Thesis for the Degree of Master of Engineering

Basic Study for Development of Hybrid Solar Air-Water Heater

By

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The Graduate School

Pukyong National University

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Basic Study for Development of Hybrid Solar Air-Water Heater
복합형 태양열 가열기 개발에 관한 기초 연구

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최 휘 웅

요 약

본 연구에서는 온수제조 혹은 공기가열 둘 중 하나만 가능한 기존의 중저온형 평판형 집열기와 달리 온수제조와 공기가열 모두 가능한 복합형 태양열 가열기를 이용하여 집열기 성능에 대한 실증 실험을 수행하였고, 이를 통해 집열기 개발에 관한 기초자료 제공 및 개발 방향 제시 등을 통한 복합형 태양열 가열기 실용화 기여를 목적으로 하였다. 실험은 공기가열 혹은 온수제조만을 수행할 때의 집열기 성능을 각각 평가하여 기존의 시스템과 비교 및 개선사항을 검토하는 단일운전, 공기가열과 온수제조를 동시에 실시하여 공조 및 급탕 설비 적용 가능성 확인 및 집열기 성능 평가를 수행하는 동시운전으로 크게 2가지 경우에 대해 수행하였다.

실험결과 온수제조만을 실시한 경우 6l/min 의 유량조건에서 변환상수는 기존 집열기와 유사한 값을 보였으나 손실계수는 액체 배관 아래에 공기채널 설치로 인하여 좀 더 큰 값을 보였다. 또한 기존 집열기와 동일 유량조건에서는 다소 낮은 성능을 보여 이후 손실계수 감소 및 저유량에서의 성능향상에 관한 연구의 필요성을 확인할 수 있었다.

공기가열 성능과 같은 경우 국외에서 연구된 여러 공기가열기의 성능과 비교해보았을 때 풍량 대비 다소 낮은 효율을 보임을 알 수 있었다. 이는 공기 유로 및 내부 설치 핀 등의 차이 때문이며 이러한 부분의 개선을 통해 집열기의 공기가열 성능 향상이 필요함을 확인할 수 있었다. 공기가열과 온수제조를 동시에 수행하는 열매체 동시운전의 경우, 실험 결과로부터 해당 집열기에서 공기가열, 온수제조가 모두 가능함을 확인할 수 있었다. 단일운전과 비교하였을 시에는 각각의 열매체 입출구 온도차는 감소하는 경향을 보였으나 높은 풍량으로 공기 측이 운전될 시 효율은 좀 더 나은 값을 보였다. 또한 기존 시스템은 온수제조가 진행됨에 따라 입구 액체 온도가 상승하여 집열기 손실이 증가하였으나 복합형 태양열 가열기는 유동 공기에서 손실열의 일부를 회수해가기 때문에 집열 효율 감소가 적어짐을 알 수 있다. 반면 이는 집열기 전체 효율의 증가이고, 액체 측이 비교적 고온영역에서 작동하게 되면 공기 측에서 열을 회수해가므로 축열시 온수제조만을 수행하는 경우보다 최종 도달온도가 낮은 값을 보일 수 있어 축열 성능에 대한 추가적인 검토가 필요함을 알 수 있었다.

이상의 결과를 토대로 복합형 태양열 가열기의 온수제조, 공기가열 성능의 개선 연구가 수행될 시 필요에 따라 온수제조와 공기가열을 모두 수행할 수 있는 집열기로서 사용될 수 있을 것으로 기대되며 연구에서 확인한 실용화 가능성을 토대로 이후 급탕 및 공조 설비 적용시의 운전 성능 확인, 경제성 평가 등에 대한 추가적인 연구가 수행될 시 기존의 중저온형 태양열 집열기를 대처할 수 있는 집열성능 및 이용도가 향상된 집열기로써의 역할을 수행할 것으로 기대된다.

Basic Study for Development of Solar Hybrid Air-Water Heater

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Abstract

With increment of interesting of renewable energy, so many researches for enhancing the efficiency of renewable energy source have been conducted. As a part of these tendencies, research about hybrid solar air-water heater that can make a heated air and hot water different with traditional flat plate solar collector for hot water or heated air has been conducted. In this study, thermal performance evaluation of hybrid solar air-water heater was conducted for providing base data and contributing practical use. Experiment was conducted in case of two operating condition including single working of

heating medium for comparing hybrid solar air-water heater with traditional flat plate solar collector and finding improvement method and simultaneous working of heating medium for confirming the possibility of applying in air conditioning and hot water supply equipment and performance evaluation.

As a result, heat removal factor is similar with traditional flat plate solar collector for hot water on 6l/min when the hybrid solar air-water heater only made a hot water but heat loss coefficient was shown a lower value than traditional flat plate solar collector because of the install of air channel under absorber and liquid pipe. And the performance of making hot water is lower on the same liquid mass flow rate of traditional flat plate solar collector. Then the necessity of performance improvement on lower liquid mass flow rate was confirmed. In case of air heating, its performance was comparatively low compared with other solar air heater investigated by other researchers. These difference results from structure of air channel and shape and arrangement of installations improving heat transfer rate such as fin, and then the ability of air heating can be improved with changing these things. In case of simultaneous working of heating medium, air and water was heated simultaneously and the temperature level of each heating medium shows lower value compared with single working that make only heated air or hot water. But total efficiency shows higher value than single working of heating medium due to the heat recovery of air side. And also the lower efficiency loss was shown in hybrid solar air-water heater because of the recovery of heat loss from liquid side to flow air compared with traditional flat plate solar collector for hot water that decreased the efficiency with increment of inlet liquid temperature. But if the liquid side working in high temperature range when the heating medium working simultaneously, it will show a lower efficiency because air take a heat from high temperature liquid, then the necessity of additory study about maximum reaching temperature in thermal storage was confirmed.

From these results, hybrid solar air-water heater is expected to replace the traditional flat plate solar collector for hot water and solar air heater if the performance of single operation is improved at lower mass flow rate of each heating medium by conducting the improvement that was confirmed from this study. And the necessity of additory study about applying of hybrid solar air-water heater to hot water supply and air conditioning system and performance evaluation was confirmed for putting hybrid solar air-water heater to practical use.

Nomenclatures

Q_u	: Total useful energy gain	[W]
Q_i	: Collector heat input	[W]
Q_o	: Heat loss	[W]
Q_{air}	: Useful energy gain of air	[W]
Q_L	: Useful energy gain of liquid	[W]
G	: Intensity of solar radiation	[W/m^2]
A	: Area	[m^2]
F_R	: Heat removal factor	[-]
$U_{L,t}$	: Overall heat loss coefficient of collector	[W/m^2 °C]
$U_{L,L}$	: Overall heat loss coefficient of liquid side	[W/m^2 °C]
$\dot{m}$	: Mass flow rate	[kg/s]
C_p	: Specific heat	[kJ/kg °C]
T	: Temperature	[°C]

Subscript

L	: Liquid
air	: Air
a	: Ambient
i	: Inlet

o : Outlet

c : Collector

t : Total

Greek symbols

τ : Transmission coefficient of glazing

α : Absorption coefficient of plate

η : Efficiency

Chapter 1 Introduction

Interesting about renewable energy is increasing with concerns about the exhaustion of energy and environmental pollution with increment of fossil fuel usage. In the Republic of Korea, energy-saving and development of renewable energy is necessary because the domestic energy generation was only 4% including renewable energy and LNG and dependence of energy on overseas was 96% at 2012[1]. In this situation, government was publish a developmental strategy of green energy industry as a detailed action plan[2]. Above this, green home supply project, supply business on local, financial support of renewable energy and install obligation of renewable energy facilities in public institution have been carried out for increment of renewable energy facilities ratio[3].

In case of overseas country, the USA is considering renewable energy policy as a main policy for job creation and regional economy recovery result from investment of new energy resources and set their sights on 25% supply of electric power using renewable energy until 2025. In case of the Japan, predicting the ratio of renewable energy in primary energy supply until 2030 and promoting technology development and introduction of renewable energy for contribution about countermeasure of global warming, relaxation of dependence on imports and creation of job and new industry[2]. With these international actions, a new policy scenario of IEA expects ratio of renewable energy in total energy production throughout the world to almost 1/3 until 2035[3]. Like this, the effort for energy saving and supplying renewable energy is conducting in many countries. At this time, energy consumption about 22.3% is occupied in building in domestic energy consumption and then the concerns about energy saving and supply of renewable energy in building have been raised[4]. Especially, heating and cooling occupy about 53% of energy consumption in building. Also the energy consumption in building occupy about 36% as a largest proportion throughout the world and the space heating and water heating in residence field occupies about 74% [5].

Therefore the efficiency increment of renewable energy in building that occupy large proportion of energy consumption is important part coincide with global trend for energy saving and extensive diffusion of renewable energy and needed a continuous development.

1.1 Research background

The effort for energy saving and extensive diffusion of renewable energy will be increased cosmopolitanly. In case of solar thermal energy among the these renewable energy, it can be applied to hot water supply system using hot water made from collector and air conditioning system using solar air heater and hot water made from solar collector can be used as heat source for absorption refrigerating machine or regenerating of liquid desiccant in solar desiccant cooling system. Also solar thermal energy is applied for electricity generation using concentrating solar system. But, traditional solar collector for construction facilities can make a only one of heated air or hot water then utilization of solar thermal energy will be increased if there are solar collector that can make heated air as well as hot water. For this, some study about hybrid solar air-water heater that can make heated air and hot water has been conducted[6-7].

The use of hybrid solar air-water heater per unit area is more than traditional flat plate solar collector for hot water or solar air heater because it can be applied to hot water supply system as well as air conditioning system by making hot water and heated air. And also it can enhance the performance of regenerating for liquid desiccant by heating liquid desiccant using hot water and exchanging moisture from liquid desiccant to heated air using heated air directly as well as using hot water as heat source for absorption refrigerating machine. Hybrid solar air-water heater that has these advantages seems to be conducting the rule correspond to energy saving and policy for increment of renewable energy supply.

1.2 Research goal

The goal of this research is to confirming the possibility of application of hybrid solar air water heater to construction facilities and contributing to practical use by conducting basic research and investigation about additory improvement. For this, performance of hybrid solar air-water heater was investigated in case of two operating methods including single working and simultaneous working.

In case of single working that make a only one of hot water or heated air, performance of hybrid solar air-water heater was compared with traditional flat plate solar collector for hot water or solar air heater by confirming temperature difference, heat gain and thermal efficiency of air or liquid side with air or liquid mass flow rate. And also improvement for enhancing performance was confirmed making reference to research conducted in the past. In the simultaneous working, temperature difference, heat gain and thermal efficiency of each heating medium was confirmed with respect to air mass flow rate at constant liquid mass flow rate. From these verifications, the possibility of making hot water and heated air simultaneously, performance of hybrid solar air-water heater when the heating medium working simultaneously and the difference between single working and simultaneous working was confirmed. Using the equations obtained from experiment conducted as stated above, maximum temperature difference between inlet and outlet heating medium of each side at single working, minimum temperature difference of air side and maximum temperature difference of liquid side at simultaneous working was also investigated with respect to external conditions. Especially thermal efficiency of each heating medium is changed by many conditions like to temperature of inlet liquid and air, air mass flow rate, solar intensity and so on when the heating medium working simultaneously, then the effect of external conditions affects thermal efficiency of each heating medium was also investigated with various external condition using equation obtained from experiment.

In this research, performance of hybrid solar air-water heater was investigated by conducting actual measurement and using equation obtained from experiment and the advantage and disadvantage was confirmed by comparing hybrid solar air water heater with traditional flat plate solar collector for hot water and solar air heater. Also the possibility of application of hybrid solar air-water heater to construction facilities and additory improvement for enhancing performance were confirmed as previously stated.

1.3 **Previous studies**

Representative previous studies about flat plate solar collector are making hot water or heated air.

In case of flat plate solar collector for hot water, many research like to local heating system using hot water in winter[8], applying into air conditioning system by sending a hot water made from collector into heating coil of AHU[9] and estimation of economic effect when the solar collector was installed in building were conducted. In summer, there are instance that solar cooling and heating system that can be used in summer as well as winter by using hot water as a heat source of absorption refrigerating machine was installed[10] and many research for applying solar thermal energy to solar absorption cooling system by using hot water made from solar collector as heat source for regenerating of liquid desiccant[11-14].

In case of using heated air made from solar air heater, many research was conducted like to applying in building as passive and active type[15], study on the improvement by changing structure of air channel and shape and arrangement of installation improving heat transfer rate such as fin[16-18], using for drying application and study on the application for air conditioning system[19-22] for using in winter. In summer, research about increment of regeneration rate of liquid desiccant with increment of air temperature that contact with liquid desiccant was conducted when the other conditions were same[23-24]. Then the regeneration rate will be increased by contacting liquid desiccant with heated air.

Chapter 2 Basic Theory

2.1 Technology of collecting solar thermal energy

2.1.1 Classification according to temperature range

Collecting of solar thermal energy is conducted by solar collector. Table 1 shows type of solar collector according to temperature range. Temperature of heating medium is decided by collector heat loss coefficient and whether concentrator is installed or not. In other word, high temperature can be obtained with low heat loss coefficient and high concentration ratio. Solar collector for low temperature is the collector that has not concentrator and flat plate solar collector and evacuated tube solar collector are typical instance. In this, higher temperature can be obtained from evacuated tube solar collector by lower heat loss coefficient than flat plate solar collector. Solar collector for middle and high temperature is the collector that contains concentrator concentrating solar radiation as high density. Generally temperature of heating medium is different with concentration ratio and the higher temperature obtained on high concentration ratio. [25].

Table 1 Type of solar collector with respect to temperature range

Type	Passive system	Active system		
	Low temperature		Middle temperature	High temperature
Temperature	Below 60°C	Below 100°C	Below 300°C	Over 300°C
Collector or system	Passive system	Flat plate, Evacuated tube	PTC type, CPC type	Dish type, Power tower

Characteristic of each solar collector with temperature range is stated as follows sentence. First, Solar collector for low temperature can be represented as flat plate solar collector and evacuated tube solar collector. Fig. 1 shows schematics of flat plate solar collector. Transparent cover that can transmit solar radiation and reduce heat loss coefficient is installed on the top of collector and absorber plate converting transmitted solar radiation to thermal energy by absorbing is installed under transparent cover, and insulation is installed at the bottom of collector. Pipe is attached in case of solar collector for hot water and in the solar air heater, it has a passage for air flow under the absorber plate. Thermal energy absorbing in absorber plate transfer from absorber plate to heating medium by pipe and passage and heating medium go to heat storage tank or utilization part.

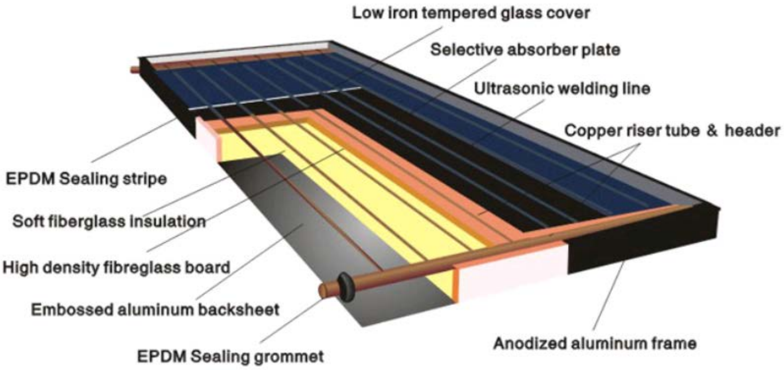


Fig. 1 schematics of flat plate solar collector

Evacuated tube solar collector is similar with flat plate solar collector but absorber plate is in vacuum tube for removing heat loss occurred from convection. Fig. 2 shows actual feature and schematics of evacuated tube solar collector. It has a higher efficiency than flat plate solar collector at high temperature, then it can be used for making heat source of absorption refrigerator as well as heating system. Also thermal efficiency can be enhanced by applying heat transfer technology using high efficiency heat transfer element substituting for pipe attached absorber plate with.

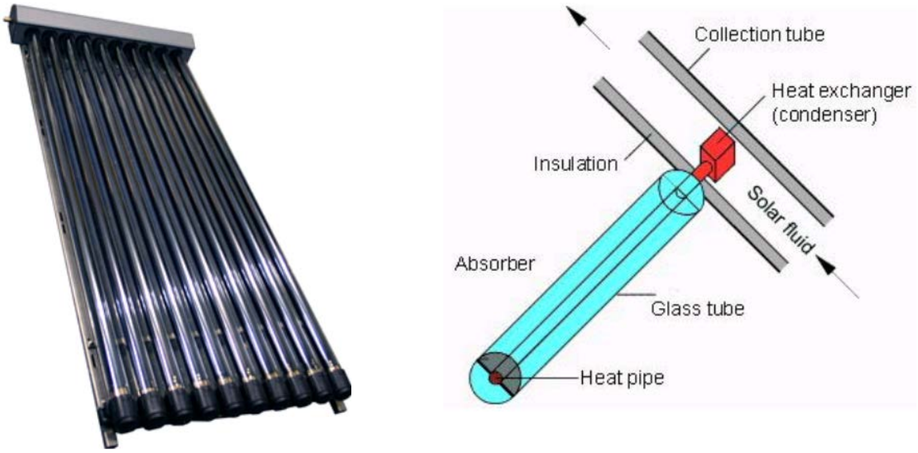


Fig. 2 Actual feature and schematics of evacuated tube solar collector

In the using of solar energy, solar radiation can be concentrated as high density for getting middle and high temperature. The equipment that concentrating solar radiation is called as concentrator and solar collector for middle and high temperature has concentrator. These solar concentrators can be divided as tracking type and fixed type. Concentrating collector that used usually has tracking system that tracing sun to top and bottom or right, left, top and bottom except CPC(compound parabolic concentrator) fixed on the ground. So, general concentrating solar collector is mainly made up of reflector, absorber and tracking system. Temperature in the range of 100°C to 1000°C can be obtained from concentrating collector then it is used for solar power generation and industrial process. Concentrating collector can be classified into CPC(compound parabolic concentrator), PTC(parabolic trough concentrator), parabolic dish and tower type according to structure. Generally, scattering sunlight is not collected at one point because of the inordinacy of an incident angle and it is the more at high concentration rate.

• Concentrating collector for middle temperature

CPC(compound parabolic concentrator) collector is made up of reflector, absorber at the center of reflector and glass as outer covering without tracking system as shown in Fig. 3. Reflector is designed to concentrating solar radiation on absorber and it can obtain temperature below 200°C due to low concentration ratio.

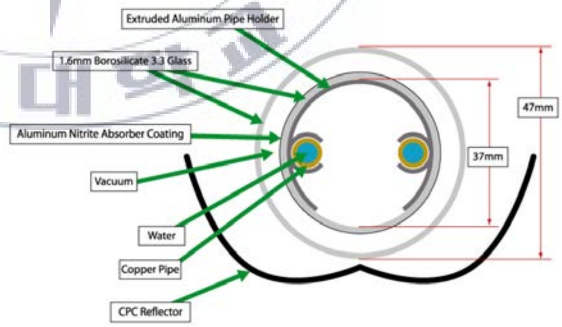


Fig. 3 Actual feature and schematics of CPC(compound parabolic concentrator)

PTC(parabolic trough concentrator) collector has parabolic reflector geometrically that concentrating parallel incident beam of solar radiation on axis of parabola. This collector tracks the solar moving up and down with absorber pipe as the center. Fig. 4 shows actual feature and schematics of PTC collector.

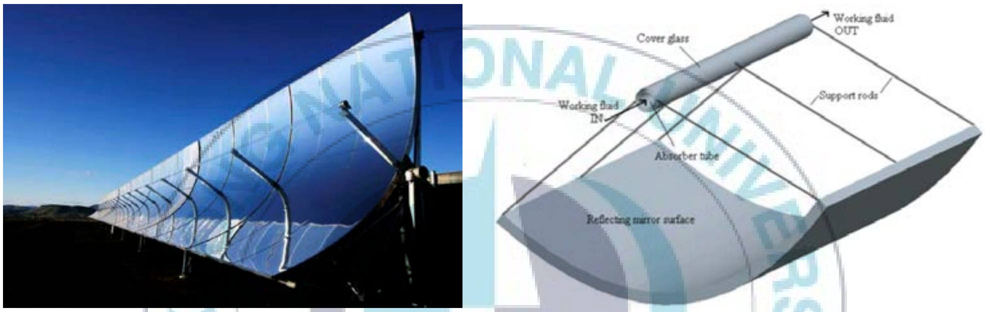


Fig. 4 Actual feature and schematics of PTC(parabolic trough concentrator)

• Concentrating collector for high temperature

Dish type collector is a concentrating collector that has a reflector shaped as a dish as shown in Fig. 5. It concentrates a solar radiation reflected from reflector on the one point and it can be used for solar power generation by installing stirling engine at absorber.

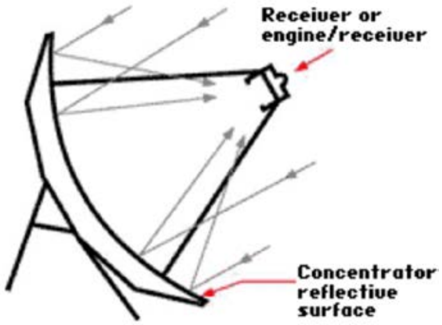


Fig. 5 Actual feature and schematics of dish type concentrating collector

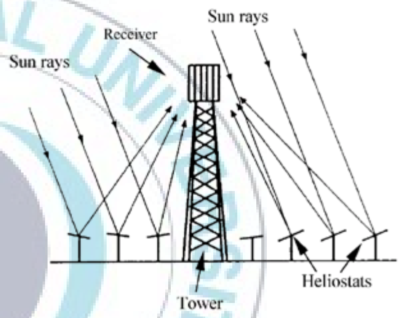


Fig. 6 Actual feature and schematics of solar power tower

Solar power tower is usually used for solar power generation. It operate a steam turbine for electricity generation by concentrating solar radiation on tower for high increment of temperature using heliostat as shown in the Fig. 6. Detail information about each solar collector can be obtained from the reference used in this paper and other related literatures[25].

2.2 Application of solar thermal energy

Application of solar thermal energy can be classified as passive system and active system according to applying drives of heating medium as shown in Table 1. Passive solar thermal system is the solar thermal system that has not drivers of heating medium as pump, air blower and active solar thermal system is the system that has drivers of heating medium for transferring heating medium to heat storage tank and part of utilization.

2.2.1 Passive solar thermal system

Passive solar thermal system belongs to the using of solar collector for low temperature and it can be classified as direct gain type, indirect gain type and isolated gain type according to application methods of heating system. Direct gain type give any amount of solar radiation into indoor from window in winter and the solar thermal energy obtained from these way can be used at night or on a cloudy day by storing at the indoor wall or floor as thermal energy. In other words, direct gain type means the system that heating indoor using direct light of solar. Indirect gain type use masonry wall or other thermal storage wall for storage of solar thermal energy and get effect of space heating by natural phenomenon like to heat conduction, convection and radiation. Solar thermal energy stored in thermal storage wall located between sun and heating space is emitted at night or cloudy day and so on. In other words, indirect gain type means space heating occurred by solar energy indirectly. General indirect gain types are Tromb Wall System and Roof Pond System. Isolated gain type is formed as collecting/storage part and usage part. That is to say, indoor heating space is isolated from collecting/storage part. In this way, space heating can be obtained from independent convective process by installing collecting/storage part at the place that separated and insulated with indoor. In other words, heating effect can be obtained independently because collecting/storage part is separated with indoor heating space. General isolated gain type is natural convection heating system and many combinations of three type illustrated above are used practically. Fig. 7 shows passive solar thermal heating system with each type.

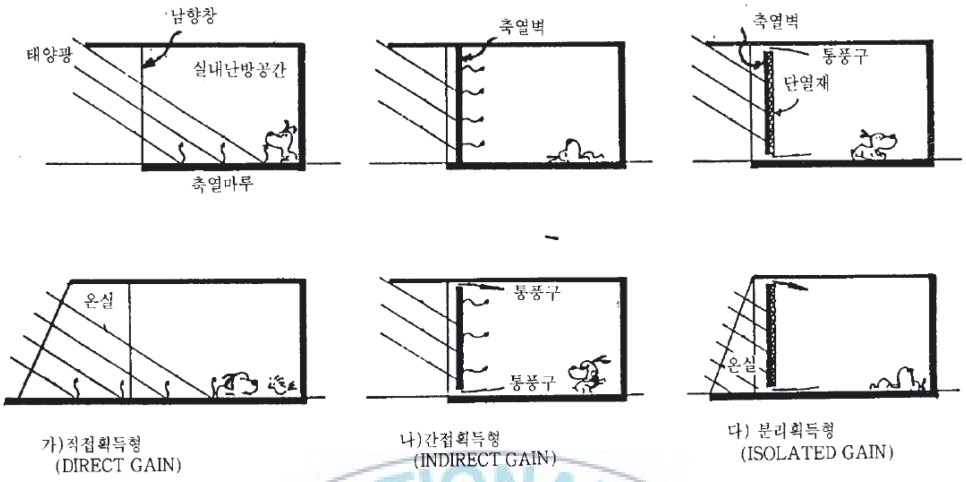


Fig. 7 Concept of passive solar thermal heating system

In case of the hot water system, passive hot water system is classified as Batch Type System, Thermosiphon System, Phase Change System and etcetera. Structure of Batch Type System is integration of collecting and storage then it has simple structure, inexpensive price and convenience of maintenance. But a lot of heat loss and freeze and burst during the cold weather is concerned when the insulation device for night was not installed. Thermosiphon system uses a heating medium for heat exchange by natural convection between collector and thermal storage tank. It is expensive than Batch type system but has no concern about freeze and burst. Fig. 8 shows natural convection solar collector for hot water. In case of phase change system, it collect the solar thermal energy using phase change material.

Then, the efficiency of collector can be changed by solar intensity but it has the advantage of freeze protection. Efficiency of phase change system is influenced by efficiency, lifetime and etcetera of phase change material.

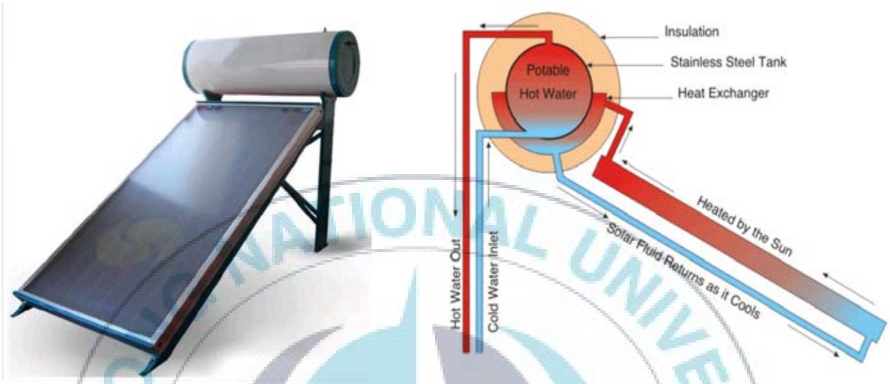


Fig. 8 Actual feature and schematics of natural convection solar collector for hot water

2.2.2 Active solar thermal system

Active solar thermal system can be classified as collecting, thermal storage, usage part and collecting temperature is decided by purpose of use.

• Utilization of solar collector for low temperature

Usually, solar collector for low temperature is used for space heating and hot water supply system. It can be classified as liquid type, air type according to heating medium and archetypal liquid type active solar thermal system is shown in Fig. 9.

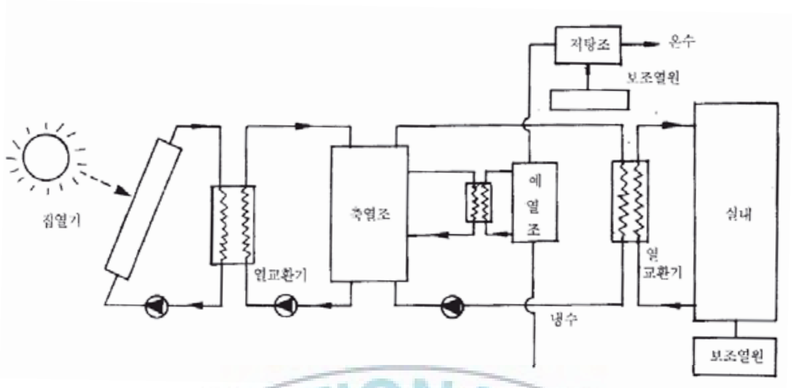


Fig. 9 schematics of archetypal liquid type active solar thermal system

This system use water or antifreeze for collecting heating medium and the water is usually used as fluid in thermal storage. Thermal energy collected from solar collector is stored in thermal storage tank and it is used for space heating and hot water supply when the necessity arises. The flow rate of heating medium for design is usually 0.015 l/sec per $1m^2$ collecting area in solar collector and the capacity of thermal storage tank is 50~100L quantity of water per $1m^2$ collecting area. Thermal efficiency is changed just slightly when the capacity of thermal storage tank is more than 50L. Whereas, effect of utilization is decreased when the capacity of thermal storage tank is large excessively because of the low temperature of water in thermal storage tank although the decrement of efficiency of solar collector is slight. Then the capacity of thermal storage tank suitably has to be designed for climatic condition of the local, characteristic of solar collector. Generally, low thermal storage capacity is designed for cold area and solar collector for high temperature and large thermal storage capacity is designed for hot area and solar collector for high temperature.

Archetypal air type active solar thermal system is shown in the Fig. 10. Heated air from solar collector is sent to indoor or gravel type thermal storage tank. Thermal energy is stored by heating gravel in thermal storage tank using heated air. Space heating can be obtained by air circulating through gravel type thermal storage tank in case of night, cloudy day or insufficiency of solar energy. Auxiliary heater is used when the thermal energy in gravel type thermal storage tank is not sufficient. Thermal energy for hot water supply system is obtained by heating storage tank as natural convection in heat exchanger and if it insufficiency, auxiliary heater is operated. Air type active solar thermal system hasn't a problem of freeze, corrosion and the other advantage of this system is that the thermal storage is used as heat exchanger and heated air is directly supplied into indoor for space heating without heat exchanger. Whereas, large heat exchanger is needed because of the low heat transfer coefficient and large thermal storage capacity is needed and a lot of power consumption is occurred because of an amount of using time of air blower when the hot water supply and cooling is necessary. More details are represented in the reference used in this paper and other related literatures[26].

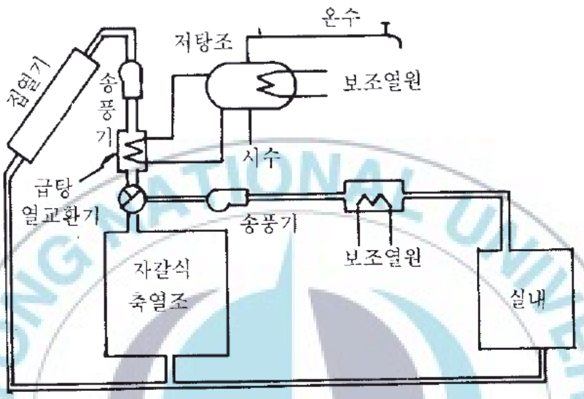


Fig. 10 Schematics of archetypal air type active solar thermal system

• Utilization of solar collector for middle and high temperature

General concentrating collector that means solar collector for middle and high temperature is used for solar power generation, industry and so on. This system use a solar thermal energy as heat source of high temperature components of traditional electric power generator. Fig. 11 shows schematics of solar power generation system using PTC.

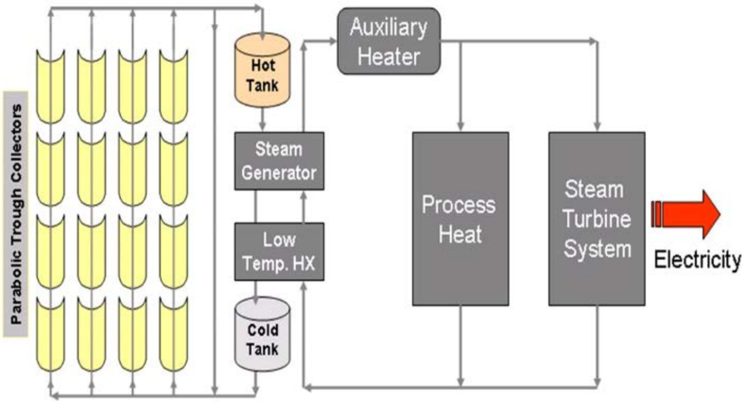


Fig. 11 Schematics of solar power generation system using PTC

Fig. 12 shows schematics of solar power generation system using dish type concentrating collector. Dish type concentrating collector focus solar radiation on axis of dish for heating fluid. Generally, stirling engine is located on axis of dish and directly generating electric power. High generating efficiency can be obtained in case of using dish type concentrating collector because it can obtain high temperature by high concentration ratio of dish type. In 2005, solar power generation system using six dish type concentrating collector as a one group is operated successfully by SES(Stirling Energy Systems, Inc.) of the USA. The maximum efficiency of this system that represented as a ratio of electric power generation quantity to incident solar radiation is approximately 31.25%. This system is working by remote control from morning to night tracking sun without system operator. In the Republic of Korea, the research about solar power generation using dish type concentrating collector usually has been conducted by KIER(Korea Institute of Energy Research). In 2006, study on the practical use of solar power generation system of 10kW using dish type concentrating collector was conducted in Jinhae, Gyeongnam and about 19% efficiency was obtained.

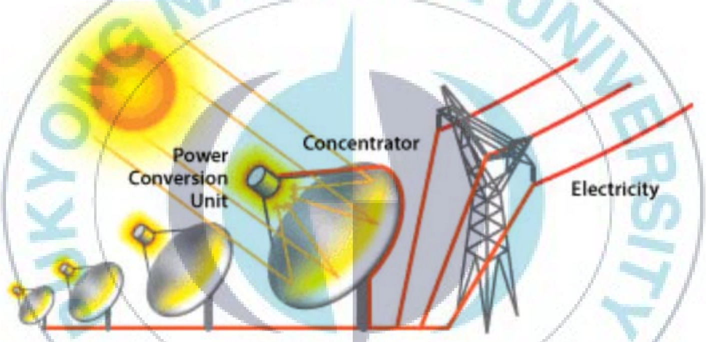


Fig. 12 Schematics of solar power generation system using dish type concentrating collector

Fig. 13 shows schematics of solar power tower system. In this system, heliostats reflecting solar radiation are installed over a wide area and they are adjusted for concentrating solar radiation on heating section of solar power tower. So, solar thermal energy can be concentrated about hundreds or thousands of times then solar power tower is very effective method for electricity generation that can be constructed as large capacity. Collecting section is heating part by concentrating solar radiation using heliostats and it can obtain thermal energy of high temperature. Then, electricity can be generated by storing solar thermal energy using various ways when the gain of solar energy is difficult [27]. In the Republic of Korea, solar power tower system of 200kW is installed in daegu by Daesung Energy Co., Ltd.

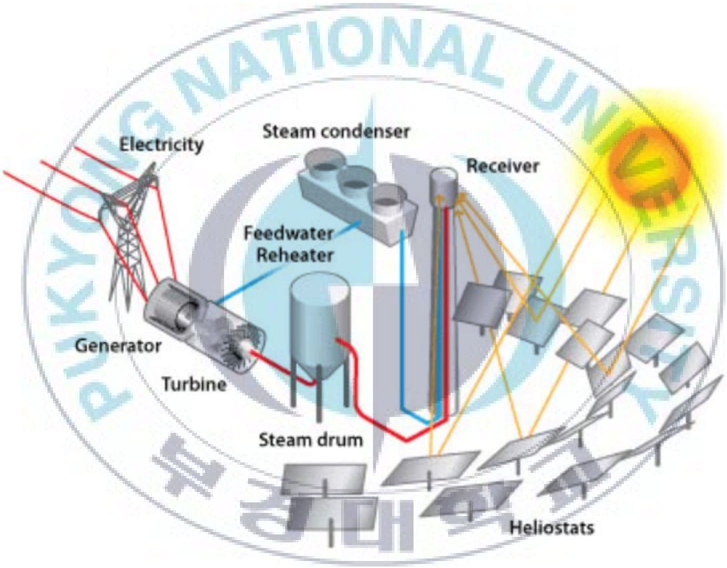


Fig. 13 Schematics of solar power tower system

2.3 Performance of a flat-plate solar collector

Performance of a flat-plate solar collector quote from reference[28] and the contents is stated below. Fig. 14 shows a schematic drawing of the heat flow through a collector and Fig. 15 shows the schematic of a typical solar system employing a flat plate solar collector and a storage tank.

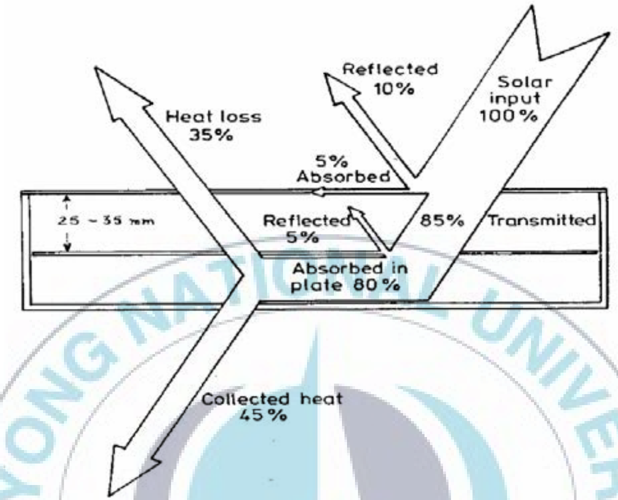


Fig. 14 Heat flow through a flat plate solar collector

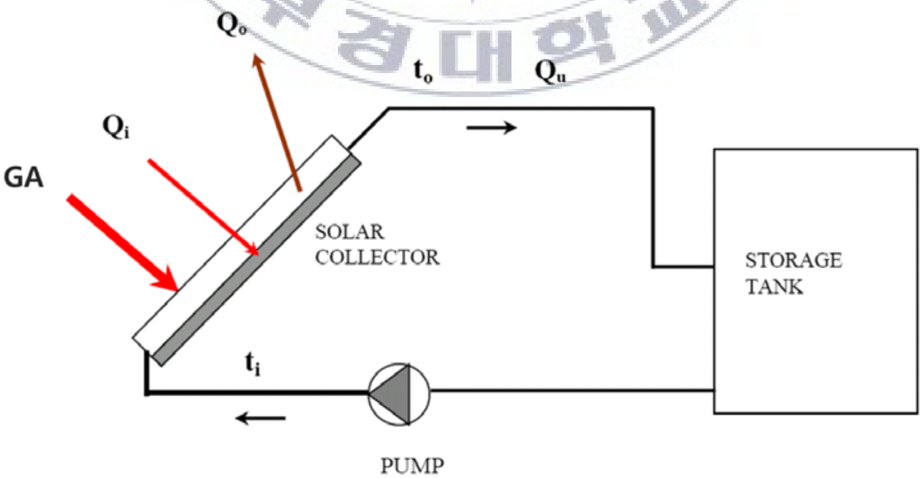


Fig. 15 Typical solar energy collection system

At this time, useful energy gain and thermal performance can be obtained by defining the singular heat flow equation step by step.

The amount of solar radiation received by collector can be expressed as the product of solar intensity(W/m^2) and collector surface area(m^2)as shown in the Fig. 15 and it can be written as equation (1).

$$Q_i = GA_c \quad (1)$$

However, as it is shown Fig. 14, a part of this radiation is reflected back to sky, another component is absorbed by the glazing and the rest is transmitted through the glazing and reaches the absorber plate as short wave radiation. Therefore actual heat gain in absorber can be obtained by multiplying the product of the rate of transmission of the cover and the absorption rate of absorber by equation (1) and the result can be written as equation (2).

$$Q_i = G(\tau\alpha)A_c \quad (2)$$

And the temperature of collector absorbs is getting higher than that of the surrounding and heat is lost to the atmosphere by convection and radiation.

The rate of heat loss depends on the collector overall heat transfer coefficient, collector temperature and ambient temperature and it can be written as equation (3).

$$Q_o = U_{L,t}A_c(T_c - T_a) \quad (3)$$

Thus, the rate of useful energy extracted by the collector, expressed as a rate of extraction under steady state conditions, is proportional to the rate of useful energy absorbed by the collector, less the amount lost by the collector to its surroundings. It can be written as equation (4).

$$Q_u = Q_i - Q_o = G\tau\alpha A_c - U_{L,t}A_c(T_c - T_a) \quad (4)$$

It is also known that the rate of extraction of heat from the collector may be measured by means of the amount of heat carried away in the fluid passed through it and it can be written as equation (5).

$$Q_u = \dot{m}C_p(T_o - T_i) \quad (5)$$

In case of equation (4), it is proves to be somewhat inconvenient because of the difficulty in defining the collector average temperature. So, it is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. This quantity is known as “the collector heat removal factor (F_R)” and is expressed as equation (6).

$$F_R = \frac{\dot{m}C_p(T_o - T_i)}{A_c[G\tau\alpha - U_{L,t}(T_i - T_a)]} \tag{6}$$

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature. It means the collector heat removal factor is the ratio of actual useful energy gain to maximum possible useful energy gain. And the actual useful energy gain is found by multiplying the collector heat removal factor by possible useful energy gain. Then the equation (4) can be rewritten as equation (7).

$$Q_u = F_R A_c[G\tau\alpha - U_{L,t}(T_i - T_a)] \tag{7}$$

Equation (7) is a widely used relationship for measuring collector energy gain and is generally known as the “Hottel-Whillier-Bliss equation”.

Collector efficiency defined as the ratio of the useful energy gain to the incident solar energy over a particular time period is expressed as follow:

$$\eta = \frac{\int Q_u dt}{A_c \int G dt} \tag{8}$$

The instantaneous thermal efficiency of the collector can be written as equation (9).

$$\eta = \frac{Q_u}{A_c G} \tag{9}$$

Equation (9) can be rewritten as equation (10) from equation (7).

$$\eta = \frac{F_R A_c [G\tau\alpha - U_{L,t}(T_i - T_a)]}{A_c G} = F_R \tau\alpha - F_R U_{L,t} \left(\frac{T_i - T_a}{G}\right) \tag{10}$$

If it is assumed that F_R, τ, α, $U_{L,t}$ are constants for a given collector and flow rate, then the efficiency is a linear function of the three parameters defining the operating condition: Solar irradiance(G), Fluid inlet temperature (T_i) and Ambient air temperature(T_a). Thus, the performance of a Flat-Plate Collector can be approximated by measuring these three parameters in experiments.

Chapter 3 Experimental Apparatus and Method

3.1 Experimental apparatus

3.1.1 Hybrid solar air-water heater

Hybrid solar air-water heater was made by installing air channel under the absorber of flat plate solar collector for hot water and it can make hot water and heated air. Actual feature of hybrid solar air-water heater is shown in Fig. 16.

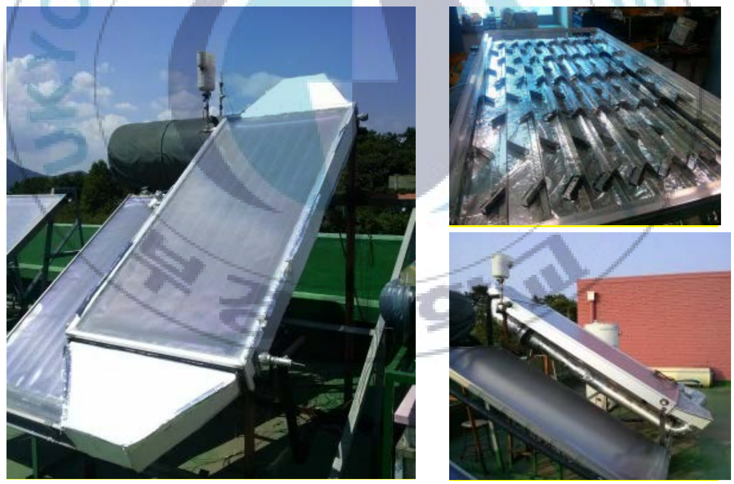
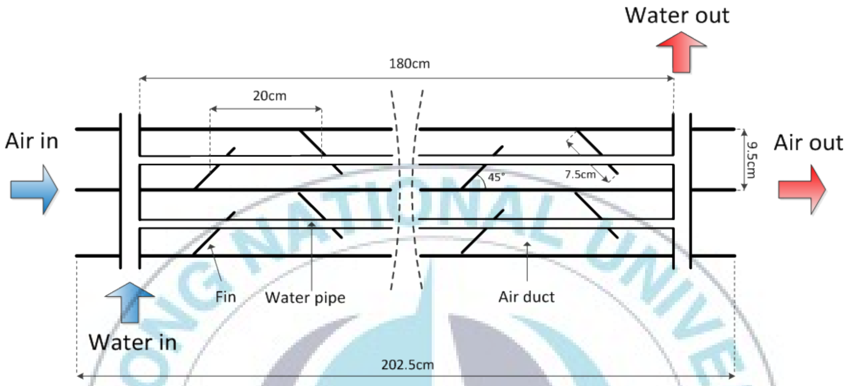
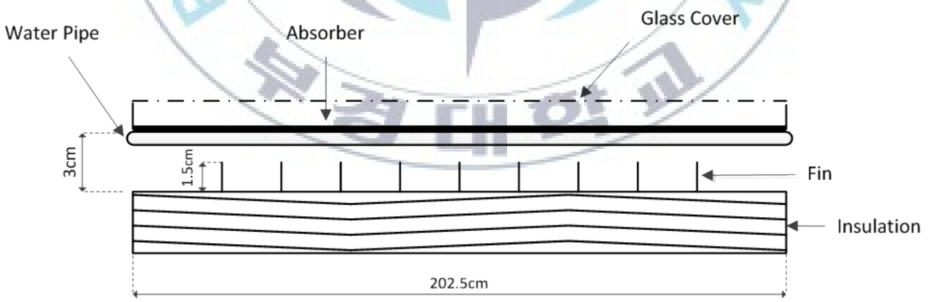


Fig. 16 Actual feature of hybrid solar air-water heater for experiment

Liquid pipe and air channel was corresponded one-to-one respectively, and this collector was composed of nine liquid pipe and air channel. Also fin was installed in air chnnel for enhancing heat transfer rate from absorber to flow air. Fig. 17 shows corros-section that representing installation space, angle, size of fin and so on.



(a) Floor plan of hybrid solar air-water heater



(b) Side view of hybrid solar air-water heater

Fig. 17 Cross-section of hybrid solar air-water heater

The installation angle of Hybrid solar air-water heater was 33° from horizontal and azimuth 171°. More detail specifications of collector is shown in Table 2.

Table 2 Specifications of the hybrid solar air-water heater

Location	Pukyong National University YongDang campus 35^{0} 6.98´N latitude, 129^{0} 5.39´E longitude
Install direction	Azimuth angle 171^{0}, Installation angle 33^{0}
Collecting method	Flat plate collector
Collector size	2.025m(L) x 1.030 m(W) x 0.140 m(H)
Transmission area	1.84775 m^2
Absorption area	1.73355 m^2
Area of flow air	0.02565 m^2
Area of air duct	0.01131 m^2

Circular duct of diameter 120mm is installed at the back side of collector and air blower is located on the side of air outlet. Fig. 18 shows schematic view of hybrid solar air-water heater applicated in building for representing the concept of hybrid solar air-water heater easily.

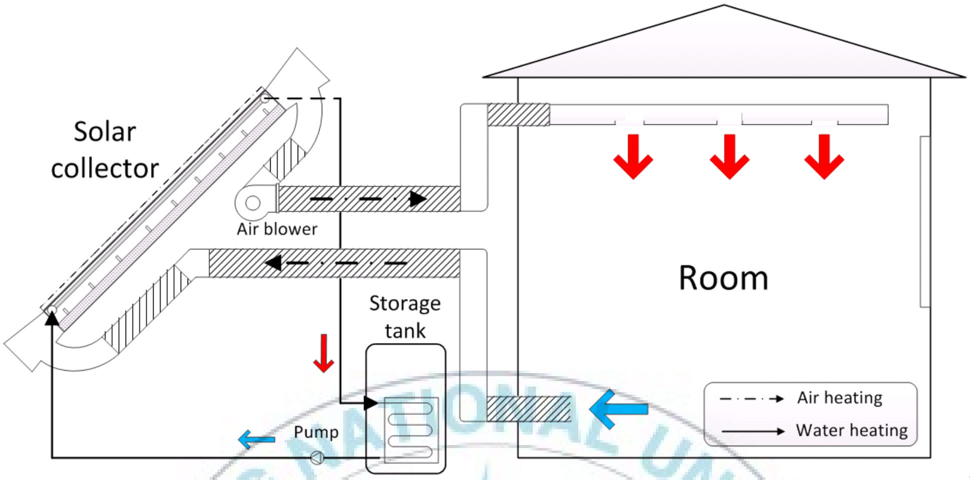


Fig. 18 Schematics of hybrid solar air-water heater system

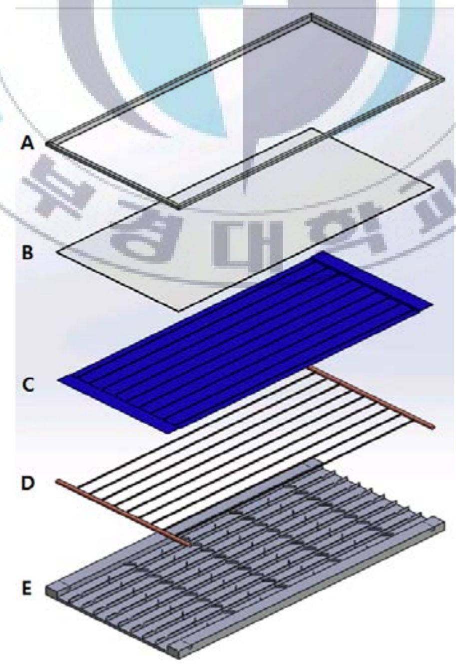


Fig. 19 components of hybrid solar air-water heater

Fig. 19 shows the components of hybrid solar air-water heater. It is composed of glass holder(A), glass(B), absorber(C) and liquid pipe(D) similar with traditional flat-plate solar collector for hot water and liquid pipe is welded to absorber. But some of insulation was displaced by air channel under the absorber plate different with traditional flat-plate solar collector. So, hot water and heated air can be made using one flat-plate solar collector.

3.1.2 Drives of heating medium

In this study, air blower for air circulating and hot water-circulating pump for liquid circulating is used for experiment and these apparatus was controlled by AC inverter for altering air and liquid mass flow rate. More details of drives of heating medium are shown in Table 3, 4.

Fig. 20 Air blower

Table 3 Specifications of air blower

Model	AD-015-020
Rated voltage	220V, 60Hz
Current	0.4A
Power consumption	80W
Maximum air flow rate	6m3/min
Revolution per minute	3420rpm
Maximum static pressure	40mmAq

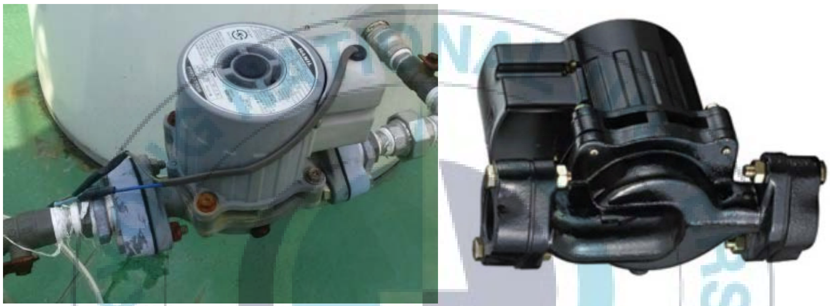


Fig. 21 Hot water-circulating pump

Table 4 Specifications of hot water-circulating pump

Model	PB-43-1-D
Rated voltage	110/220V, 60Hz
Power consumption	101W
Discharge rate	40L/min (head 3m)
Discharge head	4m
Diameter	25mm

3.1.3 Measuring devices

T-type thermocouple was installed at the air inlet and outlet side for measuring inlet and outlet air and also installed at the inside of collector for measuring mean temperature of absorber and temperature change of flow air. PT100 was installed at liquid inlet and outlet side for measuring temperature of inlet and outlet liquid. Testo435 for air mass flow rate, Solar meter for solar intensity, NetDAQ for data logging was also used for experiment. Table 5 shows the specifications of measuring devices.

Table 5 Specifications of measuring devices

Target	Item
Temperature	Thermocouple, PT100
Air velocity	testo435
Solar radiation	MS-801
Data acquisition	NetDAQ, FLUKE (U.S.A)

3.2 Experimental method

Experiment was conducted in case of two operating condition including single working that heating air or water respectively and simultaneous working that heating air and water simultaneously during the midday shown relatively constant solar intensity. In case of heating medium, outdoor air used as inlet air directly and mixture of water 60% and MEG 40% was used as liquid and properties of liquid is refer to Product Guide of MEGlobal company[29].

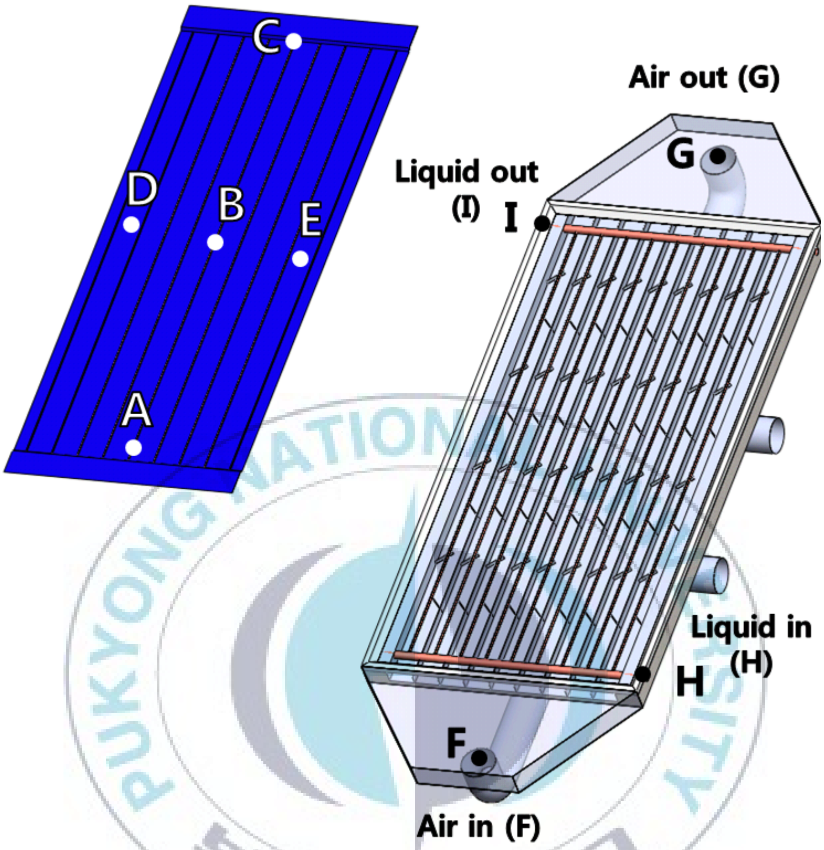


Fig. 22 Measured position of hybrid solar air-water heater

Fig. 22 shows the temperature measured position of collector. T-type thermocouple was installed at lower side(A), center (B), upper side(C), left side(D) and right side(E) for measuring mean temperature of absorber plate. In case of inlet and outlet air temperature, it was measured by installing thermocouple on the air inlet and outlet side and liquid temperature was measured by installing PT-100 at liquid inlet and outlet side.

3.2.1 Single operation

The purpose of single operation is estimation of thermal performance and comparison with traditional flat-plate solar collector when the heated air or hot water made respectively. Thus, the temperature and thermal efficiency of each heating medium was investigated with respect to air or liquid mass flow rate.

The experiment was conducted on the midday shown constant solar intensity relatively. For evaluating thermal efficiency when the hybrid solar air-water heater made only heated air, data was collected about 10 minute when the temperature relatively shown constant value on constant mass flow rate of each heating medium. After that, repeated it on the various mass flow rate conditions. In case of evaluation of thermal efficiency for only hot water also same experimental method was conducted. Table 6 shows the experimental conditions when the single operation experiment was conducted.

Table 6 Experiment conditions when the heating medium working respectively

Date	2013. 12. 20 2013. 12. 27	2014. 01. 02
Time	11:30-12:30	11:30-12:30
Operating method	Air heating	Water heating
Operating condition	Air mass flow rate	Liquid mass flow rate
	0.0203 – 0.1262 kg/s	2, 4, 6, 8, 10 l/min

The equation that is shown below is used for data analysis. Heat gain of each heating medium can be obtained by multiplying mass flow rate by specific heat and temperature difference and this is expressed as follows:

$$Q_u = Q_i - Q_o = G\tau\alpha A_c - U_{L,t}A_c(T_c - T_a)$$
$$= \dot{m}C_p(T_o - T_i) \qquad (11)$$

Overall heat loss coefficient of collector can be written as equation (12) from equation (11).

$$U_{L,t} = \frac{G\tau\alpha A_c - Q_u}{A_c(T_c - T_a)} = \frac{G\tau\alpha - [\dot{m}C_p(T_o - T_i)/A_c]}{T_c - T_a} \qquad (12)$$

Collector heat removal factor defined as the ratio of actual useful energy to maximum useful energy can be obtained from equation (13).

$$F_R = \frac{\dot{m}C_p(T_o - T_i)}{A_c[G\tau\alpha - U_{L,t}(T_i - T_a)]} \tag{13}$$

Thermal efficiency defined as the ratio of the useful energy gain to the incident solar energy is obtained from equation (14).

$$\eta = \frac{Q_u}{GA_c} = \frac{F_R A_c[G\tau\alpha - U_{L,t}(T_i - T_a)]}{GA_c} = F_R\tau\alpha - F_R U_{L,t}\frac{(T_i - T_a)}{G} \tag{14}$$

In this experiment, thermal efficiency was obtained by finding overall heat loss coefficient and collector heat removal factor calculated from heat gain and measured value.

3.2.2 Simultaneous operation

The purpose of simultaneous operation is estimation of thermal efficiency of hybrid solar air-water heater when the heated air and hot water was made simultaneously. For this, the experiment was conducted with various air mass flow rate on the constant liquid mass flow rate

4L/min because the thermal efficiency shows higher value compared with other conditions when the liquid was circulated on 4L/min[7]. Table 7 shows more details about experimental conditions when the heating medium working simultaneously.

Table 7 Experiment conditions when the heating medium working simultaneously

<table>
<tr><td>Date</td><td colspan="2">2014. 01. 04</td></tr>
<tr><td>Time</td><td>11:30-12:30</td><td>11:30-12:30</td></tr>
<tr><td>Operating method</td><td colspan="2">Air heating + Water heating</td></tr>
<tr><td rowspan="2">Operating condition</td><td>Air mass flow rate</td><td>0.0203 – 0.0950 kg/s</td></tr>
<tr><td>Liquid mass flow rate</td><td>4 l/min</td></tr>
</table>

In this study, total thermal efficacy of collector was defined by energy equilibrium for representing thermal efficiency when the air and liquid side working simultaneously. These process of induction is refer to reference[30].

Useful energy can be defined as the sum of heat gain in each heating medium and it also can be written with input and output energy as equation (15).

$$Q_u = Q_{air} + Q_L = Q_i - Q_o \qquad (15)$$

Q_i and Q_o is expressed as follows:.

$$Q_i = G\tau\alpha A_c \quad (16)$$

$$Q_o = U_{L,t} A_c (T_c - T_a) \quad (17)$$

Thus, equation (15) can be rewritten as equation (18)

$$Q_{air} + Q_L = G\tau\alpha A_c - U_{L,t} A_c (T_c - T_a) \quad (18)$$

Overall heat loss coefficient of collector can be written as equation (19) from equation (18).

$$U_{L,t} = \frac{G\tau\alpha A_c - (Q_{air} + Q_L)}{A_c (T_c - T_a)} = \frac{G\tau\alpha - (Q_{air} + Q_L)/A_c}{T_c - T_a} \quad (19)$$

Heat gain of liquid side can be written as equation (20) from "hotel-Whillier-Bliss equation".

$$Q_L = \dot{m}_L C_{p,L} \left(T_{o,L} - T_{i,L}\right) = F_{R,L} A_c [G\tau\alpha - U_{L,L} \left(T_{i,L} - T_a\right)] \quad (20)$$

At equation (20), $U_{L,L}$ is heat loss coefficient of liquid side and it considers heat gain of air side also as a loss from the perspective of liquid side. This value is changed by air mass flow rate and can be written as equation (22) from equation (21).

.

$$Q_L = Q_i - Q_o - Q_a = G\tau\alpha A_c - U_{L,L}A_c(T_c - T_a) \quad (21)$$

$$U_{L,L} = \frac{G\tau\alpha A_c - Q_L}{A_c(T_c - T_a)} = \frac{G\tau\alpha - Q_L/A_c}{T_c - T_a} = f(\dot{m}_{air}) \quad (22)$$

Actually, $U_{L,L}$ is changed by inlet air temperature and air mass flow rate. But in this experiment, $U_{L,L}$ is considered as a function of air mass flow rate only because usually outdoor air used for inlet air. Heat gain of air side can be written as equation (23) from equation (15).

$$Q_{air} = Q_i - Q_L - Q_o = \dot{m}_{air}C_{p,air}(T_{o,air} - T_{i,air}) \quad (23)$$

Heat gain of air side can be rewritten as equation (24) by substituting the equation (16), (17), and (20) to equation (23).

.

$$Q_{air} = G\tau\alpha A_c - F_{R,L}A_c\left[G\tau\alpha - U_{L,L}\left(T_{i,L} - T_a\right)\right]$$
$$-U_{L,t}A_c(T_c - T_a) \quad (24)$$

The maximum heat gain of air side can be obtained when the whole collector is at the inlet air temperature. Then, heat removal factor of air side can be written as equation (25).

$$F_{R,air} = \frac{\dot{m}_{air} C_{p,air} (T_{o,air} - T_{i,air})}{G\tau\alpha A_c - F_{R,L} A_c [G\tau\alpha - U_{L,L}(T_{i,L} - T_a)] - U_{L,t} A_c (T_{i,air} - T_a)} \qquad (25)$$

Heat gain of air side can be rewritten as equation (26).

$$Q_{air} = F_{R,air} A_c \{G\tau\alpha - F_{R,L}[G\tau\alpha - U_{L,L}(T_{i,L} - T_a)] - U_{L,t}(T_{i,air} - T_a)\} \qquad (26)$$

The thermal efficiency of a collector is defined as ratio of the useful thermal energy to the total solar radiation. So, thermal efficiency of liquid side is expressed as equation (27) from equation (20).

$$\eta_L = \frac{Q_L}{G A_c} = \frac{F_{R,L} A_c [G\tau\alpha - U_{L,L}(T_{i,L} - T_a)]}{G A_c} = F_{R,L}\tau\alpha - F_{R,L} U_{L,L} \frac{(T_{i,L} - T_a)}{G} \qquad (27)$$

Thermal efficiency of air side can be written as equation (28) from equation (26).

$$\eta_{air} = \frac{Q_{air}}{GA_c}$$
$$= \frac{F_{R,air}A_c\{G\tau\alpha - F_{R,L}[G\tau\alpha - U_{L,L}(T_{i,L} - T_a)] - U_{L,t}(T_{i,air} - T_a)\}}{GA_c} \quad (28)$$

It can be rewritten as equation (29).

$$\eta_{air} = F_{R,air}\left\{\tau\alpha(1 - F_{R,L}) + \frac{[F_{R,L}U_{L,L}(T_{i,L} - T_a) - U_{L,t}(T_{i,air} - T_a)]}{G}\right\} \quad (29)$$

In the equation (29), relation of inlet heating medium temperature, ambient temperature, solar radiation and thermal efficiency is represented. In this equation, thermal efficiency of air side is expected to increase with increment of inlet liquid temperature and decrease with increment of inlet air temperature. Total thermal efficiency of collector can be written as the sum of thermal efficiency of air and liquid side. This is expressed as follows:

$$\eta_t = \eta_L + \eta_{air} = A - B\left(\frac{T_{i,L} - T_a}{G}\right) - C\left(\frac{T_{i,air} - T_a}{G}\right) \quad (30)$$

Where,

$$A = (F_{R,air} + F_{R,L} - F_{R,air}F_{R,L})\tau\alpha$$

$$B = F_{R,L}(1 - F_{R,air})U_{L,L}$$

$$C = F_{R,air}U_{L,t}$$

Therefore, total thermal efficiency of collector can be written as heat removal factor and heat loss coefficient of two heating medium.

Chapter 4 Results and Discussion

4.1 Single operation

4.1.1 Temperature

Air heating was conducted without heating liquid for comparing thermal performance of hybrid solar air-water heater when the air was only heated with traditional solar air heater. Fig. 23 shows the measured inlet air temperature, outlet air temperature, ambient temperature and solar intensity.

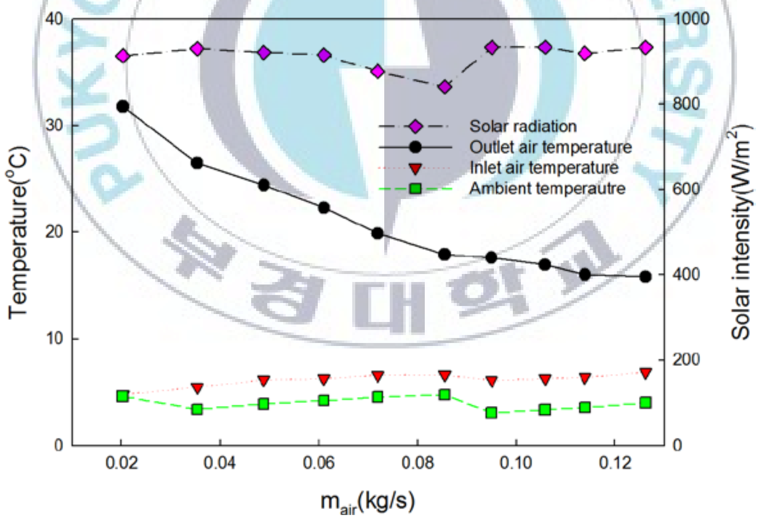


Fig. 23 Temperature profile of air side with respect to air mass flow rate when the air was only heated

Outlet air temperature was decreased with increment of air mass flow rate by decreasing of heat transfer time and the temperature of outlet air was shown from 16°C to 32°C on the about 4°C outdoor temperature.

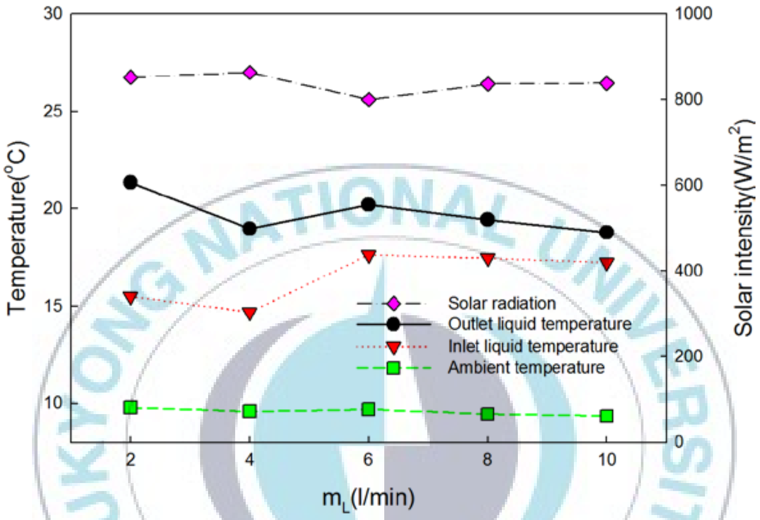


Fig. 24 Temperature profile of liquid side with respect to liquid mass flow rate when the liquid was only heated

Fig. 24 shows the measured inlet liquid temperature, outlet liquid temperature and solar intensity when the liquid was only heated for comparing thermal performance of hybrid solar air-water heater for heating liquid with traditional flat-plate solar collector for hot water.

Temperature difference between inlet and outlet liquid was decreased with increment of liquid mass flow rate by decreasing heat transfer time similar with air heating and it shown form 1.2°C to 5.8°C.

4.1.2 Heat gain

Fig. 25 shows the heat gain of air side obtained from equation (11) and measured value with air mass flow rate.

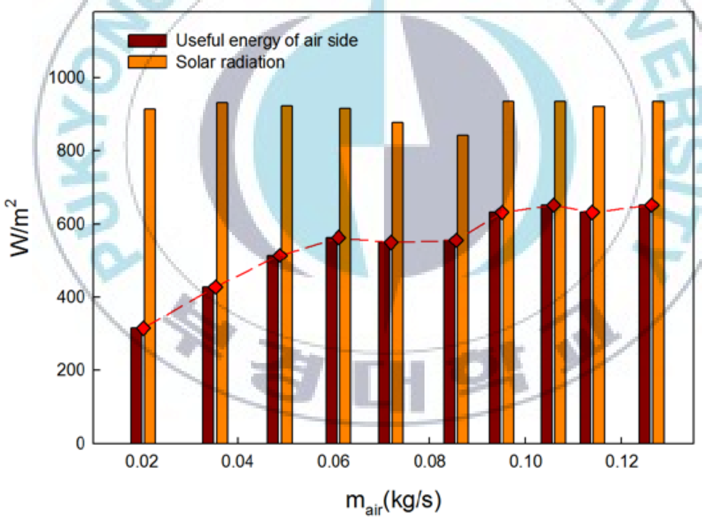


Fig. 25 Useful energy of air side with respect to air mass flow rate

The ratio of heat gain to incident solar irradiance was shown from 34.63% to 69.77% and it was increased with increment of air mass flow rate. This result signifies the increment of heat transfer rate from absorber plate and liquid pipe to flow air when the air mass flow rate was increased in air channel. Fig. 26 shows the heat gain of liquid side and measured solar intensity with liquid mass flow rate. The ratio of heat gain of liquid side to incident solar irradiance was shown minimum value 50.17% at 2L/min, maximum value 72.34% at 4L/min and the average value was shown about 65.20%. Operation condition for maximum heat gain also was confirmed from the tendency that decreased of heat gain at specific liquid mass flow rate after increased with increment of liquid mass flow rate.

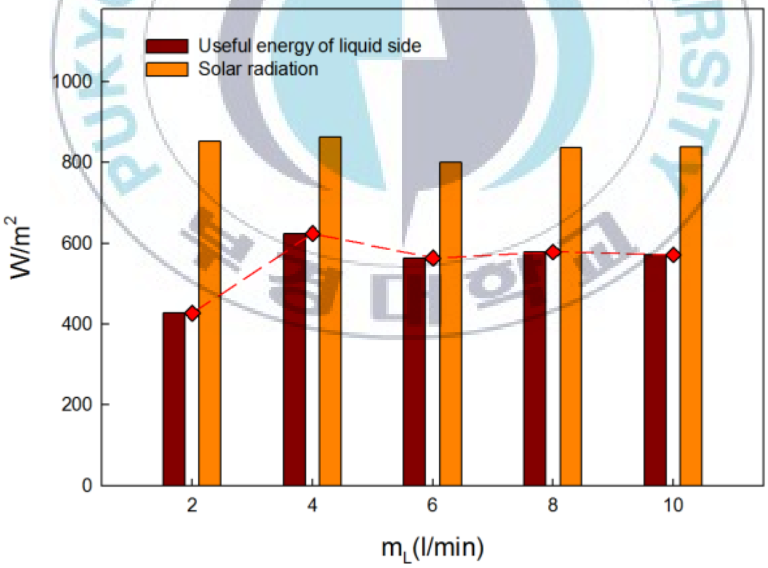


Fig. 26 Useful energy of liquid side with respect to liquid mass flow rate

4.1.3 Thermal efficiency

Fig. 27 shows the thermal efficiency obtained from equation (14) and measured value when the air was only heated . Thermal efficiency of air side was increased with increment of air mass flow rate similar with heat gain. The minimum thermal efficiency shown $\eta_a = 0.3481 - 3.9567x$ at 0.023 kg/s of air mass flow rate and the maximum thermal efficiency shown $\eta_a = 0.7151 - 4.9392x$ at 0.1262 kg/s of air mass flow rate. At this, x means the value of $(T_i - T_a)/G$.

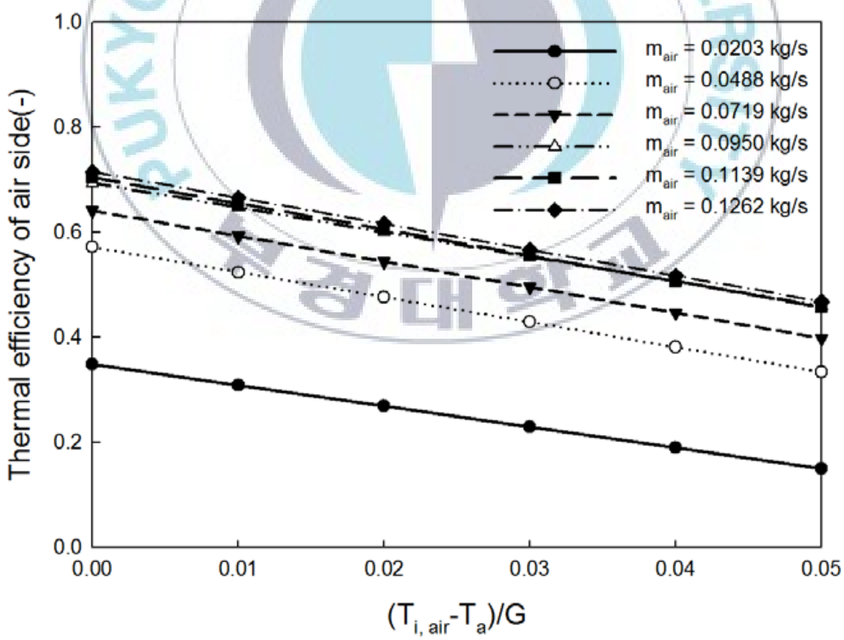


Fig. 27 Thermal efficiency of air side with respect to air mass flow rate

The possibility of usage of hybrid solar air-water heater was confirmed from the experiment result like to temperature and thermal efficiency of air side. But in the other research about solar air heater, thermal efficiency shown above 60% at 0.0208[16] and shown above 70% below 0.05kg/s of air mass flow rate[17, 18]. In other words, comparing hybrid solar air-water heater that used in this experiment to other solar air heater that studied already, it has a lower efficiency at same air mass flow rate. These differences resulted from air channel structure, fin’s shape and arrangement in the air channel then the ability of air heating can be improved by changing these things. Fig. 28 shows the thermal efficiency obtained from equation (14) and measured value when the liquid was only heated. Minimum value of thermal efficiency shown $\eta_l = 0.5662 - 9.6295x$ at 2 L/min of liquid mass flow rate and the maximum value was $\eta_l = 0.7534 - 4.9277x$ at 6L/min. From these results, it is confirmed that the effect of installation the air channel under absorber plate on heat removal factor for hot water making is slight considering the heat removal factor of flat-plate solar collector for hot water that was used for making hybrid solar air-water heater is 0.723[31]. But the heat loss coefficient was shown lower valued than traditional flat-plate solar collector because of the installing of air channel. And the thermal efficiency of hybrid solar air-water heater was shown the lower value when the hot water was made only on similar liquid mass flow rate of traditional flat-plate solar collector for hot water. So the necessity of performance improvement on lower liquid mass flow rate was confirmed. And in this experiment, the entrance and exit of air was opened then the overall heat loss coefficient can be decreased if it is closed.

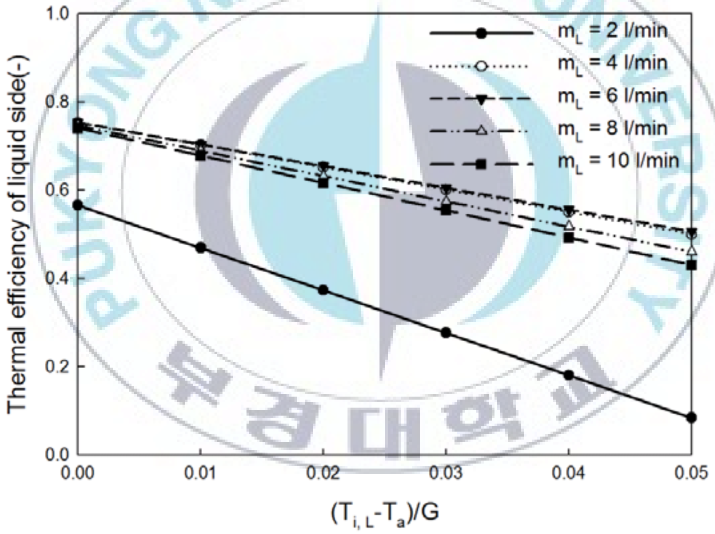


Fig. 28 Thermal efficiency of liquid side with respect to liquid mass flow when the liquid side only working

4.1.4 Performance evaluation of daily operation

The performance evaluation of daily operation that was conducted at 01/16/2014 and the result was shown in Fig. 29.

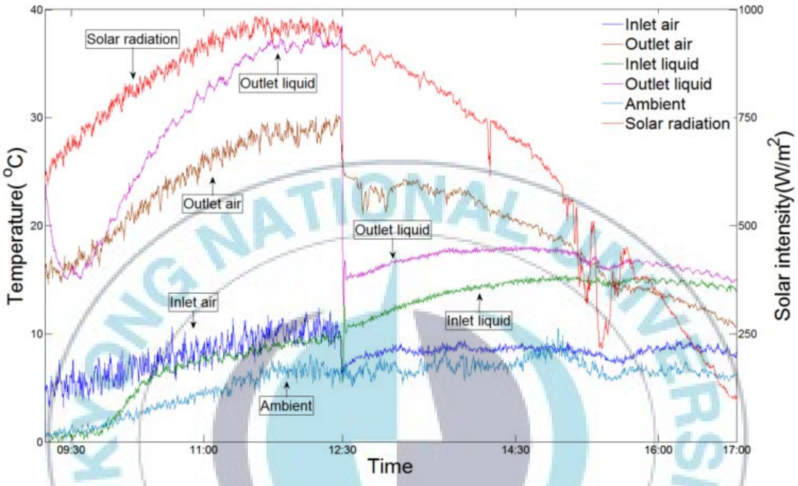


Fig. 29 Temperature profile of air and liquid side depends to time of day when liquid side working after air heating

Table 8 Experiment conditions of daily operation when the liquid side working after air heating

Date	2014. 01. 16	
Time	09:00 – 17:00	
Operating method	Air heating(before 13:00) Liquid heating(after 13:00)	
Operating condition	Air mass flow rate	0.049 kg/s
	Liquid mass flow rate	6 l/min

Liquid was heated after air heating at 12:30 and the operating condition was 3.6m/s of air velocity and 6 L/min of liquid mass flow rate. More details of experimental condition of daily operation was tabled in Table 8. Outlet air temperature was increased with increment of solar intensity and it was rising to 29℃ before air heating come to a stop. When the operation was changed from air heating to liquid heating, temperature difference of liquid inlet and outlet was shown about 4.5℃ and it was decreased with decrement of solar intensity. The temperature of circulating liquid was increased about 4℃ after liquid heating was conducted and above 10℃ was increased compared with the nine in the morning.

4.2 Simultaneous operation

Fig. 30 shows the heat removal factor of air side obtained from equation (25) and measured value with air and liquid mass flow rate when the air heating and liquid heating was conducted simultaneously.

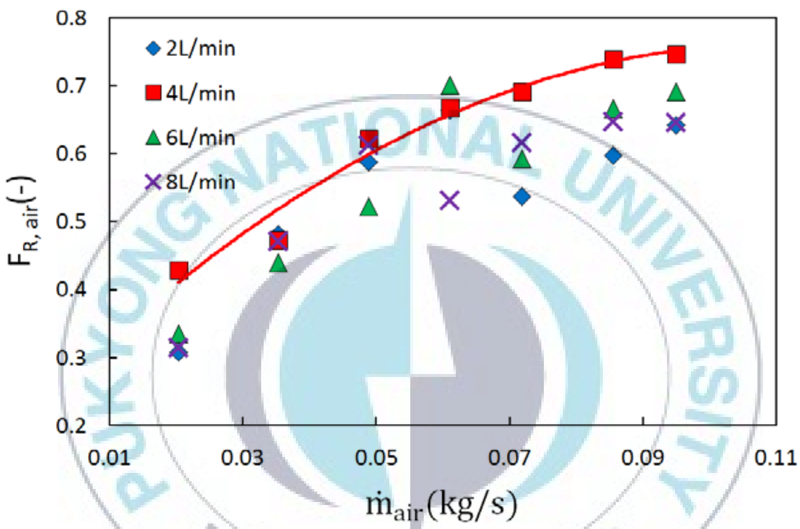


Fig. 30 Heat removal factor of air side with air and liquid mass flow rate when the air and liquid was heated simultaneously

Heat removal factor of air side was increased with increment of air mass flow rate and its value was higher at 4 L/min of liquid mass flow rate than other condition of liquid mass flow rate. Fig. 31 shows the heat removal factor of liquid side obtained from measured value. It was decreased with increment of air mass flow rate and the highest value was shown at 4L/min of liquid mass flow rate same with air side.

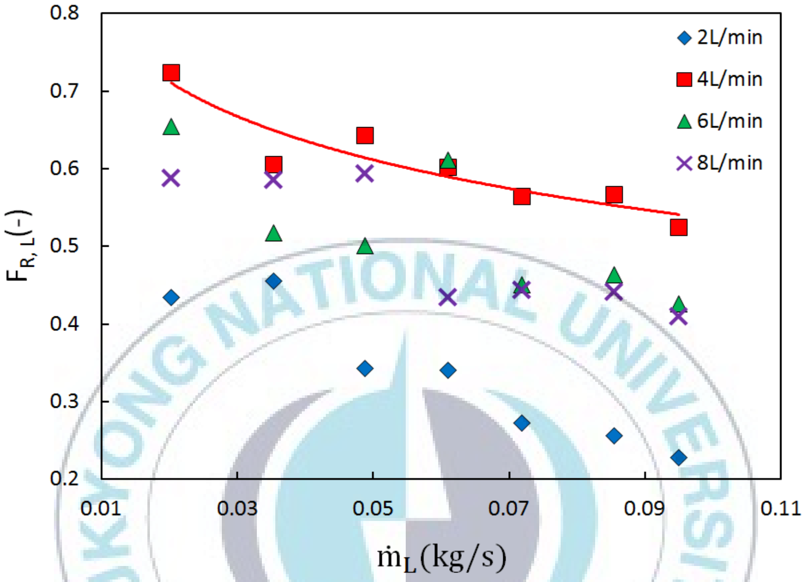


Fig. 31 Heat removal factor of liquid side with air and mass flow rate when the air and liquid was heated simultaneously

Performance of hybrid solar air-water heater was shown superior value at 4L/min of liquid mass flow rate to other conditions from Fig. 30, 31 and the former study[7]. Thus, the temperature, heat gain and thermal efficiency was investigated on constant liquid mass flow rate(4L/min) when the air heating and liquid heating was conducted simultaneously.

More details of experimental was tabled in Table 7 in experimental method of chapter 3.

4.2.1 Temperature

Fig. 32 shows the inlet air temperature, outlet air temperature, ambient temperature and solar intensity with air mass flow rate when the liquid was heated also.

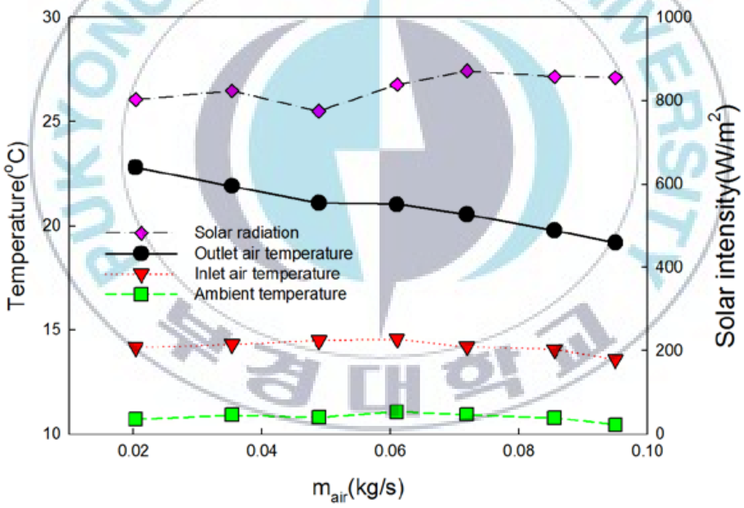


Fig. 32 Temperature profile of air side with respect to air mass flow rate when the air and liquid was heated simultaneously

Outlet air temperature was decreased with increment of air mass flow rate by decreasing of heat transfer time and the temperature of outlet air was shown minimum 19°C, maximum 23°C on the about 10°C of ambient temperature. From this, possibility of air heating was confirmed when the liquid side working simultaneously although the temperature difference between inlet and outlet air was somewhat decreased.

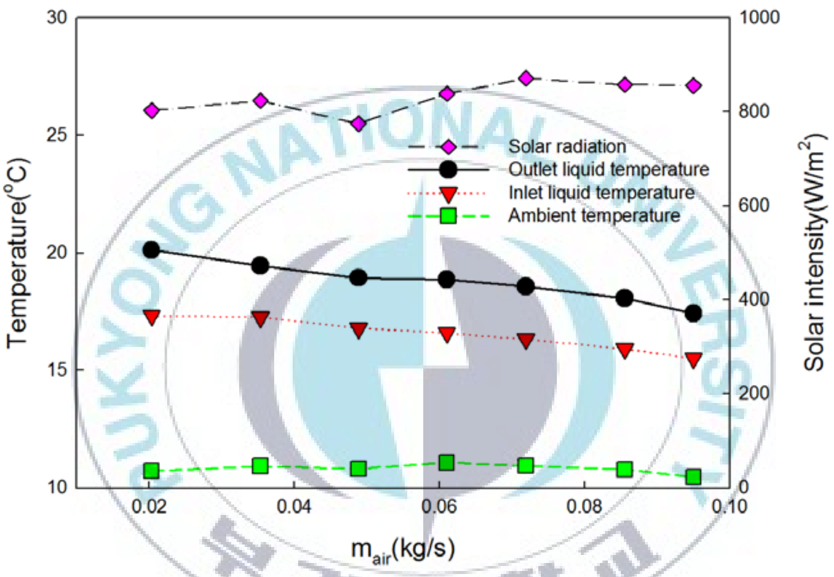


Fig. 33 Temperature profile of liquid side with respect to air mass flow rate when the air and liquid was heated simultaneously

Fig. 33 shows the temperature of liquid side with air mass flow rate when the air was heated also. Temperature difference of inlet and outlet liquid shows from 2°C to 2.8°C and the possibility of liquid heating was confirmed when the air heating was conducted also. And it can be known that the heat transfer rate from absorber to flow air in air channel was increased with increment of air mass flow rate from the result.

4.2.2 Heat gain

Fig. 34 shows the heat gain of air, liquid and total heat gain with solar intensity.

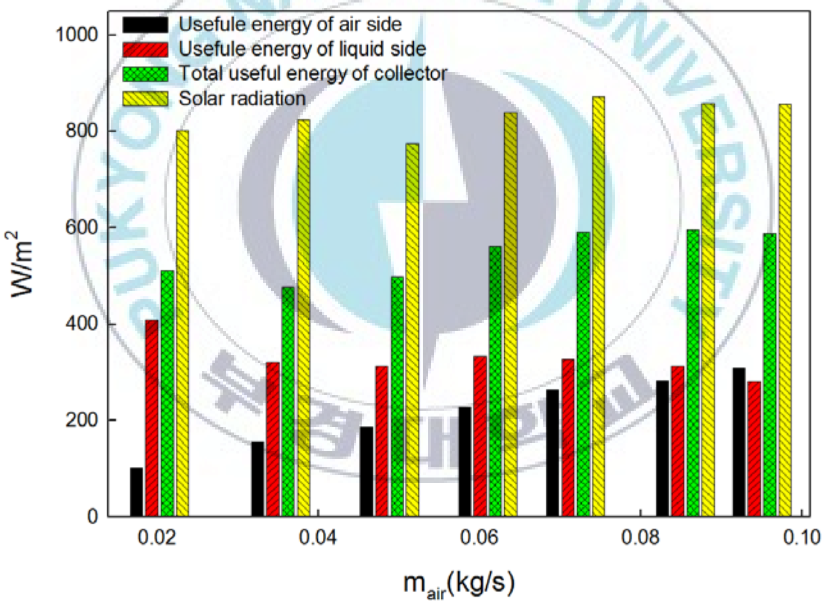


Fig. 34 Useful energy of collector and solar radiation with air mass flow rate

Liquid acquired more heat than air on the low air mass flow rate. But the heat gain of liquid was decreased and the heat gain of air was increased with increment of air mass flow rate due to the increment of heat transfer rate from absorber plate to flow air in air channel. Total heat gain in hybrid solar air-water heater was increased with increment of air mass flow rate. From this, extra heat gain was confirmed in addition to heat transfer from liquid to air by increment of air mass flow rate and it appears as if resulted from the increment of heat transfer rate from absorber to flow air as well as the heat transfer from liquid to flow air. Table 9, 10 shows the result of Fig. 32, 33 and 34 as a numerical value.

Table 9 Measured values and heat gain during two heating medium working simultaneously

$\dot{m}_{air}$ (kg/s)	T_a (°C)	$T_{i,air}$ (°C)	$T_{o,air}$ (°C)	$T_{i,L}$ (°C)	$T_{o,L}$ (°C)	T_c (°C)	Q_{air} (W)	Q_L (W)
0.0203	10.72	14.16	22.80	17.32	20.12	27.19	176.07	710.10
0.0353	10.92	14.31	21.91	17.26	19.46	26.63	269.16	557.50
0.0488	10.82	14.50	21.09	16.79	18.93	26.75	323.19	542.10
0.0610	11.08	14.56	21.03	16.59	18.87	26.24	396.41	577.60
0.0719	10.94	14.20	20.53	16.32	18.56	26.15	456.87	567.80
0.0855	10.77	14.06	19.77	15.91	18.06	25.61	489.83	544.60
0.0950	10.45	13.58	19.19	15.50	17.42	24.72	534.63	486.40

Table 10 Thermal efficiency of collector with air mass flow rate obtained from experiment when the heating mediums working simultaneously

$\dot{m}_{air}$ (kg/s)	η_{air} (%)	η_L (%)	η_t (%)	G (W/m^2)
0.0203	12.65	52.01	64.66	803.01
0.0353	18.84	39.02	57.86	824.28
0.0488	24.05	40.34	64.39	775.20
0.0610	27.26	39.72	66.98	838.94
0.0719	30.23	37.57	67.8	871.74
0.0855	32.73	36.61	69.34	858.12
0.0950	36.02	32.77	68.79	856.27

4.2.3 Thermal efficiency

Fig. 35 shows the heat loss coefficient of collector calculated from equation (19), (22) using measured value. Heat loss coefficient of liquid side was decreased with increment of air mass flow rate. This result signifies that the heat transfer from liquid pipe to flow air in air channel was enhanced with increment of air mass flow rate. Whereas, total overall heat loss coefficient of collector was slightly decreased with increment of air mass flow rate.

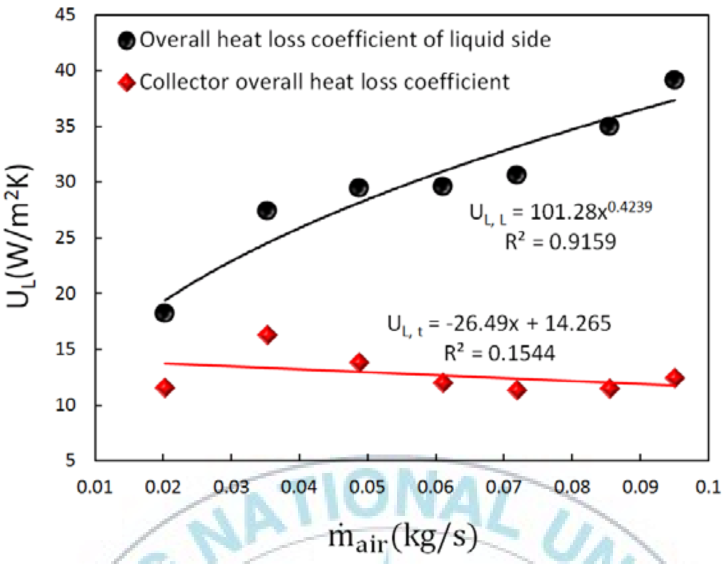


Fig. 35 Overall heat loss coefficient of collector and liquid side

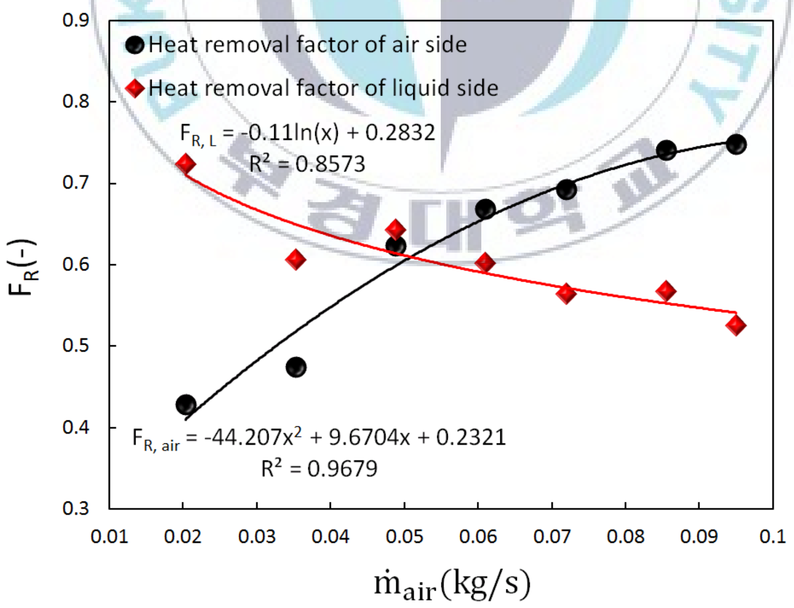


Fig. 36 Heat removal factor of air and liquid side

Fig. 36 shows heat removal factors of air and liquid side. Heat removal factor of air side was increased with increment of air mass flow rate when the liquid side was operated also. This tendency is considered as a result from increment of heat transfer rate from absorber and liquid pipe to flow air with increment of air mass flow rate. Whereas, heat removal factor of liquid side was decreased with increment of air mass flow rate due to the increment of heat transfer from liquid pipe and absorber to flow air. Fig. 37 shows the total thermal efficiency of collector obtained from equation (30) when the liquid and air was heated simultaneously.

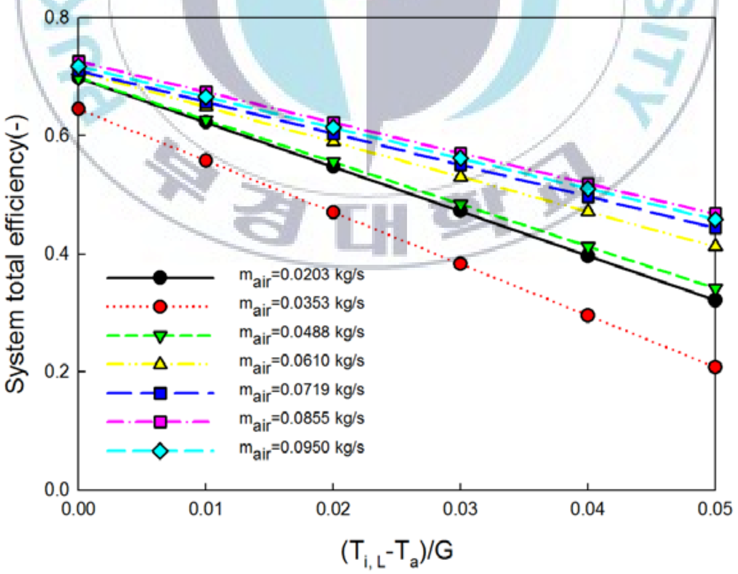


Fig. 37 Total thermal efficiency of Hybrid solar air-water heater during two heating medium working simultaneously

The measured value of $(T_{i,air} - T_a)/G$ was shown about 0 because outdoor air was used as inlet air of collector directly. Thus, the total thermal efficiency was represented with $(T_{i,\mathrm{L}} - T_a)/G$ in case of the $(T_{i,air} - T_a)/G$ is zero. Total thermal efficiency was increased and the decline of thermal efficiency was decreased with increment of air mass flow rate on the constant liquid mass flow rate. These tendencies was resulted from the increment of increment of heat transfer from absorber plate as well as liquid pipe with increment of air mass flow rate in air channel. Also, the effect of liquid side on decline of total thermal efficiency was decreased with air mass flow rate. A coefficient of total thermal efficiency calculated from measured value was tabled in Table 11.

Table 11 Result of system total thermal efficiency coefficient with respect to air mass flow rate calculated from experimental value

$\eta_t = \eta_L + \eta_{air} = A - B\left(\frac{T_{i,L} - T_a}{G}\right) - C\left(\frac{T_{i,air} - T_a}{G}\right)$			
$\dot{m}_{air}$ (kg/s)	A $(F_{R,air} + F_{R,L} - F_{R,air}F_{R,L})\tau\alpha$	B $F_{R,L}(1 - F_{R,air})U_{L,L}$	C $F_{R,air}U_{L,t}$
0.0203	0.7197	7.5363	4.9395
0.0353	0.6776	8.7485	7.7269
0.0488	0.7396	7.1434	8.8758

0.0610	0.7418	5.9207	8.0119
0.7190	0.7402	5.3267	7.8292
0.0855	0.7587	5.1689	8.4589
0.0950	0.7524	5.1981	9.2776

From the result of calculating coefficient of total thermal efficiency using measured value, increment of efficiency was confirmed with increment of air mass flow rate as stated previously. The effect of liquid side was more than air side in lower air mass flow rate, but with the increment of air mass flow rate, effect of air side was increased and effect of liquid side was decreased. But it can be known that the decline of total thermal efficiency will be decreased with air mass flow rate in case of the outdoor air was used for inlet air directly.

4.2.4 Performance evaluation of daily operation

Fig. 38 shows the result of daily operation that was conducted at 01/22/2014 when the air and liquid was heated simultaneously and the experiment conditions of daily operation was tabled in Table 12.

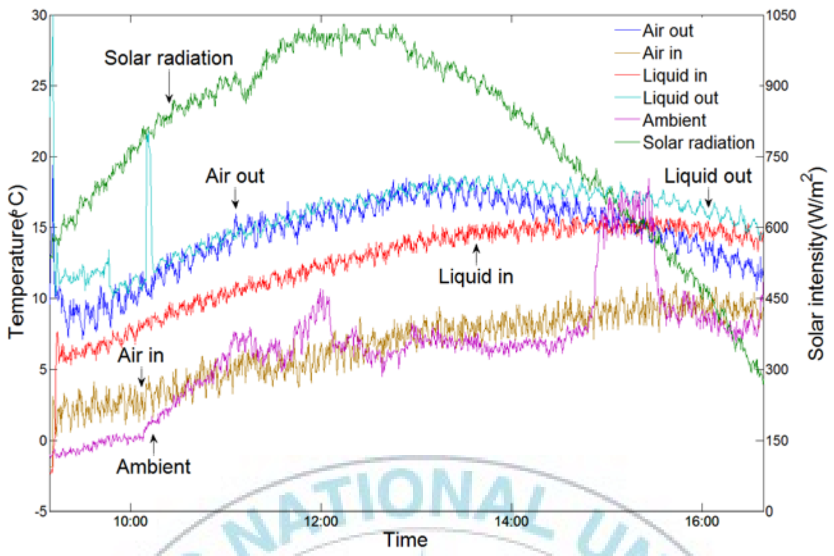


Fig. 38 Temperature profile of air and liquid side depends to time of day when heating medium working simultaneously

Table 12 Experiment conditions of daily operation when the two heating medium working simultaneously

Date	2014. 01. 22	
Time	09:00 – 17:00	
Operating method	Air heating + Water heating	
Operating condition	Air mass flow rate	Liquid mass flow rate
	0.049 kg/s	4 l/min

The maximum outlet air temperature and temperature difference between inlet and outlet air was shows about 18°C and 11°C on the about 5°C of ambient temperature and the maximum outlet liquid temperature shown about 17°C that was increased above 7°C compared with nine in the morning. From these results, lower temperature of outlet heating medium was confirmed compared with single operation although liquid and air can be heated simultaneously. It can be known that the outlet temperature of each heating medium was slightly low for applying to air conditioning and hot water supply system when the two heating medium was heated simultaneously. But the hybrid solar air-water heater that was used in this experiment has lower efficiency than other solar air heater at same air mass flow rate as stated in the result of single operation. It means the temperature of outlet air can be increased by changing fin's shape, arrangement and so on. So, by improving these things, the possibility of applying into air conditioning and hot water supply system can be increased when the air and liquid was heated simultaneously.

4.3 Collector performance with operating condition

4.3.1 Single operation

4.3.1.1 Temperature difference

Temperature difference between inlet and outlet heating medium on single operation can be written as equation (31) from equation (13).

$$\Delta T = T_o - T_i = \frac{F_R A_c}{\dot{m} C_p}\left[G\tau\alpha - U_{L,t}(T_i - T_a)\right] \quad (31)$$

The heat removal factor and overall heat loss coefficient was obtained from experiment then temperature difference can be predicted at specific operating condition. Fig. 39 shows the heat removal factor and overall heat loss coefficient of collector when the air was only heated.

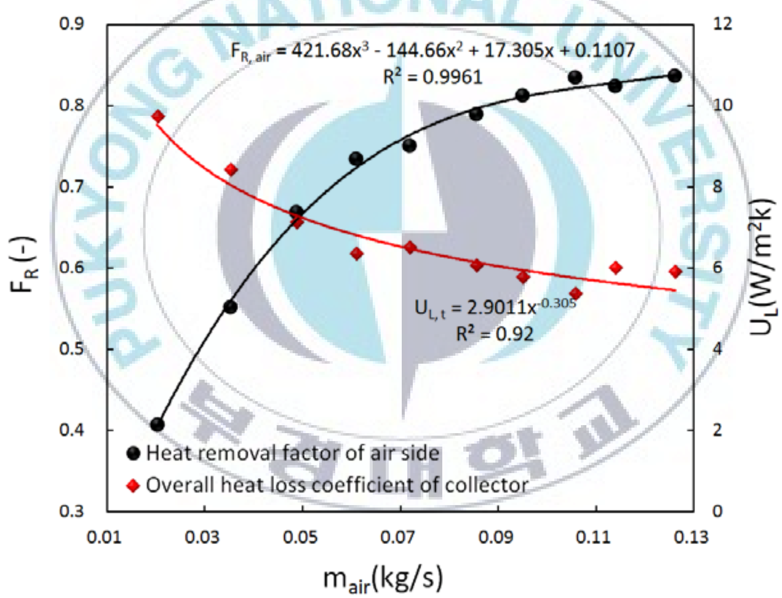


Fig. 39 Heat removal factor and overall heat loss coefficient when the air was only heated

Heat removal factor was increased and overall heat loss coefficient was decreased with increment of air mass flow rate. From these results, the heat removal factor and overall heat loss coefficient can be expressed as a function of air mass flow rate. So, temperature difference can be written as a dependent variable as follows.

$$\Delta T = T_o - T_i = f\left(F_R,\ U_{L,t},\ T_i,\ T_a,\ G\right) = f(m_{air},\ T_i,\ T_a,\ G) \quad (32)$$

Fig. 40 shows the temperature difference with solar intensity and air mass flow rate using the equation obtained from experiment.

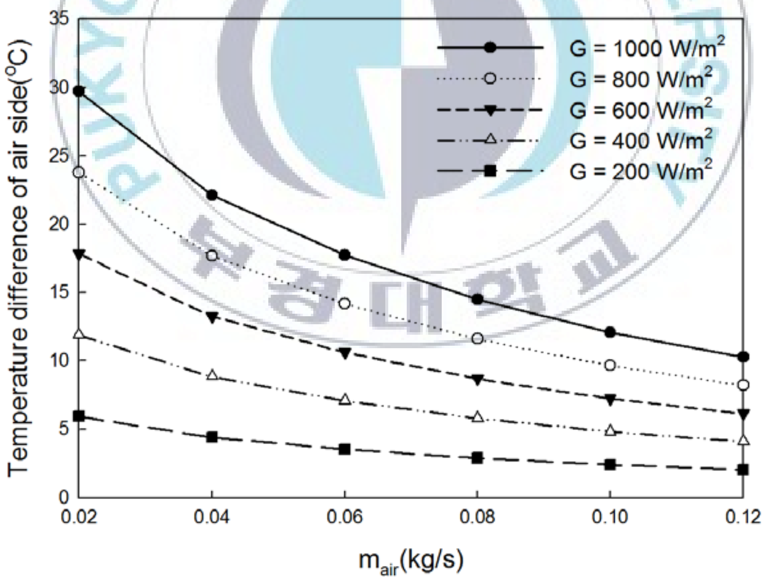


Fig. 40 Temperature difference of air side calculated using equation obtained from experiment with respect to air mass flow rate and solar radiation

Temperature difference represented in Fig. 40 is the maximum temperature difference because temperature difference between inlet air and ambient was assumed as 0. Temperature difference was increased with increment of solar intensity and decreased with increment of air mass flow rate and it was shown from 8°C to 30°C above 600 W/m^2 of solar intensity. Fig. 41 shows the heat removal factor and overall heat removal coefficient of liquid side obtained from measured value with liquid mass flow rate.

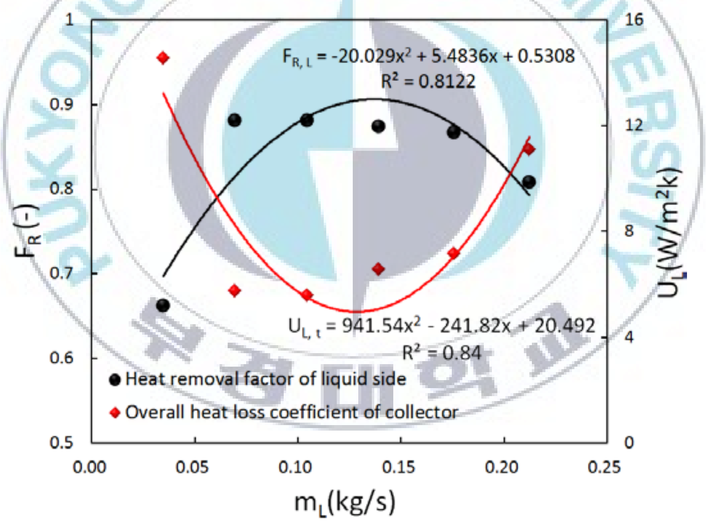


Fig. 41 Heat removal factor and overall heat loss coefficient when the liquid side working only

The experiment for liquid heating was conducted on the condition of 2 l/min, 4 l/min, 6 l/min, 8 l/min and 10 l/min as represented in Table 6 and the heat removal factor and overall heat loss coefficient represented in Fig. 41 was the value obtained each conditions of liquid mass flow rate. Fig. 42 shows the temperature difference between inlet and outlet liquid obtained from equation (31) and measured value with liquid mass flow rate and solar intensity when the temperature difference of inlet liquid and ambient was assumed as zero.

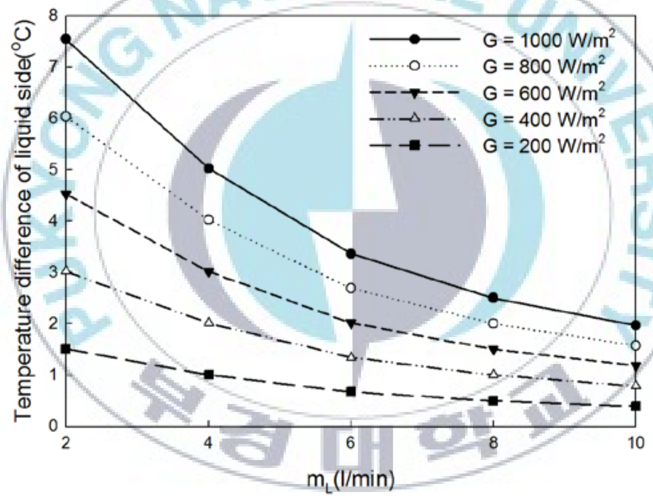


Fig. 42 Temperature difference calculated from experimental value with liquid mass flow rate and solar radiation

4.3.2 Simultaneous operation

Thermal efficiency of hybrid solar air-water heater is the function of heat removal factor, heat loss coefficient, air mass flow rate, inlet temperature of each heating medium, ambient temperature and solar irradiance. At this time, each factor is independent variable. Also heat removal factor and heat loss coefficient can be expressed as a function of air and liquid mass flow rate. In this study, only air mass flow rate was changed on constant liquid mass flow rate when the air and liquid was heated simultaneously then the heat removal factor and heat loss coefficient was acquired as function of only air mass flow rate. Thus, thermal efficiency of hybrid solar air-water heater was represented as a function of air mass flow rate, inlet temperature of each heating medium, ambient temperature and solar irradiance except liquid mass flow rate. At this time, the relation of heat removal factor to air mass flow rate or heat loss coefficient to air mass flow rate can be obtained as a regression equation from the result of experiment as shown in Fig. 35, 36. In other words, heat removal factor and heat loss coefficient of collector that was used in experiment can be predicted at specific air mass flow rate. Therefore, total thermal efficiency of hybrid solar air-water heater can be expressed as follows:

$$\eta_t = f(\dot{m}_{air}, T_{i,L}, T_{i,air}, T_a, \mathrm{G}) \tag{33}$$

Fig. 43 shows the comparison of the predicted efficiencies calculated by using the regression equation of heat removal factor and heat loss coefficient obtained from experiment with the efficiencies that was obtained from measured value. Input value for calculating was used same operating condition value(air mass flow rate, inlet temperature of each heating medium, ambient air temperature, solar radiation) measured at the experiment. Equation (27), (29) and (30) was used for calculating liquid, air and total thermal efficiency and the regression equation represented in Fig. 35, 36 was used for heat removal factor and heat loss coefficient.

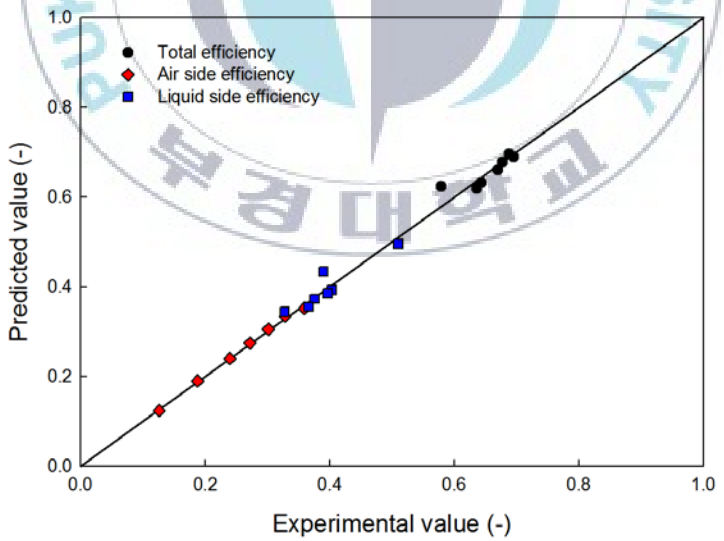


Fig. 43 Comparison of the predicted efficiency with experimental efficiency

An average error between predicted efficiency and experimental efficiency was shown 0.21% for air side, 0.52% of liquid side and 0.27% of total value. In other words, predicted efficiency and experimental efficiency was not different so much as shown in Fig. 43. So, reliable result can be predicted using regression equation obtained from measured. In this study, thermal efficiency and the relation between thermal efficiency and operating condition was confirmed using the equation obtained from experiment on various operating conditions.

3.3.2.1 Relation between thermal efficiency and operating condition

Fig. 44 shows the thermal efficiency of air side with inlet liquid temperature and solar intensity when the air mass flow rate was 0.0488 kg/s. Temperature difference between inlet air and ambient was assumed as 3.4°C from the average value of experiment. Thermal efficiency of air side was increased with increment of temperature difference of inlet liquid and ambient because air can obtain more heat gain from liquid at the high inlet liquid temperature when the other conditions are same. And also thermal efficiency of air side was decreased with increment of solar radiation when the temperature difference of inlet liquid and ambient is higher than specific value because only solar irradiance was considered as a input energy of collector.

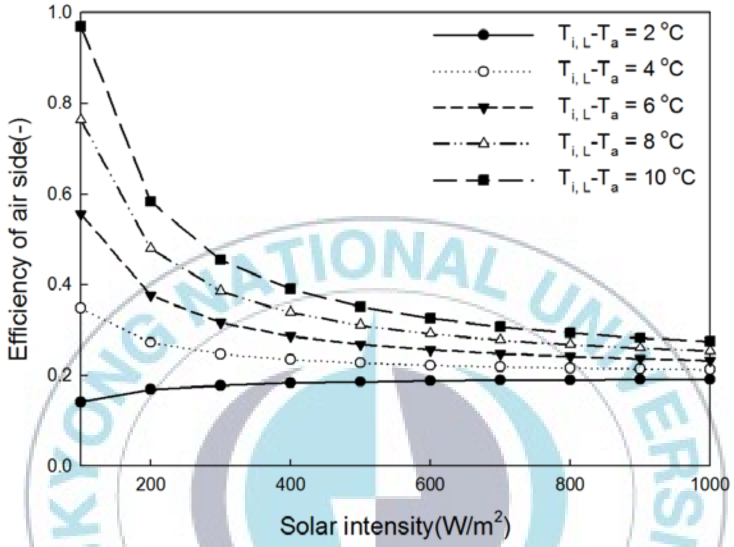


Fig. 44 Thermal efficiency of air side with respect to solar intensity and temperature different between inlet liquid and ambient when the air and liquid was heated simultaneously ($T_{i,air} - T_a = 3.4$℃, $\dot{m}_{air} = 0.0488\ kg/s$)

Actually, to maintaining 10°C of temperature difference between inlet liquid and outdoor on low solar radiation, other heat source is needed. Then the temperature difference will be increased with solar radiation and increment of thermal efficiency also predicted with increment of temperature difference between inlet liquid and ambient on actual operation. So, it can be known that the utilization of solar thermal energy will be increased by using hybrid solar air-water heater because it recover the heat loss occurred from liquid pipe when it operating at high temperature different with traditional flat-plate solar collector for hot water. Fig. 45 shows the thermal efficiency of air side with solar radiation and air mass flow rate and $T_{i,L} - T_a$, $T_{i,air} - T_a$ taken 5.7°C, 3.4°C from the average value of experiment.

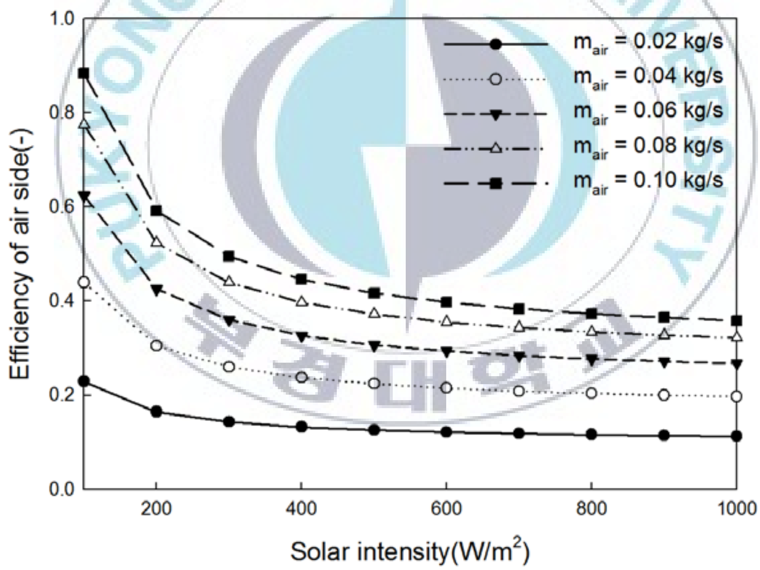


Fig. 45 Thermal efficiency of air side with respect to solar intensity and air mass flow rate when the air and liquid was heated simultaneously

($T_{i,L} - T_a = 5.7$°C, $T_{i,air} - T_a = 3.4$°C)

Thermal efficiency of air side was increased with increment of air mass flow rate because of the increment of heat transfer from absorber plate and liquid pipe to flow air. Whereas, the thermal efficiency was decreased with increment of solar radiation when the temperature difference was assumed as 5.7°C. Fig. 46 shows the thermal efficiency of liquid side calculated from equation (27).

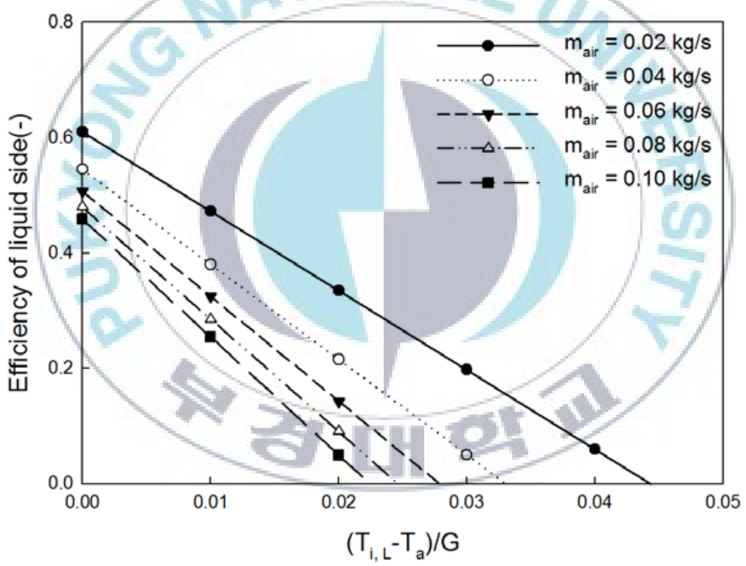


Fig. 46 Thermal efficiency of liquid side with respect to air mass flow rate when the air and liquid was heated simultaneously

Thermal efficiency of liquid side was shown relatively high value while the air heating was conducted and it was decreased with increment of air mass flow rate. It explains that the increment of heat transfer from liquid pipe and absorber plate to flow air with increment of the air mass flow rate as previously stated. But decline of efficiency was shown the lower value than traditional flat-plate solar collector for hot water because the air side was also considered as a heat loss of liquid side. As confirmed above, estimation of collector can be underestimated when the thermal efficiency was investigated with respect to only one heating medium. Hence, total thermal efficiency including heat gain of air and liquid side is needed for more accurate evaluation of collector efficiency. Fig. 47 shows the total thermal efficiency of hybrid solar air-water heater when the air mass flow rate was 0.02 kg/s. Maximum total thermal efficiency of collector was shown about 71% and it was decreased with increment of temperature difference between inlet heating medium and ambient. Total thermal efficiency of collector was increased with increment of air mass flow rate and Fig. 48 shows total efficiency when the air mass flow rate was 0.10 kg/s. Maximum total thermal efficiency at 0.10 kg/s of air mass flow rate was shown about 75.87%.

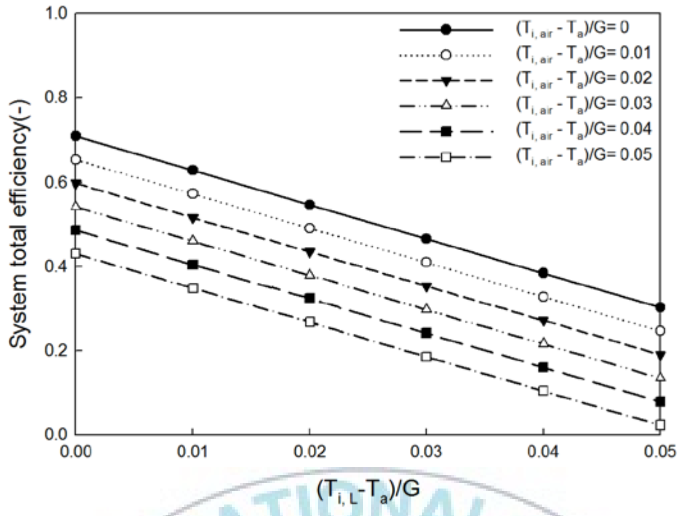


Fig. 47 Total thermal efficiency of hybrid solar air-water heater when the air and liquid was heated simultaneously, ($\dot{m}_L = 4\ l/min$, $\dot{m}_{air} = 0.02\ kg/s$)

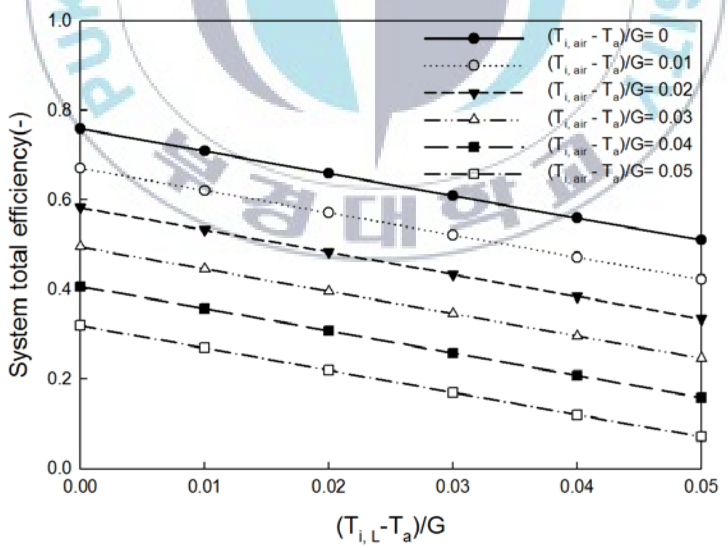


Fig. 48 Total thermal efficiency of hybrid solar air-water heater when the air and liquid was heated simultaneously, ($\dot{m}_L = 4\ l/min$,$\dot{m}_{air} = 0.10\ kg/s$)

The coefficients of total thermal efficiency obtained from experimental value were tabled in table 13 with air mass flow rate. As previously stated, total efficiency of collector was increased with increment of air mass flow rate. And also, heat loss coefficient of liquid side expressed as B in equation (30) has greater effect on total efficiency than air side on lower air mass flow rate. On the contrary to this, heat loss coefficient of air side effect to total thermal efficiency more than liquid side on the higher air mass flow rate. But generally, outdoor air is used as inlet air for collector directly. Thus the lower decline of efficiency of collector is predicted with increment of air mass flow rate.

Table 13 Result of total thermal efficiency with respect to air mass flow rate calculated from experimental value

$\eta_t = \eta_L + \eta_{air} = A - B\left(\frac{T_{i,L} - T_a}{G}\right) - C\left(\frac{T_{i,air} - T_a}{G}\right)$			
$\dot{m}_{air}$ (kg/s)	A $(F_{R,air} + F_{R,L} - F_{R,air}F_{R,L})\tau\alpha$	B $F_{R,L}(1 - F_{R,air})U_{L,L}$	C $F_{R,air}U_{L,t}$
0.02	0.7100	8.1506	5.6016
0.04	0.7149	7.4512	7.2390
0.06	0.7342	6.3169	8.2794
0.08	0.7510	5.3990	8.8891
0.10	0.7587	4.9735	8.7941

In this study, heat loss coefficient of liquid side was assumed as a function of air mass flow rate because the outlet air was used directly as inlet air of collector. Thus, the decline of efficiency was shown linear decrement with increment of temperature difference between inlet air and ambient. But actually, decline of efficiency will be decreased with increment of inlet liquid temperature because heat loss coefficient of liquid side is decreased also with increment of inlet air temperature. Hence, it is more valid that evaluating total thermal efficiency on the supposition that $(T_{i,air} - T_a)/\mathrm{G} = 0$. Fig. 49 shows total thermal efficiency with air mass flow rate on the supposition that $(T_{i,air} - T_a)/\mathrm{G} = 0$. It can be known that using $(T_{i,air} - T_a)/\mathrm{G} = 0$ is valid from measured value because the average measured value of $(T_{i,air} - T_a)/\mathrm{G}$ was shown 0.004. Total thermal efficiency was increased with increment of air mass flow rate similar with efficiency obtained from measured value. And also, decline of total thermal efficiency was largely affected by liquid side on lower air mass flow rate. On the contrary to this, it was largely affected by air side on higher air mass flow rate as previously stated. This tendency was resulted from the increased effect of air on total thermal efficiency from increment of heat gain of air side with increment of air mass flow rate.

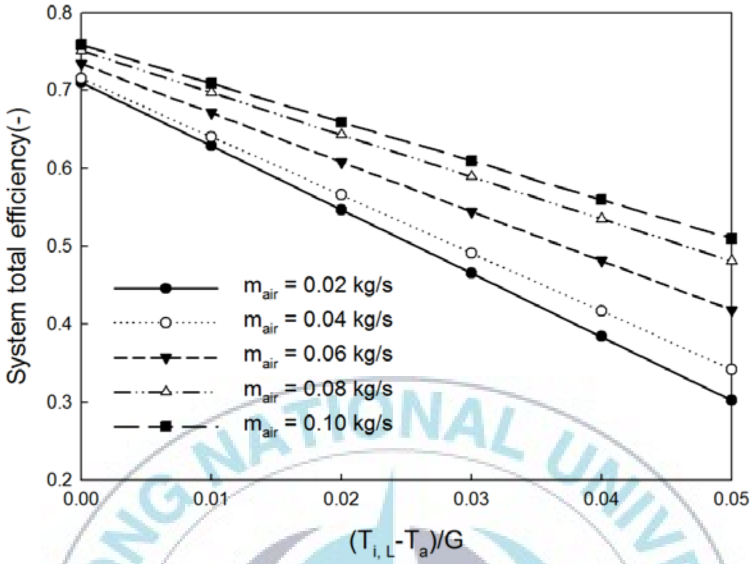


Fig. 49 Total thermal efficiency of collector with air mass flow rate when the air and liquid was heated simultaneously, ($\dot{m}_L = 4\ l/min$, $T_{i,air} - T_a = 0$℃)

3.3.2.2 Temperature difference

Collector outlet temperature is an important parameter for applying other system, design and so on. Thus the temperature difference of each heating medium was calculated using regression equation obtained from result of experiment with air mass flow rate and solar intensity when the air and liquid was heated simultaneously. Temperature difference of air side can be expressed from equation (25) as follows:

$$T_{o,air} - T_{i,air} = \frac{F_{R,air}\{G\tau\alpha A_c - F_{R,L}A_c[G\tau\alpha - U_{L,L}(T_{i,L} - T_a)] - U_{L,t}A_c(T_{i,air} - T_a)\}}{\dot{m}_{air}c_{p,air}} \quad (34)$$

Temperature difference of liquid side can be written as equation (35) from equation (20).

$$T_{o,L} - T_{i,L} = \frac{F_{R,L}A_c[G\tau\alpha - U_{L,L}(T_{i,L} - T_a)]}{\dot{m}_L c_{p,L}} \quad (35)$$

Fig. 50, 51 shows the temperature difference of each heating medium with air mass flow rate and solar intensity when it is assumed that the inlet air and liquid temperature equal to ambient temperature. In this experiment, outdoor air was used as inlet air and the temperature difference of air side is increased with increment of inlet liquid temperature. Thus the temperature difference represented in Fig. 50 is maximum value at specific operating condition. Maximum temperature difference between inlet and outlet air was shown about 9℃ when the liquid was also heated then the air and liquid heating can be conducted simultaneously. But the lower temperature difference was shown than single operation that heating the air or liquid respectively. So, an extension of collecting area or selective operating according to heat load was needed for conducting air and liquid heating simultaneously at real building.

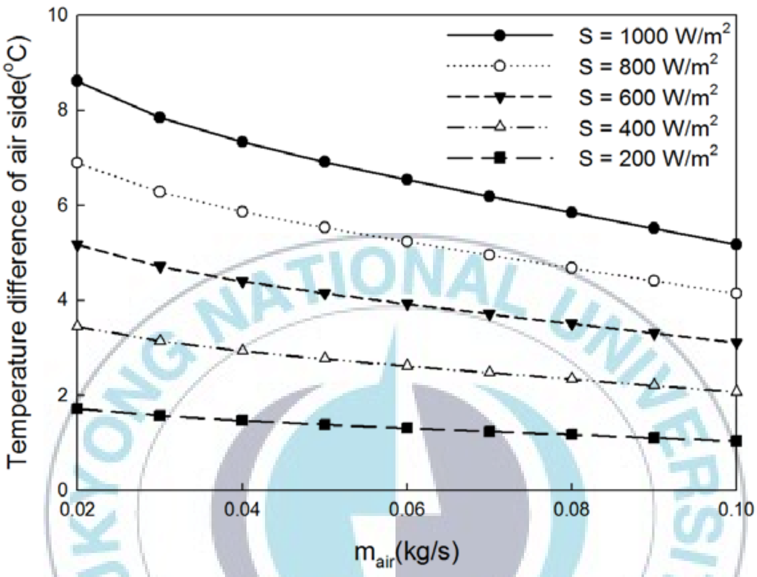


Fig. 50 Temperature difference of air side with air mass flow rate and solar intensity when the air and liquid was heated simultaneously

($\dot{m}_L = 4\ l/min$, $T_{i,air} - T_a = 0$℃, $T_{i,L} - T_a = 0$℃)

Fig. 51 shows the temperature difference of liquid side when the air was also heated. In case of liquid side, temperature difference was increased with increment of inlet air temperature. But generally, outdoor air was used as inlet air directly then the temperature difference is gradually decreased after operating was conducted. Thus, the temperature difference represented in Fig. 51 is maximum value of liquid side at specific operating condition.

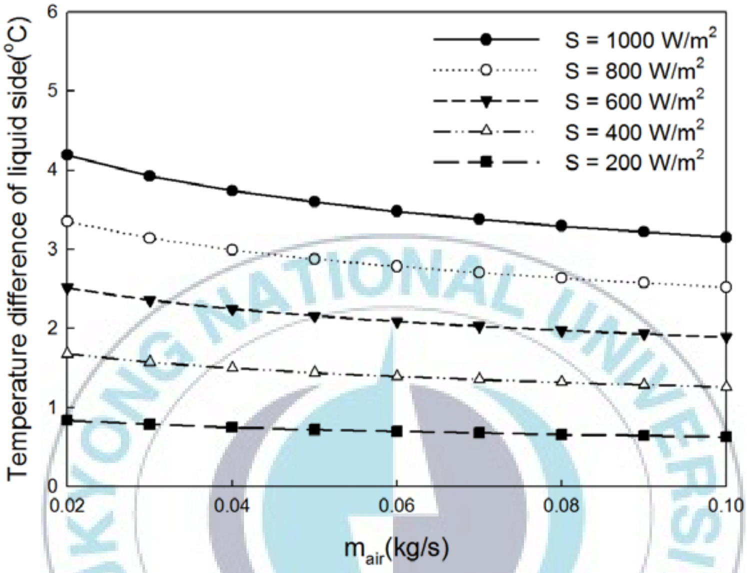


Fig. 51 Temperature difference of liquid side when the air and liquid was heated simultaneously, ($\dot{m}_L = 4\ l/min$, $T_{i,air} - T_a = 0$℃, $T_{i,L} - T_a = 0$℃)

From the result, liquid heating can be conducted when the air was also heated although the lower temperature difference was shown compared with single operation. However operation control is needed when the temperature difference reaches a specific value because temperature difference is gradually decreased after liquid heating was conducted.

Chapter 5 Conclusions

In this study, performance evaluation, confirming of improvement and the possibility to practical use of hybrid solar air-water heater was investigated. The conclusions obtained from performance evaluation when the air or liquid was heated respectively are as follows.

(1) Temperature difference between outlet air and ambient was shown form 12℃ to 28℃ in the condition of this experiment. Then, the usability of hybrid solar air-water heater for air conditioning system or pre-heater can be confirmed.

(2) The air heating performance of hybrid solar air-water heater that used in this experiment was shown lower value than other solar air heater studied by other researchers. So it is needed that improving the air heating performance by changing the structure of air channel, fin’s shape and arrangement.

(3) In case of the performance of liquid heating, heat removal factor was shown similar value with traditional flat-plate solar collector for hot water

at 6l/min of mass flow rate. Btu the heat loss coefficient of hybrid solar air-water heater has a higher value because of the installing of air channel under absorber and liquid pipe.

(4) Thermal performance of liquid heating was shown a lower value than traditional flat-plate solar collector for hot water on the similar liquid mass flow rate. So the necessity of performance improvement for hot water making on the lower liquid mass flow rate was confirmed.

The performance when the air and liquid was heated simultaneously was evaluated with the change of air mass flow rate on constant liquid mass flow rate and the conclusion obtained from the result of experiment is as follows.

(4) Air and liquid can be heated simultaneously and the temperature difference of air side and liquid side was shown from 9℃ to 13℃ and from 1.92℃ to 2.8℃ on the about 10℃ of ambient temperature.

(5) Temperature increase of each heating medium was shown lower value but the total thermal efficiency of collector was higher on the specific air

mass flow rate compared with single operation. This result shows that a part of heat loss of liquid side can be recovered from flow air.

(6) The necessity of increment of outlet air temperature by improving structure of air channel, fin's shape and arrangement was confirmed from the result of daily operation when the air and liquid was heated simultaneously because outlet air temperature was shown relatively lower value for applying to air conditioning directly.

The conclusions obtained from the evaluation of air, liquid and total thermal efficiency with respect to operating condition using the relation of heat removal factor and heat loss coefficient to air mass flow rate is as follows.

(7) Thermal efficiency of air side was increased with increment of inlet liquid temperature and air mass flow rate. From this, increment of heat gain of flow air by increasing of inlet liquid temperature and enhancement of heat transfer from absorber plate and liquid pipe to flow air with increment of air mass flow rate were confirmed

(8) Thermal efficiency of air side was shown from 10% to 50% and more value widely with respect to operating conditions

(9) The utilization of solar energy was increased by using hybrid solar air-water heater because heat loss of liquid side can be recovered from flow air different with traditional flat-plate solar collector that occurring only decline of efficiency by increment of inlet liquid temperature.

(10) Thermal efficiency of liquid side was increased with increment of solar intensity and decrement of inlet liquid temperature and it was also decreased with increment of air mass flow rate.

(11) But decline of efficiency was shown the higher value than traditional flat-plate solar collector for hot water because the air side was also considered as a heat loss of liquid side. So, necessity of research for operation method decision with heat load is confirmed because maximum reaching temperature was lower than traditional flat plate solar collector for hot water when the air and liquid was heated simultaneously

(12) Total thermal efficiency was increased with increment of air mass flow rate and the maximum value was shown 71% at 0.02kg/s of air mass flow rate and 75.87% at 0.10kg/s of air mass flow rate slightly higher than single operation.

From the result of this study, the necessity of thermal performance improvement on lower mass flow rate was confirmed by conducting the improvement that was obtained from this study and the possibility of practical use was confirmed from the result of experiment. Also the higher thermal efficiency can be obtained from the hybrid solar air-water heater by recovering heat loss of liquid side from flow air different with traditional flat-plate solar collector for hot water although it is slight somewhat. Thus, hybrid solar air-water heater was expected to replace traditional solar collector used for building equipment if the thermal efficiency on low mass flow rate is improved.

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사 사

먼저 저를 낳아주셔 이 자리에 있을 수 있도록 해주시고 부족한 가정형편에도 진학에 아무런 말 없이 제 의견을 존중하여 동의해주셨던 부모님 그리고 사랑하는 할아버지 할머니께 감사의 말씀 드립니다. 건강하게 있어주는 것 만으로도 힘이 되어주는 동생에게도 고마움을 전합니다.

석사과정에 있으면서 여러 일들이 있었으나 그때마다 힘이 되어주신 소중한 지인들이 있습니다. 힘들 때, 혹은 고민이 많을 때 마다 격려와 위로를 아끼지 않은 최창현, 정민형, 송성하, 황지훈 친구들에게 고마움을 전합니다. 대학교를 들어오면서부터 지금까지 함께하고 항상 힘이 되어준 오현택 선배님, 백종인 선배님, 동기들을 포함한 동아리 울림의 식구 여러분에게도 감사의 말씀 전합니다. 라오스 프로젝트를 하며 인생에 대한 꿈을 예기하고 이후에도 공과대학생으로서 접하기 힘든 세상을 간접적으로 접할 수 있도록 해주었으며, 여러 조언을 아끼지 않았던 변현준 사장님, 백두주 박사님, 정준용 형님을 비롯한 프로젝트 팀원들에게 고마움을 전합니다. 그리고 몇 년간 함께한 실험실 식구들인 안병화 형님, 최동원, 엄한샘, Agung Bakhtiar 박사님, Fatkhur Rokham 선배님, 대학원 동기들에게도 모두 고맙습니다. 많은 사람들이 있었기에 힘을 얻고 지금 이 자리에 있을 수 있었습니다.

또한 석사과정 동안 연구를 수행할 수 있도록 학부 때부터 많은 가르침을 주신 김종수 교수님, 금종수 교수님, 윤정인 교수님, 정석권 교수님, 김은필 교수님,

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