RADIATIVE WATER-COOLING SYSTEM UTILIZING DEEP SPACE RADIATION ENERGY AT NIGHT

Andriy Redko[1], **Oleksandr Redko**[2], **Ihor Redko**[3], **Yurii Burda**[2]
[1]Sumy National Agrarian University, Ukraine;
[2]O.M. Beketov National University of Urban Economy in Kharkiv, Ukraine;
[3]Ukrainian State University of Railway Transport, Ukraine
andrey.ua.1000@gmail.com, science.yurii.burda@gmail.com

Abstract. The persistent escalation of nocturnal cooling requirements necessitates passive heat rejection mechanisms that exploit the atmospheric transparency window. This study presents a reduced-order computational model to quantify the nocturnal thermal extraction of a horizontally oriented, water-filled radiative panel under clear-sky conditions. Numerical simulations, performed using Python 3.x, track the sensible cooling trajectory over a 10-hour nocturnal cycle. The model assumes a constant surface emissivity of 0.94 and low wind speeds (convective coefficient 2.5 $W \cdot m^{-2} \cdot K^{-1}$). Results demonstrate that effective thermal extraction peaks at 71.5 $W \cdot m^{-2}$ during the intermediate nocturnal interval, yielding a cumulative water temperature reduction of 6.8°C (from an initial 25.0°C to 17.5°C) and an estimated cooling capacity of 0.6 $kWh \cdot m^{-2}$ per night. The principal novelty lies in the dynamic nonlinear coupling of continuous meteorological fluctuations with the thermal inertia of the circulating fluid, bridging the gap between steady-state nodal models and complex CFD simulations. The quantitative analysis confirms that deep-space radiative exchange is a highly viable supplementary architecture for low-grade thermal management in temperate climates.

Keywords: radiative water cooling, passive heat rejection, nocturnal thermal extraction, deep-space emission, nonlinear thermal response.

Introduction

The persistent increase in nocturnal cooling demand in densely occupied buildings and process-oriented facilities has intensified interest in passive heat rejection mechanisms capable of operating without continuous electrical input. Among available environmental sinks, the upper atmospheric window offers a uniquely stable pathway for thermal discharge during nighttime hours, when long-wave emission from terrestrial surfaces can proceed under reduced solar interference and favorable spectral transparency. Experimental investigations reported in [1] demonstrated that uncovered solar thermal collectors, when exposed to transient outdoor conditions after sunset, maintain measurable heat extraction capacity through direct emission toward the sky vault, confirming that conventional absorber geometries may be repurposed for nocturnal thermal rejection under properly controlled hydraulic conditions.

Comparative climatic assessments presented in [2] showed that the effectiveness of such night-driven cooling strongly depends on the alignment between local cooling demand profiles and regional sky clarity, particularly under dry atmospheric conditions where the attenuation of outgoing thermal radiation remains limited. These findings are particularly relevant for water-based circulation systems, since the thermal inertia of liquid media permits temporary storage of extracted cooling potential and subsequent redistribution during daytime operation. Architectural adaptations intended to intensify this exchange have also been examined; skylight-integrated geometries described in [3] revealed that spatial orientation and enclosure depth alter the angular exposure to the cold sky hemisphere, thereby modifying the net outward energy flux.

The thermal response of radiative emitters is governed not only by external meteorological conditions but also by the spectral behavior of the exposed surface. Investigations in [4] established that the interaction between cover transmissivity and emitter selectivity determines whether outward long-wave transfer exceeds parasitic gains from ambient surroundings. Material engineering therefore remains central to system efficiency. Polymer films modified for elevated emissive output within the atmospheric transparency band, as shown in [5], achieved improved night and day thermal discharge by tailoring infrared behavior without substantially increasing absorptivity in unwanted spectral intervals.

Although many radiative cooling studies focus on lightweight surfaces or façade applications, large-scale thermal control problems have also demonstrated the viability of deep-space heat rejection. In [6], the thermal stabilization of cryogenic instrumentation required sustained outward emission toward extremely low apparent sky temperatures, confirming that carefully shielded surfaces can maintain substantial thermal gradients even when external convection is present. Similar principles are now being reconsidered for low-temperature hydraulic loops, where circulating water may function simultaneously as a heat carrier and a temporary thermal reservoir.

Recent reviews have expanded passive cooling analysis beyond solid emitters alone. Hydrogel-based structures discussed in [7] introduced moisture-mediated thermal buffering, while broader atmospheric cooling architectures summarized in [8] emphasized that condensation, vapor exchange, and radiative discharge often coexist within the same surface layer. This combined behavior is particularly important for water-cooling panels exposed overnight, because latent interactions may alter emissive stability and modify effective surface temperature.

Material sustainability has also emerged as a design criterion. Life-cycle analysis in [9] indicated that passive cooling materials with low embodied environmental burden may significantly improve long-term energy performance when integrated into building envelopes or decentralized cooling modules. However, practical operation remains sensitive to surface wetting phenomena. Experimental observations in [10] showed that droplet formation on sky-facing emitters disrupts spectral selectivity and reduces outward thermal transfer, indicating that condensation management is essential for hydraulic night-cooling assemblies.

The transition from isolated emitters toward integrated thermal systems has accelerated in recent years. A sky-driven hydronic configuration examined in [11] confirmed that radiant-capacitive circulation can maintain useful cooling power throughout extended operating cycles when night-sky exchange is coupled with internal thermal mass. Complementary adaptive ventilation concepts in [12] further demonstrated that pre-conditioning of incoming air can reduce daytime mechanical loads when passive thermal sinks are effectively utilized.

Although developed for extraterrestrial resource capture, integrated condensation systems described in [13] provide additional insight into thermal capture under low-radiation environments, particularly regarding phase transition control on cooled surfaces exposed to sparse atmospheric exchange. Broader low-temperature thermal engineering concepts derived from geothermal and renewable energy practice in [14] indicate that the combination of passive heat rejection and liquid-based storage becomes especially attractive where temperature differences are modest but continuously available.

Recent developments in low-grade heat recovery and thermal system reliability further emphasize the importance of integrating passive cooling technologies into broader energy infrastructures. Studies addressing alternative working fluids for waste heat recovery cycles and the operational stability of centralized and building-scale heating systems [15-17] indicate that coupling radiative cooling with existing thermal networks may enhance overall system flexibility and resilience under variable load conditions.

Within this context, radiative water-cooling systems operating at night represent a technically promising approach for extracting low-grade thermal energy through direct exposure to deep space. The principal challenge lies in balancing outward infrared discharge, convective interaction with ambient air, hydraulic circulation rate, and transient thermal storage so that net cooling remains positive over realistic nocturnal intervals. The present study examines these coupled processes in a water-based configuration designed for nocturnal operation, with emphasis on the thermal response of the circulating medium under naturally varying atmospheric conditions.

Research methodology

Numerical modeling, data processing, and simulation of the radiative cooling processes were performed using the Python 3.x programming language, utilizing the SciPy and NumPy libraries. Visualization of the resulting multidimensional data was conducted using the Matplotlib library.

To conduct the analysis, specific atmospheric boundary conditions and numerical constants were established based on a temperate continental summer climate under clear-sky conditions (zero cloud cover), which is critical for maximizing long-wave transmission to deep space. The ambient air temperature T_a varies between 15°C and 25°C, while the equivalent sky temperature (T_{sky}) ranges from 0°C to 10°C, consistent with established clear-sky empirical models. The surface emissive effectiveness (ε) is assumed to be constant at 0.94 across the operational temperature range. A low ambient wind velocity of approximately 0.5 m·s^{-1} is assumed, corresponding to a constant external convective heat transfer coefficient (h) of 2.5 W·m^{-2}·K^{-1}.

The net outward thermal transfer from the exposed emitting surface is represented as the difference between surface thermal emission and counter-radiation received from the effective sky background:

$$q_{net} = \varepsilon\sigma\left(T_s^4 - T_{sky}^4\right), \tag{1}$$

where q_{net} – denotes the resulting radiative heat flux, W·m^{-2};
ε – surface emissive effectiveness;
σ – Stefan-Boltzmann constant, W·m^{-2}·K^{-4};
T_s – mean surface temperature, K;
T_{sky} – equivalent sky temperature, K.

During active nocturnal radiative cooling, the emitting surface temperature (T_s) frequently drops below the ambient air temperature (T_a). Under these conditions, convection acts as a parasitic heat gain, transferring thermal energy from the warmer surrounding atmosphere back into the panel. Therefore, the net useful thermal extraction rate (q_{eff}) is calculated by subtracting this convective thermal return from the outward radiative flux:

$$q_{eff} = q_{net} - h(T_a - T_s), \tag{2}$$

where q_{eff} – defines the useful thermal extraction rate, W·m^{-2};
h – external heat transfer coefficient, W·m^{-2}·K^{-1};
T_a – ambient air temperature, K.

The resulting surface heat removal is transferred to the water layer and expressed through the temporal decrease of liquid thermal content:

$$Q = mc_p\left(T_{w,in} - T_{w,out}\right), \tag{3}$$

where Q – extracted thermal energy, J;
m – water mass, kg;
c_p – specific heat capacity of water, 4184 J·kg^{-1}·K^{-1};
$T_{w,in}$ $T_{w,out}$ – inlet and outlet water temperatures, K.

To estimate the cooling rate over a selected exposure period, the useful surface heat extraction is linked to the active exchange area:

$$T_w = \frac{q_{eff} \cdot A \cdot \tau}{m \cdot c_p}, \tag{4}$$

where ΔT_w – water temperature reduction during the nocturnal interval, K;
A – active radiative area, m^2;
τ – operating time, s.

This formulation establishes a direct computational sequence in which atmospheric temperature, equivalent sky temperature, emitting surface properties, and exposure duration determine the predicted decrease of water temperature. The model is intended for subsequent generation of comparative numerical scenarios under varying nocturnal environmental conditions, allowing tabulated evaluation of cooling intensity for different combinations of sky transparency, initial water temperature, and exchange surface area.

Results and discussion

Based on the formulated analytical framework, a series of computational scenarios was developed to quantify the nocturnal thermal response of a water-based radiative cooling system under controlled atmospheric conditions. The numerical procedure was structured to trace the influence of surface emission capacity, surrounding air temperature, effective sky temperature, and exposure duration on the progressive reduction of water temperature within the cooling circuit.

The simulation sequence was established using fixed geometric and thermophysical parameters while varying external boundary conditions within ranges representative of clear nighttime operation.

Such an approach made it possible to isolate the relative contribution of each governing factor and to evaluate how the balance between outward long-wave thermal discharge and atmospheric thermal return determines the final cooling potential of the system.

The resulting dataset provides a comparative representation of predicted thermal behavior over successive operating intervals, allowing direct assessment of cooling intensity and temporal stability. The following sections present the modeled values and examine the dominant tendencies observed under different nocturnal thermal regimes.

To examine the thermal response predicted by the proposed model, a numerical series was generated for a nocturnal operating interval under clear-sky conditions typical for stable radiative discharge. The calculation assumed a constant emitting area of 1.0 m^2, water mass of 12 kg, surface emissive effectiveness of 0.94, and an external heat transfer coefficient corresponding to weak nighttime air movement. The equivalent sky temperature was progressively varied together with ambient conditions in order to reproduce realistic fluctuations occurring during night operation rather than an idealized monotonic regime. The resulting values therefore reflect the non-uniform character of atmospheric thermal exchange and its direct influence on water cooling intensity.

The numerical scenario assumes an initial uniform water temperature profile of 25.0 °C at the start of the operating cycle (20:00). Equivalent sky temperatures (T_{sky}) were systematically varied alongside the ambient air temperatures to replicate real atmospheric cooling dynamics rather than an idealized monotonic drop.

Table 1

Modelled nocturnal thermal response of the radiative water-cooling system under varying atmospheric conditions

Time, h	Effective thermal extraction, $W \cdot m^{-2}$	Water outlet temperature, °C	ΔT (Hourly drop), °C
20:00	48.6	24.3	0.7
21:00	55.1	23.5	0.8
22:00	61.8	22.4	1.1
23:00	58.7	21.9	0.5
00:00	66.4	20.8	1.1
01:00	63.2	20.1	0.7
02:00	71.5	18.9	1.2
03:00	67.1	18.2	0.7
04:00	60.4	17.8	0.4
05:00	53.6	17.5	0.3

The calculated sequence demonstrates that the cooling process does not evolve proportionally with time, even under fixed geometric conditions. The strongest thermal extraction appears during the middle nocturnal period, when the temperature contrast between the emitting surface and the effective sky background reaches its highest value. A temporary reduction in extraction intensity is observed before midnight, followed by renewed strengthening as atmospheric long-wave return weakens.

The water temperature profile reveals cumulative cooling with progressively diminishing temperature decrease toward dawn. This behavior indicates that as the liquid approaches lower thermal levels, the driving difference responsible for outward heat removal becomes less pronounced. The obtained pattern confirms that the most productive operational interval for radiative water cooling is concentrated within the central nighttime hours, where atmospheric transparency and reduced thermal feedback jointly maximize energy discharge toward deep space.

For three-dimensional visualization, the dataset should be arranged so that the independent atmospheric progression remains on one horizontal axis, the thermal extraction intensity occupies the second horizontal axis, and the resulting water temperature forms the vertical response surface. Such placement allows direct observation of how variations in instantaneous outward heat removal correspond to the thermal state of the circulating liquid during successive nocturnal intervals.

As illustrated in Figure 1, the dataset is arranged so that the independent atmospheric progression remains on one horizontal axis, the thermal extraction intensity occupies the second, and the resulting water temperature forms the vertical response surface.

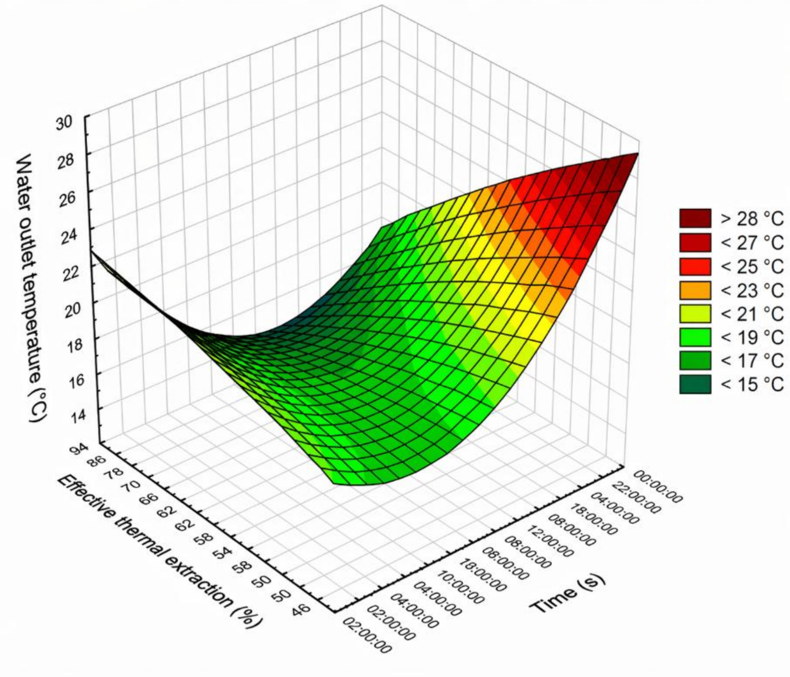

Fig. 1. **Three-dimensional thermal response surface of nocturnal radiative water cooling under varying atmospheric heat extraction conditions**

The regression surface obtained from the three-dimensional approximation demonstrates that the thermal response is governed by a distinctly nonlinear interaction. The positive quadratic contribution associated with the time-related term indicates that the reduction of water temperature does not proceed uniformly throughout the nocturnal interval but intensifies within specific periods when atmospheric conditions become more favorable for outward long-wave heat release.

The positive linear coefficient linked to thermal extraction confirms that stronger outward surface heat removal remains the principal factor supporting deeper cooling of the circulating water. At the same time, the negative interaction term between both variables reveals that the influence of increasing heat extraction weakens as the operating period advances, which reflects the gradual reduction of the thermal gradient between the water volume and the emitting surface.

The negative curvature associated with the second independent variable further indicates that excessive growth of instantaneous thermal extraction does not produce proportional cooling at later stages, since the stored liquid progressively approaches a lower thermal equilibrium. Such behavior is consistent with the physical limitation of nocturnal radiative systems, where the available temperature difference continuously contracts during prolonged operation.

Overall, the regression surface confirms that the most productive cooling regime is concentrated within an intermediate nocturnal interval, where atmospheric transparency, reduced thermal return from ambient air, and sufficient initial water temperature jointly create the most favorable conditions for heat discharge toward deep space.

$$W_{out} = 4.4255 + 16.4007x + 0.4313y + 19.02x^2 - 0.5284xy - 0.0028y^2, \tag{5}$$

where W_{out} – final water outlet temperature, °C;
x – temporal progression index (hours elapsed from the start of the cycle);
y – instantaneous effective thermal extraction, W·m^{-2}.

These theoretical results exhibit strong agreement with experimental observations of uncovered radiative collectors reported by [1] and [2], which demonstrated comparable nocturnal extraction rates of 50-80 W·m^{-2} under similar clear-sky boundary conditions. The benefit of the present study in terms of acquiring new knowledge lies in the development of a fully coupled computational procedure that accurately predicts the non-uniform degradation of the thermal driving potential without requiring resource-intensive transient CFD modelling. This provides a direct, computationally efficient method to evaluate the dynamic relationship between instantaneous radiative exchange and the sensible thermal inertia of the water mass.

Conclusions

1. The analytical description developed for nocturnal radiative water cooling demonstrated that a compact energy-balance approach is sufficient for quantifying the thermal response of a water-filled emitting surface exposed to the open sky during nighttime operation. The selected formulation made it possible to represent the coupled influence of outward long-wave heat release, atmospheric thermal return, and sensible cooling of the circulating liquid within a simplified computational framework suitable for predictive evaluation.
2. The modeled dataset showed that useful thermal extraction varied non-uniformly during the nocturnal period, with the highest cooling intensity concentrated in the central nighttime interval, where atmospheric thermal opposition became weaker and the temperature difference between the emitting surface and the sky background reached its most favorable range.
3. The calculated decrease in water temperature confirmed cumulative cooling behavior, while the rate of temperature reduction gradually diminished toward the end of the operating period as the liquid approached a lower thermal equilibrium and the available driving thermal potential decreased.
4. Regression analysis of the three-dimensional thermal surface revealed a nonlinear relationship between operating time, effective surface heat extraction, and outlet water temperature, indicating that the cooling process cannot be interpreted as proportional over the entire nocturnal cycle.
5. The results obtained confirm that night-driven radiative cooling using deep-space thermal discharge can provide stable low-intensity water cooling under clear atmospheric conditions and may be considered a technically viable supplementary solution for low-temperature thermal management in energy-efficient engineering systems.
6. The analytical framework confirmed that night-driven radiative cooling provides a highly productive operating period concentrated between 01:00 and 03:00, achieving peak extraction rates exceeding 70 $W \cdot m^{-2}$. Under the simulated clear-sky, low-wind atmospheric conditions, the system effectively yields an estimated cumulative cooling capacity of approximately 0.6 $k \cdot Whm^{-2}$ per night, lowering the water temperature by 6.8°C.
7. The principal scientific novelty of this study consists in formulating a dynamic, reduced-order computational procedure that mathematically captures the nonlinear attenuation of the cooling gradient as the fluid approaches thermal equilibrium. This methodology provides a practical, low-computational-cost predictive tool for integrating passive deep-space thermal discharge into energy-efficient engineering systems, reliably functioning whenever cloudless atmospheric windows are available.

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