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DEVELOPMENT OF GENERAL-PURPOSE ENERGY SYSTEM ANALYSIS SIMULATOR "ENERGY FLOW +M"—STATIC ANALYSIS OF SOLAR COLLECTOR

Takahiro Nakano[1*], Kiyoshi Saito[1]

[1]*School of Fundamental Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan*

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ABSTRACT

To solve current environmental problems such as global warming and declination of fossil fuels, use of less energy is essential, particularly in the fields of refrigeration and air conditioning. Thus, simulations using complex mathematical models become vital. Simulation technology faces a major challenge because the language of simulation codes varies depending on the programmer. Thereafter, others cannot duplicate the same simulation technology used by their predecessors. To address this, a modular analysis method that generalizes simulation code has been developed. With this method, the general-purpose software analyzing energy system called "ENERGY FLOW +M," a software enabling analyses that can be conducted without having to specify the model or the method of analysis used, has also been created.

The focus of this study was on the solar collector. As the solar collector uses energy from the sun, it is friendly to the global environment. In order to understand the performance of the solar collector, the construction of a simulation model was carried out. Moreover, models of the solar collector and solar radiation were loaded into "ENERGY FLOW +M" to verify their performance. Thus, this simulator allows us to execute simulations of the solar collector from anywhere via the Internet.

Keywords: ENERGY FLOW +M; Modular analysis method; Simulation; Solar collector; Solar radiation

1. INTRODUCTION

Recently, various environmental problems such as global warming and declination of fossil fuels have led to the inevitable conclusion that energy use, particularly in the fields of refrigeration and air conditioning must be reduced. Grasping system performance only by experiments, however, is no easy task. With that, pursuance of simulations using complex mathematical models is suggested.

While operating the simulation, the language of the simulation codes may not be unified if we depend entirely on the discretions of respective programmers. Accordingly, others cannot duplicate the same simulation technology used by their predecessors. This is the biggest problem in simulation technology. A modular analysis method that generalizes simulation codes has been developed to solve this issue. The adequacy of this method has already been confirmed with the compression type refrigerator and the absorption refrigerator.

* Corresponding author's email: t.nakano@asagi.waseda.jp, Tel. +81-3-52863259 Fax. +81-3-52863259

By means of this method, the general-purpose software analyzing energy system called "ENERGY FLOW +M" has been tailored. This software would allow more people to carry out different analyses of a variety of energy systems. As part of the research already described, in this study, models of the solar collector and solar radiation were loaded into "ENERGY FLOW +M" to assess its analytical capacity.

2. ENERGY FLOW +M

2.1. Modular analysis method

The modular analysis method permits the calculation of the whole energy system by connecting each element of the system. These elements are constructed by mathematical models. As a result, each module can be based on mathematical models. Additionally, each module has input and output ports. We calculate the system performance by connecting these ports.

The compression type refrigerator (Figure1) was chosen to provide an example of the calculation of an energy system. First, the output is found by calculating under respective input conditions in each module, be it an evaporator, compressor, etc. Next, input and output between adjacent elements are compared. Calculations are repeated by changing input values, until it fulfills a particular convergence condition. The notable feature of this method is that the system flow or components can be changed easily by simply changing connections, resulting in an expression of individual modules. In parallel, new energy system calculations are possible just by adding the new modules. Therefore, this method can also be applied to analyze large-scale energy systems.

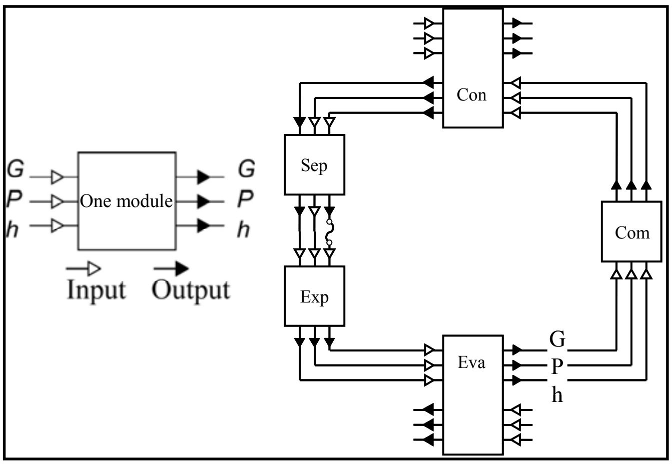

Figure 1 Thermal fluid network graph

2.2. Energy flow +M

The general-purpose simulator analyzing energy system "ENERGY FLOW +M" was developed using the modular analysis method. In this simulator, we can analyze energy systems by connecting input ports to output ports of respective components. This software enables us to analyze simply without having to consider the model or method of analysis used. The formation of this simulator is displayed in Figure 2. This simulator consists of five parts: the data input, calculation control, system calculation, element calculation and data output. Each part is assembled independently so that parts can be altered readily.

The characteristic feature of this simulator is that the energy system can be analyzed merely by using Graphical User Interface (GUI) on the Internet. An image of GUI is shown in Figure 3. This way, "ENERGY FLOW +M" can be readily accessible to anyone who wishes to analyze an energy system.

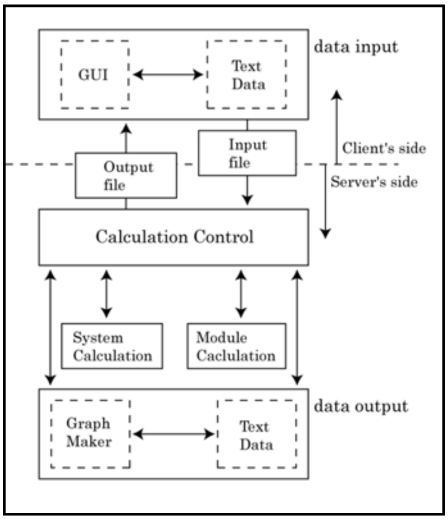

Figure 2 Formation of EF+M

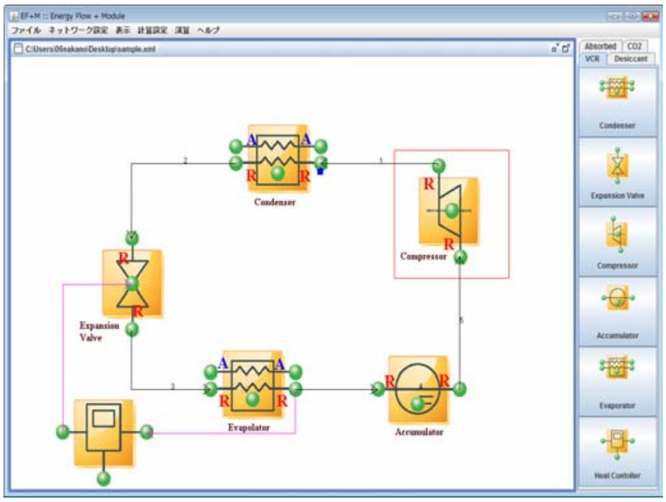

Figure 3 Image of GUI

3. SOLAR COLLECTOR

3.1. View of solar collector

A solar collector is a device that transfers energy to water and air by using solar energy. Hence, it is very friendly to the earth because does not exhaust environmental pollutants. Examples of existing solar collectors include SOLAR-COLLECTOR-SUPER-BLUE-PANEL(YAZAKI Group, Japan), CPC-SOLAR-MAX(EASTEN TECHNICS, Japan), CPC-VACUME-TYPE-SOLAR-COLLECTOR(LINUO PARADIGMA, German). The features of these solar collectors are as follows.

- SOLAR-COLLECTOR-SUPER-BLUE-PANEL

  It employs a transparent V-channel insulation which reduces heat loss that is convectively generated, and also possesses a unique selective absorber surface for high collection efficiency.
- CPC-SOLAR-MAX

  By covering the fluid conduit with a compound parabolic reflector, it provides for a wider range of angles to receive light which substantially raises the light gathering efficiency.
- CPC-VACUME-TYPE-SOLAR-COLLECTOR

  In addition to the compound parabolic reflector, it has made the fluid conduit into a two layered evacuated glass tube. As a result, it not only has a high light gathering efficiency but also good thermal insulation, which is why it is a highly efficiency solar collector.

Pictures of these solar collectors are shown in Figure 4.

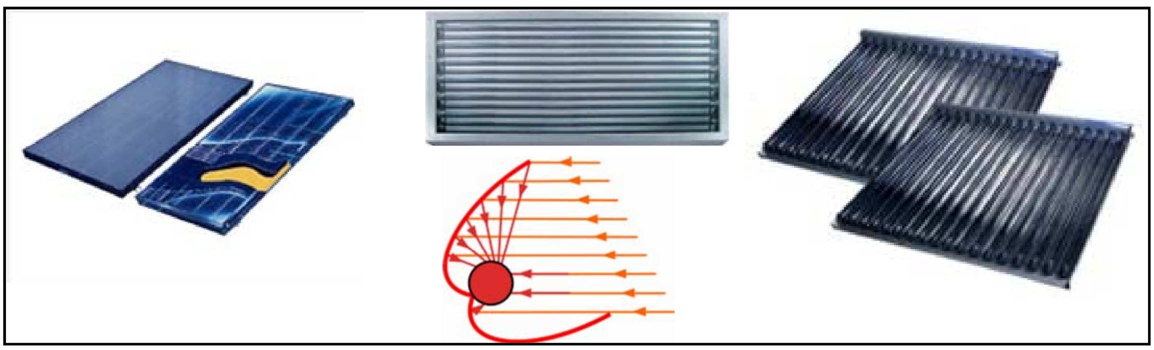

Figure 4 Solar collectors
(Left: YAZAKI Group, Middle: EASTEN TECHNICS, Right: LINUO PARADIGMA)

With the first step in analyzing solar collectors, the present study paid close attention to the flat plate solar collector, which is relatively simple compared to the others. Generally speaking, the flat plate type has one or two covers. This research concentrated on two covers which ensure higher efficiency. The solar collector consists of six parts: outlet cover, inner cover, black absorber plate, insulation, fluid conduit, and collector box. Figure 5 depicts a diagrammatic illustration.

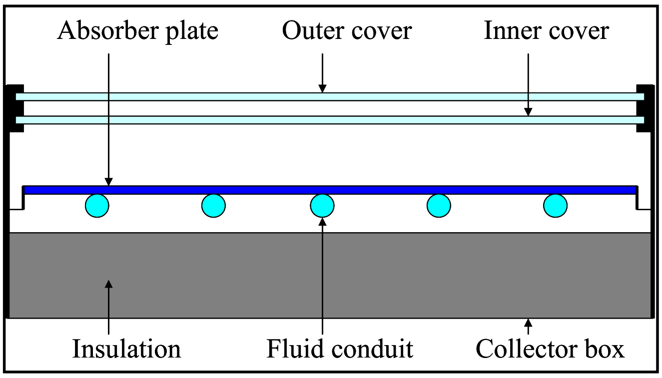

Figure 5 Flat plate solar collector

3.2. Simulation model

Next, we constructed the solar collector simulation model based on the flat plate solar collector in Figure 5. To construct the model, the assumptions are as follows.

- Steady state is achieved.
- Intratubular pressure drop is neglected.
- Fluid flow is one-dimensional.

Next, equations are exhibited. Note that Nomenclature for all equations is provided in Section 7 of this paper. The thermal network is shown below in Figure 6 and distribution of internal flow is shown in Figure 7.

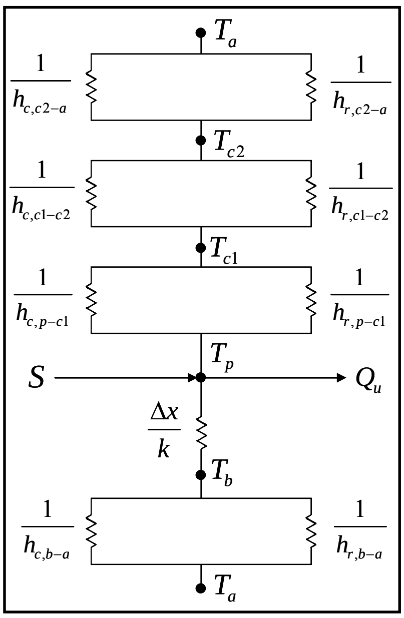

Figure 6 Thermal network

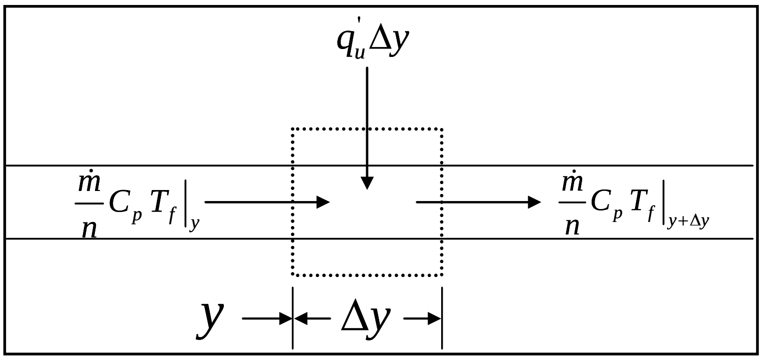

Figure 7 Distribution of internal flow

The energy balance equation is as below:

$$Q_u = A_c\left[S - U_L\left(T_{pm} - T_a\right)\right] \tag{1}$$

Absorbed solar radiation is,

$$S = G_{atm}\left(\tau\alpha\right)_e \tag{2}$$

Collector's overall heat loss coefficient is the sum of each heat loss coefficient, as shown in the equation:

$$U_L = U_t + U_b + U_e \tag{3}$$

Convection heat transfer coefficient is,

$$h_c = \frac{K}{L} Nu \tag{4}$$

And, radiation heat transfer coefficient is,

$$h_r = \frac{\sigma(T_1 + T_2)(T_1^2 + T_2^2)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1} \tag{5}$$

Absorber plate between tubes acts as a fin. Additionally, when considering heat conductance between tube and fluid, the energy obtained by tubes and fin per unit length is,

$$q_u' = WF'\left[S - U_L\left(T_f - T_a\right)\right] \tag{6}$$

Next, internal flow is brought into focus. Bearing in mind the model as illustrated in Figure 7, the energy balance per Δy length for one tube would be,

$$\frac{\dot{m}}{n} C_p \frac{dT_f}{dy} - q_u' = 0 \tag{7}$$

On the other hand, the energy actually obtained is the heat removal factor multiplied by the maximum useable energy.

$$Q_u = A_c F_R\left[S - U_L\left(T_{fi} - T_a\right)\right] \tag{8}$$

Thereby, the mean temperature of absorber plate is,

$$T_{pm} = T_{fi} + \frac{Q_u / A_c}{F_R U_L}\left(1 - F_R\right) \tag{9}$$

Lastly, each factor is denoted. Fin efficiency factor is,

$$F = \frac{\tanh\left[m(W - D)/2\right]}{m(W - D)2} \tag{10}$$

$$m = \sqrt{\frac{U_L}{k\delta}} \tag{11}$$

Collector efficiency factor is,

$$F' = \frac{1/U_L}{W\left\{1/U_L\left[D + (W - D)F\right]\right\} + 1/C_b + 1/\pi D h_{fi}} \tag{12}$$

Collector heat removal factor is,

$$F_R = \frac{\dot{m}C_p\left(T_{fo} - T_{fi}\right)}{A_c\left[S - U_L\left(T_{fi} - T_a\right)\right]} \tag{13}$$

4. SOLAR RADIATION

4.1. View of solar radiation

Solar radiation is the energy from the sun. Understanding solar radiation is imperative to analyzing solar collectors. Solar radiation is affected by time, longitude, latitude, and season. For this reason, it is necessary to calculate with high accuracy and precision.

4.2. Simulation model

In this section, the relationship between the sun and an observation point are discussed. A relationship such as that shown in Figure 8 is presumed. Assumptions regarding the construction of the simulation model are as follows;

- Diffused radiation and ground-reflected radiation is neglected.
- Amount of time direct sunshine is received per hour is one or zero.

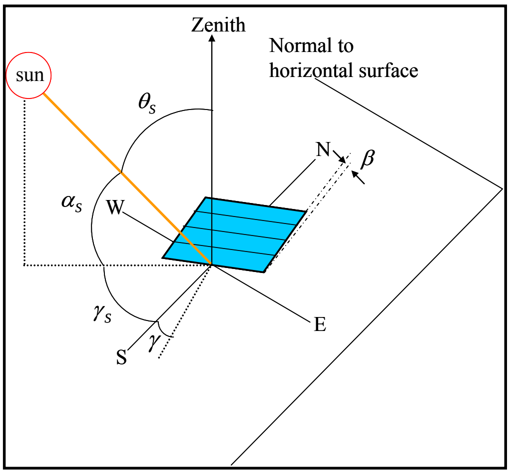

Figure 8 Relationship between the sun and a surface

Equations are referenced below. (Nomenclature is explained in Section 7) First the effect of the Earth's position on nth day per year has to be considered. From there, extraterrestrial radiation is expressed as,

$$G_{on} = G_{sc}\left(1.000110 + 0.034332\cos B + 0.001280\sin B + 0.000719\cos 2B + 0.000077\sin 2B\right) \tag{14}$$

In this regard, B of nth day is expressed as,

$$B = (n-1)\frac{360}{365} \tag{15}$$

Next, impact of longitude is considered. Apparent Solar time is,

$$\text{Solar time} = 4\left(L_{st} - L_{loc}\right) + E + \text{Standard time} \tag{16}$$

Equation of time is as follows.

$$E = \frac{229.2}{60}\left(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B\right) \tag{17}$$

And hour angle is,

$$\omega = 15\left(Solar\_time - 12\right) \tag{18}$$

From these equations, incident angle can be obtained by,

$$\theta = \arccos\begin{pmatrix} \sin\delta\sin\phi\sin\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega \\ +\cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \end{pmatrix} \tag{19}$$

Therefore, extraterrestrial incident radiation to a surface is expressed as,

$$G_o = G_{on}\cos\theta \tag{20}$$

Finally, the atmospheric influence is considered to grasp the actual amount of solar radiation which can be used. Value of available quantity of solar radiation is expressed using correction coefficients. If an hour of direct sunshine per hour is one hour, the radiation is,

$$G_{atm} = G_o\left(0.241 + 0.4280 n_h\right) \tag{21}$$

If an hour of bright sunshine per hour is zero hours, the radiation is,

$$G_{atm} = 0.1410 G_o \tag{22}$$

5. RESULTS AND DISCUSSION

The solar collector was analyzed with "ENERGY FLOW +M." in Tokyo, Japan. The dates on which analyses were carried out were January 1st and August 1st. Weather was fair and cloudy, respectively. Analysis conditions and results are shown in Table 1 and 2.

Table 1 Solar radiation

Parameter	Unit	Condition 1	Condition 2
Date	-	January 1st	August 1st
Longitude	degree	139	139
Latitude	degree	35	35
Hours of bright sunshine	h	1.0 ; 0.0	1.0 ; 0.0
Surface direction	-	South	South

Table 2 Solar collector

Parameter	Unit	Condition 1	Condition 2
Type	-	Flat plate(2covers)	Flat plate(2covers)
Refrigerant	-	Water	Water
Area of the collector	m^2	4	4
Mass flow rate	kg/s	0.05	0.05
Pressure	kPa	101.3	101.3
Temperature (input)	$^oC(K)$	30(303.15)	30(303.15)
Ambient temperature	$^oC(K)$	10(303.15)	25(298.15)

Figure 9 showed that amount of solar radiation and insolation hours were longer in summer than in winter. Figure 10 showed that the efficiency of solar collector was higher in summer than in winter. Especially during cloudy days in winter, lower efficiency was observed. The results for output temperature showed the same trend as that of efficiency. This trend is expressed in Figure 11.

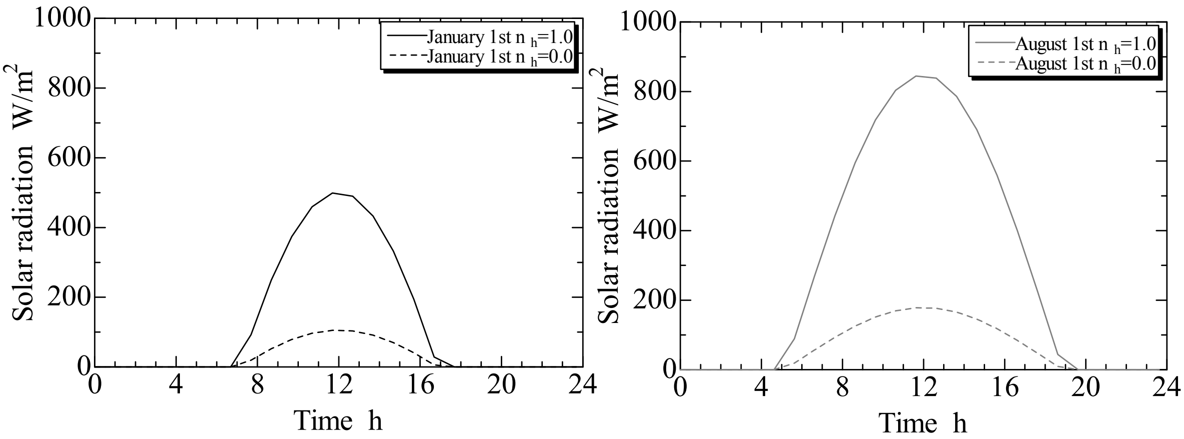

Figure 9 Solar radiation

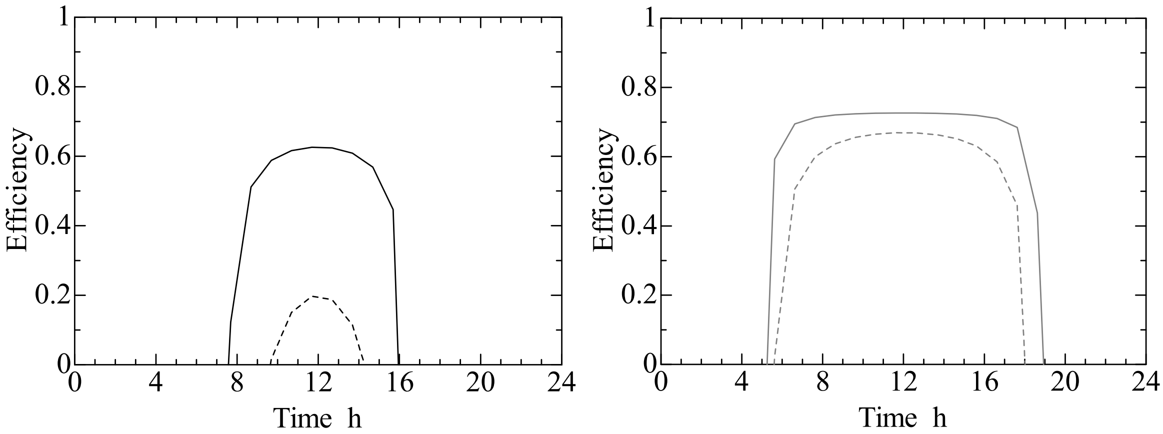

Figure 10 Efficiency of solar collector

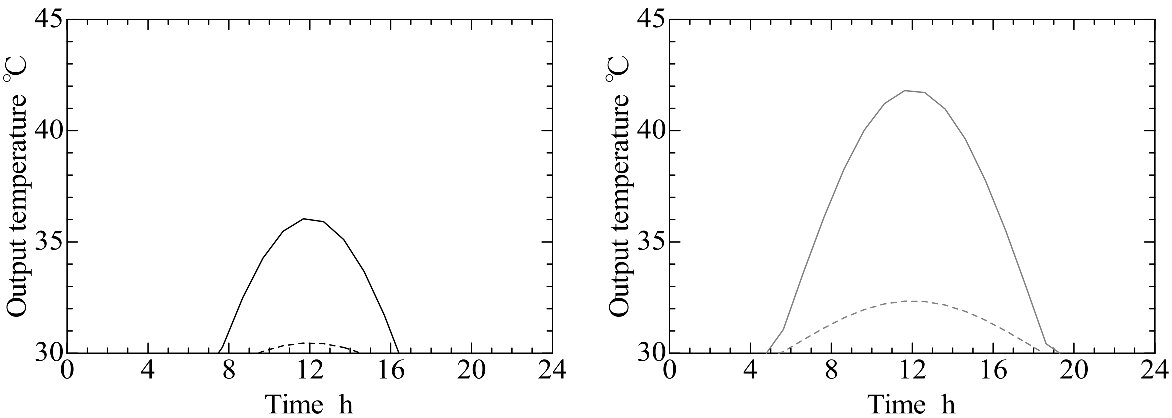

Figure 11 Output temperature of solar collector

As a whole result, it was found that efficiency decreases when there is less solar radiation. Furthermore, it would appear that the range of decline in efficiency with regards to decreased amount of solar radiation is less in summer because the ambient temperature is high during the summers as compared to winters, which reduces heat loss.

6. CONCLUSION

In this study, analysis models of the solar collector and solar radiation were constructed. Additionally, it was proved that these models can be examined on the general-purpose software analyzing energy system "ENERGY FLOW +M" with the modular analysis method. This simulator has previously been opened online. Consequently, using this simulator, anyone can analyze energy systems from across the globe.

7. NOMENCLATURE

Symbol

A	Area	(m^2)
C_b	Bond conductance	($Wm^{-1}K^{-1}$)
C_p	Specific heat	($Jkg^{-1}K^{-1}$)
D	Diameter	(m)
E	Equation of time	(h)
F	Fin efficiency factor	(-)
F'	Collector efficiency factor	(-)
F_R	Collector heat removal factor	(-)
G	Irradiance	(Wm^{-2})
h	Heat transfer coefficient	($Wm^{-2}K^{-1}$)
k	Thermal conductivity	($Wm^{-2}K^{-1}$)
K	Thermal conductivity	($Wm^{-1}K^{-1}$)
L	Longitude, length	(degree)
$\dot{m}$	Flow rate	(kgs^{-1})
n	Day of year, number	(-)
n_h	Hours of bright sunshine per an hour	(h)
Nu	Nusselt number	(-)
Q	Energy	(W)
q'	Energy per length	(Wm^{-1})
S	Absorbed solar radiation	(W)
T	Temperature	(K)
U	Overall heat transfer coefficient	($Wm^{-2}K^{-1}$)
U_L	Collector overall heat loss coefficient	($Wm^{-2}K^{-1}$)
W	Distance between tubes	(m)

Greek Symbol

α	Absorptance	(-)
β	Slope	(degree)
γ	Surface azimuth angle	(degree)
δ	Declination, plate thickness	(degree)
ϕ	Latitude	(degree)
τ	Transmittance	(-)
σ	Stefan-Boltzmann constant	($Wm^{-2}K^{-4}$)
ω	Hour angle	(degree)

Subscripts

a	Air, ambient
atm	Atmosphere
b	Back
c	Collector, cover, convection
e	Edge, effective
f	Fluid
g	Glass
i	Inlet
loc	Local
m	Mean
n	Normal
o	Outlet, extraterrestrial
p	Plate
r	Radiation
sc	Solar constant
st	Standard
t	Top
u	Useful

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