic flat - plate collectors. The proposed heating system has the features of having a quick heating response, more hot water is collected in a second reservoir to be utilized in cloudy days and eventually this system permits the utilization of all types of radiation even the fluctuated one.

In addition, our article deals with the general analysis of the factors affecting the quantitative performance of the flat - plate collector.

I. INTRODUCTION

Since last five years, a gross increase in production cost of energy resources has been observed and escalated. The three fuels (coal, oil, and natural gas) presently employed to generate electric power are depletable. Natural gas has been steadily diminishing. Oil is now declining. On the other hand, coal is rated as the prime replacement fuel for oil and gas in power stations. However, the use of coal as an energy resource in electric generation has diminished since 1965 largely because of the costs of mining and transportation, and cost of converting oil -and- gas fired boilers to accept coal as a fuel. Coal also has side pollutants such as SO_2 and Nitrogen oxides.

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So the need for renewable energy resources arises. Renewable energy resources must be evaluated on a different basis than depletable resources. Depletable resources are by definition finite, renewable are generally time based (e.g. wind, sun, hydroflow...). Thus a complete energy cycle is quantified on the daily or annual basis.

Hydro power has just about reached the saturation point, in so far as new development run -of- the river sites are concerned.

Solar energy is still elusive. Although numerous concepts have been devised and investigated to utilize this resource for the heating of commercial buildings, as well as, for power generation.

A lot of research and development is still necessary before functional systems become operational on large scale. Progress has been made in solar collector designs for practical domestic applications of heat energy. However, the advances in adapting solar collectors to electric power generation have not been so rewarding to date.

2. HEAT TRANSFER ANALYSIS

To design and compute the size, the efficiency and the cost of equipment necessary to transfer a specified amount of heat in agiven time, a heat transfer analysis must be made.

The dimensions of a solar collector, a heat exchanger, or a refrigerator depend on the amount of heat to be transmitted and on the rate at which heat is to be transferred under given external conditions.

2.1. Modes of heat transfer

Heat is transmitted by 3 distinct modes

a) Conduction

It is a process by which heat flows from a region of higher temperature to a region of lower temperature within a solid, liquid, or gaseous medium or between different media in direct physical contact.

The basic mathematical relations for heat transfer by conduction state that the rate of heat flow (flux) by conduction q_k in a material is equal to the product of

$$q_k = - k A \frac{d \Theta}{d x} \quad \text{......(1)}$$

where

k is the thermal conductivity of the material in Btu/hour/ ft^2/°F/ft.

A is the area of the medium e.g. a building wall through which heat flows by conduction in ft^2.

$\frac{d \Theta}{d x}$ is the temperature gradient through the medium in °F/ft.

Integrating equation (1) for heat flow through a wall of thickness D having a temperature Θ_1 over one surface and Θ_2 over the other, then we have

$$q_k = \frac{k A}{D} (\Theta_1 - \Theta_2) \quad \text{.............. (2)}$$

The temperature difference between the higher temperature Θ_1 and lower temperature Θ_2 is the driving potential which causes the flow of heat. Equation (2) is written in the form:

$$q_k = \frac{\Theta_1 - \Theta_2}{R_k} \quad \text{.....(3)}$$

where $R_k = \frac{D}{k A}$

Which is called the thermal resistance the wall offers.

b) <u>Radiation</u>

It is a process by which heat flows from a body at higher temperature to a body at a lower temperature when the bodies are separated in space or even when a vacuum exists between them. Radiation is the mode of heat transfer by which the sun transfers energy to the earth. The quantity of energy leaving a surface as radiant heat depends on the absolute temperature and the nature of the surface.

A perfect radiator (black body) emits radiant energy from its surface at a rate q_r given by

$$q_r = A \sigma \theta^4 \qquad \ldots\ldots(4)$$

where

q_r is the heat-flow rate in Btu/hour.
A is the surface area in ft^2
θ is the surface temperature in degrees Rankine
σ is a dimensional constant with a value of 0.1713×10^{-8} Btu/hr ft^2 $°R^4$

Real bodies emit radiation at a lower rate than do black bodies given by

$$q_r = \bar{\epsilon} A \sigma \theta^4 \qquad \ldots\ldots(5)$$

where $\bar{\epsilon}$ is the average emittance of the surface the rate of heat transfer between 2 large parallel plates with areas A_1 and A_2 can be written in the form:

$$q_{r,net} = A_1 P_{1-2} \sigma (\theta_1^4 - \theta_2^4) \qquad \ldots\ldots(6)$$

where P_{1-2} is aquantity which depends only on the surface properties, orientation and shape.

Equation (6) can be written in the same form as that for conduction heat transfer:

$$q_{r,net} = \frac{\theta_1 - \theta_2}{R_r} \qquad \ldots\ldots(7)$$

where R_r is the resistance to radiation heat transfer and is given by

$$R_r = \frac{1}{A_1 P_{1-2} \sigma (\theta_1^2 + \theta_2^2)(\theta_1 + \theta_2)} \qquad \ldots\ldots(8)$$

The method of calculation of P_{1-2} is given in heat-transfer texts.

c) Convection

It is a process that transfers heat from one region to another by motion of a fluid. The rate of heat transferred by convection q_c between a surface and a fluid can be calculated from the relation:

$$q_c = h_c A (\Theta_s - \Theta_f) \qquad ......(9)$$

where

q_c is the rate of heat flow by convection Btu/hr.
A is the base area of heat transfer by convection, ft^2.
Θ_s is the surface temperature, °F
Θ_f is the fluid temperature, °F
h_c is the convection heat-transfer coefficient, Btu/hr ft^2 °F

The thermal resistance to convective heat transfer R_c is given by

$$R_c = \frac{1}{h_c A} \qquad ......(10)$$

2.2. Compound Heat-Transfer Mechanisms

In most engineering situations, however, heat is transferred by 2 or 3 of the mechanisms acting simulataneously.

The surface of a solar-energy collector for example loses heat simultaneovsly by convection as well as by radiation to the environment. For heat loss through a combination of radiation and convection, the total rate of heat transfer q from the surface of the collector is given by the equation:

$$q = q_r + q_c = \frac{\Theta_{coll} - \Theta_{out}}{R_{cr}} \qquad ......(11)$$

where R_{cr} is the combined resistance for the 2 mechanisms, convection and radiation acting in parallel.

Θ_{coll} is the average collector - surface temperature
Θ_{out} is the outside air temperature.

3. FACTORS INFLUENCING FLAT-PLATE SOLAR COLLECTOR PERFORMANCE.

The components of a typical flat-plate collector are:

a) One or more transparent flat front plates.

b) One or more insulating zones bounded by the covers.

c) An absorbing rear plate.

Heat is removed from the rear plate by agaseous or liquid heat-transfer fluid, such as air or water.
Thermal insulation is usually placed behind the absorber to prevent heat losses from the rear surface. The front covers are generally glass that is transparent to incoming solar radiation from the absorber.

For water systems the absorber plate can be any metal, plastic, or rubber sheet that incorporates water channels, while for air systems the space above the collector plate can also serve as the conduit. Many metal products, such as the aluminum, copper, and steel absorbers are suitable for use in water or air systems.

3.1. Effect of Spacing between glass plates and temperature difference between absorber and outer plate.

Fig.1 displeys the influence of specing between glass plates for a collector consisting of 2 glass plates with a flat - black absorber surfece of roll - bonded flow channels.
When the distance between the plates is too small, heat loss occurs by conduction through the air gap. The efficiency increases with increasing air gap but reaches an asymptote at an interplate spacing of about 0.6 inch. efficiencies.

The collector efficiencies are strongly affected by the difference between the temperature of the absorber plate θ_{coll} and the outer glass plate θ_g. It is desirable to hold the absober temperature low to obtain a high efficiency, but at the sametime one must obtain a sufficiently high absorber temperature so that the heat supply to the building is at a practical temperature for space heating and storage.

As a compromise between these 2 conflicting demands, an absorber temperature of 130°F was chosen for the research.

3.2. Effect of number of glass plates and temperature difference between absorber and outer plate.

Fig. 2. reveals the effect of using a single, double, or triple plate on the efficiency under the conditions of collector absorber-plate temperature, θ_{coll} = 130°F, $D = \frac{3}{8}''$, insolation I = 150 Btu/hr ft^2 and absorptance $\bar{\alpha}_s$ and infrared emittance $\bar{\epsilon}_{ir}$ = 0.95.

The lower the number of transparent plates, the more sharply the efficiency drops with increasing temperature difference between absorber and outer glass plate, $\theta_{coll} - \theta_9$.

More solar energy reaches the absorber plate when only a single cover plate is used because the addition of a second glass plate reduces the set transmittance of the glass-plate system from 0.9 to 0.81.

At high values of $\theta_{coll} - \theta_9$ the convective heat loss becomes dominant, and the addition of a second or third plate substantially reduces this loss.

3.3. Influence of infrared emittance and temperature differences between absorber and outer plate.

Fig. 3. Shows the influence of selective coatings, with high solar absorptance and low infrared emittance, on the solar-collector efficiency under the conditions of collector absorberplate temperature θ_{coll} = 130°F, interplate spacing $D = \frac{3}{8}''$, insolation I = 150 Btu/hr ft^2, and solar absorptance $\bar{\alpha}_s$ = 0.95

3.4. Effect of solar-radiation intensity and temperature difference between absorber and outer plate.

Fig. 4. Explains the effect of solar-radiation intensity on collector efficiency under the same conditions in the

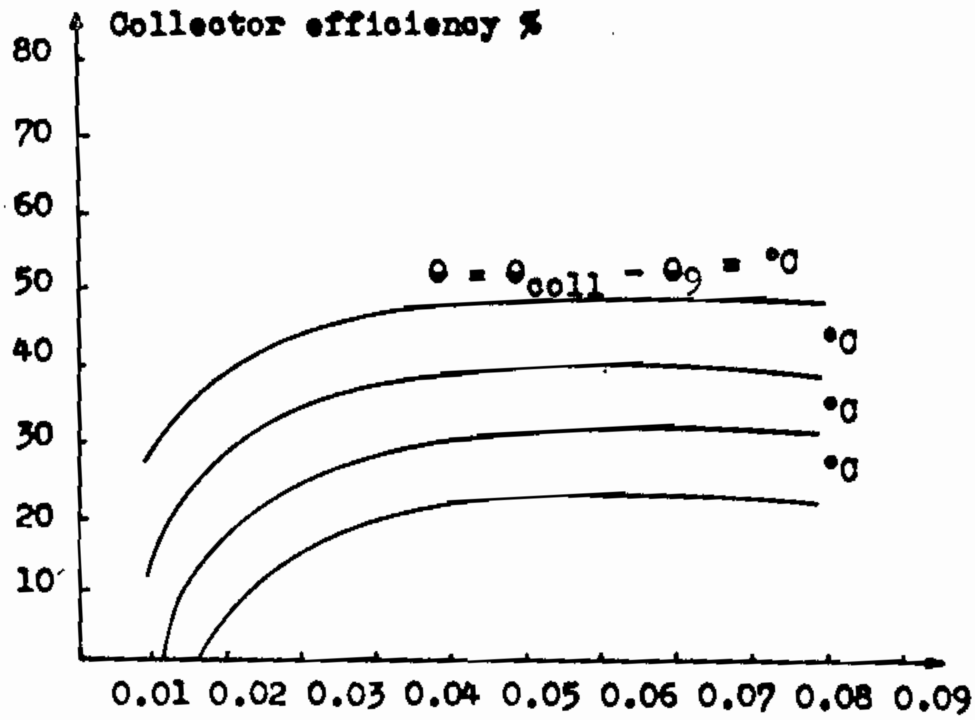

Fig. (1): Interplate spacing distance D, ft

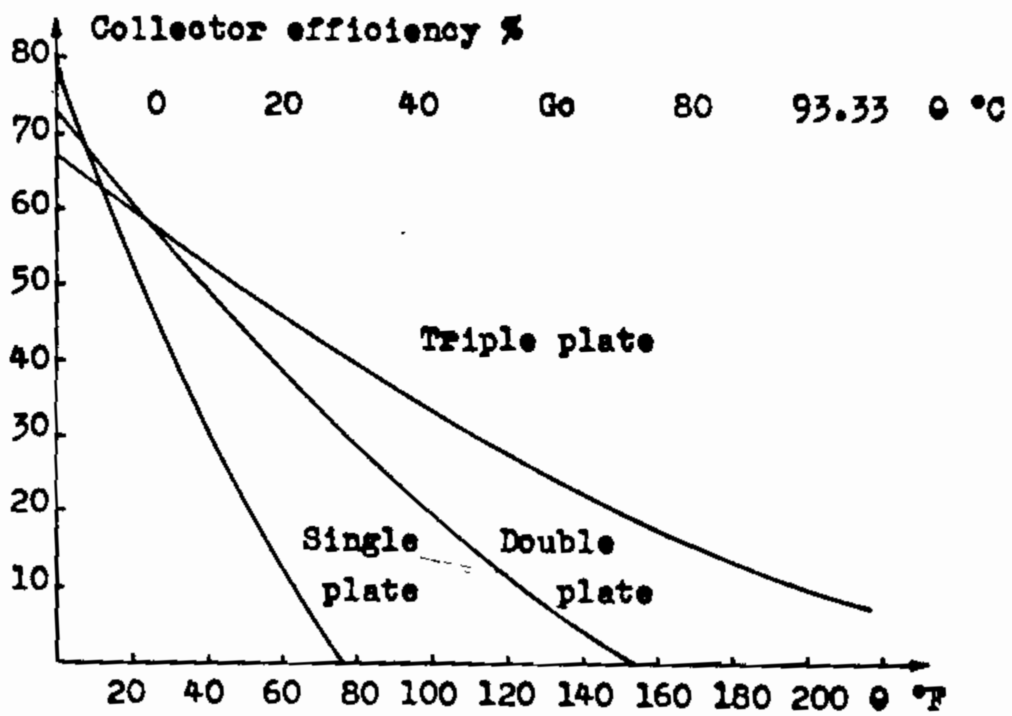

Fig. (2) Temperature difference between alosorber and outer plate.

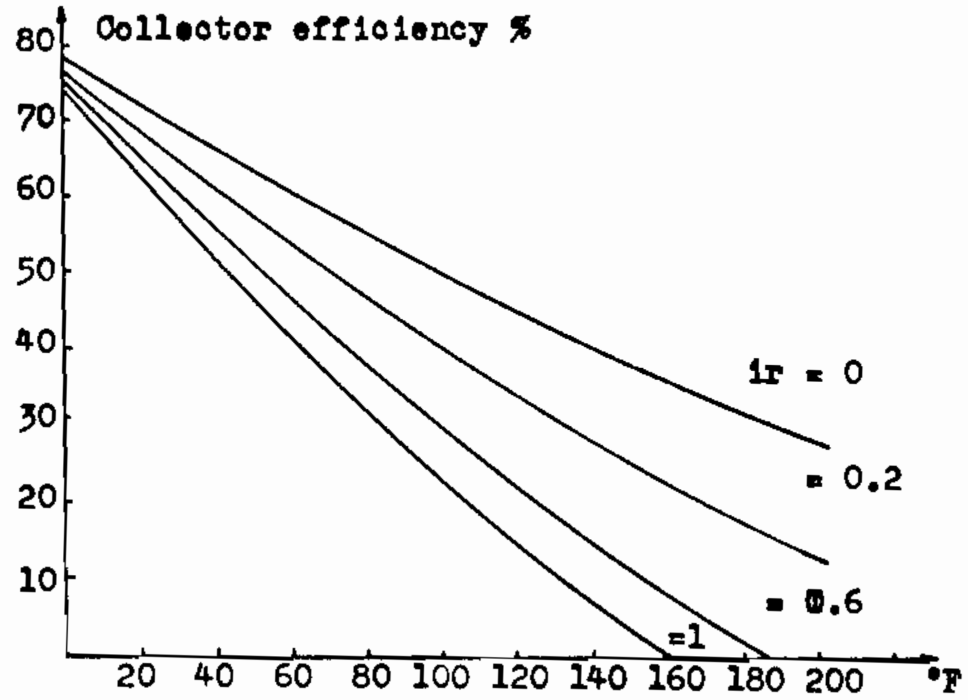

Fig. (3) Temperature difference between absorber and outer plate.

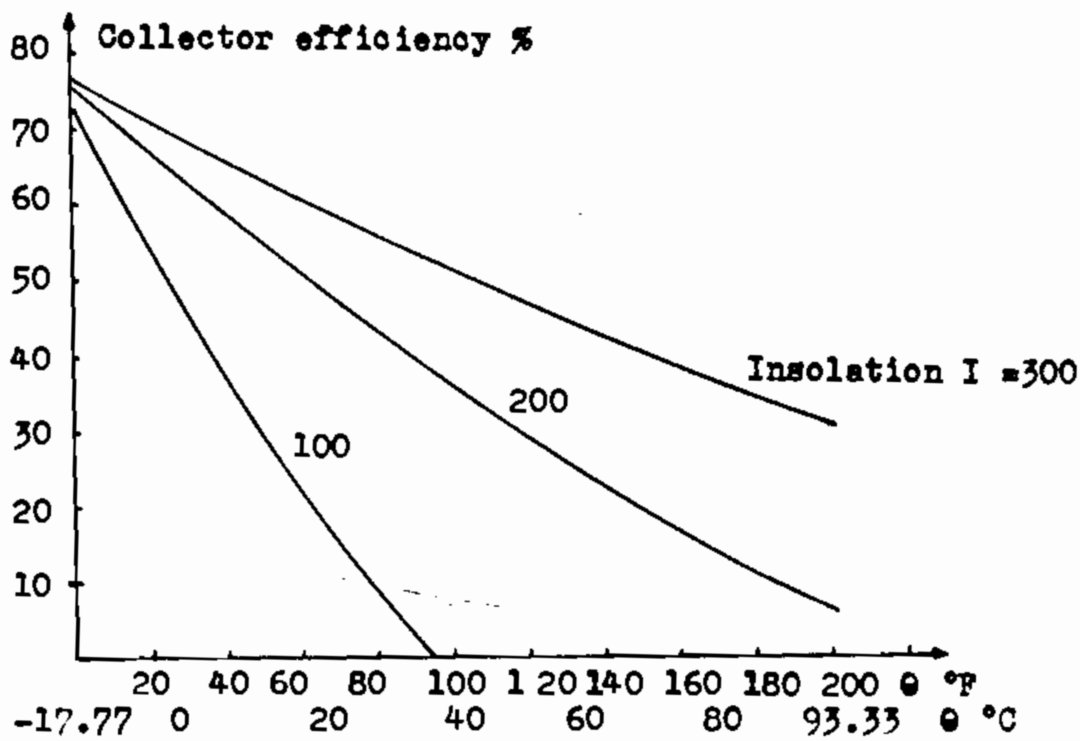

Fig.(4): Temperature difference between absorber and outer plate.

preceding items, the higher the solar - radiation intensity, the higher the efficiency at a given operating temperature. For example, if $\Theta_{coll} - \Theta_9$ is 80°F, the collector efficiency is 10% when I is equal to 100 Btu/hr ft^2, when I reaches 300 Btu/hr ft^2 the efficiency rises to 57%.

The large increase in heat collected when incident radiation is trebled is because the convective heat loss is a function of $\Theta_{coll} - \Theta_9$ only; radiative heat losses are affected mainly by the absorber temperature, which was assumed constant in both cases.

3.5. Influence of solar-radiation incidence angle and temperature difference between absorber and outer plate.

This is the angle between the surface normal and the sun's rays.

Fig. 5. illustrates this effect which is two fold: first, as the incidence angle increases, the amount of solar radiation impinging on the collector is reduced by a cosine factor, second, as the angle of incidence increases, the reflectance of the transparent cover plates increases. For values of angle of incidence greater than 50°, the transmittance of the glass plate decreases rapidly, and the reflective losses increase correspondingly. The combined impact of the cosine and reflectance effect is clearly depicted in Fig. 5. For an angle of incidence of 80° the combined effect reduces the collector efficiency by so much that in the range of $\Theta_{coll} - \Theta_9$ larger than 10°F (about - 12°C) not only will no heat be collected but the collector actually loses heat if the absorber plate temperature is kept at 130°F(about 55°C).

3.6. Variation of efficiency of collector with the time of day and days of the year and the temperature difference.

Fig. 6. displays this change under the conditions of: collector absorber-plate temperature Θ_{coll} = 130°F (55 °C),

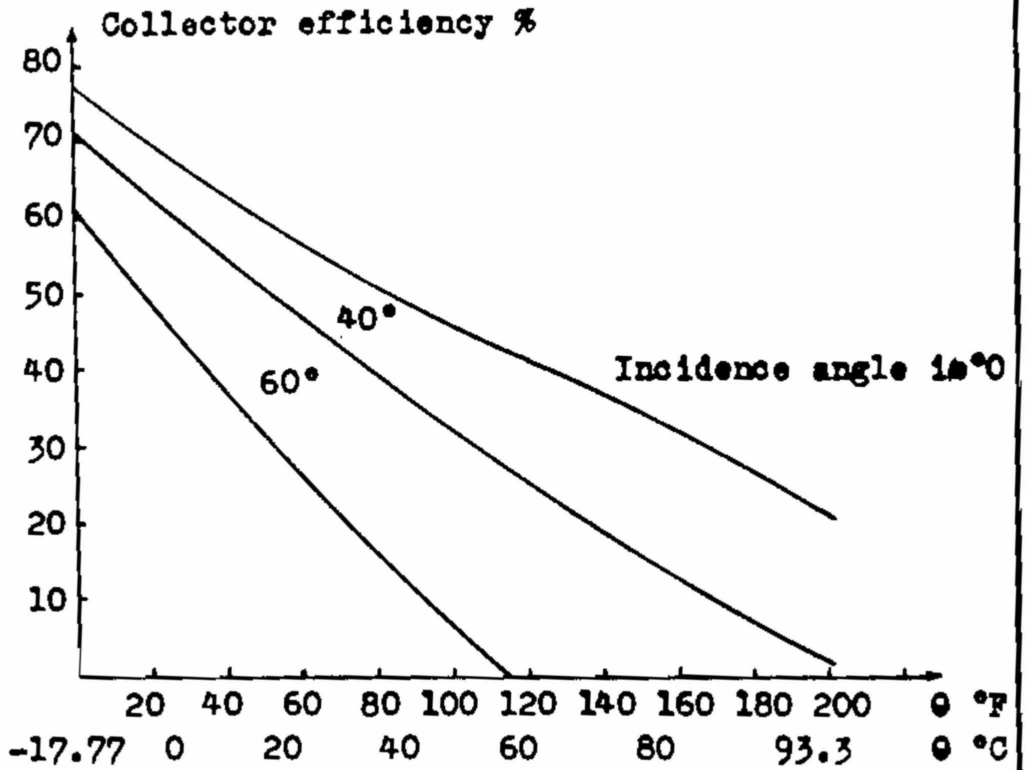

Fig.(5): Temperature difference between absorber and outer plate.

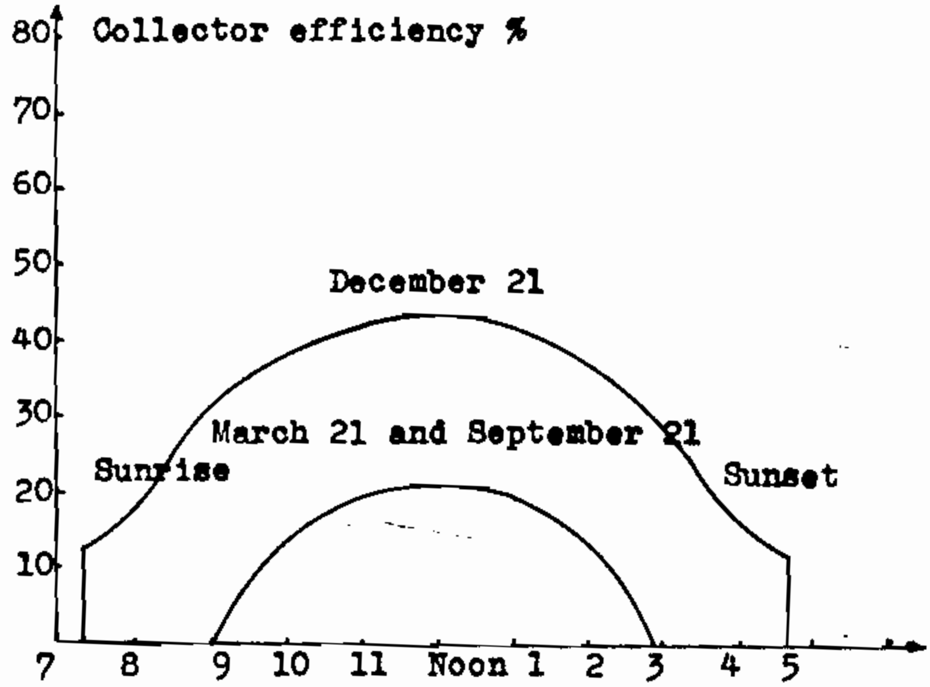

Fig. (6) Time of day

collector outer-plate temperature Θ_g = 30°F ($\simeq$ - 1°C), inter-plate spacing D = $\frac{3}{8}''$ and solar absorptance $\bar{\alpha}_s$ and infrared emittance $\bar{\epsilon}_{ir}$ = 0.95. It can be seen that between 10 A.M. and 2 P.M., the efficiency of the collector remains relatively constant. The collector efficiency during winter is higher than in fall and spring because the angle of incidence on a south facing, vertical collector is smaller in December than in March or September. This Seasonal incidence angle effect is the main reason vertical collectors are suitable for winter heating in medium latitudes.

3.7. Effect of Types of absorber coatings and temperature difference between absorber and outer plate.

The performance comparison between a single-plate collector with a selective-black coating and a double-plate collector with either a selective-black or flat - black coating is revealed in Fig. 7. This comparison is executed under the restrictions of: collector absorber-plate temperature $\Theta_{coll} \cong$ 55°C = 130°F, interplate spacing D = $\frac{3}{8}''$, insolation I = 150 Btu/hr ft^2, and solar absorptance $\bar{\alpha}_s$ = 0.95.

4. General Analysis of the Performance of a Liquid-Cooled Collector.

The most widely used measure of performance of a flat -plate collector is the efficiency η, i.e. the ratio of delivered heat to the insolation. Efficiency is not a sufficiently descriptive index by which to select a collector since the more efficient a collector is, the more expensive it usually is.

The most important properties of a working collector are the number and type of covers, type of collector surface and the collector temperature.

4.1. Number and type of covers

The most reliable material currently available for collector is glass which has a single most important property

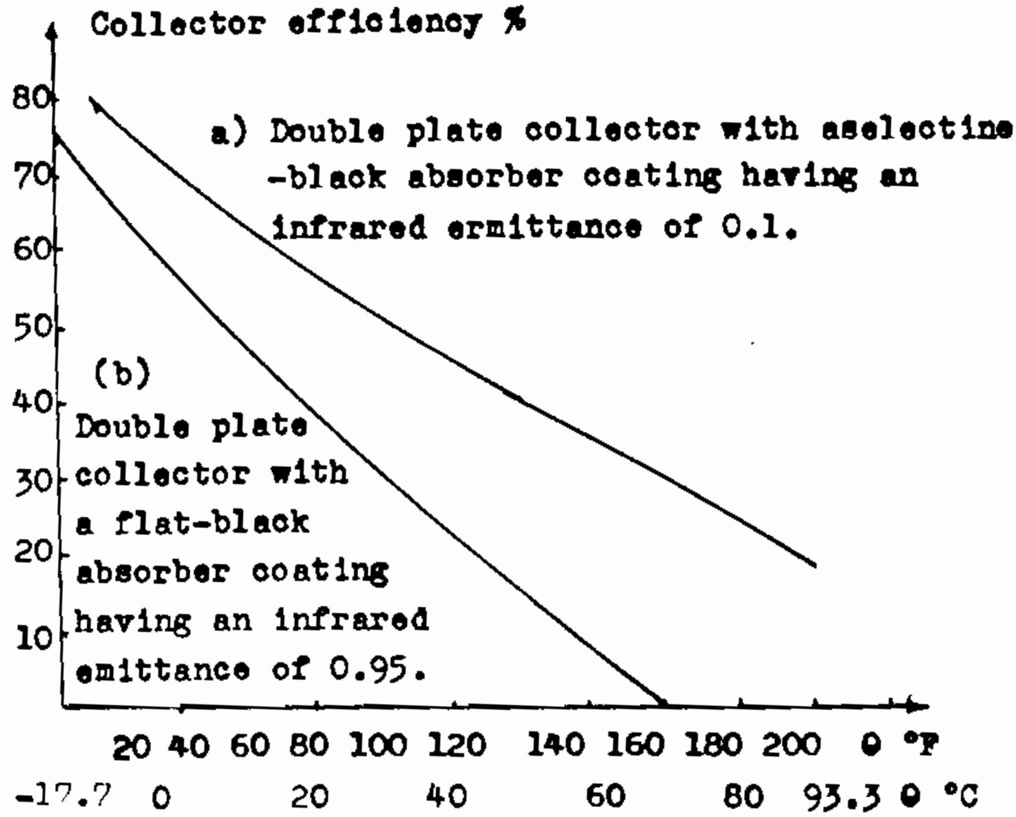

Fig.(7): Temperature difference between absorber and outer plate.

for solar collectors is the percent of solar radiation it transmits. This transmittance depends directly on the refr-active index of the glass.

The reflectance of a plate of glass varies with the incidence angle i.

An expression (the Fresnel equation) to calculate the reflection of beam rediation from one surface of a transparent solid $_{bl}$ is yielded by

$$\bar{\rho}_{bl} = \tfrac{1}{2} \left(\frac{\sin^2 (i-r_a)}{\sin^2 (i+r_a)} + \frac{\tan^2 (i - r_a)}{\tan^2 (i + r_a)} \right) \qquad \ldots\ldots(12)$$

Where r_a is the angle of refraction and

$$\sin r_a = \frac{\sin i}{r_{i,coll}} \qquad \ldots\ldots(13)$$

Where $r_{i,coll}$ is the refractive index of a collector cover. If the incidence angle is exactly 0°, a special form of the Fresnel equation must be used:

$$\bar{\rho}_{bl} = \frac{(r_{i,coll} -1)^2}{(r_{i,coll} +1)^2} \qquad \ldots\ldots(14)$$

The reflectance from several glass surfaces ρ_{bn} is then given by

$$\rho_{bl} = 1 - \frac{1 - \bar{\rho}_{bl}}{1 + (2\,n-1)\,\bar{\rho}_{bl}} \qquad \ldots\ldots(15)$$

Where n is number of collector covers.

4.2. Type of collector surface

Although much research has been done on selective surfaces, few selective surfaces are available today that have sufficient durability experience and low cost to warrant use on flat-plate collectors.

The only commercial selective surface available with lengthy field experience is the proprietary Miromit selective Black used on Miromit Solar water heaters.

Nonselective, black points with an appropriate primer are recommended for general use at this time. One Such point is Nextel TM. The Solar absorptance and infrared emittance are 0.96 for this product. This absorptance for diffuse radiation $\bar{\alpha}_{s,d}$ may be taken as $\bar{\alpha}_{s,d} = 0.9$

4.3. Collector temperature

The thermal losses of a flat-plate collector depend on the operating temperature of the collector.

The operating temperature is determined by the ultimate use to which the heated fluid is to be put and can range from 30°C (90°F) to 99°C (210°F) or higher.
The fluid flow rate through a collector may be determined from the heat balance:

$$q_a = \dot{m}\, c_f\, (\theta_{coll,in} - \theta_{coll,out}) \qquad \text{......(16)}$$

where

q_a = absorbed energy perunit collector area, Btu/hr ft^2

m = fluid flow rate per unit collector area, lb_m/hr ft^2

c_f = specific heat of fluid, Btu/lb_m °F

$\theta_{coll,in}$ =collector transportfluid-inlet temperature, °F

$\theta_{coll,out}$ = collector transport - fluid-outlet temperature, °F

For a pumped water system, the inlet-outlet temperature difference is 10 to 20 °F ($\simeq$ - 12 °C & + 7°C respectively), for a thermosiphon, about 40°F (+5°C). The average collector fluid temperature θ_{coll} may be taken as the averge of the inlet and outlet temperatures for liquid cooled collectors,

$$\theta_{coll} = \frac{\theta_{coll,in} + \theta_{coll,out}}{2} \qquad \text{......(17)}$$

An expression for the thermal loss L from such a collector by radiation and convection has been developed and is given without proof (back and edge losses assumes small).

$$L = \frac{\theta_{coll} - \theta_{out}}{\frac{1}{h_{cl}} + \frac{n/c}{\sqrt[4]{(\theta_{coll}-\theta_{out})/(n+f)}}} + \frac{\sigma(\theta^4_{coll} - \theta^4_{out})}{\frac{1}{\bar{\epsilon}_{ir,c}} + \frac{2n+f-1}{\bar{\epsilon}_{ir,g}} - n} \qquad \text{......(18)}$$

where

h_{cl} = coefficient of heat transfer from the outermost collector cover, Btu/hr ft^2 °F

C = factor to account for collector tilt in the expression for coefficient of free convection heat transfer on glass collector covers, Btu/hr ft^2 °F$^{1.25}$

$\bar{\epsilon}_{ir,c}$ = nonselective collector surface emittance

$\bar{\epsilon}_{ir,g}$ = cover emittance

n = number of glass covers

f = outer collector - cover to non-outer cover heat transfer resistance ratio.

$$h_{cl} = 1 + 0.35\,V \qquad \text{......(19)}$$

where V is the wind speed in knots.

$$C = 0.19 - 0.00078\,\beta \qquad \text{......(20)}$$

β = Surface tilt angle from horizontal

$$\bar{\epsilon}_{ir,c} = 0.95 \qquad \text{......(21)}$$

$$\bar{\epsilon}_{ir,g} = 0.90 \qquad \text{......(22)}$$

$$f = 0.76 \times 10^{-0.037\,V} \qquad V \leq 8 \qquad \text{......(23 a)}$$

$$f = 0.36 \times 10^{-0.020(V-8)} \qquad 8 < V \leq 17 \qquad \text{......(23 b)}$$

$$f = 0.24 \times 10^{-0.011(V-17)} \qquad V > 17 \qquad \text{......(23 c)}$$

4.4. Calculation of collector efficiency.

It is defined as the ratio of output, q_a, to input, $I_{b,coll} + I_{n,d}$:

where $$\eta = \frac{q_a}{I_{b,call} + I_{n,d}}$$

$I_{h,d}$ is the diffuse component, note that the insolation on a horizontal surface I_h consists of a direct (beam) component and a diffuse (skylight) component.

$I_{h,d}$ is approximately given by

$$I_{h,d} = 0.78 + 1.07\alpha + 6.17\ CC \qquad \text{......(24)}$$

where

α = Solar-altitude angle, deg.

CC = cloud cover (CC = 0 indicates a clear sky, CC = 10 indicates the sky is fully covered with clouds)

The horizontal beam component $I_{n,b}$ is the difference

$$I_{h,b} = I_h - I_{h,d} \qquad \text{......(25)}$$

The incident beam component normal to the collector $I_{b,coll}$ is then:

$$I_{b,coll} = \frac{I_{h,b} \cos i}{\sin\alpha} \qquad \text{......(26)}$$

Also q_a is given as follows:

The amount of energy absorbed by the absorber plate I_{coll} is the insolation diminished by cover and absorbing - surface reflectance losses (second order ground reflection effects are ignored)

$$I_{coll} = I_{b,coll}(1 - \bar{P}_{bn})\bar{\alpha}_{s,b} + I_{h,d}(1 - \bar{\rho}_d)\bar{\alpha}_{s,d} \qquad \text{...(27)}$$

The value of I_{coll} is a property of the collector independent of the operating temperature of the collector.

The amount of energy delivered to the working fluid q_a is I_{coll} diminished by thermal losses L (equation 18)

$$q_a = I_{coll} - L \qquad \text{......(28)}$$

5. Proposed Solar heater system

Solar energy due to its nature as a time based resource must be used as a side source of energy. But due to clear sky of our country, almost a complete dependence upon a solar energy source can be in consideration.

Sun radiation also varies from place to place, but the most practical use must be on the temperature ranges 40-60°C.

Flat plate collectors are usually a doubly metalic plate that acquires channels in which heat conveyer liquid passes.

Collector plate must be directed to face radiation, and treated by black painting which improves the selectivity of the collector, and simult aneously avoids accumulation on the surface outwards.

Up to this horizental plate, there's a glass plate which prevents heat losses in addition to protecting the metalic plate from atmospheric effects. Fig. 8.

Conducting plate is prepared by heat isolators as for the part non-exposing to sun.

The container is inside a metalic box of stainless steel.

However, we need to have more experiments on other materials, to improve recent rechnologies on market.

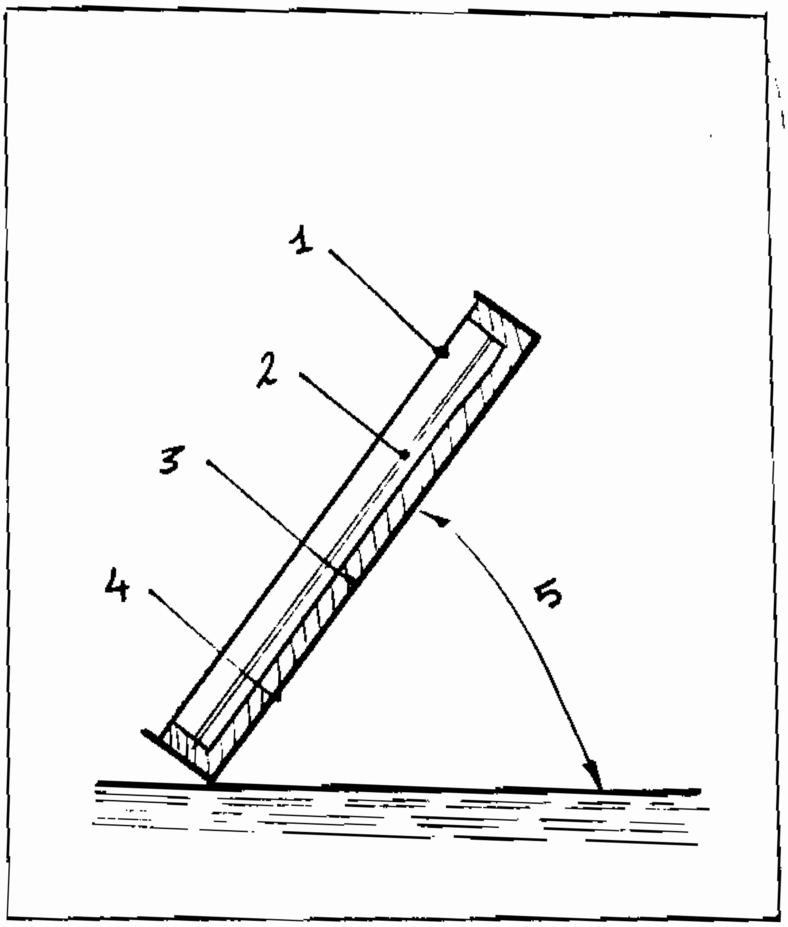

Fig. (8): Solar collector model.

1) glass-plate 2) collector
3) isolator 4) Collector box
5) dngle

Utilization of power collected by collector is as follows; conducting path of collector is hydroulically connected to heating reservoir, the last makes the heat exchange between collector and liquid (a mixture of water and salts).

These last two processes prevent rise of boiling point of water and decrease freezing point.

The heated liquid goes up to water heater (by thermal effect), or it may need a pump if the heating reservoir has been stopped at alow level (Fig. 9).

In the case of getting high temperature (i.e. better heating performance), we must increase the number of collectors and operate them on parallel.

We propose a heating system which has the following basic features.

- a quick heating response, i.e. the ability of providing not water in the first reservoir.
- more hot water collection in the 2nd reservoir, (preparation reservoir) which can be used on cloudy days, because reservoirs are interconnected in a series.
- cold water from transporting pipe feeds the 2nd one, while heated water is taken from the 1st only.

There is no confusion of mixing hot and cold water. The system shown in Fig. 10 also permits utilization of all types of rediation even in fluctuating radiation.

6. CONCLUSIONS

Due to the weather clearness and hot temperature ranges in EGYPT, we have a better utilization of solar energy. This is achieved by great efforts of groups work and scientific teams. This paper proposes a new solar heater system using a doubly metallic flat-plate collectors. This solar heater has

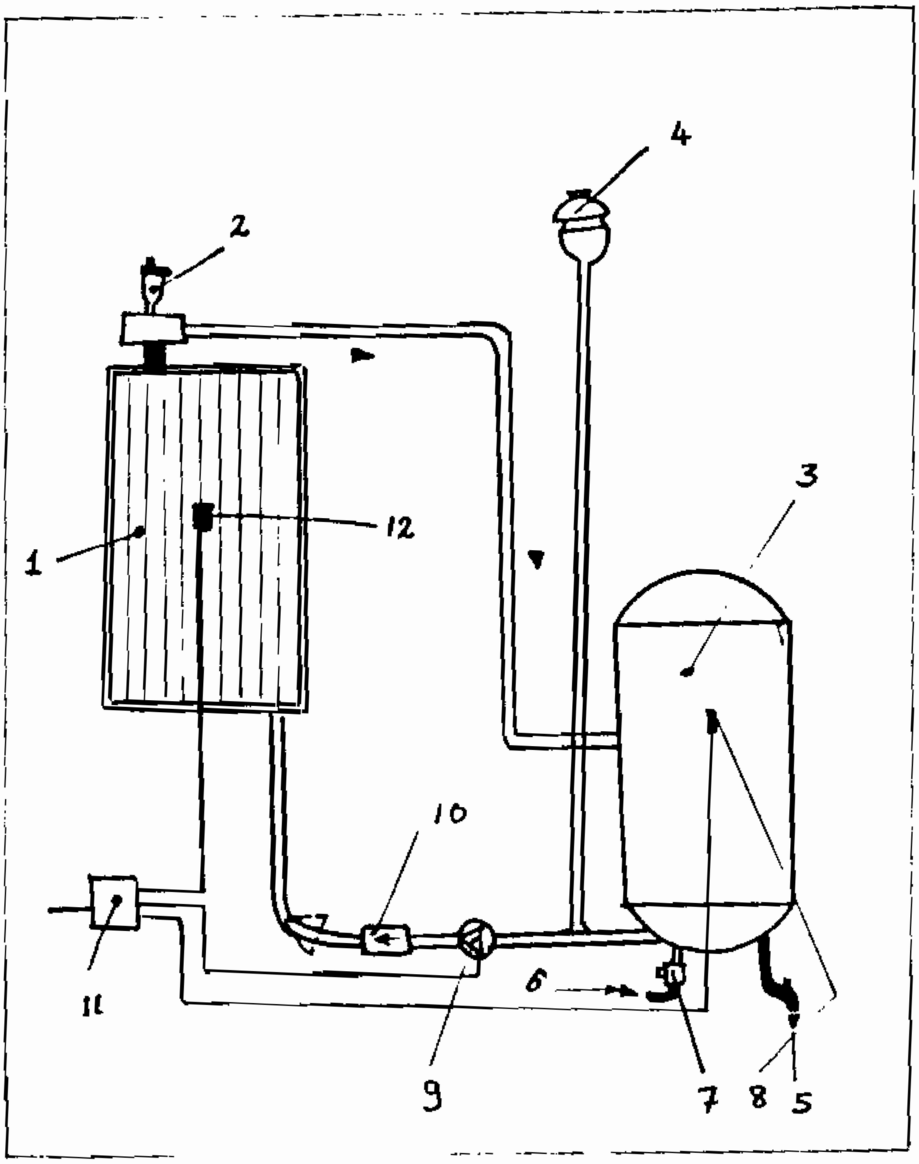

Fig. (9) Schematic diagram of solar collector and heat reservoir.

1) solar collector 2) ventilating value
3) reservoir 4) expansion centainer
5) heated water outlet 6) cold water inlet
7) altsmatic value 8) test gauge
9) cycles instrument 10) one way value
11) electronic heating control.
12) test gauge for collector.

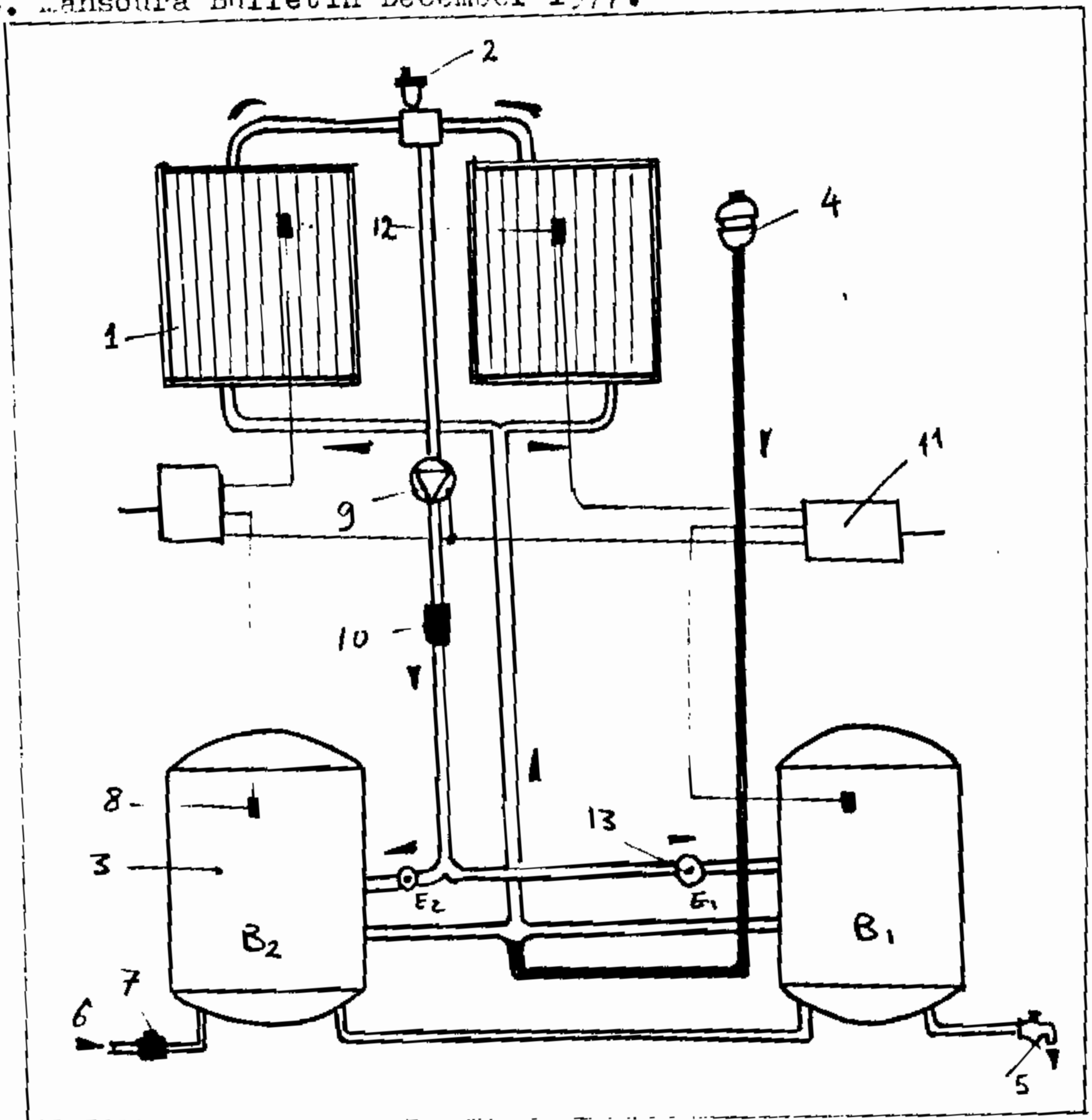

Fig. (10): The proposed system.

1) solar collector
2) ventilating valve
3) reservoir
4) expansion container
5) heat water out let
6) cold water inlet
7) automatic valve
8) test gauge
9) cycles instrument
10) one way valve
11) electronic heating control
12) test gauge for collector
13) electronic valve.

good features of having quick heating response, more hot water is collected in a second reservoir to be used in rainy days and moreover, this system permits the utilization of all types of radiation.

Graphical representation of the influence of the various factors on the performance of the 2 glass plates with a flat - black absorber surface displays the following conclusions:

a) The collector efficiency increases with increasing the air gap.

b) The difference between the temperature of the absorber plate and the outer glass plate strongly affects the collector efficiency.

c) The lower the number of transparent plates, the more sharply the efficiency drops with increasing the temperature difference between absorber a nd outer glass plate.

d) The selective coatings with high solar absorptance and low infrared emittance affect the solar collector efficiency.

e) The higher the solar-radiation intensity, the higher the efficiency at a given operating temperature.

f) As the solar-radiation incidence angle (which is the angle between the surface normal and the sun's rays) increases, the amount of solar radiation impinging on the collector is reduced by a cosine factor and the reflectance of the transparent cover plates increases.

g) The time of a day affects the efficiency of the collector.

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