

Fabrication and testing of a Non-Glass Vacuum-Tube Collector for Solar Energy Utilization

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ABSTRACT: An evacuated tubular solar collector was fabricated from acrylics for improved resistance to shattering. A plasmatron was employed to apply a thin gas-barrier coating to the surfaces of the plastic tube to prevent/alleviate gas infiltration. Experiments were conducted to investigate the effect of vacuum level on the performance of the non-glass vacuum-tube solar collector. A finned heat pipe was inserted in the evacuated tube for solar energy collection and heat transfer to a water tank. Time variations of temperatures on the heat pipe surface and in the water tank were recorded and analyzed for different degrees of vacuum in the collector. A comparison between the steady-state temperatures of the non-glass collector and a commercial glass vacuum-tube collector was made to assess the feasibility of the use of evacuated plastic tubes for solar energy collection.

Keywords: non-glass, solar energy collection, vacuum-tube collector, ZnO coating.

1. INTRODUCTION

With the official effectuation of the Kyoto Protocol in 2005, most countries today have to assume the duty of reducing greenhouse gas emissions. This global agreement and recent soaring oil prices have boosted the use of renewable energy for sustainable development. Compared to

other renewable energy, solar energy is very reliable and cost-effective, and there is a long history of solar energy utilization dating back to Greeks' design of solar architecture and ancient solar agricultural applications.

Among the various solar energy applications, solar water heating (SWH) is probably the simplest and most prevalent

method of harnessing the sun's energy. The collector is the key component of a SWH system. Flat-plate collectors were the most common collector design for SWH prior to the arrival of vacuum-tube collectors. Vacuum-tube collectors [1-8] can achieve fairly high temperatures, thus have higher heat transfer rates and work potentials and can be used for solar-cooling and power-generation applications.

Two types of vacuum-tube collectors have been developed for SWH: single-tube and double-tube. The former involves a flat or curved metal stripe attached or soldered to a heat pipe or water pipe in an evacuated glass tube. The latter consists of two concentric cylindrical glass tubes. The inner tube is coated with an absorptive coating. The jacket between the two glass tubes is evacuated to reduce heat loss.

One major drawback of glass-tube collectors is that glass breaks easily. The inherent weakness of glass material makes it expensive to fabricate and ship vacuum-tube solar collectors. To alleviate this problem the authors and a few other researchers (e.g., [6]) have developed non-glass solar collectors for improved shattering resistance. Presented in this paper are preliminary results of the heat transfer experiment of the authors' vacuum-tube collector fabricated from acrylics. The relationship between the vacuum level inside the non-glass tubular collector and the behavior and performance of the collector were investigated.

2. Experimental Apparatus and Procedure

Plastics such as acrylics are highly transparent to solar flux and have much better resistance to shattering than glass. The vacuum-tube solar collector investigated in this paper was composed of an acrylic tube and a finned heat pipe, as shown in Fig. 1. The acrylic tube was selected due to its low price and commercial availability. The tube was 450 mm long, 70 mm in diameter, with a wall thickness of 10

mm. The two ends of the tube were sealed with acrylic caps.

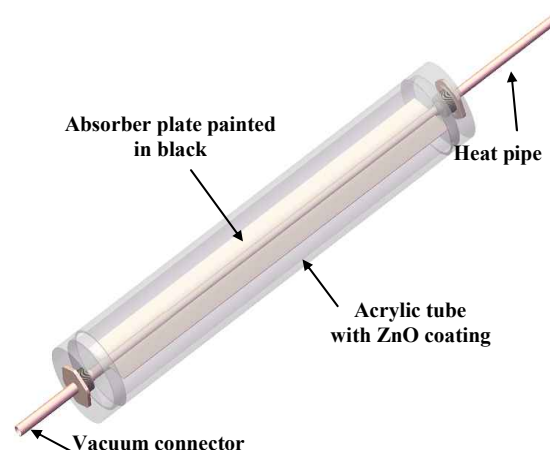


Figure 1: Non-glass solar collector.

The performance of the heat pipe has a profound effect on radiation energy collection and transfer. The heat pipe in the present investigation was made from a thin-walled copper tube, 550 mm long, 8 mm in outer diameter, with ethyl alcohol as the working fluid. A thin copper sheet, 380 mm by 56 mm, was attached to the copper tube to increase the surface area for radiation absorption as depicted in Fig. 2. The surface of the absorber plate and the copper tube surface facing the radiation source were painted with a black coating by ThurmaloX.

The cold end of the heat pipe protruded out of the top plastic cap and was immersed in an insulated water tank. A vacuum connector was connected to the bottom of the tubular collector for evacuating gases in the collector.

The hurdles and difficulties to overcome when plastic tubes are used for solar energy collection were discussed in [9]. Unlike glass and quartz that are perfectly airtight, air infiltration takes place through tiny pores in plastics. The infiltration rate depends on the texture and thickness of the plastics and the pressure difference. In addition, gases initially contained in plastics may be released when the ambient pressure drops considerably. These effects make it difficult

to maintain a high degree of vacuum in a plastic tube.

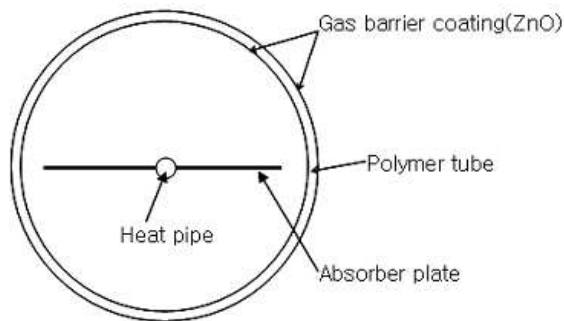


Figure 2: Cross-sectional view of the tubular collector.



Figure 3: ZnO coating on the acrylic tube surface using a plasmatron.

Two remedies were tried in the present investigation to alleviate air infiltration and release of contained gases. The first method is to spray the surfaces of the acrylic tube with a gas-barrier coating to prevent or slow down gas leakage into the evacuated tube. Shown in Fig. 3 is the setup for coating a thin layer of ZnO on the acrylic tube surface using a plasmatron. The change in transmittance to solar flux due to the ZnO coating can be seen in Figs. 4 and 5. The bare acrylic tube has a transmittance almost identical to that of glass. The coated tube has a slightly lower transmittance due to the radiation absorbed by the ZnO coating.

The second method of maintaining a high degree of vacuum in the acrylic tube was to connect the tube to a header-type

vacuum chamber (see Fig. 6) equipped with pressure monitoring and controlling devices and a vacuum pump.

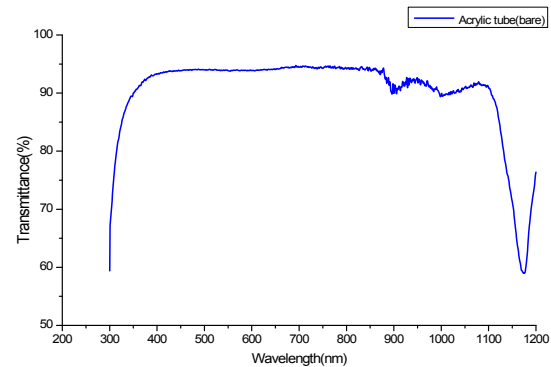


Figure 4: Transmittance of a bare acrylic tube.

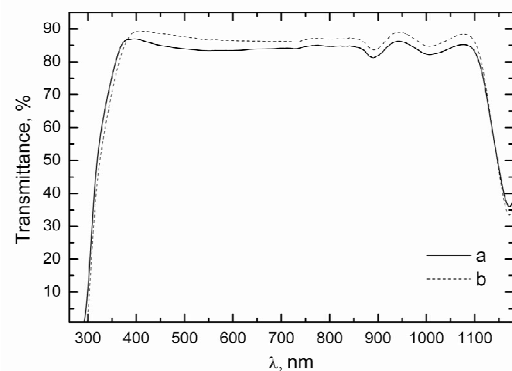


Figure 5: Transmittances of the acrylic tube with ZnO coating. (a) at 1 atm; (b) at 0.01 torr.

The pressure inside the acrylic tube was monitored by a vacuum gauge. A solenoid valve and a pressure controller turned on and off a vacuum pump connected to the exhaust line to maintain the desired degree of vacuum in the tube. LabVIEW was used to save and analyze the experimental data in a real-time mode.

A solar simulator consisting of 20 halogen lamps (maximum power = 75 W each) was used in our experiments to generate a heat flux of 800 W/m^2 on the absorber plate with a mean error of $\pm 25 \text{ W/m}^2$. Four K-type thermocouples were attached to the back of the absorber plate, and the fifth thermocouple was placed in the gap between the back of the absorber plate and the acrylic

tube, as shown in Fig. 7. A data acquisition system by AGIIENT was used for temperature measurements. Temperature variations were measured over a 10-hour period for two levels of vacuum, 0.01 and 5 torr, in the tube.

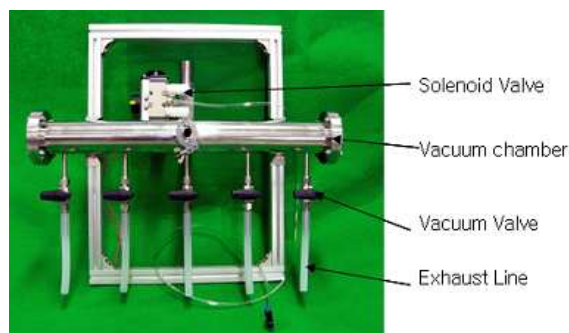


Figure 6: Header-type vacuum chamber.

Due to the inexpensive vacuum chamber we built and the air infiltration and gas-releasing problems, the highest vacuum level our experimental apparatus can reach was about 0.01 torr. During the experiment at 0.01 torr the vacuum level was closely monitored, and intermittent outgassing was needed to keep the pressure in the tube close to 0.01 torr. The vacuum chamber was ventilated after 8 hours or less of operation to remove gases accumulated in the chamber.

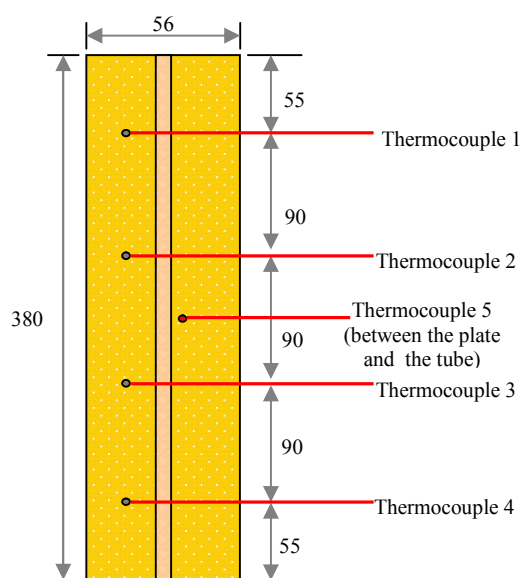


Figure 7: Locations of thermocouples. (distances are in mm)

3. RESULTS AND DISCUSSION

Listed in Table 1 are the initial and final temperatures of the absorber plate and the air in the evacuated tube. Plotted in Figs. 8 and 9 are the time variations of these temperatures over an 8-hour period. As can be seen in these 2 figures, it took about 2 hours for the temperatures of the collector to reach an equilibrium state. In these experiments the cold end of the heat pipe was insulated. The surrounding temperatures were about the same. Thus the reduction in heat loss when the vacuum level changed from 5 to 0.01 torr was very small.

Table I : Initial and final temperatures of the non-glass vacuum-tube collector.

	0.01 torr		5 torr	
	Initial temperature [°C]	Final temperature [°C]	Initial temperature [°C]	Final temperature [°C]
TC 1	27.3	99.1	22.8	95.0
TC 2	27.3	101.4	22.2	98.2
TC 3	27.3	96.7	20.3	100.0
TC 4	27.4	102	21.3	97.7
TC 5	27.4	55.0	19.5	53.1
Average of plate temp.	27.3	99.8	21.7	97.7

The equivalent thermal circuit of the solar collector with the cold end of the heat pipe inserted in a water tank is shown in Fig. 10. The thermal resistance of the heat pipe is generally small in comparison with the resistances between the heat pipe and the surroundings. The resistance associated with heat conduction through the top plastic cap is independent of the gas volume inside the evacuated tube. As the aspect ratio of the gas volume increases, the major heat loss paths are expected to be natural convection and radiation from the heat pipe surface to the surroundings. The vacuum level in the tube has little effect on the radiation resistance since the gas layer in the tube is too thin to significantly attenuate

radiation. Reduction in tube pressure affects only natural convection inside the tube.

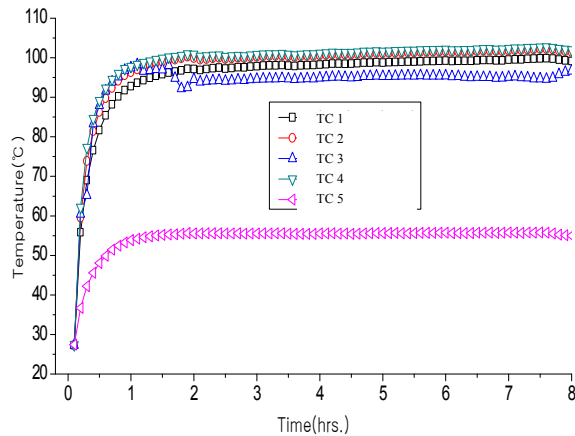


Figure 8: Temperature variations in the experiment at 0.01 torr.

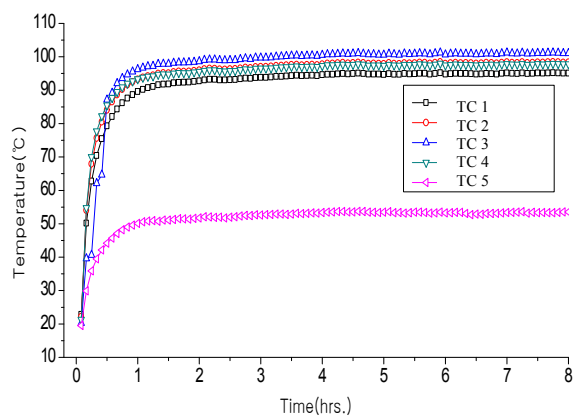


Figure 9: Temperature variations in the experiment at 5 torr.

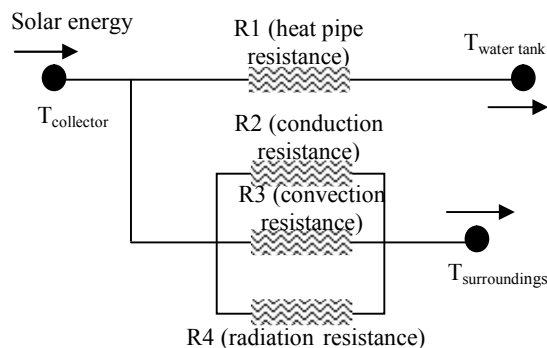


Figure 10: Thermal circuit of the vacuum-tube solar water heater.

The Knudsen number based on the tube diameter was less than unity for the vacuum levels in our experiments. Thus natural convection inside the tube was in the continuum-flow regime. For laminar natural convection in most enclosures, the Nusselt number is proportional to the $1/4$ power of the Rayleigh number except for very high aspect ratios or very low Rayleigh numbers [10]. In the continuum-flow regime, the thermal conductivity of air is weakly dependent of pressure (for instance, Na and Zou's experiments [11] showed only 21% decrease in air thermal conductivity for pressures from 760 to 0.6 torr). The Prandtl number is also almost independent of pressure, but the kinematic viscosity is a linear function of the reciprocal of pressure [10]. Thus, the convection coefficient at 0.01 torr should be about 0.045 (the reciprocal of the square root of 500) of that at 5 torr. The small difference between the results of the two pressures indicates that the aspect ratio of the enclosure is high and/or the Rayleigh number is low. The effective and actual thermal conductivities become the same in this case. Since the air thermal conductivity is independent of pressure, the rate of heat loss by natural convection becomes independent of pressure once the Rayleigh number drops below a critical value.

Table 2 lists the experimental results of the non-glass solar collector at 0.01 torr and a commercial single-glass tubular collector (vacuum level = 10^{-5} mbar = 0.0000076 torr). In these experiments the cold end of the heat pipe was immersed in a water tank and the heat transfer rate can be determined from the temperature rise and the mass and specific heat of water in the insulated tank. Time variations of the temperatures are plotted in Figs. 11 and 12.

As shown in Table 2, the performance of the commercial glass-tube collector is slightly better than the non-glass vacuum-tube collector we developed. One reason is the transmittance of the non-glass tube is

0.86 compared to the 0.91 transmittance of glass due to the ZnO coating.

Table II: Initial and final temperatures of the non-glass collector and a single-glass tubular collector.

	Non-glass collector at 0.01 torr		single-glass commercial collector (SEIDO 5)	
	Initial temp.(°C)	Final temp.(°C)	Initial temp.(°C)	Final temp.(°C)
Heat pipe (bottom)	22.9	62.5	23.4	68.7
Heat pipe (top)	23.0	59.8	23.5	69.3
Water tank(bottom)	22.9	55.4	23.4	60.6
Water tank(top)	22.9	49.7	23.5	58.4
Average (heat pipe)	23.0	61.2	23.5	69
Average (water tank)	22.9	52.6	23.5	59.5

The major difference is the vacuum levels in these two evaluated collectors. The extremely high degree of vacuum in the commercial collector results in a thermal conductivity much lower than that of air in the continuum-flow regime. The heat loss to the surroundings is therefore about 15% lower for the commercial glass-tube collector.

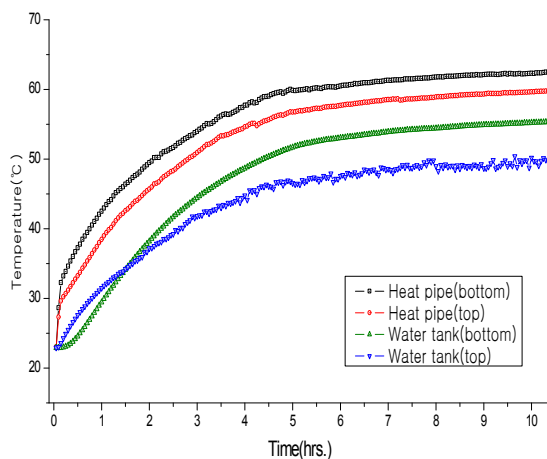


Figure 11: Temperature variations of the non-glass collector.

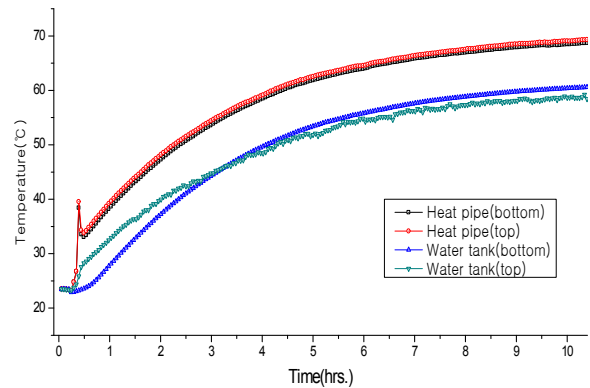


Figure 12: Temperature variations of the commercial single-glass collector.

4. CONCLUSION

A vacuum-tube solar collector was fabricated from acrylics and the effect of vacuum level on the heat transfer of the collector was investigated experimentally. A film of ZnO was coated on the acrylic tube surfaces to reduce the leakages of ambient air and the gases contained in acrylics into the evacuated tube. The ZnO coating caused a small percentage of decrease in transmittance of the acrylic tube. In the vacuum range of our experiments, the change in vacuum level was found to have little influence on the heat loss associated with natural convection inside the tube. Compared to a glass-tube collector at a much higher vacuum level, the heat loss of the non-glass collector with natural convection in the continuum-flow regime is about 15% higher.

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