110 Transactions of the Korean Society of Mechanical Engineers Vol. 7, No. 1, pp. 110~121, 1983.

<Technical Paper>

A Thermal Performance Test Loop Design for Liquid-Heating Solar Collectors

Moon-Hyun Chun*, Seh-Beom Han and Ki-Chul Cha*****

(Received August 27, 1982)

액체식 태양열 집열기의 열성능 평가시험 루우프설계

전문헌 · 한세범 · 차기철

초록

ASHRAE 표준을 참고로 하여 한국과학기술원(KAIST)에서 수정한 집열기 시험 장치의 주요 부품의 설계도면 및 Specification 등을 제시하였다. 또한 ASHRAE 표준 시험 절차를 재분석하고 KAIST에서 수정한 Test Loop를 시험하기 위한 실험절차의 개요도 설명하였다. ASHRAE 표준상의 가장 중요한 실험인 (1) 집열기 시간 상수 실험과 (2) 수직에 가까운 입사각에 대한 효율 실험 및 (3) 입사각 수정 계수 실험 등을 실제 태양 아래에서 실험하여 그 결과도 그림으로 제시하였다.

본 연구를 통해서 얻은 결과로부터 다음과 같은 결론을 얻을 수 있었다. 한국 과학 기술원에서 설계한 집열기 시험 장치는 ASHRAE의 표준 절차에 따라 액체 가열식 집열기의 열효율을 측정하기 위한 실용적 장치임을 알 수 있다. 일반적으로 ASHRAE 표준 93-77은 합리적인 절차라고 할 수 있다. 그러나, 최소일사량 규정(즉, 630W/m² 미만이 되어서는 안된다고 하는 ASHRAE 규정) 같은 것은 일사량이 적은 기후 조건하에서는 다소 하향 조정하여도 정확한 효율 곡선을 얻을 수 있다고 하겠다.

Nomenclature

A : Transparent frontal area for a flat-plate collector, m²
C_p : Specific heat of the transfer fluid, J/kg-°C
F_R : Collector heat removal factor, defined by Eq. (2)
I : Total solar irradiation incident upon the aperture plane of collector, W/m²
$K_{\alpha\tau}$: Incident angle modifier, defined by Eq. (7)
$\dot{m}$: Mass flow rate of the transfer fluid, kg/s
q_u : Rate of useful energy extraction from the collector, W
T_a : Ambient air temperature, °C
$T_{f,e}$: Temperature of the transfer fluid leaving the collector, °C
$T_{f,e,\mathrm{initial}}$: Temperature of water leaving the collector at the beginning of a specified time period, °C
$T_{f,e,t}$: Temperature of water leaving the collector at a specified time, °C
$T_{f,i}$: Temperature of the transfer fluid entering the collector, °C
T_p : Average temperature of the absorbing surface for a flat plate collector, °C
U_L : Solar Collector heat transfer loss coefficient, W/m²-°C

---

* Member, Korea Advanced Institute of Science and Technology
** Member, Samcheok Technical College
*** Member, Korea Advanced Institute of Science and Technology

$(\tau\alpha)_e$: Effective transmittance absorptance factor, dimensionless

$(\tau\alpha)_{e,n}$: Effective transmittance at normal incidence, dimensionless

η : Solar collector efficiency, defined by Eq. (4)

1. Introduction

The use of solar energy for space heating, cooling, and supplying domestic hot water to residential building has been increasing at a considerable rate since the oil-shock has brought the public awareness of the limit of conventional fossil fuel. This trend has produced a number of new solar collectors of different designs, each claiming high efficiency and potentially signigicant fuel savings if used. The rapid rise in the number of new solar collectors appearing on the market requires some form of unified approach to specifying efficiency that will make possible the comparison between various models. In order that tests on different solar collectors conducted at different times shall be comparable, it is necessary that the test define the governing equation of the collector and the test should be conducted according to the same procedure using a standard test loop.

A review of solar collector test methods reveals that there has been a considerable effort by previous investigators [1-6] to develop a standard test procedure to determine the thermal performance of solar collectors:

A proposal for testing and rating solar collectors based on thermal performance was first made by the U.S. National Bureau of Standards (NBS) in 1974 [1-3]. The procedure prescribed that a series of outdoor steady-state tests be conducted to determine the near-normal-incidence efficiency of the collector over a range of temperature conditions. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) subsequently developed a modified version of the NBS procedure which was adopted in February, 1977, as ASHRAE Standard 93~77 [5]. This standard is similar to the NBS procedure but calls for additional tests to determine the collector time constant as well as an incident angle correction factor that can be applied to the near-normal-incidence efficiency to determine collector performance both early in the morning and late in the day [5]. Reference [2] gives a comprehensive review of testing procedures both proposed and used throughout the world.

In the present work an effort has been made, first, to build a test apparatus in accordance with AHSRAE Standard 93-77 for water-heating collectors and a series of tests have been conducted [7, 8] to re-evaluate the ASHRAE Standard test procedure for solar collectors in a manner similar to the NBS effort [6]. As a result of eliminating some impractical areas of the test loop recommended by the ASHRAE [5] and introducing some modifications to the existing designs [5] a modified configuration of the Standard Test Loop for the liquid-heating solar collector has evolved.

The purpose of this paper is to present the outline of the modified test loop of the Korea Advanced Institute of Science and Technology (KAIST) along with engineering drawings and specifications of main components that are required to build the modified test loop.

In addition, the results of the three primary tests in the standard test procedure [5], the time constant, near-normal-incidence efficiency, and incident angle modifier tests, that are conducted outside under real sun conditions using the KAIST test loop, are presented in graphical form.

2. Governing Equations of Solar Collector Efficiency

For a given collector its thermal performance varies depending upon many parameters, such as operating temperature, liquid flow rate, solar insolation, orientation, tilt, time of day, wind conditions, outdoor temperature and clearness of the local sky, etc. [3]. A brief summary of equations that govern the thermal efficiency of solar collectors is included here for completeness in discussion. It has been shown by previous investigators that the performance of a flat-plate solar collector operating under steady-state conditions can be described by the following relationship [3, 5]:

$$\begin{aligned}\frac{q_u}{A} &= I(\tau\alpha)_e - U_L(T_p - T_a)\\ &= \frac{\dot{m}C_p}{A}(T_{f,e} - T_{f,i}) \qquad (1)\end{aligned}$$

where q_u, A, I etc. are as defined in the nomenclature. To assist in obtaining detailed information about the performance of flat plate collectors and to preclude the necessity for determining the average temperature of the receiver surface (T_p), it has been convenient to introduce a parameter F_R defined by

$$F_R = \frac{\text{(actual useful energy collected by a flat plate collector)}}{\text{(useful energy collected if the entire flat plate collector surface were at the inlet fluid temperature)}} \qquad (2)$$

The parameter F_R is sometimes called as the collector heat removal factor [9]. Introducing this factor into Eq. (1) results in

$$\begin{aligned}\frac{q_u}{A} &= F_R[I(\tau\alpha)_e - U_L(T_{f,i} - T_a)]\\ &= \frac{\dot{m}C_p}{A}(T_{f,e} - T_{f,i}) \qquad (3)\end{aligned}$$

If the solar collector efficiency is defined as

$$\begin{aligned}\eta &= \frac{\text{(actual useful energy collected)}}{\text{(Solar energy incident upon or intercepted by the collector)}}\\ &= \frac{q_u/A}{I} \qquad (4)\end{aligned}$$

then the efficiency of the flat-plate collector is given by [5]:

$$\begin{aligned}\eta &= F_R(\tau\alpha)_e - F_R U_L \frac{(T_{f,i} - T_a)}{I}\\ &= \frac{\dot{m}C_p(T_{f,e} - T_{f,i})}{AI} \qquad (5)\end{aligned}$$

Eq. (5) indicates that if the efficiency is plotted against $(T_{f,i} - T_a)/I$, a straight line will result where the slope is equal to $F_R U_L$ and the y-intercept is equal to $F_R(\tau\alpha)_e$. In reality, U_L is not a constant but rather a function of the temperature of the collector and of the ambient weather conditions. In addition, the product $(\tau\alpha)_e$ varies with the incident angle between the solar radiation and the collector [3, 5].

The collector test procedures developed by the NBS and ASHRAE [3, 5] are, in effect, the result of the effort to control the test conditions so that a well defined efficiency "curve" can be obtained with a minimum of scatter. All the test loops designed by previous investigators [1-6] are an integral part of the test procedure and they are all designed to measure, at least, the mass flow rate of the transfer fluid ($\dot{m}$), the difference in fluid temperature between the inlet and outlet of the collector ($T_{f,e} - T_{f,i}$), and the insolation (I) all simultaneously and under steady-state conditions.

3. Outline of the Modified Test Loop Design

The main factors that have been taken into consideration in the modified test loop design are:

First, build the test loop such that both the inlet temperature of the water ($T_{f,i}$) and the water flow rate ($\dot{m}$) can easily be controlled to a constant level and kept for at least 20 minutes with a minimum effort. Second, make it possible to measure all the critical data such as the rate of incident solar radiation on to the collector (I) as well as the rate of energy addition to the water as it passes through the collector, simultaneously and all under steady state conditions.

A representative testing configuration for liquid-heating solar collectors recommended by ASHRAE [5] is shown in Fig. 1 to compare with the modified test loop designed by KAIST group shown in Fig. 2. Major differences between the two test loops are as follows:

(1) The test loop specified in the ASHRAE Standard [5] has only one storage tank, whereas the present system contains two storage tanks connected in series. The Purpose of connecting two storage tanks in series is to damp out thermal transients and to keep the inlet temperature of the collector at a constant level for sufficiently long time (for about 20 minutes).

(2) In Fig. 1, the electric heater is located between the circulating pump and the flow meter. This configuration was not practical to maintain a constant inlet temperature of the collector. Therefore, removable electric heaters are installed inside storage tanks as shown in Fig. 2. In addition, a bypass line is added from the collector inlet to the

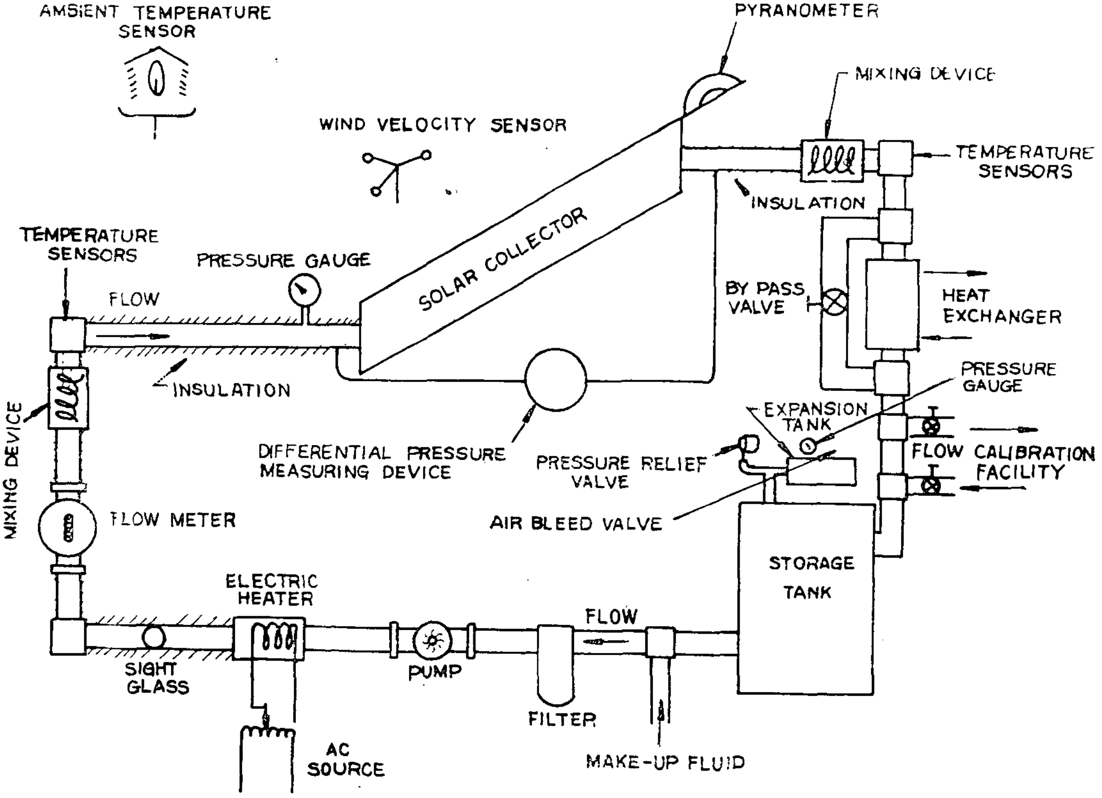

Fig. 1 Closed-loop testing configuration for a solar collector when the transfer fluid is a liquid (ASHRAE).

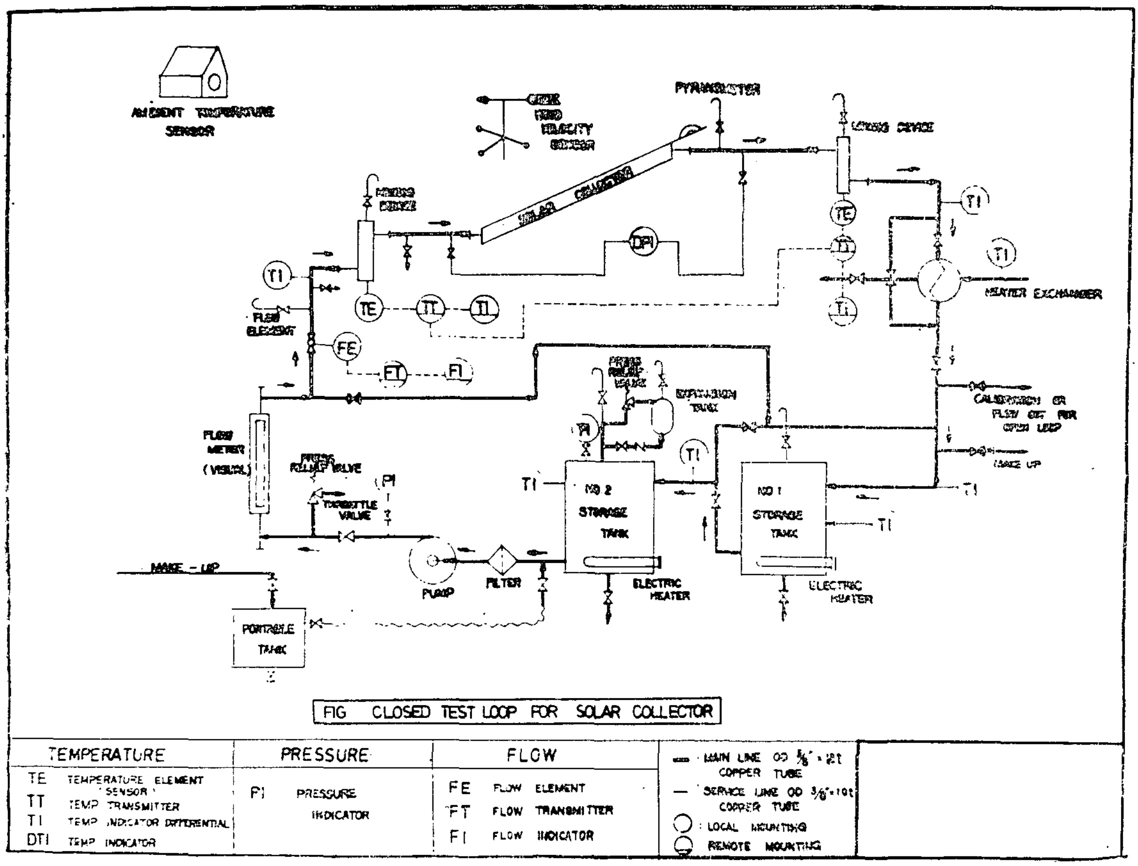

Fig. 2 Schematic diagram of KAIST test stand for liquid-heating solar collectors.

collector outlet in order to reduce the temperature difference between the top and the bottom of the storage tank. This bypass line also permits periodic calibration of the flow meter in place.

(3) Temperature sensors are also added on both inlet and outlet of the tube sides and the shell sides of the heat exchanger as shown in Fig. 2.

Other than the differences noted above, both test loops shown in Figs. 1 and 2 are closed loops similar in principle and design. Main components of the KAIST test loop such as heat exchanger, storage tanks, and expansion tanks, in particular, are all fabricated at KAIST machine shop according to the engineering drawings prepared by present workers to meet technical specifications of each component.

As shown in Fig. 3, the KAIST test loop consists of an integral test stand capable of supporting a typical flat-plate collector at a chosen orientation while containing the flow loop within the test house. The tested collector can be adjusted over a wide range of tilt angles (0~90°) and orientations (0~360°) and easily mounted to or removed from the support structure. The whole test stand is located on the flat roof-top of KAIST building to run experiments under real sun conditions.

An isometric view of the test loop is shown in Fig. 4. Engineering drawings (i.e., a plan view and a front view) for piping arrange-

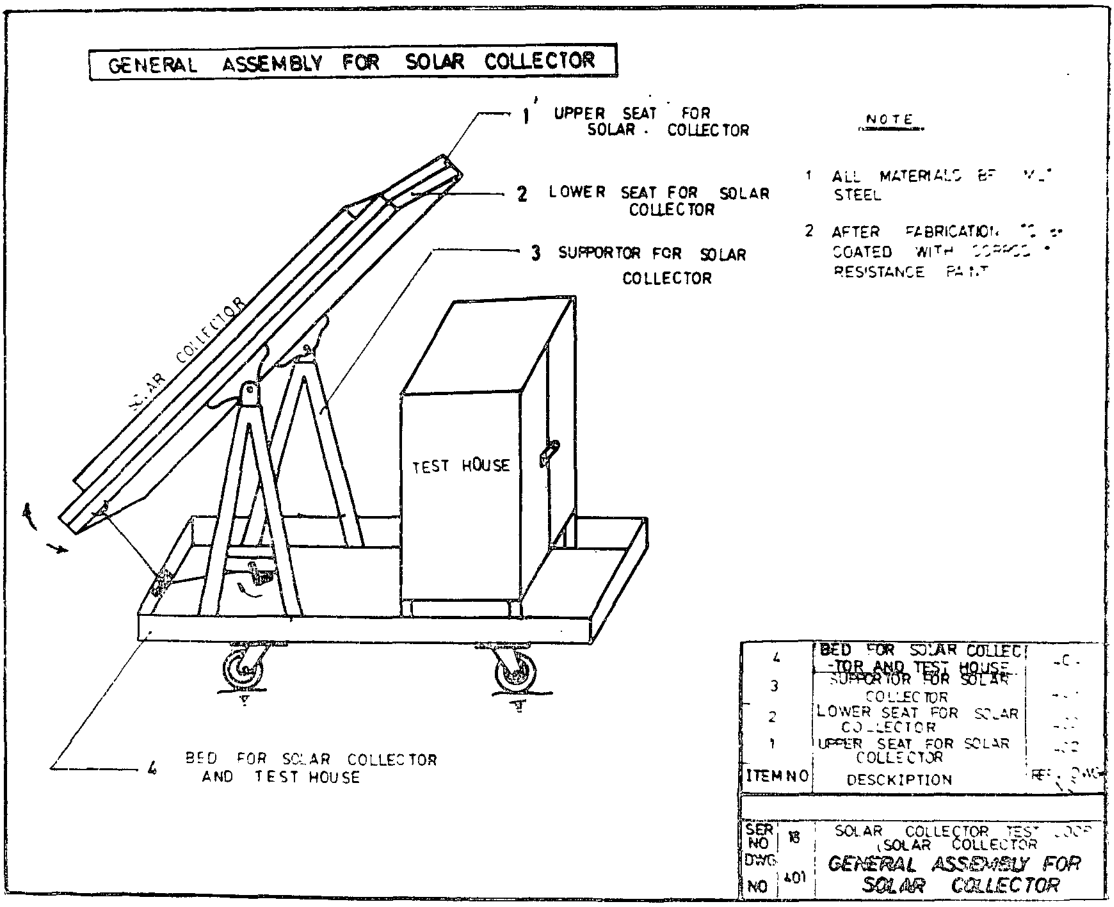

Fig. 3 General assembly view of KAIST test stand for liquid-heating solar collectors.

Table 1 Specifications for the equipment and sensors used in the KAIST test loop.

Equipment/Sensor	Specification
1. Water-to-water heat exchanger	Single-pass counter-flow shell and tube type heat exchanger; effective heat transfer surface area=0.323m^2, tube O.D.=0.95cm, tube length=30cm, no. of tubes=36, tube material=copper.
2. No. 1 storage tank	Volume=0.0389m^3 (dia.=30cm, height=55cm) 0.5KW immersion heater=2, material=s.s.
3. No. 2 storage tank	Volume=0.0529m^3 (dia.=35cm, height=55cm) 0.5KW immersion heater=2, material=s.s.
4. Expansion tank	Volume=0.0035m^3 (dia.=15cm, height=20cm) material=s.s.
5. Pressure relief valve	Pressure setting=2.1kg$_f$/cm^2 (30psi)
6. Filter	5-micron particulate fluid filter.
7. Pump	Max. 30l/min. (when head=12m), power 125W

8. Flow meter	Brooks instrument model No. 1110-08H2G/A; 0-9.65*l*/min (0-2.55GPM), accuracy=±2% of the reading.
9. Pyranometer	Eppley radiometer model PSP; develop an emf of 8.43×10^{-6} volts/watt-m^2, response time=1sec., temperature dependance=±1% over ambient temperature range −20 to +40°C.
10. Temperature	1) A 304 s.s. sheathed chromel-alumel quick disconnect thermocouple assembly (model No:. OMEGA CASS-18U-12) 2) Visual thermometer; mercury-in-glass thermometer, accuracy=±0.5°C.
11. Strip chart	HP model 7100B; 2pen-multi-range input span, accuracy=±0.2% of full scale, response time=0.5 sec. for full scale
12. Digital multimeter	1) HP model 3465A; accuracy=±0.03% of reading, sample rate=2.5 readings per sec. 2) HP model 3435A; response time=1.6 sec. to within 3 digits of final value on one range, accuracy=±0.1% of reading +2 digits. (up to 200mV range).

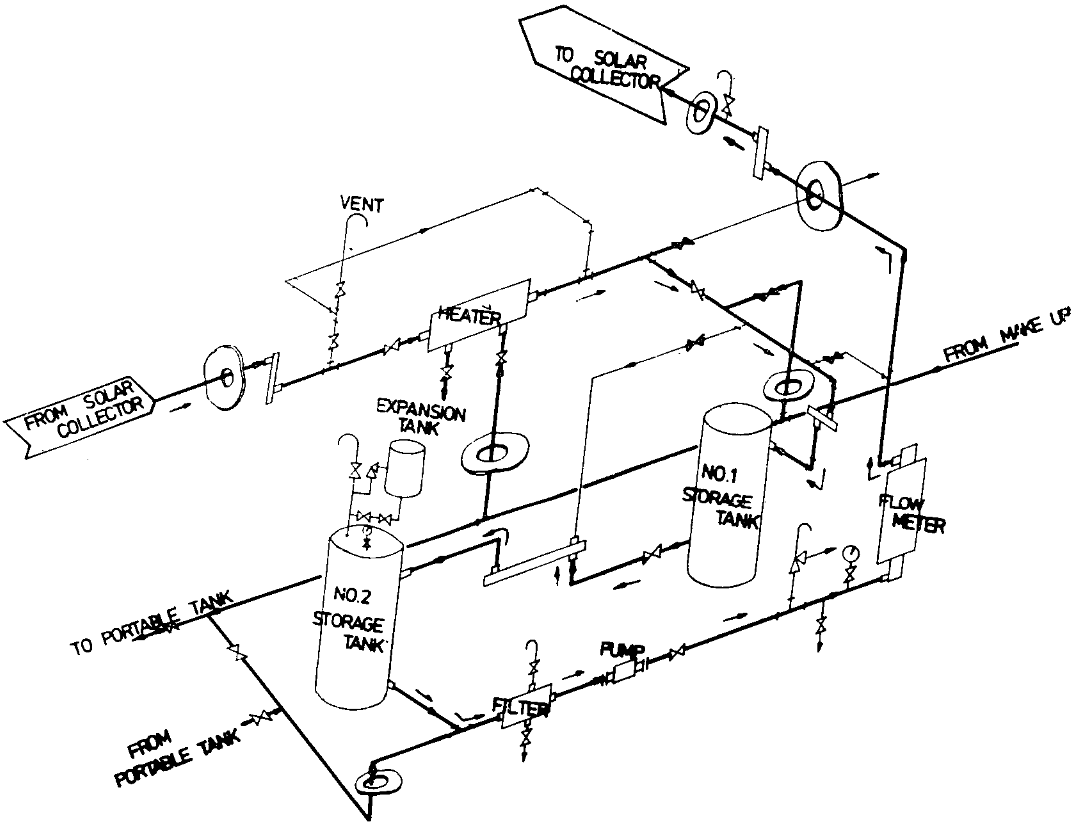

Fig. 4 Isometric view of the test loop inside the test house.

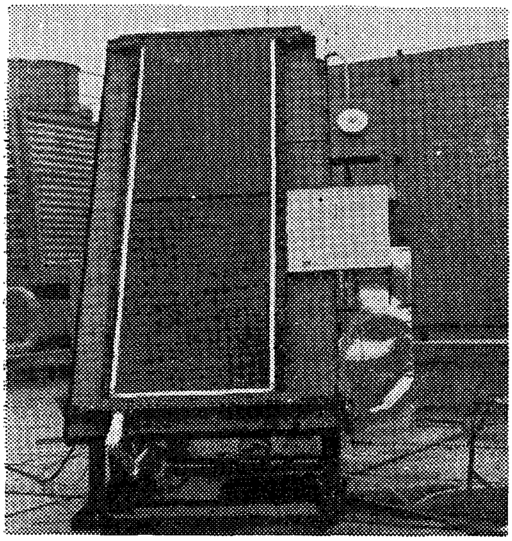

Photo 1 Test stand for liquid-heating solar collector at KAIST.

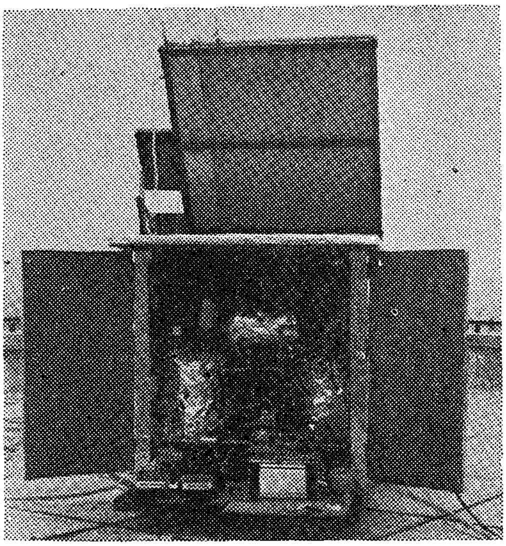

Photo 2 Test stand for collector as seen from the rear.

ment can be found in Ref. 8. Design drawings of main components such as the heat exchanger, storage tanks, and mixing devices for thermocouple can also be found in Ref. 8. The specifications for the main equipments and sensors are summarized in Table 1.

A close-up of the test loop with a flat-plate collector mounted to the top of the support frame is shown in photo 1. Photo 2 shows the loop from the back and, as can be seen, all equipment is enclosed within the housing and is insulated to minimize heat loss and to sufficiently protect from the environment.

4. Testing Procedure, Experimental Results and Discussion

A series of tests have been conducted to examine the performance of the modified test loop of KAIST following the general testing procedure of ASHRAE Standard 93-77 [5]. The Standard [5] calls for the determination of the thermal efficiency of the solar collector by obtaining values of instantaneous efficiency for a combination of values of incident insolaion, ambient temperature, and inlet fluid temperature. This requires experimentally measuring the rate of incident solar radiation onto the solar collector as well as the rate of energy addition to the transfer fluid as it passes through the collector, all under steady state or quasi-steady state conditions. In addition, it is required to perform tests to determine the time response characteristics of the collector as well as how its steady state thermal efficiency varies with the incident angle between the direct irradiation and the collector.

4. 1. Experimental Determination of Collector Time Constant

The first performance test to be conducted on the solar collector is the determination of its "time constant". The method for conducting this test is given in Ref. [5]. Following is the outline of the method used in the present work: The initial temperature of the water, $T_{f,i}$, is adjusted to within ±1°C of the ambient temperature while circulating the water through the collector at the flow rate of 2.92lpm (0.02kg/s-m^2, which is a recommended value of ASHRAE) and maintaining steady-state conditions with an incident solar flux of greater than 740W/m^2 (ASHRAE recommends I to be greater than 790W/m^2). The incident solar energy is then abruptly reduced to zero by shielding the collector from the sun by shading with a white opaque cover suspended above the collector. The temperature of the water at the inlet, $T_{f,i}$, and outlet, $T_{f,e}$ are continuously monitored as a function of time. The "time constant" is finally obtained by determining the time required for [5]:

$$\frac{T_{f,e,t}-T_{f,i}}{T_{f,e,\text{initial}}-T_{f,i}}=0.368 \qquad (6)$$

where $T_{f,e,t}$ and $T_{f,e,\text{initial}}$ are as defined in the nomenclature.

The above procedure is repeated three times and the average value is taken as the time constant. The time constants of the solar collector No. 1 and No. 2 listed in table 2 are found to be around 67 and 108 seconds respectively. According to the NBS report [6] the time constants of the solar collectors No. 3 and No. 4 listed in table 2 are 102 and 108 seconds. The time constant of the solar collector No. 1 seems to be rather smaller than others. However, the time constants of collectors No. 1 and No. 2 measured in the present work using the KAIST test loop seem to be reasonable values when they are compared with the time constants of the solar collectors No. 3 and No. 4 which are obtained by NBS [6] for slightly different collectors.

Table 2 Description of solar collectors tested at KAIST and at NBS [6].

Collector No.	Heat transfer fluid and flow rate (kg/s-m^2)	Aperture area(m^2)	Gross collector area(m^2)	Absorber	Glazing	Absorber tube	Remarks
1	Water: 0.02 and 0.04	2.25	2.43	Black nichrome selective surface ($\alpha \geq 0.93$, $\varepsilon \leq 0.11$)	Single-glass	Copper	Made by domestic manufacturer
2	Water: 0.0136	2.88	2.93	Black silicon coating ($\alpha \geq 0.92$, $\varepsilon \leq 0.08$)	Single-glass	Copper	〃
3	Water: 0.032	1.61	1.68	Aluminum roll-bond, black paint	Double-glass	Copper	Tested by NBS(Ref. 6)
4	Water: 0.0353	1.79	1.96	Steel, black-chrome selective surface	Single-glass	Copper	〃

4.2. Experimental Determination of the Collector Thermal Efficiency

ASHRAE Standard [5] recommends that at least 16 "steady-state" efficiency values should be obtained over a range of temperature differences between collector fluid and ambient air in order to draw an "efficiency curve" for the collector. The results of the efficiency tests for solar collectors No. 1 and No. 2 are shown in Fig. 5 along with the efficiency curves of solar collectors No. 3 and No. 4 reported by NBS [6] in order to make a qualitative comparison. All data were taken ±1 hour symmetrical with solar noon. Test data are obtained over the entire range of $(T_{f,i}-T_a)/I$ values primarily by changing the inlet temperature of the collector, $T_{f,i}$, and the range of the integrated average irradiation measured in the plane of the collector is between 300W/m^2 and 800W/m^2 as shown in Fig. 5 (ASHRAE recommends that this value should not be less than 630W/m^2).

The time interval over which the experimental data are collected and integrated is at least 5 minutes. All data are taken while the incident angle is close to zero (ASHRAE recommends that the orientation of the collector should be such that the incident angle measured from the normal to the collector surface should be less than 30°, during the period in which test data is being taken).

To examine the effect of water flow rate through the collector on the thermal efficiency, data are taken for two different levels of flow rate for the solar collector No. 1 (i.e., equivalent flow rates of 0.02kg/s-m^2 and 0.04kg/s-m^2). It can be observed from the efficiency curves of the collector No. 1 shown in Fig. 5 that increased flow rate raises collector efficiency for operational conditions of lower $(T_{f,i} - T_a)/I$ values. These efficiency values are based on the collector aperture area given in Table 2.

In order to examine the reliability and the capability of the modified test loop of KAIST, it is desirable to test solar collectors whose thermal efficiencies are already known. However, it was not possible for present authors to obtain a solar collector whose thermal efficiency curve is available. Therefore, the reliability of the KAIST test loop is examined indirectly and qualitatively: As shown in Fig. 5, thermal efficiency test results of the solar collectors No. 1 and No. 2 are compared with the results of NBS test [6]. Major characteristics of the solar collectors No. 1, No. 2, No. 3, and No. 4 are shown in Table 2. It can be seen from Fig. 5 that the general trend of the efficiency curves of the present work are in good agreement with the NBS results.

In addition, in order to examine the reproducibility of the thermal efficiency curves, the steady-state efficiency tests are repeated many times under the same conditions as shown in Fig. 5, and the result shows that the efficiency curve is reproducible for a given flow rate through the collector.

It may be inferred from these tests that the accuracy to which the efficiency can be determined is limited mainly by the accuracy to which the independent variables I, $\dot{m}$, C_p, and $(T_{f,i} - T_a)$ can be measured.

4.3. Experimental Determination of Collector Incident Angle Modifier

The significance of the incident angle modifier to the test procedure is that the thermal efficiency values are determined for the collector at or near normal incidence conditions. Therefore, the y-intercept of the "efficiency curve", such as Fig. 5, is equal to $F_R(\tau\alpha)_{e,n}$ (this factor denotes the effective transmittance absorptance factor at normal incidence).

ASHRAE Standard [5] recommends that four separate efficiency values should be determined under test conditions such that the average incident angles between the collector and the solar radiation for the four test conditions should be respectively, approximately 0, 30, 45 and 60 degrees.

For each data point, the inlet temperature of the water is controlled to within ±1°C of the ambient air temperature. In this case, it can be shown that the relationship between the incident angle modifier, $k_{\alpha\tau}$, and the efficiency is given by [5]:

$$k_{\alpha\tau} = \frac{\eta}{F_R(\tau\alpha)_{e,n}} \tag{7}$$

where $F_R(\tau\alpha)_{e,n}$ is obtained as the intercept of the efficiency curve (Fig. 5). Different values of $k_{a\tau}$ can be computed for the different incident angles using Eq. (7). In this way, the incident angle modifier are determined for a wide range of incident angles. The results are shown in Fig. 6 for the collector No. 1 and it is compared with the test results of the NBS [6] for collectors No. 3 and No. 4 listed in Table 2.

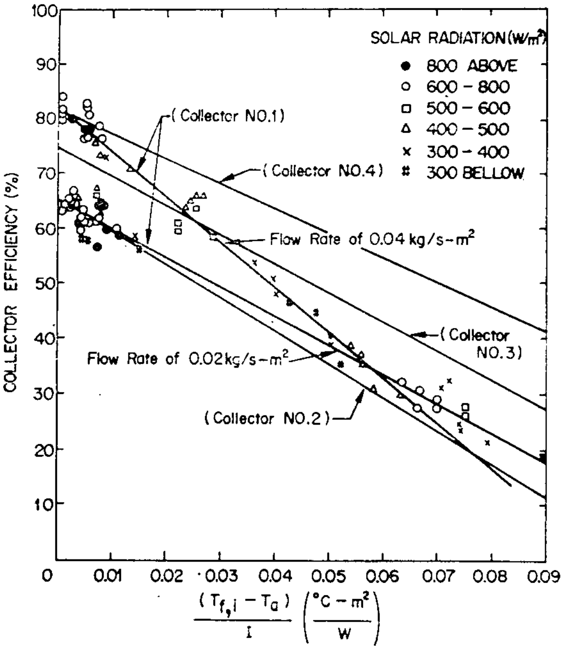

Fig. 5 Experimental results of the near-normal incidence effciency test for water-heating solar collector.

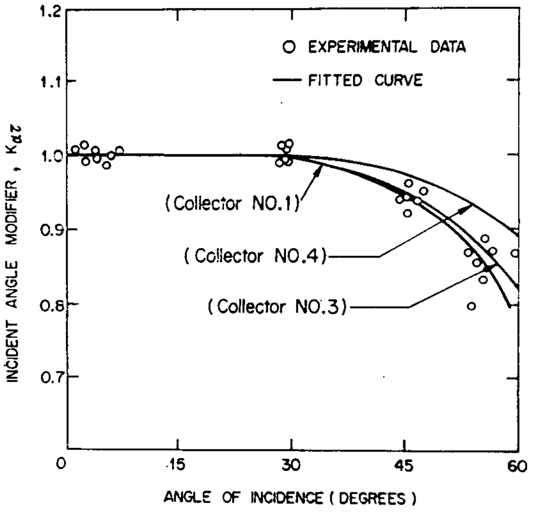

Fig. 6 Incident angle modifier test for liquid-heating solar collector.

It can be observed from Fig. 6 that the incident angle modifier ($k_{a\tau}$) begins to decrease when the angle of incidence reaches somewhere around 30°. This shows that at below 30°, the effect of the angle of incidence on thermal efficiency of the collector is negligible. This conclusion agrees with implications of the ASHRAE Standard [5] which states that for tests conducted to determine thermal efficiency at near-normal incident conditions, the orientation of the collector shall be such that the incident-angle (measured from the normal to the collector surface or aperture) is less than 30° during the period in which test data is being taken.

Also, it can be observed from Fig. 6 that the general shape of the "incident angle modifier" versus "angle of incidence" curve obtained in the present work (for collector No. 1) agrees very closely with that of the NBS results (for collectors No. 3 and No. 4)

5. Summary and Conclusion

The outline of the modified test loop of KAIST based on ASHRAE Standard has been presented along with engineering drawings and specifications of main components of the test loop for liquid-heating solar collectors. Also, a summary of experimental procedure used to examine the modified test loop and to re-evaluate the ASHRAE Standard test procedure has been given. The three primary tests in the ASHRAE Standard, the time constant, near-normal-incidence efficiency, and incident angle modifier test are conducted outside under real sun conditions using the KAIST test loop and results of these tests are presented in graphical form.

Based on the test results of this study and a qualitative comparison with the results of the NBS [6], following conclusions may be made: The modified test loop of KAIST design proved to be a practical apparatus in order to determine thermal efficiency of the liquid-heating solar collectors in accordance with the ASHRAE procedure. In general, the ASHRAE Standard 93-77 proved to be a reasonable procedure. However, some of the rigorous restrictions of the standard, such as the weather conditions that specifies the minimum integrated average irradiation values (not to be less than 630W/m^2) to conduct outdoor tests to determine efficiency and incident angle modifier can be further lowered under different weather conditions.

Acknowledgement

This study was part of a research program funded by the Korea Science and Engineering Foundation.

References

1. J.E. Hill and T. Kusuda, "Methods of Testing for Rating Solar Collector Based on Thermal Performance," NBSIR 74-635, Dec. 1974.
2. J.E. Hill, E.R. Streed, G.E. Kelly, J.C. Geist, and T. Kusuda, "Development of Proposed Standards for Testing Solar Collectors and Thermal Storage Devices," NBS Technical Notes 899, Feb. 1976.
3. J.E. Hill and E.R. Streed, "A Method of Testing for Rating Solar Collectors Based on Thermal Performance," Solar Energy, Vol. 18, No. 5, 1976.
4. H. Tabor, "Testing of Solar Collectors," Solar Energy, Vol. 20, 1978.
5. "Methods of Testing to Determine the Thermal Performance of Solar Collectors," ASHRAE Standard 93-77, ASHRAE, 345 East 47th Street, New York, New York, 10017, 1977.
6. J.E. Hill, J.P. Jenkins,, and D.E. Jones, "Experimental Verification of a Standard Test Procedure for Solar Collectors," Center for Building Technology, National Bureau of Standards, Washington, D.C., Jan. 1979.
7. K.C. Cha, "A Study on the Method of Testing Thermal Performance of Flat Plate Liquid Type Solar Collectors According to the ASHRAE Standard," M.S. Thesis, Dept. of Mechanical Science, Korea Advanced Institute of Science and Technology, Feb. 1982.
8. S.B. Han, "A Study on the Design and Standardization of the Testing-Loop for the Flat-Plate-Liquid-Type Solar Collectors," M.S. Thesis, Dept. of Mechanical Engineering, Dankook University, 1982.
9. J.A. Duffie and W.A. Beckman, "Solar Energy Thermal Processes," Wiley, New York, 1974.