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Solar Energy Collection using a Double-layer Roof

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***Abstract*—**The purpose of this study is to investigate the efficiency of a double-layer roof in collecting solar energy as an application to the areas such as raising high-end temperature of organic Rankine cycle (ORC). The by-product of the solar roof is to reduce building air-conditioning loads. The experimental apparatus are arranged to evaluate the effects of the solar roof in absorbing solar energy. The flow channel is basically formed by an aluminum plate on top of a plywood plate. The geometric configurations in which the effects of absorbing energy is analyzed include: a bare uncovered aluminum plate, a glass-covered aluminum plate, a glass-covered/black-painted aluminum plate, a plate with variable lengths, a flow channel with stuffed material (in an attempt on enhancement of heat conduction), and a flow channel with variable slanted angles. The experimental results show that the efficiency of energy collection varies from 0.6 % to 11 % for the geometric configurations mentioned above. An additional study is carried out using CFD simulation to investigate the effects of fins on the aluminum plate. It shows that due to vastly enhanced heat conduction, the efficiency can reach ~23 % if 50 fins are installed on the aluminum plate. The study shows that a double-layer roof can efficiently absorb solar energy and substantially reduce building air-conditioning loads. On the high end of an organic Rankine cycle, a solar pond is used to replace the warm surface water of the sea as OTEC (ocean thermal energy conversion) is the driving energy for the ORC. The energy collected from the double-layered solar roof can be pumped into the pond and raise the pond temperature as the pond surface area is equivalently increased by nearly one-fourth of the total area of the double-layer solar roof. The effect of raising solar pond temperature is especially prominent if the double-layer solar roofs are installed in a community area.

***Keywords*—**solar energy collection, double-layer solar roof, energy conservation, ORC, OTEC

I. INTRODUCTION

IN heavily industrialized countries like Taiwan, a steady supply of electricity has become an important issue faced by both the government and the industries. Power generated from low-grade energy resources has become an inevitable option for countries like Taiwan. Low-grade heat from renewable energy sources is considered to be a good candidate to generate electricity. Among those sources, a combination of OTEC and solar energy using organic Rankine cycle is a potentially viable measure in converting low-grade heat into power generation and in other applications. Hung et al. [1] analyzed ORC/OTEC systems and they identified working fluids which are suitable for converting the energy of warm surface sea water into power. Unfortunately, the estimated efficiencies are well below ~10 % as the heat source is the surface water of the ocean, shown in Fig. 1.

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They also studied using a solar pond as an alternative for the warm surface sea water; and much higher efficiencies, as shown in Fig. 2, can be achieved if the solar pond supplies a higher water temperature between 40 to 60℃. Therefore, a solar pond with a high water temperate would be an ideal modification to an ORC/OTEC system. The main purpose of this study is to seek an extra energy source to raise the solar pond temperature, e.g., using a solar energy collection device – a double-layer solar roof.

A by-product benefit of the solar roof is reducing radiation heat which might penetrate the building roof; and consequently, reducing building air-conditioning loads. It was estimated [2] that radiation heat which penetrates the roof contributes 30 % of the air-conditioning loads in a normal family in semi-tropic area like Taiwan. The solar energy emitting on the roof is usually 2 to 3 times higher than those on façade and various side walls. If the radiation heat can be insulated from penetrating the roof, the building air-conditioning loads would consequently be reduced dramatically. A double-wall, triple-roof experimental solar house was built in a hot and humid area [3]. The results of monitoring the house for one year have shown that the double-wall, triple-roof designs are effective for insulating and removing heat from the building's envelope.

These heat-insulating and exhausting strategies can maintain the diurnal fluctuation of indoor air temperature to within 2℃ on a typical mid-summer day. In addition, 300 liters of hot water at temperatures of 35–54℃ can be obtained on any sunny day throughout the year, and most of the hot water can be supplied by the integrated solar system. Using double-layer air channels on the envelop of an experimental chamber, Chiu [4] showed that, without any mechanical ventilation device, a naturally-induced air circulation can developed and three-fourths of the radiation heat is blocked from entering the chamber. Khedari et al. [5] used a roof solar collector (RSC), which is made by using concrete roofing tiles on the outside and gypsum board on the inside, to minimize the fraction of the solar flux absorbed by the dwelling (insulation) on one hand; and to induce a natural ventilation which allows thermal comfort on the other hand. They studied the length and tilt angle of the RSC on its performance, and they found the optimum length of the SRC is shorter than 100 cm and the tilt angle is 30^{o}. Huang [6] analyzed the double-layer roof and estimated the buoyancy-driven air flow rate which can be applied to building cooling in a passive mode. Other researches on double-layer solar roof can be found in Refs. 7 – 11. It is conclusive that the idea of using a naturally occurred air flow which carries part of the radiation heat away is a viable and effective measure in building thermal shielding as well as energy collection.

The purpose of the current study is to optimize the double-layer solar roof in terms of the efficiency of carrying away radiation heat in order to reduce building air-conditioning loads and supply an extra energy source of the solar pond for the OTEC/ORC applications.

II. Experimental Setups and Performance Optimization

The basic configuration of a double-layer solar roof, as shown in Fig. 3, is composed of two parallel plates in which air is driven by buoyancy due to absorption of radiation heat. The energy carried away by the air flow is calculated by the following equation:

$$Q = \int_0^t [\dot{m}\ .\ Cp\ .\ (T_{out} - T_{in})dt]$$

where $\dot{m}$ is the air mass flow rate exiting from the top of the channel, c_p is the thermal capacity of the air, T_{in} and T_{out} are the entrance and exit air temperature, respectively, and Q is the total energy collected in the time period of 0 to t. The efficiency of energy collection is defined as the ratio between the collected energy and the incident solar radiation on the top surface of the double-layer solar roof, as expressed as

$$\eta_{th} = \frac{Q_{total}}{Q_{solar}} = \frac{\int_0^t [\dot{m}\ .\ Cp\ .\ (T_{out} - T_{in})dt]}{Q_{solar}}$$

In order to optimize the energy collection of the double-layer roof, a series experiments are carried out to perform a parametric study. The papameters under investigation include: (1) an uncovered alumnium plate, (2) a glass cover of the alumnium plate (in an attempt on reducing energy loss due to forced convection), (3) a black-painted alumnium plate (in an attempt on increasing radiation absorption), (4) a variation on the dimensions of the plates, (5) an introduction of stuffing material (in an attempt on increasing heat conduction of the alumnium plate), and (6) a variation of the slanted angle of the plates.

Case 1 Uncovered alumnium plate

This is the base case for further comparisons in parametric analysis. The experiment is carried out during 11:00 to 14:00 in July. As shown in Fig. 9, the ambient temperature varies from 27.3 to 32.3℃, the air velocity at the channel exit varies from 0.05 to 0.15 m/s, and the air temperature at the exit of the channel varies from 37.3 to 50.7℃. The average solar intensity is 0.713 kW/m^2. The efficiency of energy collection is rather low (0.6%) in Case 1.

Case 2 Glass-covered alumnium plate

In order to reduce force convection, the alumnium plate is covered with a glass plate in case 2 as shown in Fig. 10. The gap between the glass cover and the alumnium plate is 3 mm. As shown in Fig. 11, the ambient temperature varies from 27.3 to 33.5℃, the air velocity at the channel exit varies from 0.1 to 0.2 m/s, and the air temperature at the exit of the channel varies from 37.3 to 45.9℃. The average solar intensity is 0.724 kW/m^2. As compared with the base case, Case 2 does not exhibit a better performance in air exit temperature possibly due to the reflection of sunlight on the glass plate; nevertheless, it performs better in air exit velocity, i.e., the gross energy collection is increased. The efficiencie of energy collection and efficiency ratios based on Case 1 of all cases are listed in Table 1. The efficiency of energy collection is 0.9% for Case 2-- still unsatisfactorily low.

Case 3 Glass-covered and black-painted alumnium

In an attempt on increaseing the absorption of the sunlight, the alumnium plate is coated with a black paint as shown in Fig. 12. As shown in Fig. 13, the ambient temperature varies from 30.7 to 34.9℃, the air velocity at the channel exit varies from 0.30 to 0.45 m/s, and the air temperature at the exit of the channel varies from 70.6 to 78.3℃. The average solar intensity is 0.752 kW/m^2. As compared with the base case, Case 2 exhibits a much better performance both in air exit temperature and air exit temperature due to a much higher value of radiation absorptivity of the black alumnium plate. The efficiency of energy collection raises sharply to 6.5%.

Case 4 Glass-covered and black-painted alumnium plate with a shorter length of channel

The efficiency of energy collection may be a function of the channel length. In Case 4 the length of the channel is shorten to 2.4 m. As shown in Fig. 14, the ambient temperature varies from 27.4 to 32.1℃, the air velocity at the channel exit varies from 0.15 to 0.25 m/s, and the air temperature at the exit of the channel varies from 48.7 to 60.1℃. The average solar intensity is 0.513 kW/m^2. Case 4 does not perform better than Case 3 in air exit temperature and air exit velocity; however, it yields a higher efficiency of energy collection (9.7%) as the solar radiation intensity is much lower than Case 1 and the energy absorption is more efficient near the entrance region of the channel. It also shows that a long double-layer solar roof is not necessary in otder to achieve a high efficiency of energy collection.

Case 5 Glass-covered and black-painted alumnium plate with a shorter length of channel stuffed with heat-conducting material

In an attempy on increasing heat conduction of the alumnium plate to air flow, the channel is stuffed with steel wires (shown in Fig. 15) in Case 5. As shown in Fig. 16, the ambient temperature varies from 27.2 to 33.6℃, the air velocity at the channel exit varies from 0.1 to 0.15 m/s, and the air temperature at the exit of the channel varies from 40.7 to 49.2℃. The average solar intensity is 0.313 kW/m^2. Contrary to what is expected, Case 5 does not perform better than Case 4 as the efficiency of energy collection drops to 5.7% possibly due to a greater pressure drop occurred in the channel and/or a poor contact between the alumnium plate and the steel wires; and consequently, it results in a lower air mass flow rate. This case suggests that heat conduction of the alumnium plate and

TABLE I
EFFICIENCIES OF ENERGY COLLECTION AND RATIOS OF EFFICIENCIES

CASE	EFFICIENCY OF ENERGY COLLECTION（%）	RATIO OF EFFICIENCY BASED ON CASE 1
CASE 1	0.6	1
CASE 2	0.9	1.5
CASE 3	6.5	10.8
CASE 4	9.7	16.2
CASE 5	5.7	9.5
CASE 6	11.0	18.3

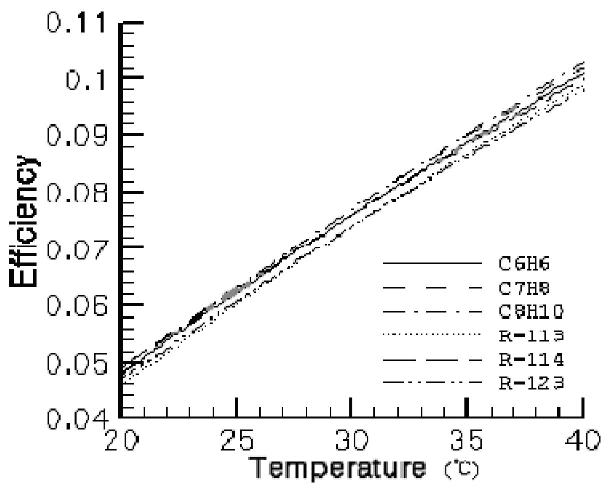

Fig. 1 Efficiency as a function of heat source (Using ocean surface water as the source)

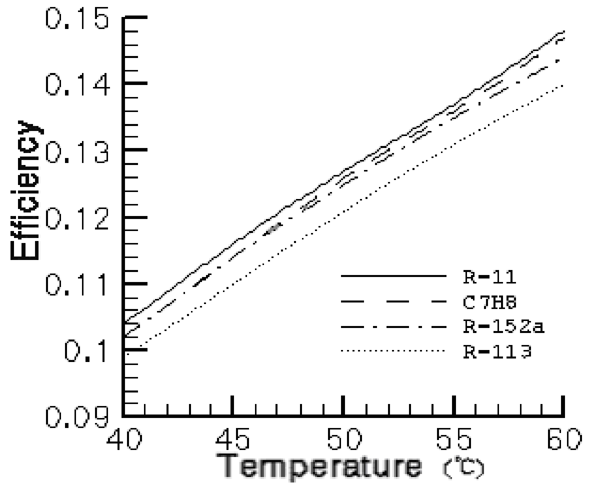

Fig. 2 Efficiency as a function of heat source (using solar pond as the heat source)

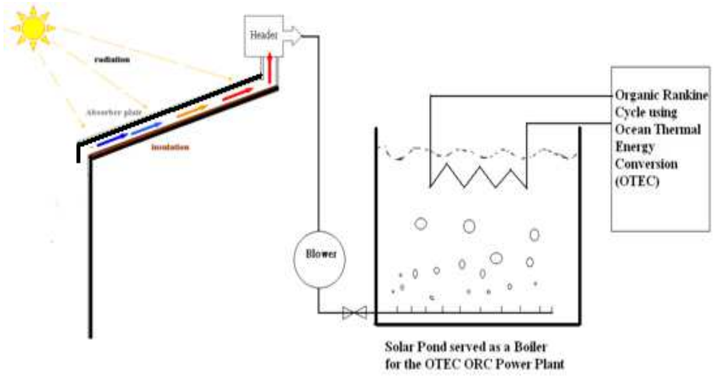

Fig. 3 Schematics depiction of the double-layered solar roof and solar pond system used in OTEC/ORC

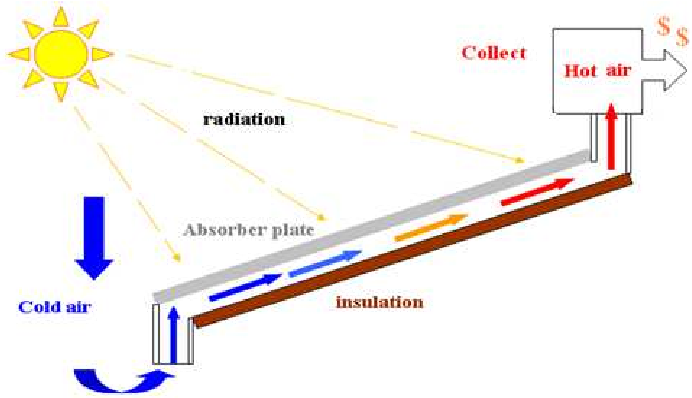

Fig. 4 Schematic depiction of the double-layer solar roof

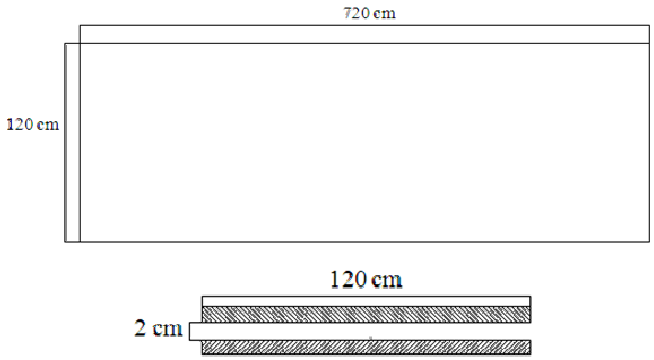

Fig. 5 Double-layer channel

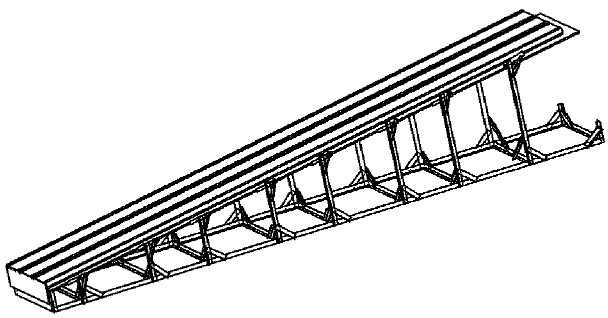

Fig. 6 Schematic depiction of double-layer channel

(a)

(b)

Fig. 7 (a) Bottom wood plate, and (b) Top aluminum plate

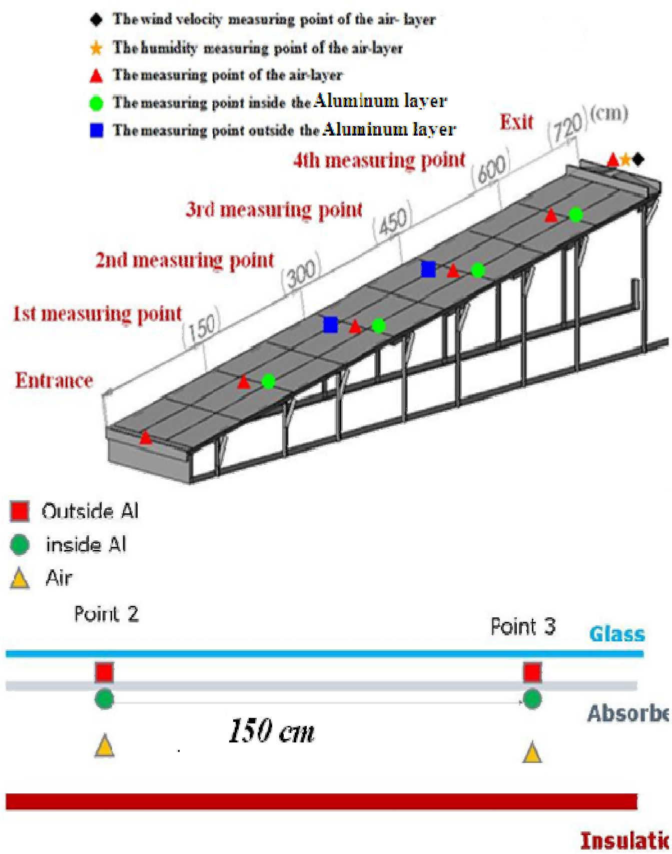

Fig. 8 Locations of measuring points

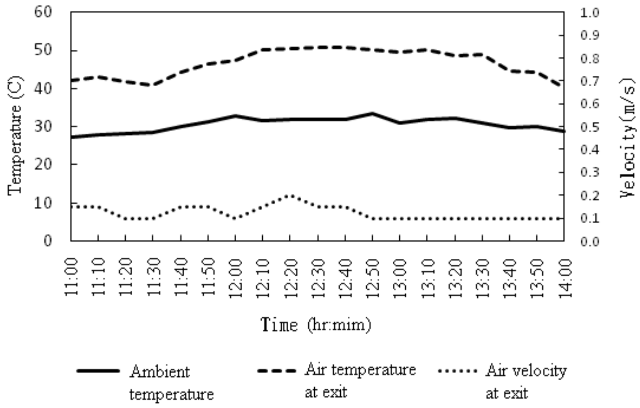

Fig. 9 Ambient temperature, air temperature and velocity at exit for Case 1

Fig. 10 Glass-covered aluminum plate (Case 2)

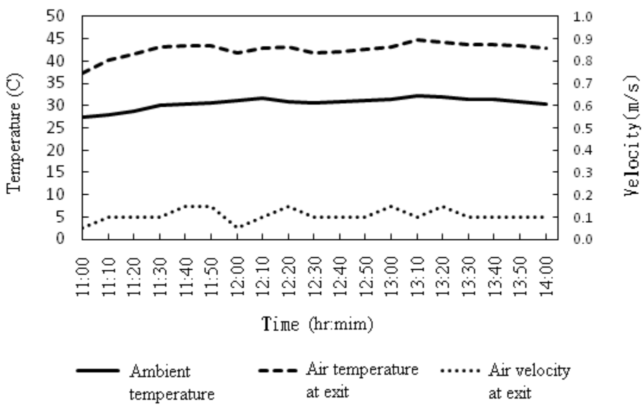

Fig. 11 Ambient temperature, air temperature and velocity at exit for Case 2

Fig. 12 Black-painted aluminum plate (Case 3)

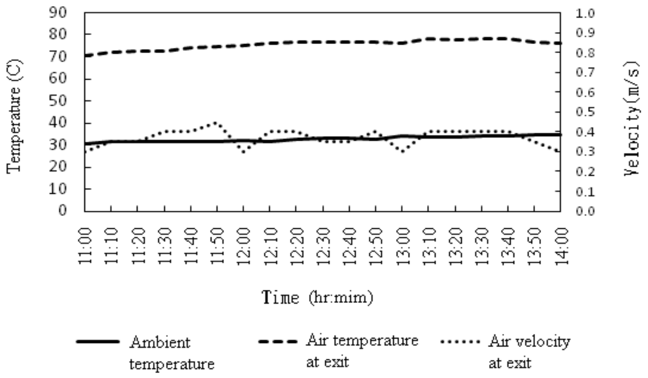

Fig. 13 Ambient temperature, air temperature and velocity at exit for Case 3

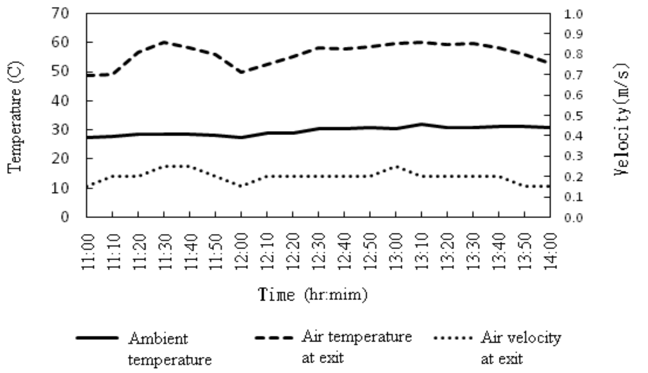

Fig. 14 Ambient temperature, air temperature and velocity at exit for Case 4

Fig. 15 Steel wire-stuffed channel (Case 5)

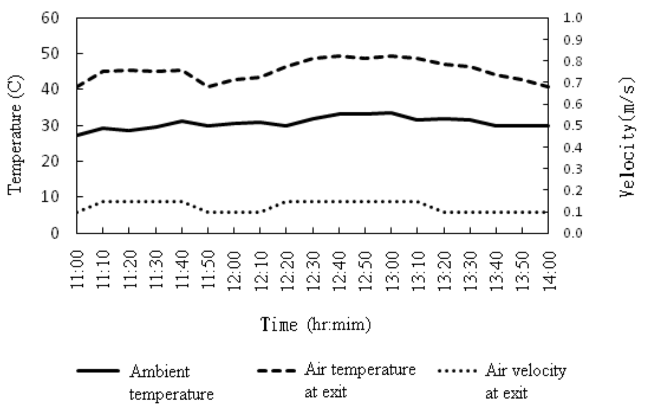

Fig. 16 Ambient temperature, air temperature and velocity at exit for Case 5

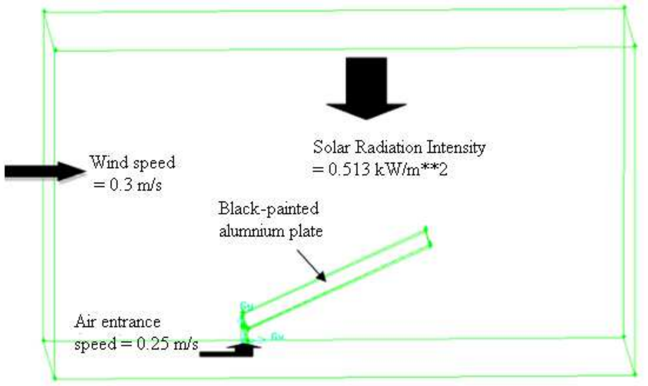

Fig. 17 Geometric simulation of Case 4

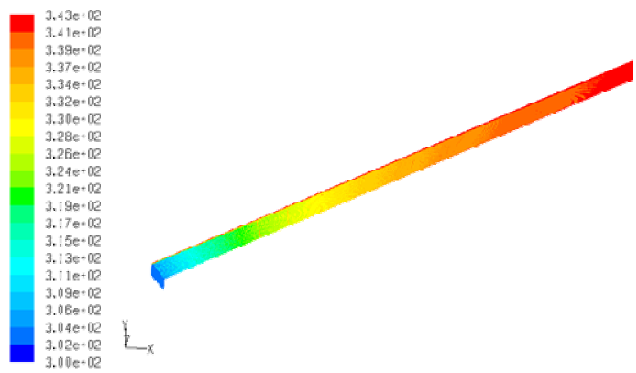

Fig. 18 Numerical simulations of air temperatures in the channel for Case 4

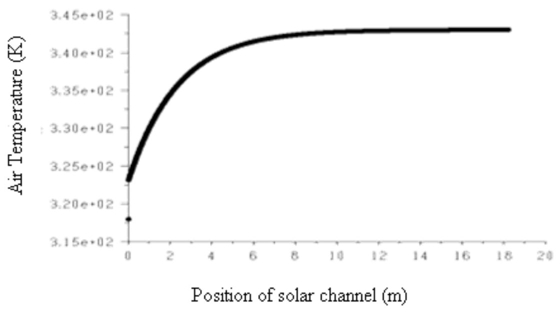

Fig. 19 Numerical predictions of air temperature along the solar channel

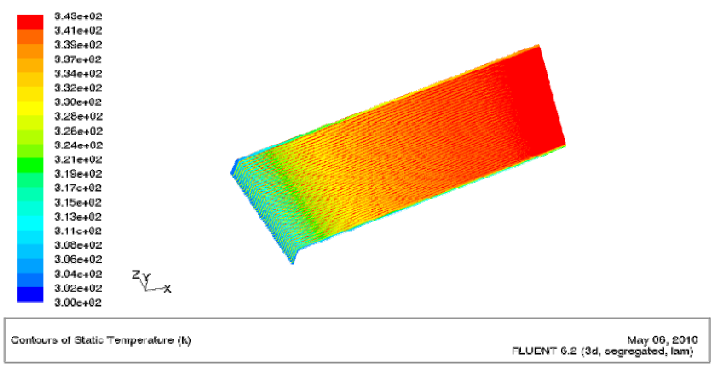

Fig. 20 Numerical prediction of air temperature in the channel for the case of 50 fins

pressure drop of the channel have to be compromised to reach an optimal performance.

Case 6 Glass-covered and black-painted alumnium plate with a shorter length of channel slanted at a shallow angle (23^o)

In an attempt on maximizing the solar radiation intensity, the solar roof is slanted to a less steep angle, i.e., 23^o. As shown in Fig. 14, the ambient temperature varies from 29.3 to 33.6℃, the air velocity at the channel exit varies from 0.2 to 0.3 m/s, and the air temperature at the exit of the channel varies from 49 to 61.8℃. The average solar intensity is 0.562 kW/m^2. As expected, Case 6 yields a higher efficiency of energy collection than Case 4 due to a higher solar radiation intensity. However, an even shallower slant angle would impair air buoyancy; and consequently, reduce air mass flow rate.

The experimental results show that the efficiency varies from 0.6 % to 11 % for the geometric configurations mentioned above. Among all the parameters under consideration, the single parameter which affects and enhances the efficiency of energy collection the most is the solar absorptivity of the aluminum plate, i.e., a black-painted aluminum plate absorbs a much higher amount of solar energy than uncoated plate.

In the light of enhancing heat conduction by introducing stuffed material in the channel, efforts should be emphasized on enhancing heat conduction yet with a tolerable increase of pressure drop. A simple geometric modification which may fulfill both requirements is by installing fins on the aluminum plate. Due to its difficulties in fabrication, the aluminum plate with fins is analyzed using numerical simulations. However, an agreement between experiments and numerical simulations must be verified prior to performing a full-blown simulations of the fins. The next section describes a detailed procedure of the numerical simulations.

III. Numerical Simulations and Prediction of Fin Performance

The numerical simulations are carried out using FLUENT 6.1 [12]. In order to simplify calculations, the air flow in the channel is assumed to be imcompressible, laminar, and in a steady state. The geometry simulation is shown in Fig. 17. The comparison between experiments and numerical simulations is performed for Case 6 in which the alumnium plate is glass-coated, black-painted, the channel has a shorter length of 2.4 m, and the slanted angle is 23^o. The numerical results are shown in Figs. 18 and 19. The predicted air exit temperature at 2.4 m is 56.8℃ while the average measured value is 55.4℃. The favorable agreement in air exit temperature lays a foundation for further numerical simulations of conduction-enhancing fins on the alumnium plate. Figure 19 also shows that the air exit temperature does not increase substantially beyond ~ 6 m, i.e., a solar channel longer than 6 m would not yield a better energy absorption ability. The numerical simulations are performed for cases of various numbers of fins: 1, 3, 5, 10, 20, 40, and 50 fins. A typical prediction of air temperature in the channel is shown in Fig. 20 for the case with 50 fins. The predicted air exit temperature, alumnium plate temperature, and the air mass flow rate at exit are shown in Fig. 21. The efficiency of energy collection can reach 23% for the case with 50 fins. This shows that by adding fins the alumnium plate can conduct a much more amount of heat to the air; and thus, increase the efficiency.

IV. Discussion and Conclusions

A. Total power collection for the solar pond of OTEC/ORC application

Using OTEC as the heat source and heat sink of an organic Rankine cycle has shown its feasibility in generating power. Previous studies carried out by the author showed that the efficiency of an ORC with OTEC is well below ~10% which is unsatisfactorily low for an economic operation. An alternative in this matter is to replace the warm seawater by a solar pond as the heat source of the ORC in an attempt on raising the efficiency. The main conclusion of the current study is that the solar pond temperature can be substantially raised by introducing an extra amount of solar energy into the pond by collecting solar energy from building rooftops using a double-layered roof design. The energy collected in such a fashion will be transferred directly into the pond from the bottom in the form of air bubbles, which hopefully, also cause some turbulence to homogenize pool temperature. The current study shows that the double-layer solar roof can collect ~23% of the total solar radiation incident on the solar roof, i.e., the surface area of the solar pond is virtually increased by nearly a factor of one-fourth of the total area of the solar roof. This is particularly viable and practical if the double-layer solar roofs are installed on building tops of a community area.

B. Reduction of building air-conditioning loads

A windfall of this double-layered roof design is to reduce thermal radiation directly transmitting into the building; and hence, reduce air conditioning loads especially in summer seasons. Based on a normal family house, the electricity consumed for air conditioner is around 30 kW-hr. The utility bill saved due to a 1.2 X 2.4 m^2 double-layer solar roof is around 0.5 $ in Taiwan area.

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