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태양열 이용을 위한 직접접촉식열교환기(DCHX)의 작동에 관한 실험적 연구

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An Experimental Study on the Performance of a Direct Contact Heat Exchanger(DCHX) for Solar Application

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Abstract

태양열의 이용에 있어 직접접촉식 열교환기(DCHX)는 여러 가지 잇점을 제공한다. 그중에서도 제일 부각되는 것은 폐쇄형 열교환기의 대체에 다른 경비 절약과 작은 온도차에서도 열교환이 가능한 뛰어난 열성능일 것이다. 본 연구는 액-액 타입의 직접접촉식 열교환기에 대한 열성능 실측을 통하여 직접 접촉 열교환에 대한 이해를 증진하고 아울러 태양열에의 적용성을 평가하고자 하였다. 실측 시스템은 집열기와 펌프 그리고 직접접촉식 열교환기로 구성되어 있는데 작동유체의 종류에 따라 서로 다른 두 가지 방법에 의해 열교환기 내로 유입되도록 하였다. 작동유체로는 Texatherm 46과 물이 사용되었는데 이는 이들 유체가 서로 섞이지 않고 높은 온도(<150°)에서도 화학적으로도 안전하며 열적으로도 비교적 양호한 성능을 가지고 있기 때문이다. 본 연구는 실측을 통해 열교환기 내에서의 미미한 열성층화 현상에 대한 메카니즘을 확인하였으며 아울러 열교환기의 작동유체에 따라 작동의 안정성과 열적 성능(11% 차이)이 다르게 나타날 수 있음을 보여주고 있다.

Keywards : 직접접촉식 열교환기(DCHX), 태양열이용(Solar application), 열성능(Thermal performance), Texatherm 46

Nomenclature

$\dot{m}$	mass flow rate(g/s)
A	cross-sectional area(㎠)
Q_{gain}	heat gain (of the water column)(kJ)
c_f	specific heat(J/kgK)
$T_{f,in}$	temperature of incoming working fluid(℃)
T_w	temperature of water column inside DCHX(℃)
T_{46}	temperature of Texatherm 46 column Inside DCHX(℃)
ε	heat exchanger effectiveness
	(subscripts)
in	incoming
out	outgoing
w	water
46	Texatherm 46

1. Introduction

There have been many breakthroughs in utilizing the solar energy more efficiently and more economically. The use of the direct contact heat transfer concept is one of such developments that enabled the exploitation of solar energy more competitive and attractive in many areas of its possible application$^{1)}$. The use of a Direct Contact Heat Exchanger (DCHX), if properly applied, could give a good solution to the issues brought about in a wide of energy systems including solar. It will not only allow a technical solution to the problem but also several benefits. Primarily these include the elimination of the cost of a closed heat exchanger and the ability to operate with much lower temperature differences. The temperature driving force required for the conventional heat exchanger is greatly reduced because of the direct contact between the two fluids without any intervening solid surfaces$^{2)}$. Systems using DCHXs, however, are quite similar to systems using indirect heat exchangers in many respects. In these systems, the DCHX unit can be combined with the thermal storage unit, or alternatively, it can be used separately from the storage unit, much like an external (to storage) closed heat exchanger system. Hence either the DCHX system or the closed heat exchanger system can operate with the same number of pumps/loops. Some flow directions may be different between the two types of systems, depending on the fluids used in the DCHX system. This is because the DCHX generally relies upon the force of gravity to accomplish the fluid flow within the device. In most direct contact liquid-liquid heat exchangers, oil or hydrocarbon with a density less than water is normally used as the dispersed working fluid-the working fluid that is dispersed in a DCHX. In this case, the lighter fluid is injected into the DCHX(so-called, "spray column") through a perforated device(or a sparger) at the bottom of the DCHX. This arrangement sometimes requires the control of the interface at the top of the DCHX which is formed by the coalescence of the dispersed working fluid. The interface must remain fixed as water is introduced into the DCHX immediately below the interface. In addition, the rate of coalescence of the dispersed working fluid(arising as small droplets) has to be controlled appropriately as it influences the location of the interface. The rate of coalescence can be catalyzed by introducing a honeycomb structure at the desired honeycomb location[3]. This, however, requires that the material be preferentially wet by the dispersed phase(i.e., the working fluid).

Apart from the arrangement above, considerations could be made to use a liquid that are heavier and immiscibe with water. Of course, the liquid should have the higher boiling and lower freezing temperatures[4]. If one could find such a liquid for the working liquid, it becomes possible to eliminate the internal structures to enhance the coalescence of the dispersed working fluid mentioned above. The perforated plate at the top of the DCHX evenly breaks the working fluid into small particles and uniformly distributes them before they start their journey through the water body contained in the DCHX. There is no need for a device to catalyze the coalescence of droplets or to adjust the interface with the water as in the case of the light working fluids. However, this does not mean that heavier fluids perform better than lighter fluids as there are many factors influencing the thermal behavior of a working fluid associated with the operation of a DCHX. In the present investigation, two working fluids, Texatherm 46(density : 0.872 at 15℃) and water, were examined for the operation of a liquid-liquid type DCHX in exploiting the solar energy. A series of outdoor tests were conducted measuring their performance during the hours of bright sunshine.

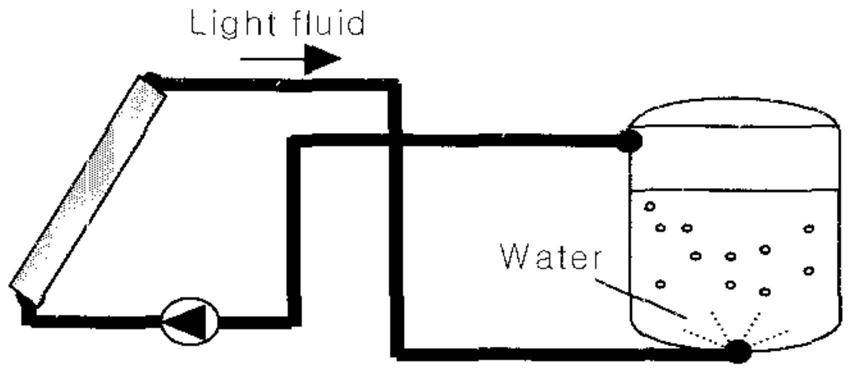
2. Experimental investigation

A series of outdoor tests were carried out using the experimental system whose major components are the DCHX, circulation pump, and solar collector. The DCHX was equipped with a device to distribute (sparge) the working fluid heated by the solar collector. Depending on its density relative to the liquid in which the working fluid is dispersed, the device is located either at the bottom or at the top of the DCHX. The system was constantly monitored with the aid of a computer during its operation and the temperatures at various locations were recorded.

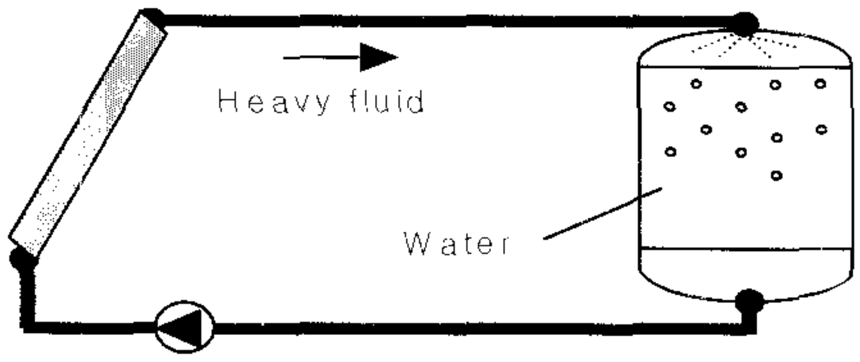
2.1 Experimental apparatus

The DCHX is a carefully sealed acrylic cylinder of 40cm in diameter, 140cm in height and 5mm in thickness. Depending on the selection of working fluid, different flow arrangements are made. When the working fluid(Texatherm 46) is injected into a liquid(water) which is heavier than the working fluid itself, case(a) in Figure 1, a sparger is located at the bottom of the DCHX.

Figure 2 shows the cross-shaped sparger fabricated with 4 pieces of metal pipe in the present work for injecting lighter(than water) fluids from the bottom of a DCHX. Each metal pipe has the dimensions of 15mm in diameter and 18cm in length. Small holes of 1.6mm in diameter are drilled onto the pipe at a regular interval of 20mm. The cross-shape geometry has been chosen to uniformly disperse the working fluid and prevent the early coalescence of droplets. As the pump activates the working fluid into motion, it passes through the sparger becoming small droplets(the dispersed phase) and exchange heat with the column of water (the continuous phase) contained in the DCHX. These droplets coalesce in the upper section of the DCHX to form an interface with the water phase. It is important to maintain the exit (for the working fluid) always above the interface in this arrangement, which could be easily achieved by adjusting the flow rate. The working fluid makes its way out of the DCHX via this exit and flows through the solar collector collecting the sun′s energy.



(a) A working fluid injected into a lighter fluid



(b) A working fluid dispersed in a heavier fluid

Fig 1. Schematic diagram of the experimental setup

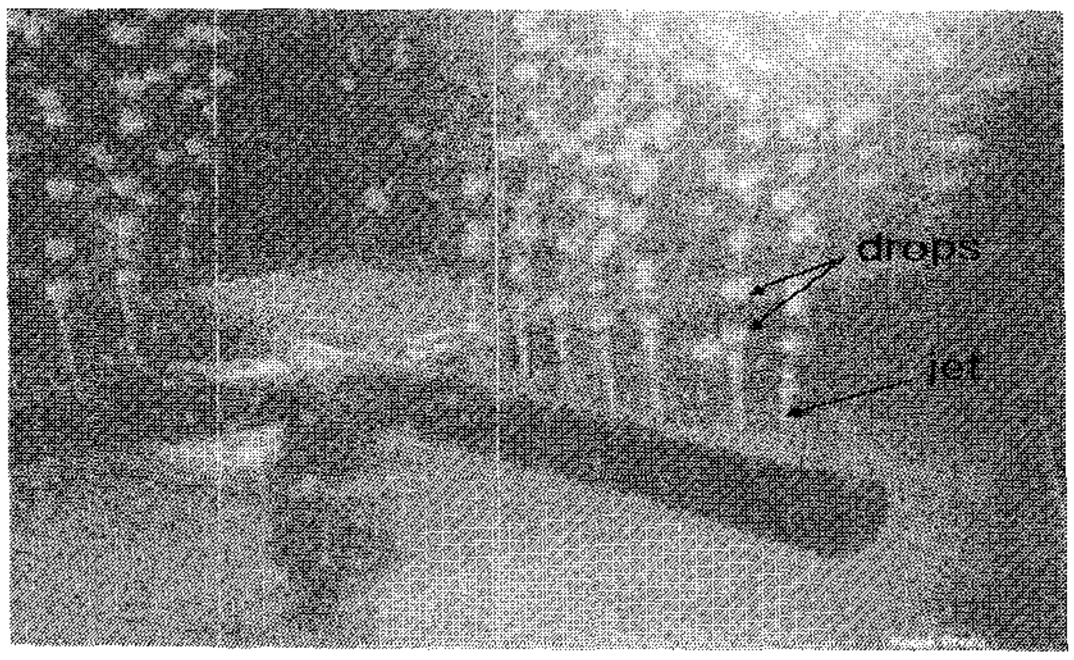


Fig 2. A cross-shaped sparger and rising drops

In contrast to the above, the working fluid could be introduced from the top of a DCHX. The case (b) in Figure 1 illustrates such a case where the water is dispersed from the upper section of the DCHX. The sparger near the top of the unit distributes the incoming hot liquid across the entire horizontal surface of the water. As this liquid streams through small holes in the sparger and reaches the water surface, it breaks up into small nearly spherical droplets affording a large heat transfer area per unit volume of water. As droplets pass down through the column of water, heat is transferred from them to the water phase, and the droplets are collected into a liquid pool under the water, which supplies the collector pump. At this time, again, the inlet flow rate is adjusted continually to keep the boundary of water-dispersed working fluid constant, and to make the inlet flow rate equal to that of the outlet flow rate to maintain steady operation.

Copper-constantan thermocouples were used to measure temperatures at various locations of the DCHX. Especially, those measuring the temperatures within the DCHX were placed inside of a brass pipe that was aligned along the centerline of the DCHX. The distance between thermocouples were 5cm~10cm where the total of 20 points were measured in this fashion.

2.2 Working fluids

Texatherm 46 is based on highly refined paraffinic base oils with inherently good thermal and oxidation stability, allowing operation at high temperatures for extended periods. It is recommended for use as heat transfer fluid in a temperature range from -15℃ up to a maximum bulk temperature of 315℃. Especially, its high thermal conductivity and low viscosity at the relevant operating temperatures ensure high heat transfer rates with limited pumping energy. Low vapor pressures at elevated temperatures will also minimize evaporation, vapor lock and cavitation, eliminating the need for high pressure piping and equipment.

2.3 Experimental procedures

Two sets of the experimental apparatus were fabricated that had the identical physical dimensions. These allowed the performance measurement of the two different working fluids (Texatherm 46 and water) under the same mode of operating conditions. Besides those within the DCHX,the temperatures at the inlet and outlet of each major component(DCHX, solar collector) were measured along with the ambient temperature and solar flux. Flow rates were adjusted between 90~150 litre/min and the heat gain of the liquid(continuous phase) inside the DCHX was monitored. Temperature readings were scanned for every 20 seconds before they are averaged and stored at a five minute interval. In one occasion, water was circulated through the collection loop and the heat gain of Texatherm 46 inside the DCHX was analyzed. This would yield some insights as to the thermal performance of other liquids when they are applied using the concept similar to the present work.

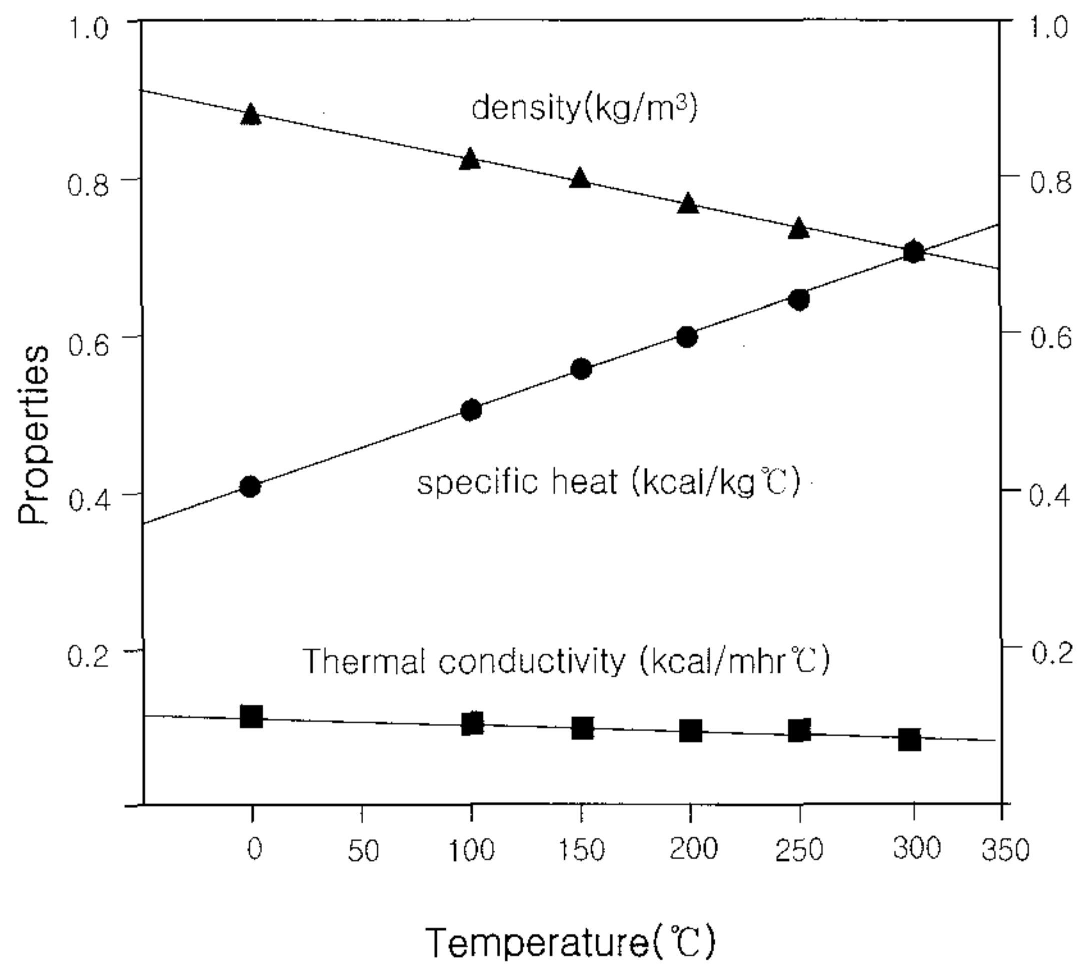


Fig 3. Physical properties of Texatherm

3. Discussion of results

All of the test results reported in this paper were obtained from a series of outdoor measurements. The hydrodynamic and thermal characteristics of the dispersed working fluid were examined to assess the technical feasibility of using the direct heat transfer concept for the utilization of solar energy. It is interesting to note how the differences in the physical properties of different fluids affect the operational mechanism and performance of a DCHX.

3.1 Formation and motion of droplets

Drops are formed by two distinct mechanisms when a liquid is discharged from a hole. At low flow rates, drops are formed as the working fluid passes through the small holes in the sparger. The effect of surface tension deems quite apparent. For Texatherm 46 at 35℃, this dropwise mode of discharge from the sparger persisted when the flow rate was less than 0.8 liter/min. At high flow rates, the working fluid forms tiny jets instead of small drops as it streams through the small holes in the sparger. The formation of drops is then followed by jet break-ups. Figure 2 shows the formation and grow of jets from the holes of a sparger before they break up to create drops. These jets extended about 10mm into the water, which are visible as slender cylinders in the figure.

The geometrical shape and size of drops changed with the temperature of the working fluid. In the case of Texatherm 46 at a flow rate of 2.5 liter/min, the size of prevalent drops grew smaller from 5~6mm at 20℃ to 4mm at 35℃ in diameter while their shape changed from elliptic to nearly spherical. This is somewhat comparable where the change in drop sizes were more apparent with the variation the air space below the sparger and the flow rate. The drop size of 1~2mm deems most effective to maximize heat transfer regardless of the working fluid.

3.2 Temperature field

Figure 4, 5 and 6 show the performance data for different working fluids. Each experimental system was composed of a DCHX and a solar collector as stated above. Each test commenced at 9am and ended at 4pm without any interruption.

Measurements were made under the same conditions and the pump was on at all times during the test period. The flow rate was regulated at a value of 1.5 liter/min producing jets as shown in Figure 2.

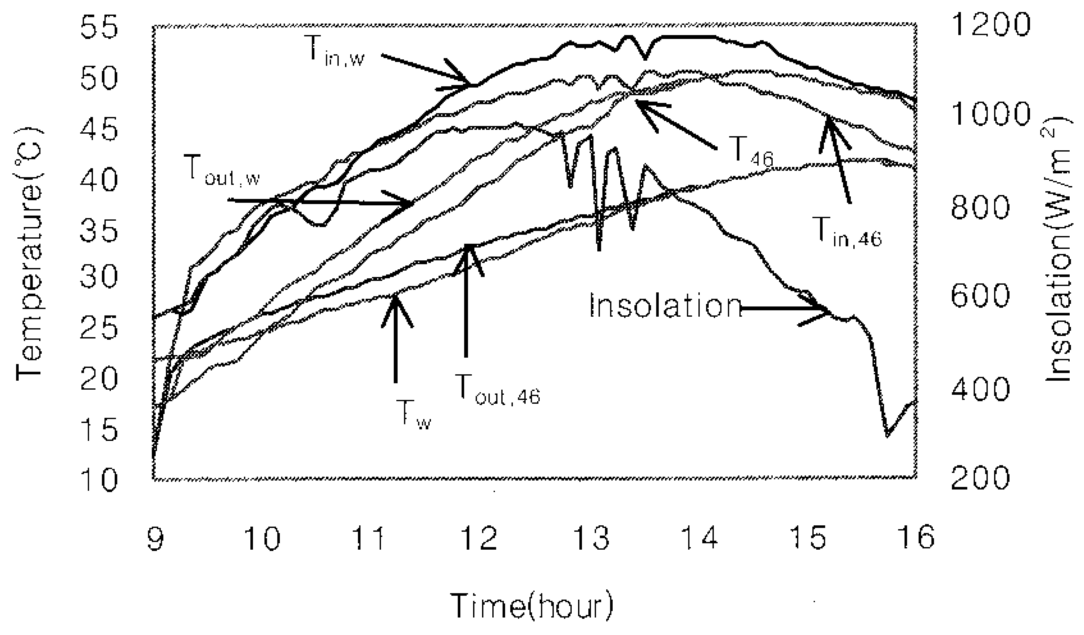
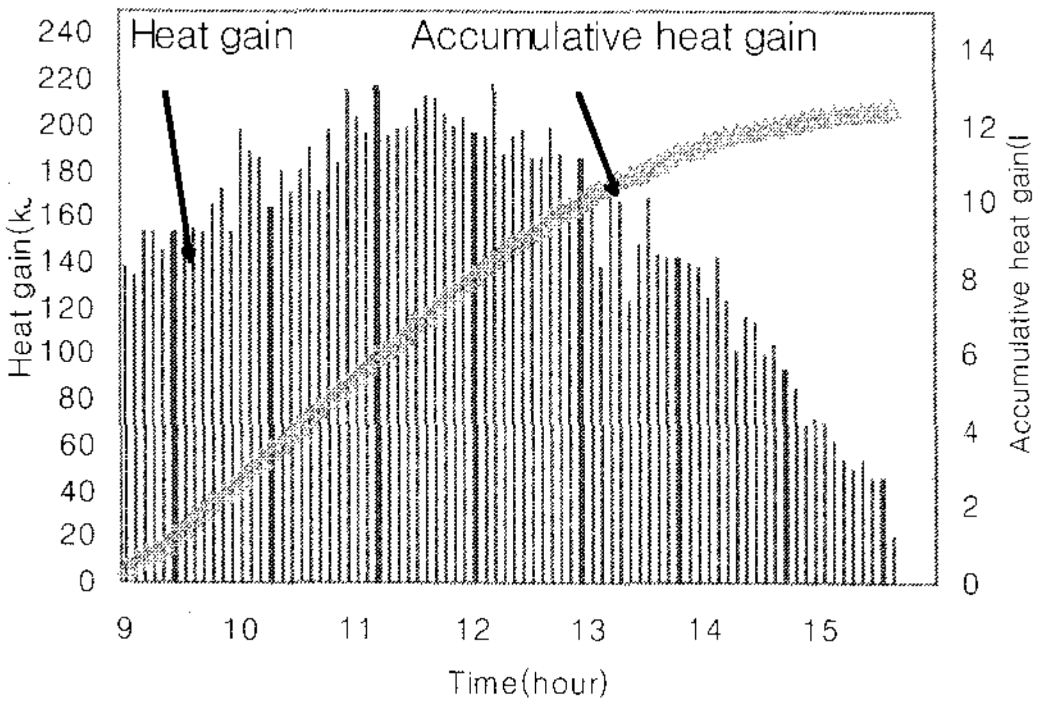
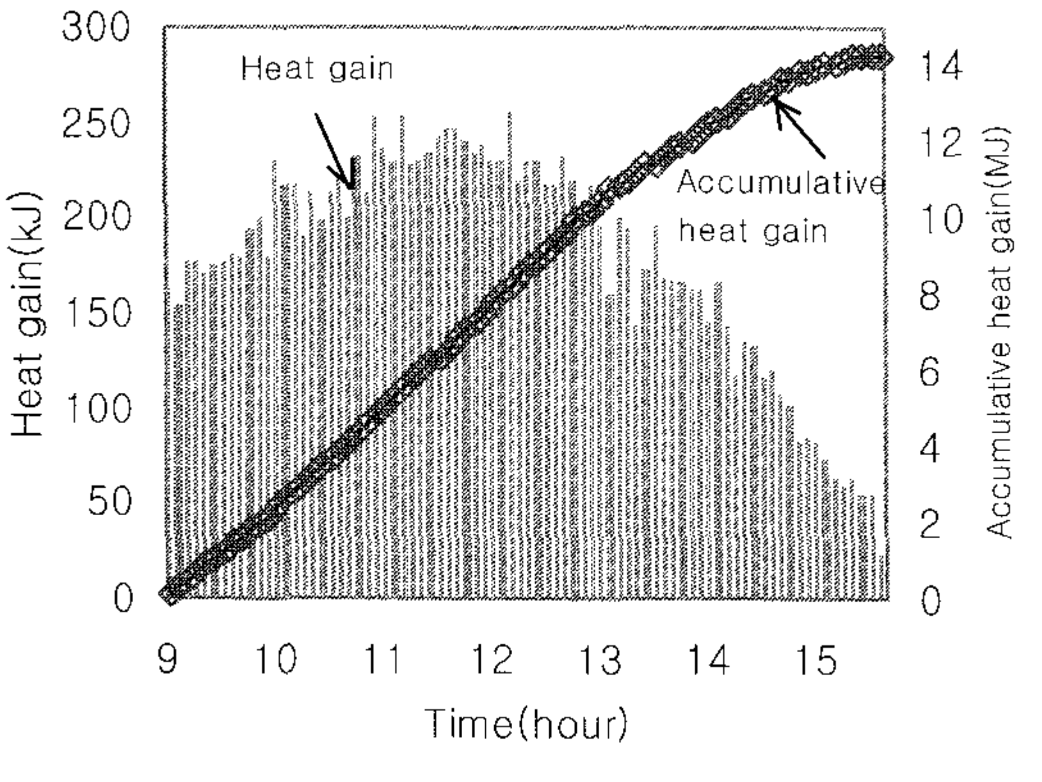


Fig 4. Time variation of temperatures at different location

Figure 4 shows a sharp rise in the temperature of the incoming working fluid with the onset of flow. This is because the solar collector was already exposed to the sun and the working fluid contained in its riser and header tubes became hot. The temperature rises more than 30℃ from its initial value before it starts to decay from 2pm. This decay in temperature is certainly caused by the decline of solar radiation and outdoor ambient conditions. Moreover, the continuous operation of the pump at a constant flow rate(1.5 liter/min) would definitely give rise to this development. The temperature difference between the incoming working fluid and the heat storage medium becomes smaller and smaller until it collapses to a point near 4pm. For the case of water, its temperature($T_{in,w}$) fell below that of Texatherm 46(T_{46})in the last minutes indicating no useful gain from the impinging solar rays on the collector. Throughout the hours of operation, heat transfer took place so vigorously within the heat exchanger such that the temperature difference of less than 1℃ was observed between the outgoing dispersed working fluid and the water. The temperatures monitored give some intuition into the performance of Texatherm 46 and water in use with a simple DCHX. This, however, does not mean that the differences between them will always be present to the same

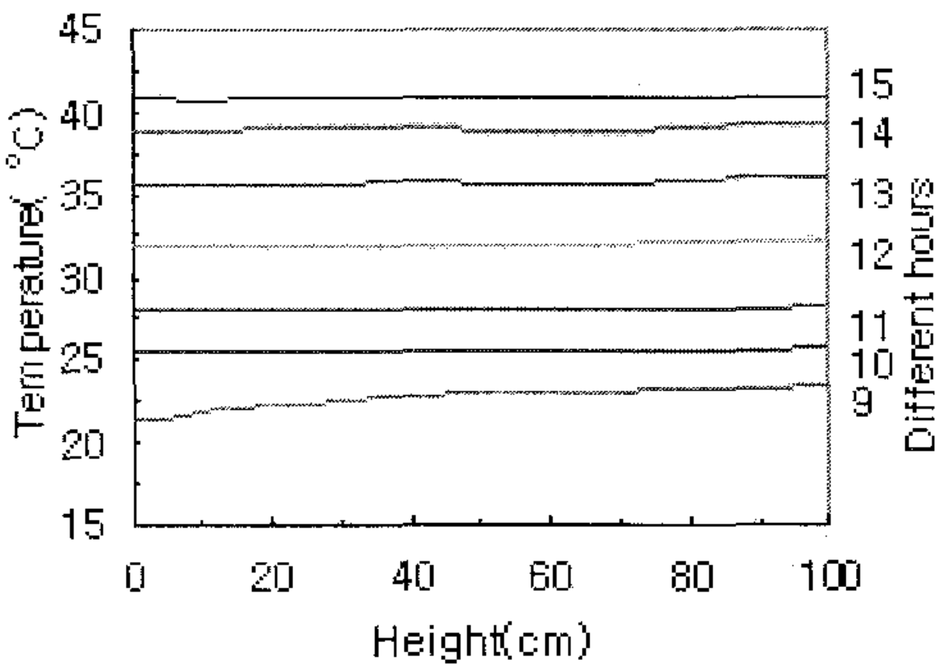


(a) Case of Texatherm 46

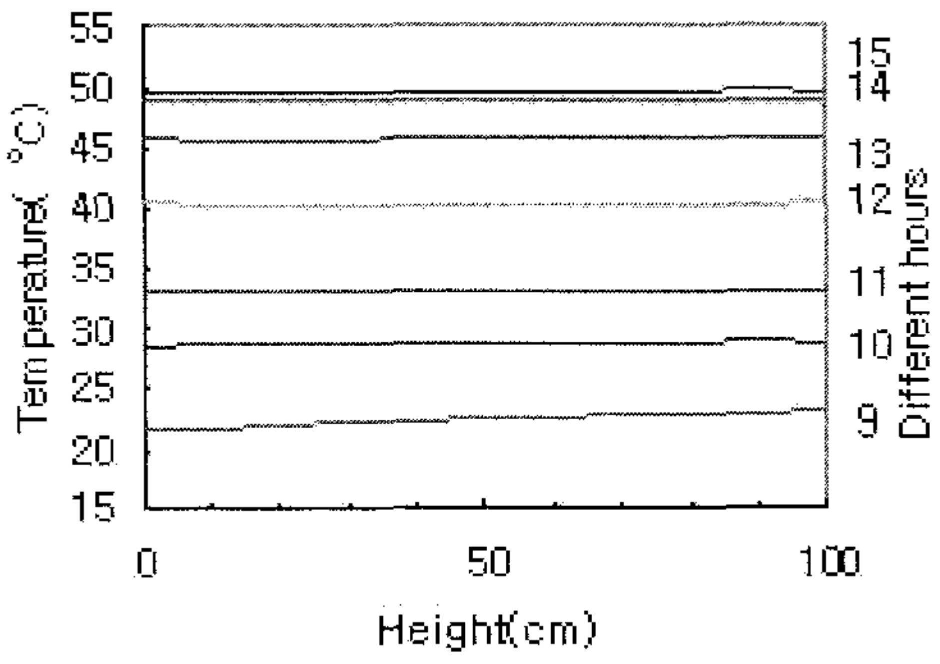


(b) Case of wat

Fig 5. Heat gains



(a) case of Texatherm 46



(b) case of water

Fig 6. Temperature variation of heat storage medium at different heights and times extent even when other fluids are used instead. More solar energy could be extracted from the solar heated collector when the water was circulated through the collection loop instead of Texatherm 46.

There are differences in instantaneous heat gain at different times. Figure 5 presents the heat gain for every 5 minutes and its accumulative value throughout the period ofoperation. The heat gain could have been somewhat greater if the heat exchanger were reinforced with insulation materials. It is easy to see the influence of solar radiation in the light of the insolation data given in Figure 4.

Figure 6 gives the temperature distribution of the heat storage medium at various times. Case (a) represents the operation of the system with Texatherm 46 as the working fluid and water as the heat storage medium. In contrast, case (b) is the result when Texatherm 46 and water switched their roles. No temperature stratification was observed in the heat exchanger column. This was observed in both cases despite the differences in the working fluid and its flow direction. All thermocouples in contact with water showed almost identical temperatures once the flow motion took place. It appears that the convective currents within the water column quickly destroy the source of their creation - the thermal stratification. Apparently, the water depths used in the present work were more than sufficient to extract most of the thermal energy from the drops. It would be desirable to have some information as to the appropriate depths of the water column. Further work should be pursued in this regard.

3.3 Heat exchanger effectiveness

The overall performance of the DCHX in the present work could be quantified by defining the heat exchanger effectiveness(e) in such a way that it gives the ratio of the actual heat gain(Q_{gain}) of the water column to the maximum possible heat transfer from the incoming working fluid. Here the maximum possible heat transfer refers to the case when there exists no temperature difference between the two fluids in heat communication. This is only possible when the heat exchanger is infinitely long and maximum possible heat transfer can take place. The definition is similar to that of the well-known heat exchanger effectiveness except that it involves only one stream of flow. Knowing the mass flow rate($\dot{m}$), the temperature($T_{f,in}$) and specific heat(c_f) of the incoming working fluid, the expression for the effectiveness(e) could be written as :

$$\varepsilon = \frac{Q_{gain}}{\dot{m}\, c_f\ (T_{f,\,in}\quad T_w)}$$

where T_w is the temperature of the water column.

The above experimental data gave $\varepsilon = 0.84$ for the case of water and $\varepsilon = 0.73$ for the case of Texatherm 46. This discrepancy could come from the differences in the physical properties of the two working fluids and the flow arrangements in dispersing them.

4. Conclusions

A liquid-liquid type direct contact heat exchanger (DCHX) was experimentally studied to assess its thermal performance in utilizing the solar energy. Texatherm 46 and water were used either as the heat storage medium or as the working fluid. Observations were made regarding the hydrodynamic and thermal characteristics of these fluids as one fluid constantly collects the solar energy to store it in the other. Depending on its relative density to the heat storage medium, the working fluid was introduced either from the bottom or from the top of the DCHX unit. The mechanism of drop formation appears to be very important as it dictates the drop size and consequently affects the overall thermal performance of the DCHX. Sparging the working fluid from top with an air space (as in the case of water) deemed more efficient in making appropriate sizes of drops. The air space allows the working fluid to free fall and to collide with the surface of the heat storage medium (Texatherm 46) breaking up into small drops of 1mm~2mm in diameter appropriate for utmost heat transfer. No thermal stratification was observed in the water column regardless of the flow direction of the dispersed working fluid. When measured in terms of the heat exchanger effectiveness, there was a discrepancy of 11% where water outperformed Texatherm 46 as the working fluid.

Acknowledgement

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