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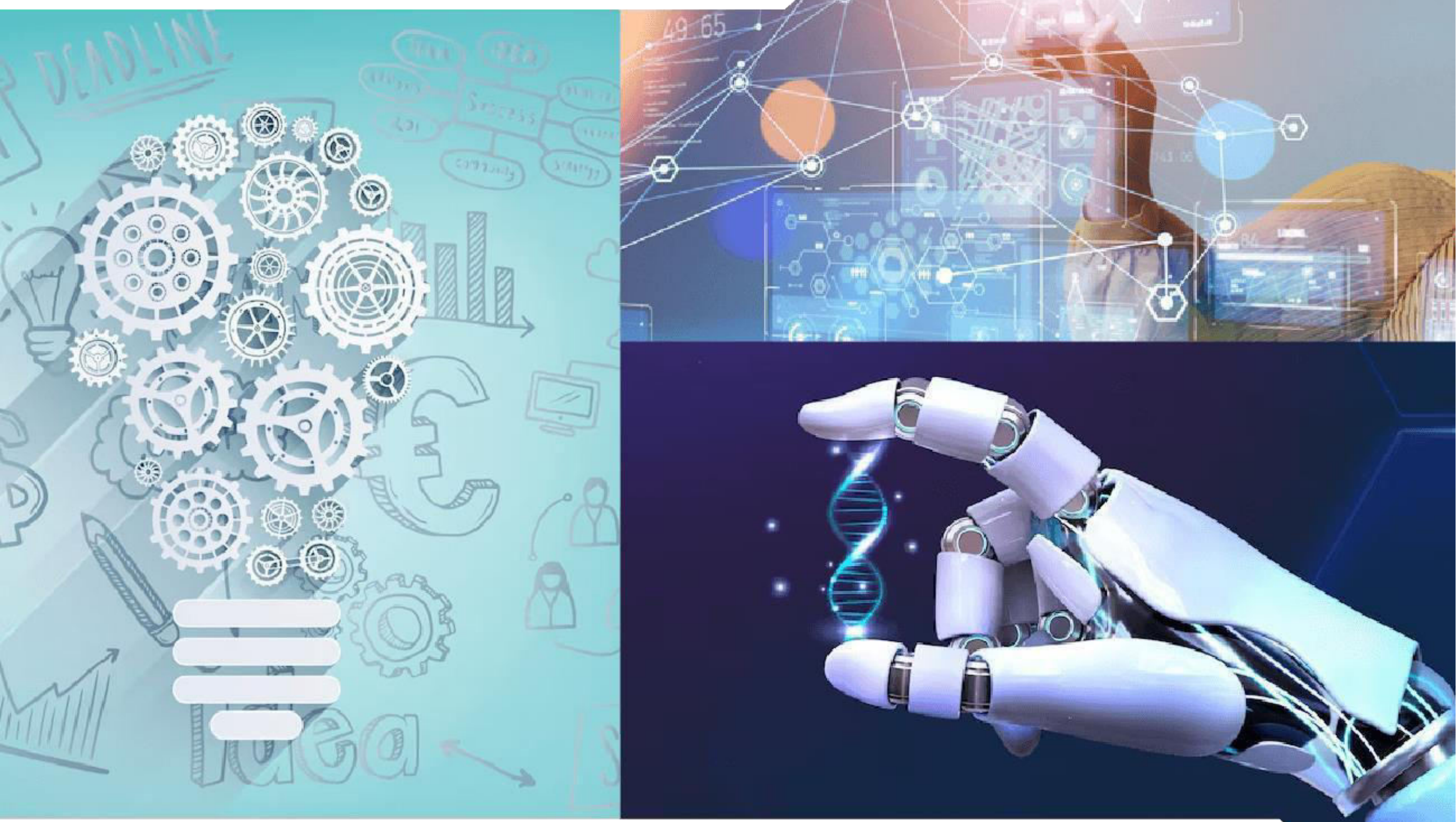

International Journal of Advanced Research in Education and TechnologY (IJARETY)

Volume 12, Issue 4, July-August 2025

Impact Factor: 8.152

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

INNO SPACE SJIF Scientific Journal Impact Factor

doi crossref

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International Journal of Advanced Research in Education and TechnologY(IJARETY)

IJARETY SSN: 2394-2975 | www.ijarety.in| | Impact Factor: 8.152| A Bi-Monthly, Double-Blind Peer Reviewed & Refereed Journal |

|| Volume 12, Issue 4, July - August 2025 ||

DOI:10.15680/IJARETY.2025.1204041

Recent Advances in Defrost Systems for Refrigeration and Heat Pump Applications: A Review

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ABSTRACT: Frost accumulation on heat exchangers degrades cooling and heating performance, necessitating periodic defrost cycles. This review surveys defrost methods for **domestic refrigerators** and **air-source heat pumps (ASHPs)**, comparing conventional techniques (electric-heater defrost, reverse-cycle/hot-gas defrost, warm-brine defrost) with advanced strategies (air-bypass schemes, thermal storage, and smart control). Reverse-cycle (hot-gas) defrost generally achieves the fastest thawing (highest defrost efficiency ~56–61%) [1], whereas standard electric-heater defrost (EHD) has lower efficiency (~40–45%)[1]. Novel methods can greatly improve performance: for example, an air–bypass design with heater cut defrost time by ~62% and energy by ~61% [2]. Machine-learning and vision-based control (e.g. threshold or image-detection of frost) can reduce unnecessary defrosts, e.g. achieving ~8.3°C optimal thresholds [3] or reducing defrost cycles by 75% [4]. Tables compare methods on metrics (energy use, defrost time, cost/complexity). Overall, advanced defrost techniques offer substantial energy savings and maintain capacity, at the expense of increased system complexity.

I. INTRODUCTION

Frost forms on evaporator coils when humid air condenses and freezes, creating an insulating layer that reduces heat-transfer and increases energy use[5][6]. In frost-free refrigerators and freezer compartments, automatic defrost cycles (e.g. heating the coils) are used to remove frost periodically. Similarly, **air-source heat pumps (ASHPs)** operating in cold, humid conditions require defrosting of the outdoor coil to restore heating capacity. However, defrosting temporarily halts cooling/heating and consumes extra energy. Improving defrost efficiency is thus crucial for system performance.

Typical defrost methods include **electric-heater defrost (EHD)**, where resistance heaters warm the evaporator, and **reverse-cycle/hot-gas defrost (RCD)**, which reroutes hot refrigerant to the evaporator. Warm-brine or water circuits can also provide heat for defrost. Each method has trade-offs: RCD tends to defrost faster with less energy (since it uses refrigerant latent heat), whereas EHD is simpler and cheaper but consumes more energy [6][5]. Recent innovations include bypass-air circulation with heaters, thermal-energy storage (phase-change materials), and sensor-based control (frost detection using cameras or data models). This paper reviews these approaches, focusing on **domestic refrigeration** and **ASHP systems**, with comparative analysis of performance metrics (energy use, defrost time, cost, complexity).

II. DEFROST METHODS IN DOMESTIC REFRIGERATION

Frost-free home refrigerators traditionally rely on electric heaters integrated in the evaporator. A study by Bansal et al. [8] found that only ~30% of the electrical defrost heat actually melted frost, with defrosting raising overall freezer energy use by ~17.7% [5]. In other words, standard EHD is relatively inefficient: high heater temperatures (500–560°C) are needed, and much heat is wasted on the cabinet and other components. For example, an electric heater's defrost efficiency was measured at only 30.3% [5], confirming that defrost substantially increases power draw.

Alternate heater designs and control modes have been explored to improve EHD performance. For instance, Shah et al. found that glass-tube heaters achieved slightly higher defrost efficiency (≈32%) than common Calrod or U-type heaters[7], though detailed power metrics remain low overall. Pulsed or stepwise power control can more uniformly distribute heat and improve efficiency, but practical gains are modest [7]. A novel **air-bypass circulation** method (used in cold storage) embeds heaters in the coil fins and circulates warm air across the coils, rather than directly heating the

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space [2]. Yin et al. [5] demonstrated this approach: defrost time fell by ~62% and energy by ~61% compared to traditional EHD[2], and defrost efficiency rose to ~78% (nearly three times that of standard EHD). This shows that re-routing airflow can greatly enhance defrost efficiency in freezer applications.

Passive frost-retardant techniques (hydrophobic coatings, microstructured fins) can delay frosting but are beyond our scope. Instead, **demand-controlled defrost** has gained attention. Sensor-based schemes only initiate defrost when frost exceeds a threshold, saving unnecessary cycles. Huang et al. [20] used machine learning on fridge sensor data to optimize a **time–**temperature-**differential (t–ΔT)** defrost strategy. They found an optimal ΔT ≈8.3°C: triggering defrost when fridge-wall temperature rose by 8.3°C over ambient minimized power use while maintaining capacity [3]. In testing, this ML-guided t–ΔT control outperformed the fixed-timer method under high ambient conditions, reducing energy and improving cooling [8].

Vision-based methods are also emerging: Rahman et al. [21] developed an image-processing system for domestic refrigerators. A camera observes the evaporator, and frost thickness is estimated via K-means segmentation of images. Their approach achieved a frost-thickness prediction error of ~13.7%, outperforming conventional capacitive (15.2%) or photoelectric (17.5%) sensors [9]. Such techniques could enable precise, on-demand defrosting. Similarly, in ASHPs (see below), camera-based detection can trigger defrost only when needed, greatly reducing cycles.

Table 1 compares common defrost strategies for household refrigerators on key metrics. Electric-heater defrost is simple and low-cost but energy-intensive, whereas advanced methods (warm-brine, PCM, smart control) can cut energy use at the cost of complexity.

Defrost Method	Energy Use	Defrost Time	Cost/Complexity	Notes/Performance
Electric Heater (standard)	High (COP drop)	Moderate (slow)	Low (simple)	Efficiency ~30%, raises energy use ~18% [5]; most common in fridges.
Electric Heater, pulsed/stepped power	Moderate energy saving	Moderate (slightly faster)	Low–Medium (requires control)	Pulsed modes improve heat distribution slightly [7].
Warm Brine (water loop)	Moderate (uses waste heat)	Fast (continuous warming)	High (pump, coils, controls)	At ~30°C supply, efficiency ~40–45% (≈EHD); at low temps (10–20°C) very low (16–29%) [1].
Air-Bypass + Heater (cold storage)	Low (saves ~61%)	Fast (62% shorter)	Medium (air duct, valve)	Time –62%, energy –61% vs EHD [2]; ~78% defrost efficiency.
Phase-Change Material (PCM) Storage	Low (buffers frost heat)	Slower (delays defrost)	Medium (PCM cost)	PCM panels stabilize temp; Gin et al. showed slight energy savings during frost/door loads [10].
ML/Model-Based Control	Low (on-demand)	Optimal (as needed)	High (computing & sensors)	LightGBM optimized t–ΔT control reduced unnecessary defrosts [3].
Vision-Based Control	Low (camera-triggers)	Optimal (as needed)	High (camera + image software)	Zhao et al. (ASHP) cut defrost frequency ~75% and raised COP ~11% [4] (analogous benefits expected in fridges).

III. DEFROST METHODS IN AIR-SOURCE HEAT PUMPS

ASHP outdoor coils accumulate frost during cold, humid operation, necessitating periodic defrost. The **standard methods** are **reverse-cycle defrost (RCD)**, which reverses the refrigerant flow (outdoor coil becomes condenser), and **hot-gas bypass**, which sends compressor discharge to the outdoor coil while isolating the indoor coil. Both use the pump's own heat, but interrupt heating.

Comparative tests show RCD is rapid and efficient: Klingebiel et al. [15] reported that RCD yielded defrost efficiencies of 56–61% (depending on ambient conditions), much higher than electric defrost [1]. In contrast, using low-grade waste heat (warm-brine) at 10–20°C led to only 16–29% efficiency [1] (though at 30°C supply it matched EHD at ~40–45%). Electric-defrost in ASHPs is less common (it requires a large heater upstream of the coil), but yields performance similar to refrigerators: inefficient and energy-intensive.

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Advanced and hybrid methods have been studied to reduce defrost penalties. Thermal-storage and **phase-change materials (PCM)** have been used to supply heat: e.g. an auxiliary PCM–heat exchanger stores heat during operation, then releases it during defrost (so-called "frost-retarding" techniques) [11]. In an ASHP context, Qu et al. found that using heat storage before defrost could cut defrost time by 71–80% and energy use by 65–85% compared to normal RCD[12].

A novel **Air Heat Absorption Defrosting (AHAD)** method [16] uses a reverse-Carnot cycle: ambient air heat is absorbed via an auxiliary circuit to continuously heat water (for heating) even while defrosting. In a 710 kW ASHP test, AHAD maintained heating capacity (315.7 kW average during defrost) and achieved a cumulative COP ~9.3% higher than standard RCD [13]. In other words, AHAD enabled uninterrupted heating, higher effective heating capacity, and smaller supply-temperature fluctuations than RCD.

Ma et al. [18] studied **hot liquid subcooling defrost** in a multi-unit ASHP: they sequentially defrosted outdoor units using hot liquid refrigerant from the condenser. This scheme delivered "rotational" defrost without stopping all units. The result was 10–20% higher heating capacity and energy efficiency than hot-gas bypass defrost [14]. In short, using stored or drawn heat sources (air or liquid) can significantly boost ASHP performance.

Sensor-based controls are also emerging in heat pumps. Zhao et al. [22] implemented **machine-vision defrost control**: cameras analyzed coil images to compute a "frosting degree" and triggered defrost when needed. In comparative tests, this vision method increased COP by ~10–12% and total heat output by ~7% (versus traditional timers), while cutting defrost frequency ~75% [4]. The reduced defrost frequency means less wasted compressor cycling and more continuous heating.

Table 2 summarizes ASHP defrost strategies. Conventional RCD and hot-gas methods are contrasted with newer approaches (heat storage, liquid subcooling, AHAD, vision/ML). Advanced methods tend to reduce energy consumption and maintain heating during defrost, but add complexity or cost (additional heat exchangers, valves, or control systems).

Defrost Method	Energy Use	Defrost Time	Cost/Complexity	Notes/Performance
Reverse-Cycle (Hot-Gas)	Low (efficient use of heat)	Short (fast defrost)	High (4-way valve, controls)	Highest defrost efficiency (~56–61%) [1]; interrupts heating cycle.
Electric Heater	High (external power)	Moderate (slower)	Medium–High (heater, wiring)	Reduces heating capacity severely; no heat pump COP. Rare in ASHPs.
Warm Brine Defrost	Moderate (uses waste heat)	Short (continuous heat)	High (pumps, heat exchangers)	At 30°C supply, ~40–45% efficiency [1]; uses external fluid loop.
Hot Liquid Subcooling	Lower (captured condenser heat)	Moderate	High (additional piping)	+10–20% heating capacity and efficiency vs hot-gas [14].
PCM Heat Storage (Frost-retarding)	Very Low (stored heat)	Delayed/shortened	High (PCM costs)	Can greatly shorten defrost (–71–80% time) and –65–85% energy [12].
Air Heat Absorption (AHAD)	Low (air-sourced heat)	Moderate (continuous heat)	High (auxiliary loop)	9.3% higher cumulative COP, continuous heating during defrost [13].
Vision/ML-based Control	Lowest (on-demand defrost)	Short (just-in-time)	High (sensors + ML)	Increases COP by ~11–12%, reduces defrost cycles 75% [4].

IV. RESULTS AND DISCUSSION

The comparative metrics show clear trends. **Reverse-cycle defrost** is generally the most energy-efficient (since it uses latent heat) and fastest, but requires expensive valves and sacrifices immediate heating. **Electric defrost** is cheap and robust for small fridges, but wastes substantial energy and inflates power use[5]. Hybrid methods (air bypass or liquid subcooling) that redirect heat from the system or environment can cut defrost energy by over half [2][14]. For example,

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inserting an air-bypass flow into a freezer with a heater halved both defrost time and energy [2]. In ASHPs, novel schemes like AHAD or sequential subcooling enable **continuous heating** during defrost, improving user comfort and overall efficiency [13][14].

Smart control techniques dramatically reduce unnecessary defrost cycles. Data-driven thresholding (e.g. ML-predicted frost levels) and image analysis outperform fixed timers. Huang et al.'s LightGBM strategy, for instance, optimized defrost thresholds to minimize power usage [3]. Zhao et al. showed that visual detection could cut ASHP defrost frequency by 75%[4]. These methods require added sensors and computation, but achieve clear energy savings by avoiding over-defrosting.

Both domains indicate trade-offs: **high-efficiency defrost** often means **higher system cost/complexity**. Warm-brine or PCM defrost (requiring extra pumps, fluids, or storage media) have more components than simple electric heaters. Vision/ML control adds cameras or computing. Yet as energy codes tighten, these costs may be justified by operating savings. The studies reviewed consistently find that an adaptive or waste-heat-based defrost system can reduce energy consumption by tens of percent compared to conventional methods [2][3].

V. CONCLUSION

Defrost strategies for refrigerators and heat pumps are evolving beyond simple time-based heaters. **Reverse-cycle (hot-gas) defrost** remains highly effective and efficient, but novel methods can significantly improve performance. In cold-storage and ASHP applications, incorporating ambient heat (via air-absorption or hot liquid loops) or thermal storage can maintain heating during defrost and cut cycle losses [13][14]. In domestic fridges, precise controls using real-time frost detection (via sensors, algorithms, or images) enable on-demand defrosting, saving energy while preserving cold capacity [3][4]. Comparative data (Tables 1–2) emphasize that defrost energy use varies widely (from heavy penalties in naïve EHD up to large savings with smart control). The main challenge is balancing **energy savings vs. cost/complexity**. Future work should focus on affordable sensor integration, and on leveraging latent/waste heat for continuous defrosting, to maximize efficiency of frost-free refrigeration systems.

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International Journal of Advanced Research in Education and Technology

ISSN: 2394-2975 Impact Factor: 8.152

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