RadCool: a Web-enabled Simulation Tool for Radiative Cooling

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Abstract: Thermophotovoltaic (TPV) systems can generate electricity from high-temperature heat sources via thermal radiation. However, the intense heating of a photovoltaic (PV) cell can greatly reduce the overall efficiency of the system. Therefore, it is critical to develop techniques to keep the PV cells close to ambient temperature without consuming energy. Radiative cooling is a passive technique that dissipates heat into remote space via thermal radiation. A simulation tool to predict the performance of radiative cooling systems would be particularly helpful in designing new experiments. The current TPV model simulation tool, TPVexpt, can calculate the theoretical performance of the TPV system. However, it does not consider the thermal management of the PV cell. A new tool, Radcool, is created to complement TPVexpt as well as to predict the performance of a radiative cooling system in general. The main design considerations of Radcool include: (1) the area ratio between the PV cell and the cooling emitter, and (2) the cooling emitter materials. The cooling performance is evaluated by equilibrium heat transfer analysis. Radcool has been validated with the existing experiment, but more experiments need to be done to confirm the generality of the system and modeling approach. In the future, this radiative cooling model can be connected directly with the existing TPV model, so that TPV systems will become more efficient for real world applications. The radiative cooling technique is not limited to TPV systems; other potential applications include solar cell cooling, infrared detectors, and sensitive electronic devices that are used outdoors.

Keywords: Radiative cooling, thermal radiation, thermophotovoltaics, radiative heat transfer

1. Introduction

Thermophotovoltaic (TPV) systems convert high-temperature input heat into thermal radiation, which illuminates photovoltaic (PV) cells, to generate electricity via the PV effect [1]. Possible heat sources for such systems include waste heat, combustion, and concentrated sunlight, which can potentially reduce the dependence on traditional fuel sources. In comparison, conventional p-n junction solar cells, which directly convert solar energy into electricity through the PV effect, are limited to a conversion efficiency of approximately 31% under unconcentrated sunlight, mainly because of sub-bandgap and thermalization losses, according to Shockley and Queisser [2]. Solar TPV systems, in contrast, use a thermal absorber-emitter as an intermediary to tune the emitted range of photon energies above the PV bandgap, thus suppressing sub-bandgap and thermalization losses. Therefore, solar TPV systems can potentially reach much higher efficiency than traditional solar cells. The theoretical maximum efficiency that TPV systems can reach is found to be 54% for unconcentrated sunlight, and 85% for full concentration [3]. In contrast, the best-demonstrated conversion of thermal radiation to electricity is 23% [4], while the full solar thermophotovoltaic efficiencies including all stages have been reported around 5.8% [5]. Therefore, there is still a great deal of room for improvements in TPV and solar TPV systems to approach these maximum possible efficiencies.

Previous work sought to increase TPV efficiency by reducing photon energy loss, including lowering the bandgap of the PV cells and designing the selective emitter and filter [6]. First, by lowering the bandgap, the PV cells can harvest more photons and therefore increase its short-circuit current. Second, using a selective emitter decreases the number of photons emitted with energy below the bandgap of PV cells, so that sub-bandgap photon losses can be greatly reduced. Research has shown that using refractory metals such as tungsten (W) as an emitter increases the conversion efficiency because of its high melting point and favorable selective emissive properties [7]. Third, adding selective filters can transmit photons above the bandgap of the PV cell and reflect the sub-bandgap photons back to the emitter, which is a process called photon recycling [6]. Besides reducing photon energy loss, the heating of the PV cell from high heat input is another concern. For fundamental thermodynamic reasons, TPV cells perform best at low temperature. As the temperature increases, the efficiency of the system can potentially be cut in half; furthermore, cooling the cell by 1-2℃ can extend its lifetime by 20% [8]. Therefore, maintaining the optimal temperature of the PV cell is crucial for high performance. Generally, this will be a temperature as close to ambient as is practical. At the same time, it is also important not to use energetically costly methods of cooling, since this will cancel out the benefit of more efficient TPV operation.

The traditional approaches for cooling the PV devices use conduction and convection via highly conductive metal-based heat sinks, cooling fans, or water-cooling. However, TPV systems operate in a vacuum, so the traditional methods, especially convection, are not effective.

A viable alternative for cooling the PV cells of a TPV system in a vacuum is radiative cooling. Radiative cooling passively cools the device by dissipating excess heat into remote space via thermal radiation [8, 9, 10]. The advantage of radiative cooling is that it does not require energy input, which may potentially increase the overall system efficiency, compared to active cooling approaches. Radiative cooling has already shown promising results in cooling the device in recent experiments; it can achieve temperature decreases up to 42 ℃ under the sunlight [11]. The design of the device focuses on the minimal absorption of solar irradiance and maximum emittance within the atmospheric window (8-13 µm) [8, 9, 11, 12]. To match the specification of the design, photonic crystals (PhCs) are used. The advantages of PhCs are that they can be made from common materials and can be tuned to match the atmospheric window for maximal cooling. Raman *et al*. have demonstrated that the radiative cooler is able to cool to 4.9 ℃ below the ambient temperature by using a photonic reflector [13]. In addition, other research has shown that by adding 2D-periodic photonic crystal structures of low-iron soda-lime glass can further increase the cooling effect on the PV diode, and the TPV conversion efficiency increase 18% relative [9]. Therefore, PhCs have shown promising results in enhancing TPV efficiency. Besides nanophotonic radiative coolers, other radiative cooler designs include bulk, gaseous, and composite materials [8]. Still, there are many degrees of freedom in designing these systems, so testing radiative cooling devices with various parameters without any clear guidance could be extremely tedious. However, by creating a simulation tool for radiative cooling, it becomes possible to quickly find potential high-performance materials and designs, which are suitable for direct fabrication and experimental characterization.

Until now, no simulation tool has been available to accurately model the radiative cooling device. By creating a simulation tool for radiative cooling, one can directly design experiments for higher performance. The primary design features of a radiative cooler are the emitter structure (which itself can have several distinct materials and geometries), as well as the area ratio between the PV cell and the cooling emitter. The proposed design uses low-iron soda-lime glass as the emitter, due to its low absorption of solar irradiance but high emittance in mid-infrared [9]. Implementing the design into the simulation tool can save time in designing the experiment, while allowing comparison of theoretical performance with experimental results afterwards. Developing the tool will be valuable in designing and experimenting with the radiative cooling devices. It also helps to gather meaningful data using less time and resources.

Furthermore, the performance of TPV can potentially be increased significantly by incorporating radiative cooling into the currently existing TPV simulation, which is called TPVexpt. The model is fairly accurate in calculating the performance of the TPV systems. It takes into account realistic factors such as the heater and emitter size, PV cell properties, and the alignment of the heater and the PV cell [14]. It has previously been used for analyzing different refractory metals as emitters [7]. However, TPVexpt does not currently consider the temperature change of the PV cell associated with different cooling mechanisms. As discussed above, the PV cell may dramatically increase in temperature during operation and reduce the performance of the system. Therefore, radiative cooling becomes an important way to effectively reduce the operating temperature of the cell, and thereby improve the system efficiency. Finally, the predictions of this new software tool will be fed directly into ongoing experimental efforts, which will potentially result in higher experimental TPV system efficiencies.

2. Methodology

TPVexpt, a simulation tool that models TPV system performance, was published in 2015. The tool allows the user to input the material of the selective emitter, type of filter, parameters for heater and emitter, PV cell properties, and the alignment of the system. It also accounts for thermal/electrical non-idealities and realistic geometries. The outputs of the simulation include emittance, reflectivity, efficiency, emitted power, and heat loss. TPVexpt is able to model the TPV system in several aspects and predict the performance accurately [14]. However, TPVexpt assumes the temperature of the heater, the emitter, and the PV diode operate at a given temperature. In reality, the temperature of the PV diode depends on various factors and should be managed with proper cooling.

To help predict the PV diode temperature and optimize the TPV system design, a new tool, RadCool, is introduced. The main purpose of the tool is to model a radiative cooling device. RadCool is created not only to complement TPVexpt, but also to predict the performance of a radiative cooling system in general.

RadCool is created by using the Rappture toolkit on nanoHUB.org. The Rappture toolkit is an open source development platform that provides basic infrastructure for an interactive interface, which allows the developer to focus more on the algorithm for the tool rather than the setup of the interface.

To calculate the cooling effect of the system, the energy balance equation is used, where the heat input equal to the heat output. The input and output powers in the example of a TPV system are shown in Figure 1.

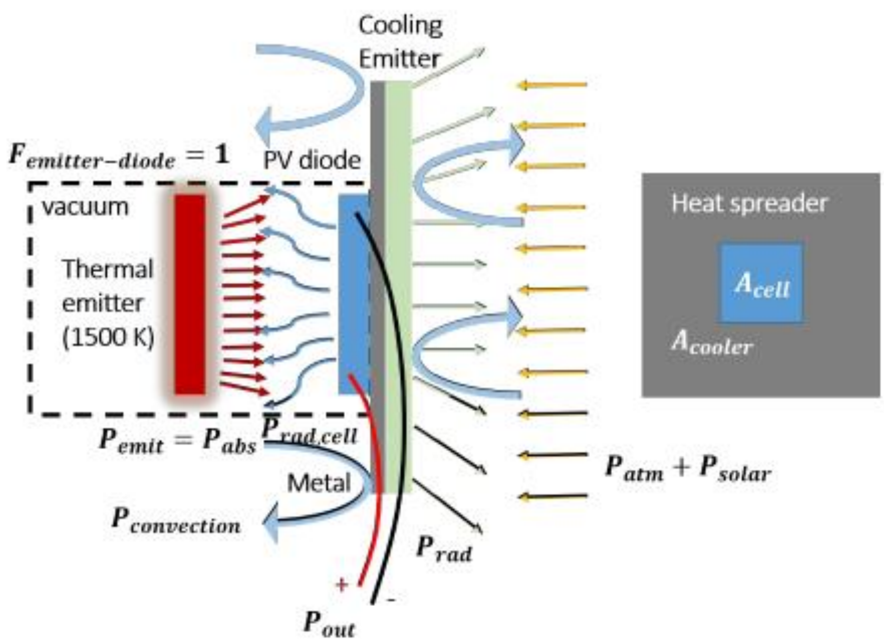

Figure 1. Schematic of the TPV system with a radiative cooler. The thermal emitter and the PV diode are inside a vacuum chamber and the cooling emitter is exposed to ambient conditions. The arrow shows the heat flow between the system and the environment (adapted from [9]).

The heat inputs include the power absorbed by the PV diode (P_{abs}), the absorbed radiation from the atmosphere (P_{atm}), and the solar absorption (P_{sun}). The heat outputs include the radiation emitted from the cooler (P_{rad}), the radiative recombination of the PV diode ($P_{rad,cell}$), the current output from the PV diode (P_{out}), and the convective power loss (P_{conv}). These input and output values yield the steady-state heat balance equation [9]:

$$P_{abs}(T_{Emitter}) + P_{atm}(T_A) + P_{solar} = P_{rad}(T_A, T_{cell}) + P_{rad,cell}(T_{cell}) + P_{out}(T_{cell}) + P_{convection}(T_A, T_{cell}) \quad (1)$$

The absorbed and emitted power (P_{abs}, P_{atm}, P_{sun}, P_{rad}) are calculated by integrating over the emittance and absorptance spectra of different components [15]. The electrical output power (P_{out}) is calculated by using the detailed balance for the equilibrium cell temperature and the input spectrum. Lastly, the convective power (P_{conv}) is calculated based on the temperature difference between the PV cell and the ambient temperature [9].

Equation 1 shows the energy balance equation specifically for the TPV system. However, in the simulation tool, we would like to use a more generalized heat load (still called P_{sun}) and radiative cooling system (as shown in Figure 2), so that it can be applied to other problems. As such, the PV cell can be dropped, thereby eliminating the P_{out} and $P_{rad,cell}$ terms in Equation 1. Based on these assumptions, the new energy balance equation can be simplified to:

$$P_{sun} + P_{atm}(T_{amb}) = P_{rad}(T) + P_{cond+conv} \quad (2)$$

In future work, the tool can be connected with the TPV model to increase its accuracy.

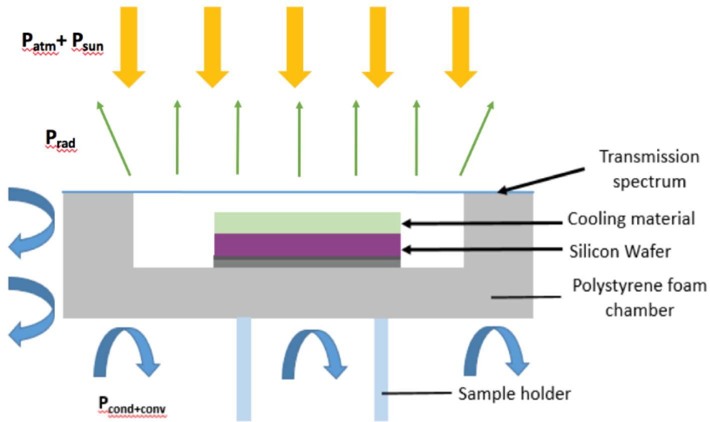

Figure 2. Generalized radiative cooling system.

The tool is separated into three phases: heat load, cooler, and environment. In the heat load phase, as shown in Figure 3, the users enter parameters for the heat load. Users are able to select from the standard solar spectra provided in the drop down menu: AM1.5G and AM1.5D, but there are also options for uploading a customized spectrum, zero input heat, and entering a constant heat load [W/m^2] (circle 1 in the figure). Specifically, the "input intensity" is used to calculate the solar absorption, by integrating over spectral intensity values at different wavelengths [$\mathrm{W/m^2 \cdot nm}$]. The equation is shown below:

$$P_{sun} = C * A * \int_0^{\infty} d\lambda \varepsilon(\lambda) I_{AM1.5}(\lambda) \qquad (3)$$

Here, C is the solar concentration factor, A is the area of the heat load that absorbs solar irradiance, and the integral is over the product of the emissivity of the sample and the solar irradiance. One assumption made here is that the incidence angle is zero, which implies dual-axis solar tracking.

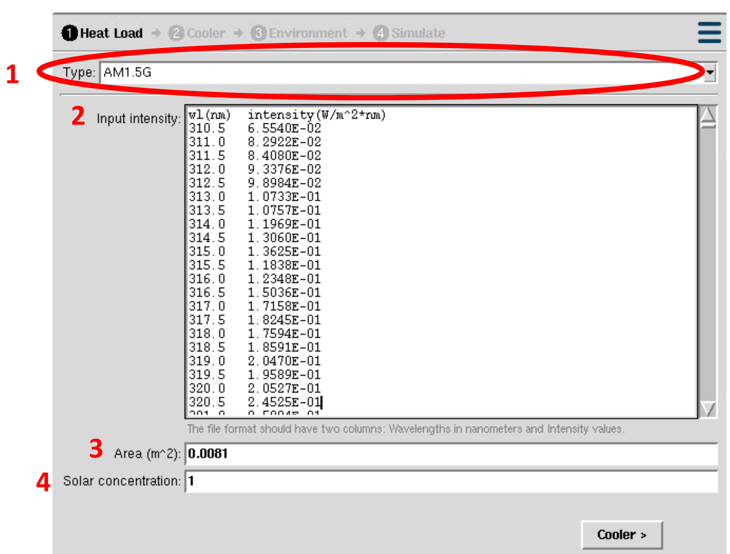

Figure 3. The "Heat Load" phase for RadCool. Users are able to (1) use the standard solar spectra provided in the drop-down menu or to (2) enter a customized input intensity; other sections include (3) heat load area, and (4) solar concentration.

In the cooler phase, as shown in Figure 4, the users can either enter the emittance spectrum of the cooler or use the provided examples. The provided examples include angular dependent emittance of bare silicon wafer and silicon wafer with soda-lime glass on top. For user defined cooler emittance, both angular averaged values or spectrum at specific angles are acceptable. If emittance values at specific angles are chosen, the user should enter emittance values at 0°, 20°, 40°, 60°, 70°, 80°, and 85°. The angles are chosen so that the angular dependence of emittance and its impact on the radiated power can be accurately represented at a modest computational cost. These values are then used to find the sample absorption at the incident angle and the thermal radiated power by the sample which is:

$$P_{rad} = A * \int d\Omega \cos\theta \int_0^\infty d\lambda I_{BB}(T,\lambda)\varepsilon(\lambda,\Omega) \quad (4)$$

Here, A is the area of the cooling emitter, $\int d\Omega$ is the angular integral over a hemisphere and I_{BB} is the spectral radiance of a blackbody at temperature T, which can be calculated by:

$$I_{BB} = \frac{2hc^2}{\lambda^5 * \left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1\right]} \quad (5)$$

where h is the Planck constant, c is the speed of light, λ is the wavelength, and k_B is the Boltzmann constant [15].

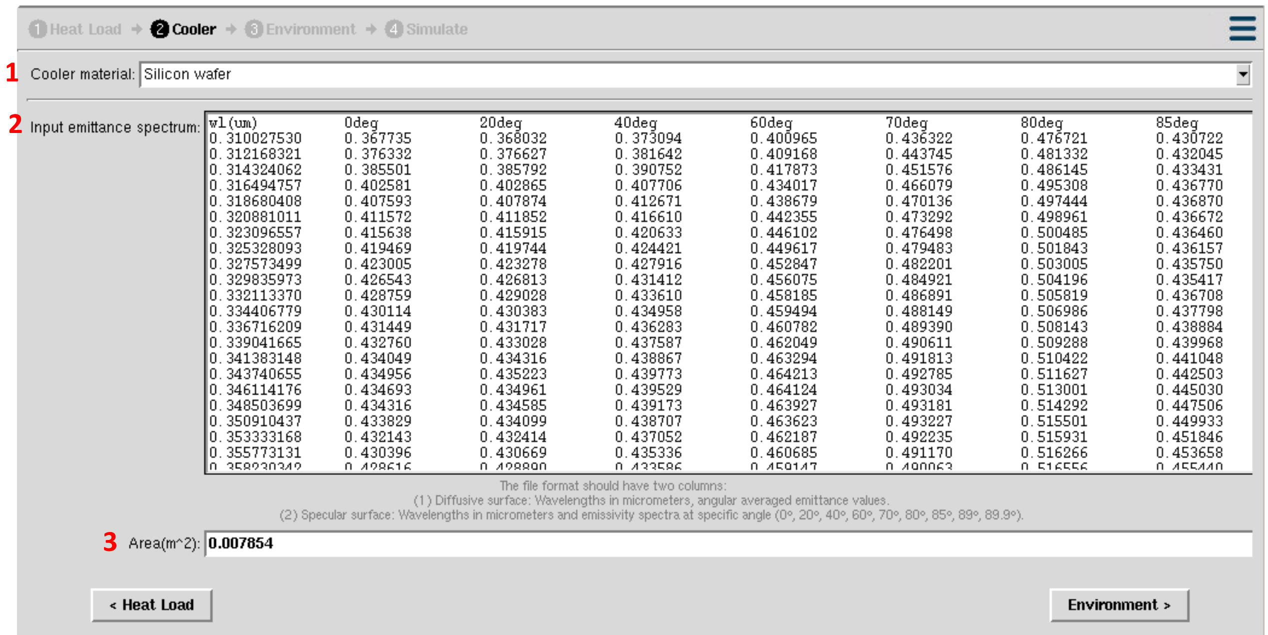

Figure 4. The "Cooler" phase for RadCool. Users are able to (1) select cooler materials provided or (2) enter either angular averaged emittance values or emittance values at specific angles, and (3) the cooler area.

Lastly, the environment phase is shown in Figure 5. The inputs are the parameters related to the testing environment and experimental conditions, including atmospheric spectrum, ambient temperature, transmission spectrum, convection coefficient, and conduction values. They are used to calculate the absorbed radiation from the atmosphere, convective and conductive power loss. The atmospheric spectra provided are simulated by MODTRAN. MODTRAN is a simulation tool that model atmospheric transmittance and radiance [16]. The absorbed thermal radiation from the atmosphere is [15]:

$$P_{atm} = A * \int d\Omega cos\theta \int_0^\infty d\lambda I_{BB}(T,\lambda)\varepsilon(\lambda,\Omega)\varepsilon_{atm}(\lambda,\Omega) \quad (6)$$

where $\varepsilon_{atm}(\lambda,\Omega)$ is $1 - t(\lambda)^{1/cos\theta}$, and $t(\lambda)$ is the atmospheric transmittance at normal.

The experimental data provided for ambient and chamber (where samples are enclosed) temperature was collected on May 31st, 2017, a spring day by the graduate mentor, Zhiguang Zhou. The transmission spectrum provided by UV-VIS-NIR spectrophotometer and FTIR measurement on a polyethylene film. The purpose of the polyethylene film is to reduce the convective heat transfer between the cooling system and the atmosphere. The conduction and convection power loss are calculated as follows:

$$P_{cond} = K * \frac{A}{L} * (T - T_{chamb}) \quad (7)$$

$$P_{conv} = 2 * h_c * A * (T - T_{chamb}) \quad (8)$$

where K is the thermal conductivity [W/m · K], A is the sample holder area [m^2], L is the sample holder length [m], h_c is the convective coefficient [W/m^2K], and T_{chamb} is the chamber temperature measured experimentally.

(a) (b)

(c) (d)

Figure 5. The "Environment" phase for RadCool. **(a)** In tab atmosphere, users are able to (1) choose the atmosphere spectra provided (midlatitude winder/summer day) in the drop down menu or (2) enter custom atmosphere spectrum. Other sections include the (3) convection coefficient, (4) thermal conductivity, (5) sample holder area, and sample (6) holder length. **(b)** In tab ambient temperature, users should (2) enter the data of the ambient temperature during the experiment. **(c)** In tab chamber temperature, users should (2) enter the data of the chamber temperature during the experiment. **(d)** In tab transmission spectrum, users are able to choose (1) the polyethylene film, none, or (2) enter the customized transmission values.

With all the data collected, the steady-state temperature T of the sample is determined by Equation 2. The equation is solved by using Python function solver (fsolve). The output of the tool is shown in Figure 6. The output graphs include all the input parameters as a function of wavelengths, output power as a function of time, comparison between the sample and ambient temperature, and the radiative cooling fraction, which is calculated by dividing radiated power over the sum of the absolute of output values. For the "Report" option, it shows the average input/output data and the average emissivity over the transparency window, which is the integral of the total emitted power over the range of sky-transparent window (8-13 μm) divide by the emission in the same wavelength range for the blackbody at the same temperature. In the next section, we will discuss the comparison of the tool output to the actual experimental measurements.

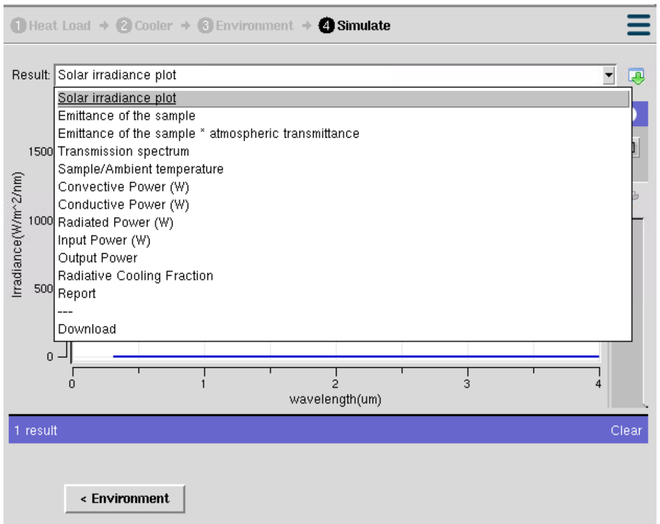

Figure 6. Simulation output of the RadCool tool.

3. Results and Discussion

The experimental data was collected by the graduate mentor, Zhiguang Zhou, on May 31st, 2017 at night. The experimental setup consists of a silicon wafer with soda-lime glass as the cooling material on top, a piece of polyethylene film and a polystyrene foam chamber. Because the experiment was carried out at night, the only input heat is from convection and conduction. The area ratio of the heat load and the cooler is 1. The ambient temperature measured by a thermometer at the time of the experiment is around 290 K. The experimental and simulated results are shown in Figure 7.

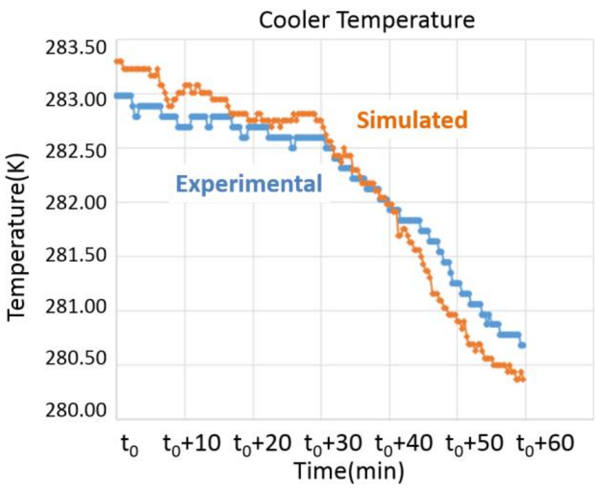

Figure 7. Temperature of the cooler (both experimental and simulated) as a function of time.

The deviation between experimental and simulation data (root-mean-square error) is only 0.25 Kelvin. The remaining discrepancy between two data set may be due to using average convective coefficient in the simulation tool. In addition, the experiment shows cooling approximately 10 K below ambient, which is significant.

Overall, RadCool can model a radiative cooling system accurately. However, more experiments need to be tested to validate the simulation tool – e.g., during the daytime, with a solar heat load.

4. Conclusions

RadCool allows users to input the parameters of heat load, cooling materials, and environmental conditions. The output graphs include the comparison between the sample and ambient temperature and all the input/output parameters. RadCool can successfully model radiative cooling systems in a graphical interface. The result of the validation shows a root-mean square error of 0.25 K. However, more experiments need to be done to confirm the generality of the system and modeling approach. Future validations include adding a solar heat load, using different cooler materials, and testing under different atmospheric conditions. In the future work, RadCool can be connected directly with the existing TPV model, which will help design better and more efficient TPV systems. RadCool is not limited to use in TPV systems; other potential usages include solar cell cooling, infrared detectors, automobile cooling, and sensitive devices that are used outdoors.

5. Acknowledgements

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6. References

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