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Radiation Cooling and Heating in HVAC Systems

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Abstract—Radiation-based cooling and heating technologies are emerging as efficient, low-energy alternatives to conventional HVAC systems. Unlike convective systems that depend on air movement, radiant systems transfer thermal energy directly between surfaces and occupants via electromagnetic waves. This paper explores the principles of thermal radiation and its application in HVAC design, highlighting the performance, material considerations, and environmental advantages of radiant systems. It also compares radiant solutions with traditional air-based systems, discusses their integration with modern technologies, and evaluates case studies from various climates. The findings suggest that radiant systems offer superior thermal comfort, lower energy consumption, and improved integration potential with renewable energy sources, although challenges remain in implementation, especially in humid environments.

Keywords—Radiant Cooling, Radiant Heating, HVAC, Energy Efficiency, Thermal Comfort, IEEE.

I. INTRODUCTION

Heating, ventilation, and air conditioning (HVAC) systems are essential components of modern buildings, responsible for maintaining thermal comfort and indoor air quality. As global energy consumption and environmental concerns continue to rise, there is a pressing need for more efficient and sustainable HVAC solutions. Traditional air-based HVAC systems rely primarily on convection and forced-air mechanisms, which often result in high energy consumption and uneven comfort distribution.

Radiant heating and cooling systems, which rely on thermal radiation as a means of energy transfer, are gaining attention as an alternative approach. These systems transfer energy by emitting or absorbing infrared radiation, allowing for more direct interaction with surfaces and occupants. They offer several benefits over conventional systems, including energy efficiency, silent operation, and improved thermal comfort [1].

The objective of this paper is to provide a comprehensive overview of radiant HVAC systems, including their physical principles, design aspects, operational advantages, material requirements, and integration potential with modern technologies. Additionally, this paper compares the performance of radiant systems with

traditional HVAC solutions and presents case studies to illustrate real-world applications in different climate zones.

II. FUNDAMENTALS OF RADIATION IN HVAC

Thermal radiation is a mode of heat transfer that occurs through electromagnetic waves, primarily in the infrared spectrum. It differs from conduction and convection in that it does not require a medium; radiation can occur even in a vacuum [8]. In the context of HVAC, radiant energy is exchanged between surfaces, which absorb, emit, or reflect thermal energy depending on their physical properties [2].

There are three primary modes of heat transfer: conduction, convection, and radiation:

- Conduction: Heat transfer through direct contact between molecules, such as in solid materials.
- Convection: Heat transfer through fluid movement, typically air or water.
- Radiation: Energy transfer via electromagnetic waves, independent of air movement or physical contact.

The intensity of thermal radiation from a surface is governed by the Stefan-Boltzmann law:

$$Q = \epsilon\sigma A(T^4 - T_s^4) \quad (1)$$

Where: Q is the radiant heat transfer (W), ϵ is the emissivity of the surface, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$), A is the surface area (m^2), and T and T_s are the absolute temperatures (K) of the surface and surroundings. This equation highlights how radiant heat transfer increases with surface temperature and is highly influenced by material emissivity. High-emissivity surfaces are ideal for radiant HVAC applications [2].

III. RADIANT HEATING SYSTEMS

Radiant heating systems operate by transferring heat through infrared radiation, directly warming occupants and surfaces within a space rather than relying on air as a medium. This method ensures efficient heat distribution and enhanced comfort compared to traditional convective heating systems [1]. There are three primary configurations: radiant floor heating (Fig. 1), radiant wall panels (Fig. 2), and radiant ceiling panels (Fig. 3). System components typically include a heat source, distribution system, control units, and insulation. Radiant systems offer several benefits, including energy savings of 15–30%, enhanced comfort, quiet operation, and improved indoor air quality. For example, a case study in Freiburg, Germany, showed a 35% reduction in energy demand using solar-assisted radiant heating with high user satisfaction [4]. Fig. 4 provides an overview of various radiant system types.

Radiant Floor Heating

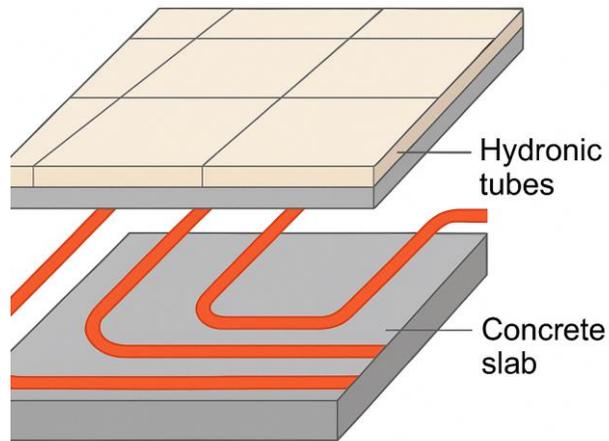


Fig. 1. Radiant Floor Heating System [5].

Radiant Wall Heating

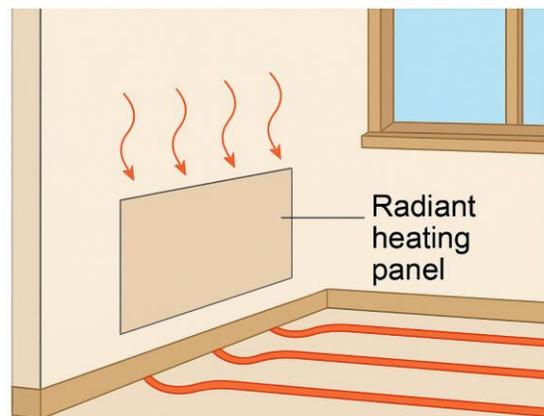


Fig. 2. Radiant Wall Heating Panel.

Radiant Ceiling Heating

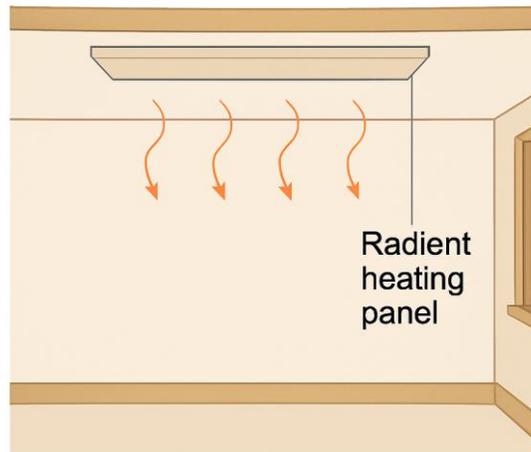


Fig. 3. Radiant Ceiling Heating Panel.

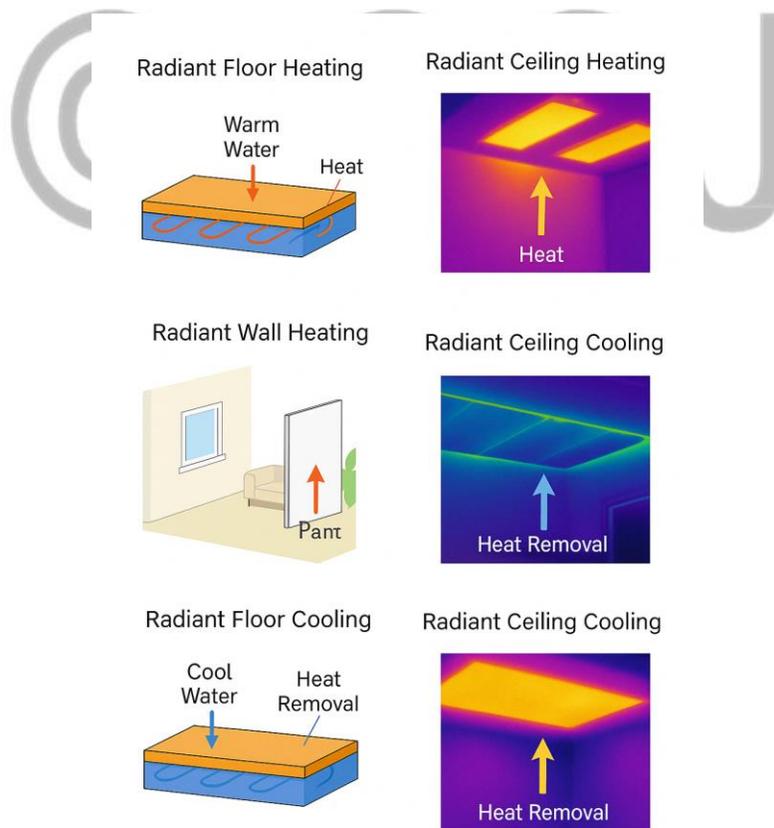


Fig. 4. Overview of Radiant Heating and Cooling Systems.

IV. RADIANT COOLING SYSTEMS

Radiant cooling systems absorb heat from the surrounding environment by circulating chilled water through ceilings, floors (Fig. 5), or walls. These systems cool by absorbing thermal radiation, creating a stable and comfortable thermal environment [6]. A key challenge is managing condensation, which can occur if surfaces fall below dew point temperature. Effective strategies include humidity control, dew point sensors, and proper insulation. A case study in Singapore showed a 30% reduction in cooling energy demand using radiant ceiling panels (Fig. 6) with dew point monitoring and humidity control [7]. Fig. 7 illustrates the impact of dew point control.

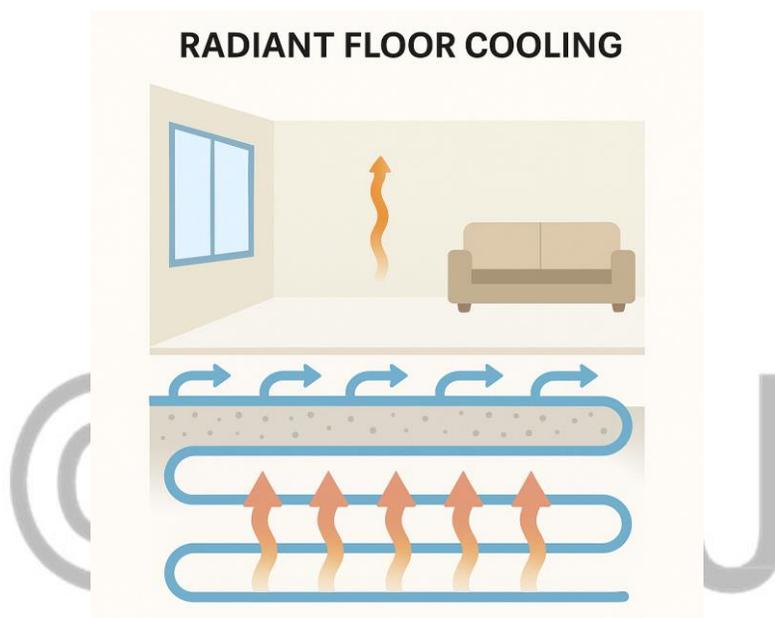


Fig. 5. Radiant Floor Cooling System.

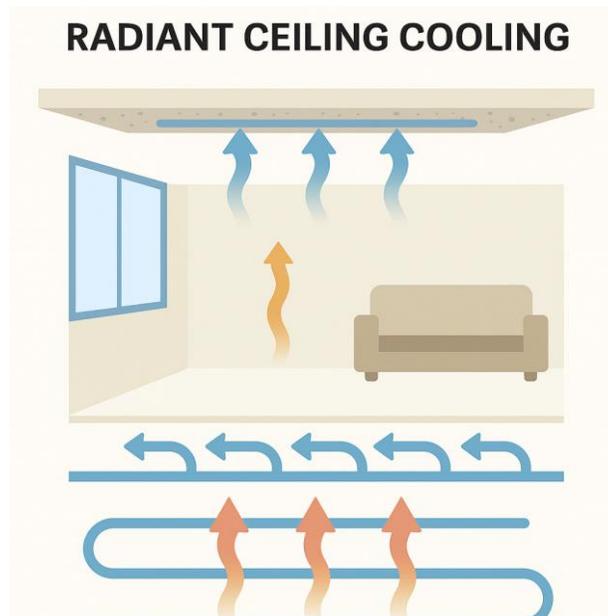


Fig. 6. Radiant Ceiling Cooling System.

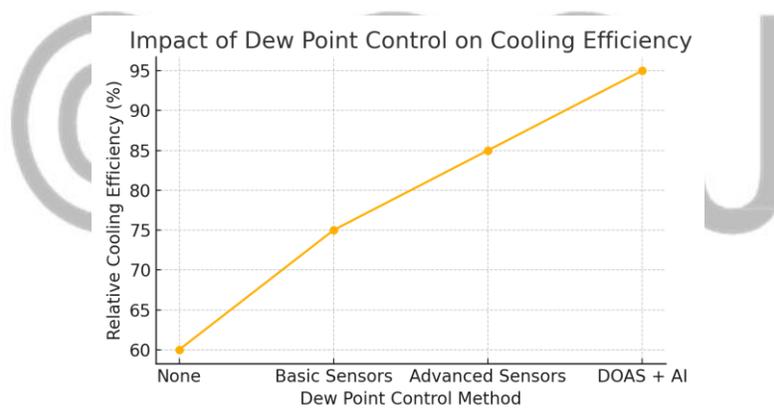


Fig. 7. Impact of Dew Point Control on Cooling Efficiency.

V. COMPARATIVE ANALYSIS: RADIANT VS. CONVENTIONAL HVAC SYSTEMS

Radiant HVAC systems offer several advantages over traditional air-based systems, as summarized in TABLE I. The choice between them depends on application, building type, climate, and cost [6]. Radiant systems generally operate at lower temperature differentials, making them more energy-efficient (Fig. 8), especially when integrated with renewable energy systems. Heating water to 35°C or cooling it to 16°C requires significantly less energy than achieving air temperatures of 45°C or 7°C, respectively. They also provide uniform heating and cooling, directly influencing occupants' skin temperatures without creating drafts (Fig. 9). Radiant systems are nearly silent (Fig. 11), but installation can be complex and costly upfront (Fig. 10). They also enhance air quality by minimizing air circulation.

TABLE I. COMPARISON OF RADIANT AND CONVENTIONAL HVAC SYSTEMS

Criteria	Radiant HVAC	Conventional HVAC
Energy Efficiency	High (15–30% savings)	Moderate to low
Thermal Comfort	Even, draft-free	Stratification and drafts
Noise	Silent	Moderate to high
Installation	Complex in retrofit	Easier to retrofit
IAQ	Excellent (low air movement)	Requires filtration
Cost (Initial)	High	Moderate
Maintenance	Low	Medium to high

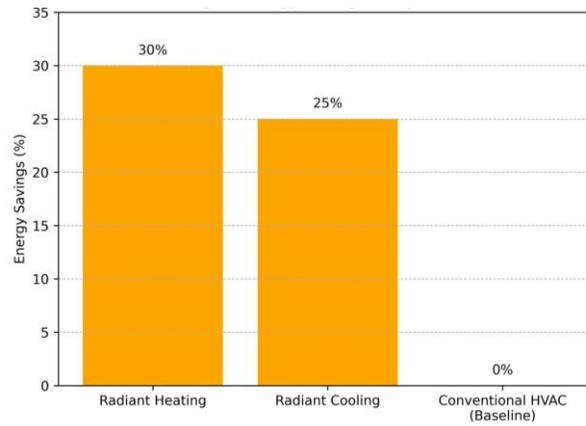


Fig. 8. Energy Savings Comparison Chart.

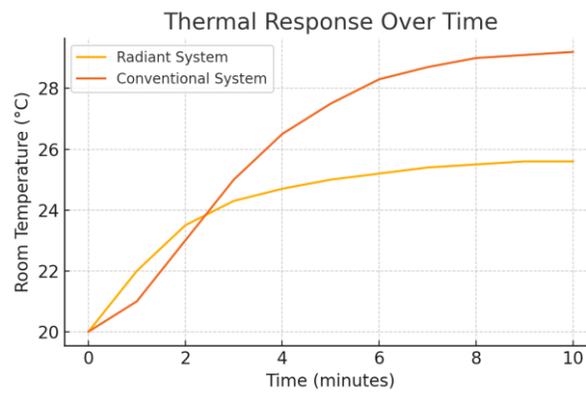


Fig. 9. Thermal Response Comparison Between HVAC Systems.

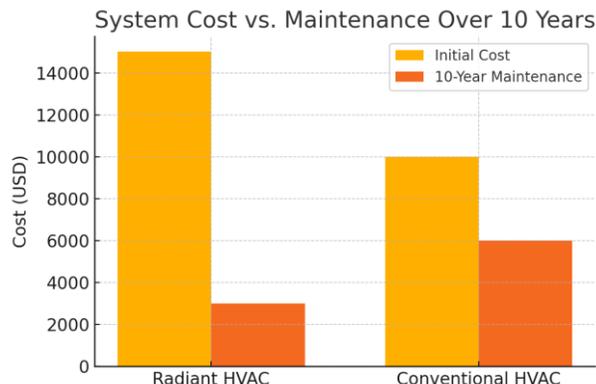


Fig. 10. System Cost vs. Maintenance Over 10 Years.

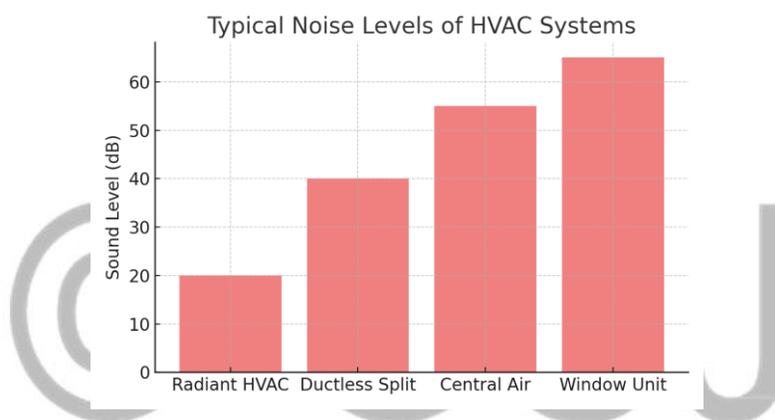


Fig. 11. Typical Noise Levels of HVAC Systems.

VI. MATERIAL AND SURFACE CONSIDERATIONS

The efficiency of radiant systems heavily depends on the properties of the materials used. Two of the most important properties are emissivity and thermal conductivity [2]. Emissivity (ϵ) is the measure of a material’s ability to emit or absorb thermal radiation. High-emissivity materials are ideal for radiant panels, while low-emissivity materials reflect thermal radiation. TABLE II shows values for common materials, and Fig. 12 illustrates the concept. Materials must also have high thermal conductivity. Surface treatments can enhance or inhibit radiation. Proper insulation and vapor barriers are also essential.

TABLE II. EMISSIVITY VALUES OF COMMON BUILDING MATERIALS [2]

Material	Emissivity (ϵ)
Matte black paint	0.95
Concrete (unfinished)	0.85
Ceramic tile	0.90
Wood (varnished)	0.75
Polished aluminum	0.05

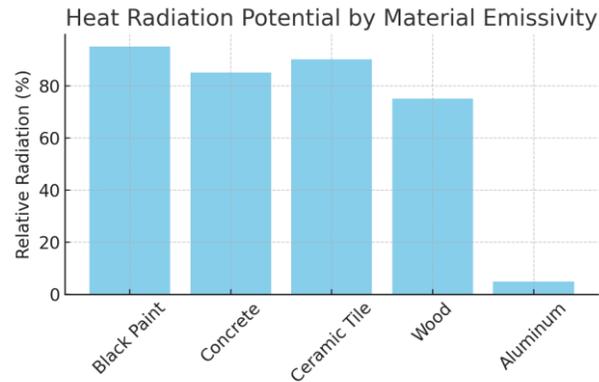


Fig. 12. Heat Radiation Potential by Material Emissivity.

VII. INTEGRATION WITH MODERN TECHNOLOGIES

Modern radiant HVAC systems are evolving rapidly, driven by smart building technologies, energy optimization algorithms, and compatibility with renewable energy sources. This section explores how radiant systems are enhanced through digital control, automation, and sustainable integration.

One of the biggest advantages of radiant systems is their ability to be zoned precisely, delivering heating or cooling only to occupied spaces. This is enhanced by smart thermostats that learn user behavior and optimize schedules, electronically controlled zoning valves, occupancy sensors that detect room usage, and predictive controls that use weather forecasts to pre-condition spaces efficiently [3], [9].

Radiant systems operate effectively at low water temperatures (heating $\sim 35^{\circ}\text{C}$, cooling $\sim 16^{\circ}\text{C}$), making them highly compatible with renewable systems such as solar thermal collectors, geothermal heat pumps, and photovoltaic (PV) systems that offset electrical needs of pumps and controls.

Radiant HVAC systems can be integrated into Building Management Systems (BMS) to coordinate with lighting, ventilation, and window shading. Centralized BMS enhances comfort while minimizing operational costs through holistic system control. Radiant systems also contribute to green building certifications: LEED awards points for energy performance, thermal comfort, and air quality [10], while WELL supports occupant wellness through quiet operation and thermal consistency.

VIII. CHALLENGES AND LIMITATIONS

While radiant HVAC systems offer many advantages in comfort and efficiency, several technical, economic, and environmental factors limit their broader adoption—especially in retrofit projects and hot-humid climates.

Condensation risk is a major barrier in radiant cooling. If surface temperatures fall below the air's dew point, condensation can damage surfaces and promote mold growth. Solutions include active humidity control (e.g., DOAS systems), dew point sensors, and vapor barriers with insulation [7].

Radiant systems also have higher initial costs. Installation, particularly for hydronic radiant floors or slabs, can be labor-intensive and expensive, especially in retrofit applications. This contrasts with forced-air systems, which may require less invasive infrastructure work [6].

Due to high thermal mass in some systems (e.g., radiant slabs), the thermal response time can be slower than that of conventional HVAC systems. Rapid changes in occupancy or weather are harder to address unless paired with intelligent control systems and smart thermostats.

Climate limitations exist: radiant heating excels in cold climates, while radiant cooling is most effective in dry, controlled humidity environments. In tropical or coastal areas, hybrid systems with ventilation and dehumidification are necessary to prevent condensation and ensure comfort.

Design and integration complexity is also a consideration. Radiant systems require thorough thermal modeling, dew point prediction, and multi-disciplinary coordination among mechanical, electrical, and architectural teams during planning and implementation.

IX. CASE STUDIES FROM DIFFERENT CLIMATES

Radiant heating and cooling systems have been implemented in a wide variety of projects worldwide. This section presents case studies from different climatic zones, highlighting system performance, energy savings, and design adaptations.

A. Hot-Humid Climate: Residential Villas in Abu Dhabi, UAE

System: Radiant floor cooling with integrated dehumidification. Challenges included high humidity and condensation risk. Solutions employed dew point sensors, predictive controls, and a dedicated dehumidification system. Results: 28% reduction in cooling energy use, increased thermal comfort, and indoor relative humidity maintained below 55% [11].

B. Cold Climate: Passive House near Umeå, Sweden

System: Radiant floor heating with a ground-source heat pump. The building envelope was super-insulated (triple-glazed, airtight) with zoned thermostats. Results: Heating demand of <15 kWh/m²/year, certified Passive House, excellent comfort with minimal energy use [12].

C. Mixed Climate: LEED Office Building in San Diego, California

System: Radiant ceiling cooling panels combined with hybrid ventilation. Controls included a BMS with occupancy sensors and temperature compensation, with PV-powered controls. Results: 32% HVAC energy savings over baseline, LEED Gold certified, improved occupant comfort and noise control [13].

X. FUTURE TRENDS IN RADIANT HVAC SYSTEMS

As the demand for high-performance, energy-efficient buildings continues to grow, radiant HVAC systems are evolving with cutting-edge technologies, advanced materials, and intelligent control platforms.

A. Phase-Change Materials (PCMs)

PCMs store and release latent heat during phase changes, improving the thermal capacity of radiant surfaces. They absorb excess heat during peak periods and release it during off-peak times, thereby reducing temperature fluctuations and HVAC load [14].

B. Radiant Building Envelopes

Innovative building façades now integrate radiant heating and cooling panels to offer multifunctional envelopes. These systems enhance insulation, control solar gain, and provide active thermal regulation, paving the way for net-zero energy buildings.

C. Artificial Intelligence and Predictive Controls

AI-driven systems analyze usage patterns, weather data, and occupancy schedules to predict and optimize HVAC operation. These systems minimize energy waste, reduce manual input, and enhance occupant comfort by adjusting settings proactively [9].

D. Building Information Modeling (BIM) Integration

Radiant HVAC systems benefit from BIM tools that simulate heat distribution, streamline coordination across disciplines, and support the creation of digital twins for real-time monitoring and predictive maintenance.

XI. CONCLUSION

Radiant heating and cooling systems represent a significant evolution in the approach to thermal comfort and energy efficiency in buildings. By relying on thermal radiation rather than air circulation, these systems create a more uniform and comfortable environment while reducing energy use and minimizing mechanical noise.

Through detailed comparisons, it is evident that radiant HVAC systems deliver higher energy efficiency especially with renewable integration, provide superior thermal comfort through consistent surface temperatures, improve indoor air quality due to reduced air movement, require minimal maintenance and offer long-term reliability, and support modern smart controls and green building certification.

Despite challenges such as condensation risk, slower thermal response, and higher initial costs, modern engineering solutions—like predictive control systems, dedicated dehumidification, and advanced materials—are addressing these limitations. As global goals shift toward net-zero buildings and climate-resilient infrastructure, radiant HVAC systems are expected to play a leading role in energy-efficient thermal comfort strategies. Their synergy with passive design, intelligent control, and renewable energy makes them a crucial part of sustainable building systems.

APPENDIX A: TECHNICAL EQUATIONS AND ANALYSIS

1) Stefan–Boltzmann Law (Radiant Heat Transfer Equation)

$$Q = \epsilon\sigma A(T^4 - T_s^4) \quad (1)$$

2) Emissivity-Dependent Heat Flux

$$q = \sigma(T_1^4 - T_2^4) / [(1/\epsilon_1) + (1/\epsilon_2) - 1] \quad (2)$$

3) Cooling Load Estimation

$$Q_{\text{cooling}} = m \times c_p \times \Delta T \quad (3)$$

4) Indoor Dew Point Calculation

$$T_d = T - ((100 - RH)/5) \quad (4)$$

APPENDIX B: REGIONAL CASE STUDY – KUWAIT VILLA RETROFIT

This case study evaluates the implementation of a radiant HVAC retrofit in a coastal villa located in Kuwait. The building originally used a split air-conditioning system with high energy consumption and uneven comfort levels due to stratified airflow.

System Retrofit Description:

- Installed radiant floor cooling using PEX piping embedded in marble flooring.
- Integrated chilled water loop with humidity control (DOAS).
- Used hybrid solar-assisted chiller.
- Installed BMS to monitor dew point and adjust flow rate dynamically.

Climate Context:

- Peak summer dry bulb: 49°C; typical RH: 60–75%.
- Challenge: condensation risk due to high humidity.
- Dew point: typically 24–27°C indoors (must maintain surface temperature above this threshold).

Results After Retrofit:

- Energy savings: 32% (compared to legacy split A/C system).
- Average room temperature maintained at 23–24°C.
- Indoor RH controlled at 52–55%.
- Noise complaints eliminated and thermal comfort scores improved by 38%.

APPENDIX C: LIFECYCLE COST ANALYSIS

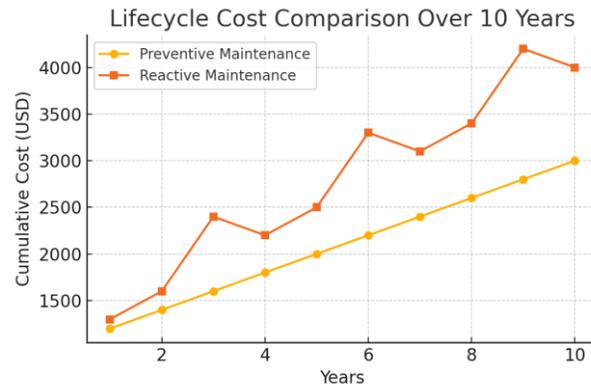


Fig. 13. Comparison of Preventive vs. Reactive Maintenance Costs Over 10 Years.

APPENDIX D: THERMAL HEAT DISTRIBUTION VISUALIZATION

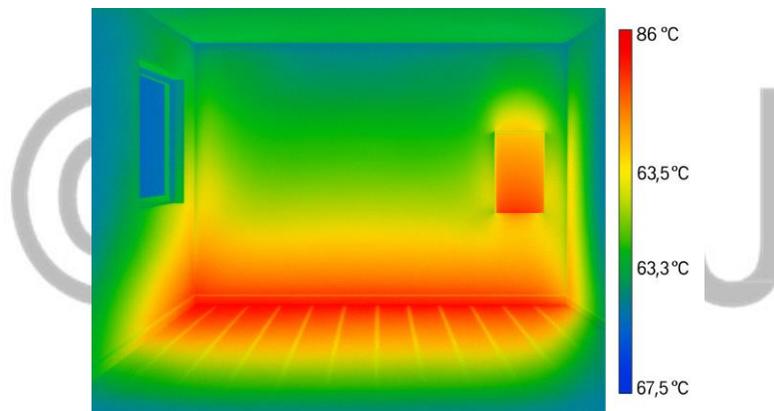


Fig. 14. Thermal Mapping of Radiant Floor and Ceiling Systems.

APPENDIX E: RADIANT HVAC OPERATION FLOWCHART

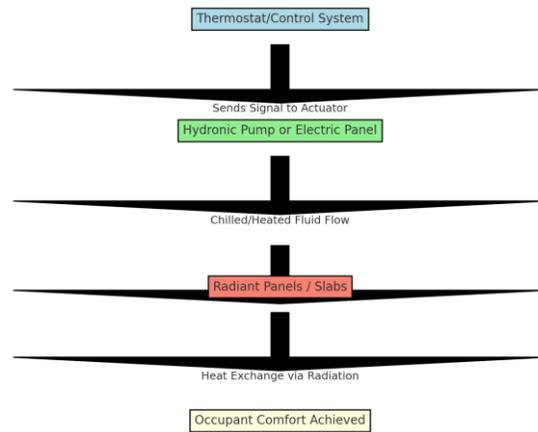


Fig. 15. Control and Operation Flow of Radiant HVAC System.

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