

Harnessing Solar Energy with Bi-directional Thermodiodes

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ABSTRACT: Based on the working principle of thermosyphon, several thermodiode designs which allow heat to be transferred in the desired direction but block the heat flow in the opposite direction were developed and tested for solar heating applications. More recently thermodiodes with easily alterable direction of heat flow, so-called bi-directional thermodiodes, were invented and their performances tested and optimized for both summer-cooling and winter-heating of buildings and shelters. Presented in this paper are a review of single-phase thermodiodes applied to solar energy utilization and energy-efficient buildings.

Keywords: bi-directional, thermodiode, solar energy utilization

1. INTRODUCTION

In many solar energy applications as well as other heat transfer processes, it is necessary to direct the flow of heat in a desired direction but block the heat flow in the opposite direction. Heat transfer devices of this feature are termed thermodiodes – analogous to the electrical diodes which are commonly employed in electrical circuits for rectification. Heat pipe thermodiodes have been applied to fine temperature control of spacecraft components, electronics in missiles, and cryogenic applications [1]. Thermodiodes with fast shut-down time can be used as a thermal switch. Thermodiodes with variable-conductance, which can be achieved by insulating part of the heat source or sink surface area, are routinely used in thermal control and precision temperature

calibration on satellites and electronic devices and components.

Except for liquid metals, thermal conductivities of most fluids are very low, thus the Peclet number (the product of the Reynolds and Prandtl numbers - it has the physical interpretation of the ratio of convective heat transfer to heat conduction in the flow direction) of a natural convection loop is typically very high under the designed conditions, and axial conduction is negligible. Consequently heat is transferred effectively by convection if the body-force vector in Fig. 1 is pointing from the heat sink to the heat source. The thermodiode is under forward bias in this case. The thermodiode is said to be reverse biased if the body-force vector is pointing in the direction of increasing fluid density, and only heat conduction takes place in the loop between the heat source and sink.

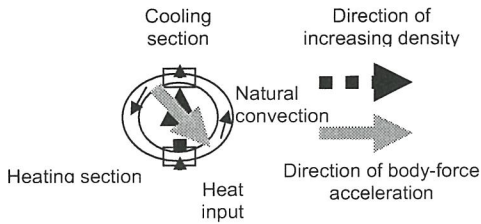


Figure 1: Natural convection induced in a thermosyphon

The simplest form of a thermodiode is given in Fig. 2, which consists of two insulated vertical branches with two horizontal connections of uniform surface temperature. The loop is filled with a fluid which remains in one phase during operation and the cross-sectional area of the flow channel is constant. The lower case s in the drawing is the one-dimensional coordinate along the loop and T_H and T_L are the loop surface temperatures of the heated and cooled sections, respectively. The space between the heat source and sink is well insulated.

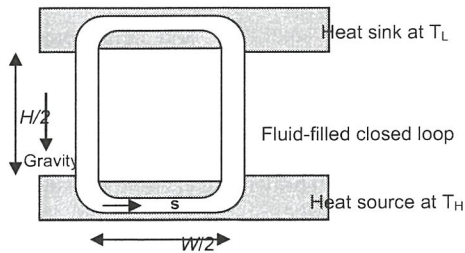


Figure 2: Rectangular – loop thermosyphon with insulated vertical branches ($T = T_H - T_L$).

The heat leakage rate of this diode under reverse bias can be estimated from:

$$Q_{rev} = 4 \pi r^2 \kappa \Delta T / H \quad (1)$$

if only heat conduction through the fluid in the two vertical branches takes place. Other thermodiode configurations designed and tested by the authors and co-workers include the bayonet diode and the loop-and-tank diode depicted in Figs 3 and 4 [2,3]. The

bayonet thermodiode is a variation of the tank-and-tongue liquid diode developed by Jones [4] for space heating. More insulation was added to Jones original design for less heat conduction loss between the tank and the tongue, and a longer cavity was used in the bayonet diode for more surface area facing the outdoors. In addition, a guide vane is inserted in the cavity and the flow channel connecting the tank and the cavity to reduce heat exchange between the ascending and descending streams. The measured efficiency of the bayonet diode under forward bias was about the same as that of Jones tank-and-tongue diode. The advantages of the bayonet diode are a larger cavity surface area for more solar energy absorption, and a longer channel between the cavity and the storage tank. The latter alteration allows more thermal insulation to be added between the heat source and sink, and less heat conduction loss through the connecting channel when the diode is reverse biased.

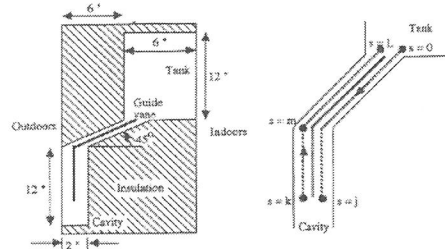


Figure 3: Configuration and coordinate system of the bayonet thermodiode. Diode dimensions are in inches [2].

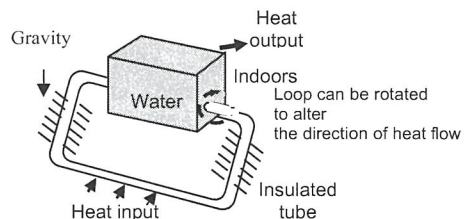


Figure 4: The loop-and-tank bi-directional thermodiode.

3.BI-DIRECTIONAL THERMODIODES

If the direction of heat flow of a thermodiode can be easily altered, the diode is called a bi-directional diode. Depicted in Figs. 5-7 are a few bi-directional thermodiode designs devised by the authors from their research of solar systems and energy –efficient building envelopes. The plane-type bi-directional thermodiode (Fig. 5) is composed of two vertical plates and several fluid-filled rectangular loops with their horizontal segments soldered to the plates. The joints between the horizontal segments and the branches connecting the horizontal segments can rotate freely. With one vertical plate fixed and the other plate free to move vertically, the direction of heat flow of this thermodiode can be easily reversed.

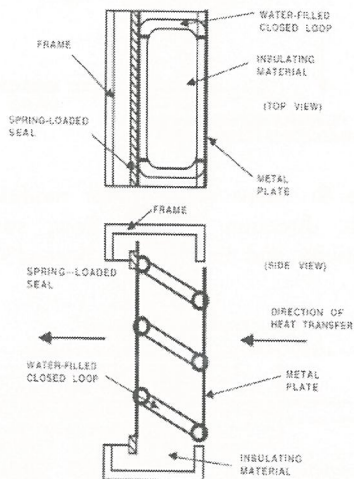


Figure 5: Plane-type bi-directional thermodiode.

The equivalent thermal circuits of the plane-type thermodiode under forward and reverse bias are plotted in Fig. 8 [5]. When the heated horizontal segment of a rectangular loop is below the cooled segment, the diode is forward biased, and there are four thermal resistances in parallel for heat transfer between the two vertical plates (see Fig. 8(a)).

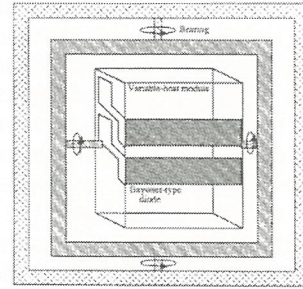


Figure 5: Three bayonet diodes mounted on a Gimbals mechanism for easy change of heat flow direction.

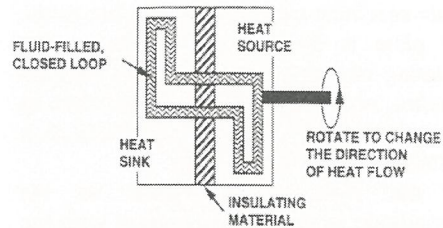


Figure 7: Another bi-directional thermodiode design based on the liquid-fin idea.

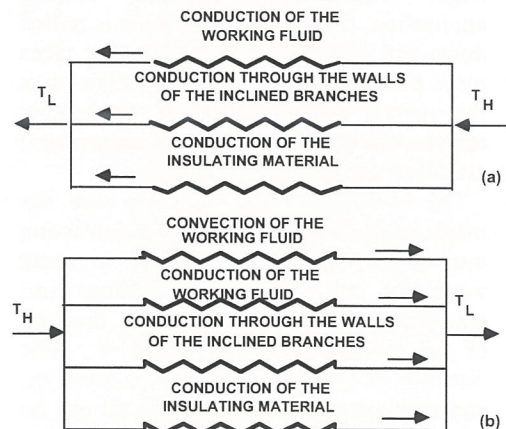


Figure 8: Equivalent thermal circuits and involved heat transfer modes of the plane-type thermodiode under (a) forward bias and (b) reverse bias.

Depending on the magnitude of four thermal resistances, the conduction and convection resistances of the working fluid in the loops, and the conduction resistances of the walls of the inclined branches and the insulating materials between the vertical plates, the dominant mode of heat transfer through the thermodiode is determined. Since the convective resistance is much smaller than the other three resistances after natural convection has been induced throughout the loops, heat can be effectively transferred from the left to the right vertical plate. If the thermodiodes are reverse biased, that is, if the heated horizontal segment of a loop is above the cooled segment, there are no flow circulations throughout the loops. In this case heat transfer from the hot to the cold plate is by conduction through the insulating material, the fluid in the inclined branches, and the walls of the branches as represented by the three parallel conduction resistances in Fig. 8(b).

If the right vertical plate of the thermodiode in Fig. 5 is in contact with the indoor air, the plate should be pushed up when the desired direction of heat flow is from the outdoors (left plate) to the indoors (right plate). For summer cooling application, the right vertical plate is pulled down and effective heat transfer only takes place from the indoors to the outdoors when the outdoor temperatures (the atmospheric temperature and the night sky temperature) are below the indoor temperature.

The bi-directional thermodiode was the major component of a "smart" construction module investigated by the authors in recent years for energy-efficient buildings and emergency shelters. A schematic diagram of the module is shown in Fig. 9. The direction of heat flow, surface absorptivity, and heat capacity of the module all can be adjusted for maximum energy efficiency and/or maximum degree of comfort under various weather conditions. Operations of the module for winter heating and summer cooling are tabulated in Table 1. Solar energy is utilized in the winter for space

heating. As a result the outdoor-facing surface is adjusted to be highly absorptive during the daytime and the direction of heat flow is from the outdoors to the indoors. Since a surface which absorbs radiation efficiently also emits radiation efficiently (this is known as Kirchhoff's law in thermal radiation), the outdoor surface should change to highly reflective to reduce radiation loss at night in the winter.

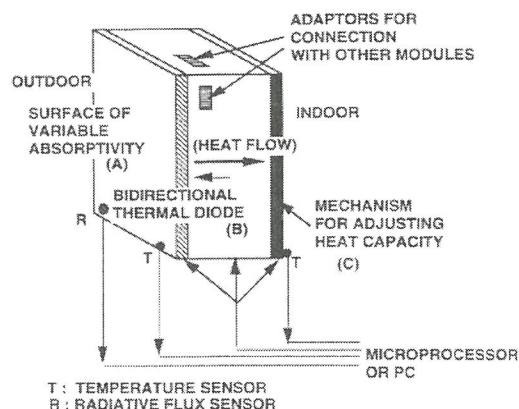


Figure 9: Smart construction module of variable direction of heat flow, surface absorptivity, and thermal capacitance [3].

Table 1. Operation of the smart module.

	Winter Heating		Summer Cooling	
	Day	Night	Day	Night
(A) Variable direction of heat flow	From the outdoors to the indoors	Little heat leakage to the outdoors	Little heat leakage to the indoors	From the indoors to the outdoors
(B) Variable surface absorptivity	Highly absorptive	Highly reflective	Highly reflective	Highly absorptive
(C) Variable heat capacity	(Depends on indoor-outdoor temperature difference and the desired operation condition)			

One method to alter the surface absorptivity is to paint the surface in black and white strips and to use rectangular plates pivoted vertically to the intersections of the black and white strips as depicted in Fig. 10. One side of the rectangular plates is painted in black and the other side in white. The entire surface will turn into black or

white when the plates are flipped to the right or to the left. Another design of variable surface absorptivity is to use a flexible sheet of highly reflective material. The sheet is wound on two cylindrical rollers and can be scrolled up and down to cover a black surface. Installation of a blind of reflective surface in front of a black surface serves the same purpose.

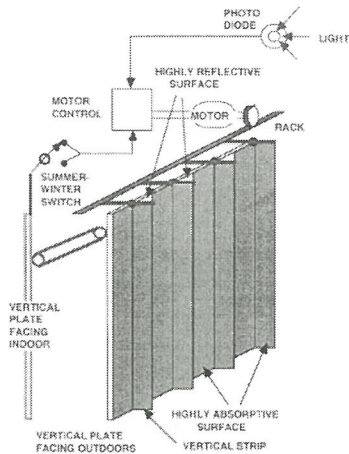


Figure 10: A smart module design using tilted loops to alter the direction of heat flow and vertical strips to change its surface absorptivity.

For winter heating, the thermal diode between the indoor and outdoor surfaces allows heat flow from the outdoors to the indoors when the outdoor surface is heated by solar flux, but blocks the flow of heat in the opposite direction at night. The setting of the direction of heat flow and surface absorptivity are just the opposite for summer cooling application. The outdoor surface is highly reflective during the day for less solar heating, but changes to highly absorptive at night to transfer heat to the sky by radiation. The desired direction of heat flow of the diode for summer cooling is from the indoors to the outdoors.

Operation of the mechanism that changes the heat capacity of the module depends on the weather conditions and the occupancy of

the building. For winter heating, the heat capacity of the module should be set low when the building is occupied and a fast warm-up of the indoors is desired. A low heat capacity allows the module temperature to rise rapidly during heating. When the indoor temperature reaches a comfortable level, the heat capacity is adjusted high to store excess energy input for later use.

When the outdoor surface is heated by solar energy but the building is not occupied, the heat capacity should be set high for immediate storage of solar energy. For summer cooling, a large heat capacity is needed to hold a large amount of energy when the building is occupied and the outdoor air temperature is high. A small heat capacity, on the other hand, allows the indoor temperature to quickly drop when the outdoor temperature is low.

A few methods for altering the heat capacity of the smart module were proposed by the authors [6] and are illustrated in Figs. 11 and 12. The pressure of the phase-change material in the cylinder in Fig. 11 can be altered by the movement of the piston, which changes the phase-change temperature.

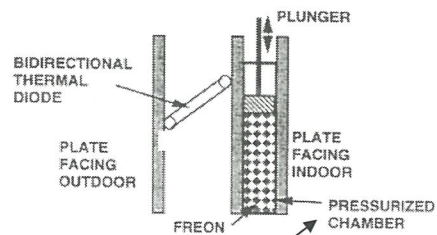


Figure 11: A conceptual design of variable specific heat for the smart module.

The pivoted partition in Fig. 12 is well insulated and can change the amount of fluid in the tank that is in direct contact with the streams entering and leaving the tank during mixing, thus changing the heat capacity of the thermodiode. If heat conduction through the insulated partition is

negligible, the diode heat capacity is reduced by 50 % when the partition is tilted by 45 degrees from its original position.

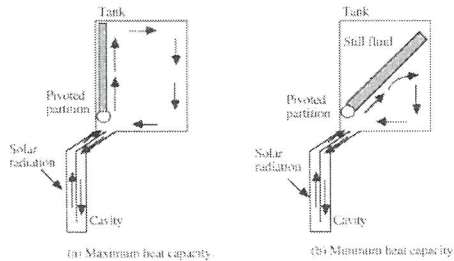


Figure 12: Water tank with a pivoted partition for adjustable thermal capacitance.

The best combination of the controls of direction of heat flow, heat capacity, and surface absorptivity is determined by a PC (Personal Computer) or a microprocessor for maximum energy efficiency and/or most comfortable indoor temperature. The adaptors on the module allow several modules to be connected together and controlled by a PC or a microprocessor. Only one set of temperature and radiation sensors are needed and mounted on a master module (usually the center one). The smart module takes advantage of the rapid developments and significant cost drops in microprocessor and sensor technologies in the past two decades to automatically optimize the performances of building and shelter envelopes for different weather conditions.

Unlike solar house design which is part of the building and cannot be moved freely from one location to another, the module can be mass - manufactured and stored in one place and shipped to another place to be quickly assembled as building or shelter envelopes. Several modules can be connected together and controlled by a microprocessor, with temperature and radiation sensors mounted on one master module to operate all the modules.

The bayonet-type thermodiode demonstrated that its efficiency can reach an

efficiency about 50 % which was among the highest of all single-phase thermosyphons.

Switching from winter heating to summer cooling operation was done by manually turning the bayonet thermodiodes upside down in the spring. An alternative method to alter the direction of heat flow of the bayonet thermodiode is the crossed-channel design depicted in Fig. 13. In this design several bayonet diodes are stocked up and the valves at the centers of the crossed flow channels control the direction of natural convection between the cavity and the storage tank of the diode.

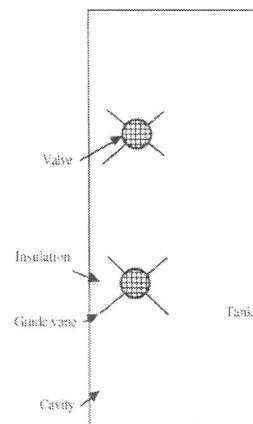


Figure 13: Bayonet diodes connected through a valve for easy change of the heat flow direction.

A prototype consisting of one pair of bayonet thermal diodes and a cylindrical valve was constructed to demonstrate the working principle of this diode design for alterable direction of heat flow (Fig. 14). Since one of the diode cavities will make no contribution to convective heat transfer in this design (the top cavity in Fig.13 for winter heating, and the bottom one for summer cooling), this design is more suitable for a large number of diode pairs installed on a tall wall.

Other designs of bi-directional thermodiodes were also proposed by the authors [6], and are shown above in Figs. 5 to 7.

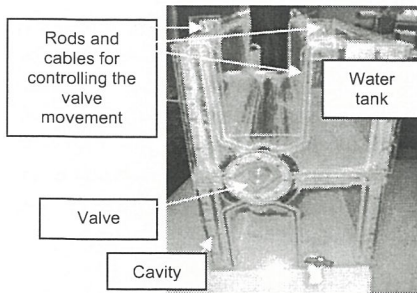


Figure 14: Photo of a bayonet diode pair connected through a cylindrical valve.

One major advantage of the rectangular-loop diode over the bayonet diode design is that the direction of heat flow can be easily reversed by moving one of the two vertical plates up or down as shown in Fig. 15 with a motor-driven indoor plate and a fixed outdoor plate for automatic direction change of the heat flow.

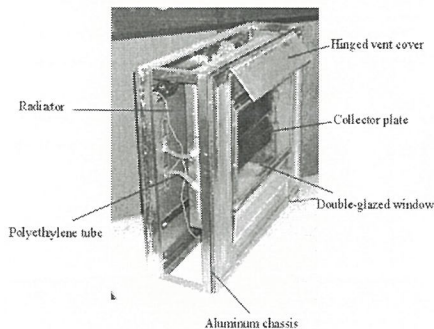


Figure 15: A bi-directional thermodiode system [7].

The side walls and insulation of the diode were removed to reveal the details of the diode interior. Indoor test results of a diode equipped with a small water tank are shown in Fig. 16 for two-hour heating followed by a three-hour cooling phase.

Temperatures in these plots were measured by thermocouples whose locations are marked in Fig. 17. The diode system in this test was heated by a radiant heater that produced a heat flux about

800 W/m^2 on the absorber plate during heating. The humps in the absorber plate and radiator inlet temperatures marked the onset of a throughflow in the loop. Before that, water in the horizontal segment of the loop was heated up very rapidly, but the buoyancy force was not sufficient to induce a throughflow, and the fluid temperatures in the radiator remained at their initial temperatures. After the onset of a global convection cell throughout the loop, the absorber plate and radiator inlet and outlet temperatures increased at the same rates until a steady state was reached. During the cool-down phase the radiant heater was turned off and the radiator temperatures dropped the slowest due to its large thermal capacitance.

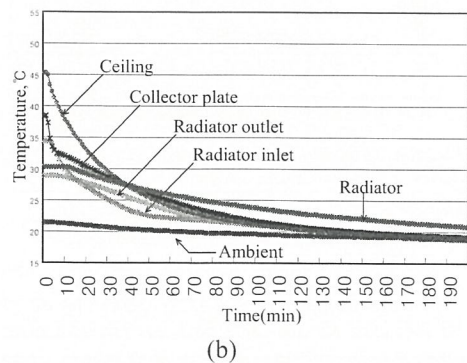
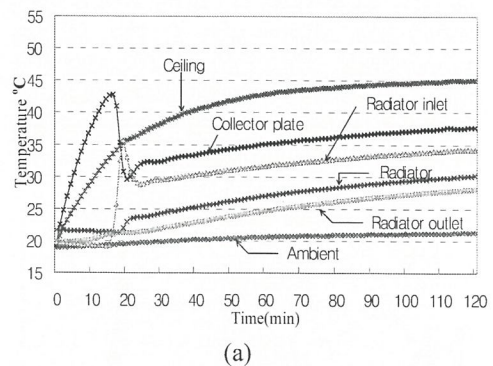


Figure 16: Indoor test results for a radiation flux of 800 W/m^2 . (a) Heating phase. (b) Cooling phase.

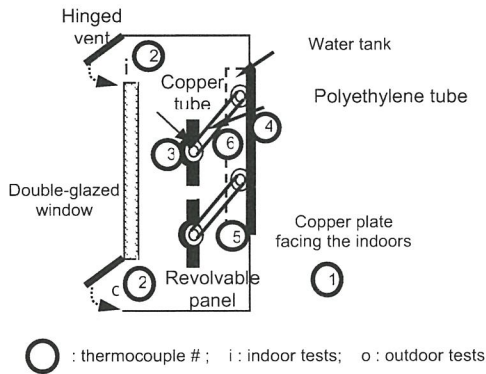


Figure 17: Thermocouple locations of the thermodiode system used in Chun et al.'s indoor tests.

The same heat flux was applied to the absorber plate when the diode was reverse biased (the radiator plate in Fig. 17 was pulled down). The nearly invariant radiator temperature in Fig. 18 clearly demonstrated the diode design can effectively prevent heat flow in the undesired direction.

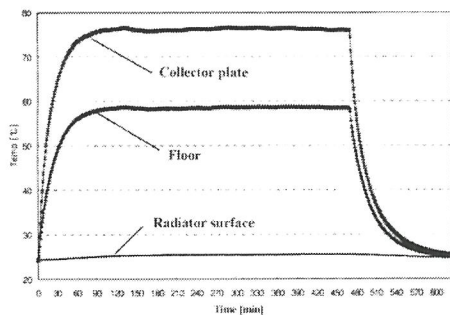
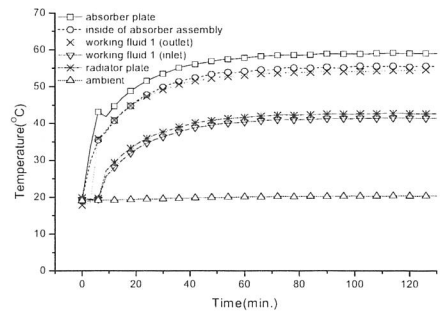


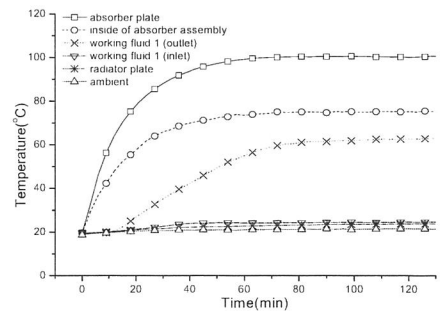
Figure 18: Temperature variations of the plane-type thermodiode system under reverse bias.

As might be expected, the time for the onset of a throughflow decreased from 20 to 10 minutes as the heat flux on the absorber plate increased from 400 to 800 W/m². The steady-state temperature of the radiator inlet increased from 34 °C for 400 W/m² heat flux, to 48 °C for 800 W/m² heat flux.

Figure 19 shows indoor test results when ethyl alcohol and silicon oil are used as the working fluid. Unlike Fig 16 (a), there are no appreciable humps indicating the onset of a throughflow in the loop. More work is underway to investigate the influence of working fluid on the operation of the rectangular-loop diode.



(a)



(b)

Figure 19 Indoor test results for a radiation flux of 1,000 W/m²: (a) ethyl alcohol, (b) silicon oil(100cSt)

4. CONCLUSION

Different types of bi-directional thermodiode designs are investigated for winter heating and possible summer cooling. A thermodiode is designed such that its thermal resistance inside under forward bias

is typically very small in comparison with other thermal resistances along the heat flow path for low-temperature applications of solar energy such as space heating. By running a series of tests and theoretical analyses, it is found that the dominant thermal resistances for winter heating and summer cooling are the resistances associated with natural convection on the indoor and outdoor surfaces and radiation to the night sky when the diode is used for summer cooling. Unless these thermal resistances can be considerably reduced through the use of fins, forced convection, and greater night sky view factor, any improvement in diode heat transfer design would not have a significant impact on the overall thermal resistance and heat transfer rate.

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