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Review of Heat Transfer Enhancement Techniques in Domestic Refrigeration Systems

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ABSTRACT

Domestic refrigeration is responsible for roughly 15–20% of residential electricity use worldwide. With the enforcement of the Kigali Amendment and evolving energy efficiency standards, improving the performance of the Vapor Compression Refrigeration Cycle (VCRC) has become a key objective. This paper presents a detailed review of heat transfer enhancement (HTE) methods, focusing on passive structural changes, nanofluids, and Phase Change Materials (PCM). A comparative assessment is provided on evaporator tube designs, specifically V-notched, U notched, and square-notched configurations. Experimental results show that while square-notched tubes can degrade system performance, both U- and V notched profiles enhance the Coefficient of Performance (COP). The U-notched design achieves a peak COP of 1.99, outperforming plain tubes, which reach only 1.74. These findings are consolidated to guide the development of more energy efficient home cooling systems.

Keyword - Refrigeration, Heat Transfer Enhancement, Domestic Refrigerator, Vapour Compression Refrigeration Cycle.

1. INTRODUCTION

The Vapor Compression Refrigeration Cycle (VCRC) remains the primary technology for household refrigeration and food preservation. In such systems, overall efficiency largely depends on how effectively heat is exchanged in the evaporator and condenser. As the refrigerant undergoes phase transitions evaporating at low pressure and condensing at high pressure thermal resistance at the tube walls often limits performance. The rate of heat transfer (Q) follows the basic equation:

$$Q = U \cdot A \cdot \Delta T_{lm}$$

where U represents the overall heat transfer coefficient, A is the surface area available for heat exchange, and $\Delta T_{lm}$is the log-mean temperature difference.

To improve the Coefficient of Performance (COP), researchers focus on HTE strategies that increase either U or A. Enhancing U typically involves disrupting the thermal and viscous boundary layers in the refrigerant flow, whereas increasing A may involve adding fins or internal surface features like micro-grooves. HTE methods fall into three broad categories:

1. Passive Techniques: These require no external power input and rely instead on modified surface structures (e.g., notched tubes, inserts) or fluid additives like nanofluids to induce turbulence and boost heat transfer.

2. Active Techniques: These depend on external energy sources such as vibrations, electric fields, or mechanical agitation which are often impractical for compact domestic units.

3. Compound Techniques: These combine passive and active approaches to achieve greater overall improvement.

Modern refrigeration faces two major challenges: rising demand for higher energy efficiency and the global shift toward low Global Warming Potential (GWP) refrigerants like R600a (isobutane) and R290 (propane), mandated by the Kigali Amendment. These natural refrigerants differ significantly in thermophysical properties such as latent heat and viscosity from traditional HCFCs. As a result, conventional smooth-tube heat exchangers are often unable to fully exploit their potential. This underscores the need for advanced evaporator designs, including U- and V-notched tube geometries, to maximize thermal performance without causing excessive pressure drop (ΔP).

2. LITERATURE REVIEW

Todrov et.al. [1] developed a table-top refrigerator evaporator design based on virtual prototyping. By examining four different geometries of serpentine curves and modifying the axis, they utilized CFD models to analyze performance. Their results indicated that specific modifications to the serpentine axis could increase the heat flow rate by up to 7%.

Sushma Garad et.al. [2] studied numerical analysis of square-notched twisted tape inserts in a tube by varying the pitch with air as the working fluid. The investigation, conducted at Reynolds numbers ranging from 35,000 to 45,000, found that heat transfer enhancement for double-slot square-notched inserts was approximately 19.57%, 44.31%, and 75.59% for pitches of 150 mm, 125 mm, and 100 mm, respectively, compared to a plain tube.

Bodius Salam et.al. [3] experimentally investigated tube-side heat transfer coefficients and friction factors for turbulent flow in circular tubes fitted with rectangular-cut twisted tape inserts. Using water as the working fluid and varying Reynolds numbers from 10,000 to 19,000, they observed that Nusselt numbers were enhanced by 2.3 to 2.9 times compared to smooth tubes, albeit with an increase in friction factors.

David J. Kukulla et.al. [4] studied the development of enhanced heat transfer through tubes by comparing non-textured stainless steel tubes with rigidized textured enhanced tubes. Their research across various alloys and flow conditions demonstrated that the 2EHT series of enhanced tubes could increase heat transfer by as much as 106% to 138% depending on the specific configuration.

P. Murugesan et.al. [5] studied the heat transfer and friction factor characteristics of circular tubes fitted with plain twisted tapes (PTT) and U-cut twisted tapes (UTT). Experimental results showed that tubes equipped with UTT provided significantly higher heat transfer rates and thermal enhancement factors (ranging from 1.03 to 1.28) compared to both PTT and plain tubes across various twist ratios.

S. Tabatabaeikia et.al. [6] studied heat transfer enhancement in heat exchangers by employing various types of inserts and modifying tube geometries. Their findings suggested that increasing the inclined angle from 10° to 30° could improve performance by 5% to 11%, while V-cut twisted tapes specifically provided roughly 10% better heat transfer than plain twisted tubes under identical conditions.

Sombat Tamna et.al. [7] experimentally investigated heat transfer enhancement in round tubes using double twisted tapes combined with 30° V-shaped ribs. Using air at Reynolds numbers from 5,300 to 24,000, they found that while a blockage ratio of 0.19 yielded the highest heat transfer, the maximum thermal enhancement factor of 1.4 was achieved at a blockage ratio of 0.09.

U. Arunachalam et.al. [8] carried out an experimental study on flows in circular tubes with V-cut twisted tape inserts using Al_2O_3-Cu/water hybrid nanofluids. They reported that the hybrid nanofluid alone improved the heat transfer coefficient by 25.8% compared to water, and when combined with tape inserts, the enhancement reached 42% over water in a plain tube.

3. PASSIVE HEAT TRANSFER ENHANCEMENT

Passive methods improve heat transfer by modifying surface design or adding substances to the working fluid, disrupting the thermal boundary layer without relying on external power sources such as fans or pumps. This makes them highly attractive for boosting the Energy Efficiency Ratio (EER) of household appliances.

3.1 Air-Side Enhancement (Condenser)

In natural convection systems, heat dissipation on the air side is typically the limiting factor due to air's low thermal conductivity compared to refrigerants.

Louvered and Wavy Fins: These fin designs interrupt the development of a laminar boundary layer. Louvers function like small secondary fins that redirect airflow, while wavy patterns create a more complex flow path, increasing how long air stays in contact with the hot surface.

The Science: Enhancing the Nusselt number ($N_u = \frac{hD}{k}$) directly improves the convective heat transfer coefficient (h).

Vortex Generators (VGs): Typically shaped like triangles, VGs induce swirling motions called longitudinal vortices. These draw cooler air from the outer flow toward the heated tube surface while pushing warmer air away.

Benefit: This mixing delays flow separation, helping maintain attached airflow over the condenser surface for greater effectiveness.

Fin Spacing & Pitch:

Trade-off: Increasing fin count raises surface area (A), but spacing below 6 mm can lead to overlapping boundary layers. This results in trapped, stagnant air between fins, restricting airflow and reducing cooling performance.

3.2 Refrigerant-Side Enhancement (Evaporator)

Inside the evaporator, the refrigerant undergoes phase change (liquid to vapor), and maintaining liquid contact with the tube walls is crucial for efficient evaporation.

Micro-channel Tubes: These have hydraulic diameters often under 1 mm, offering a high surface-area-to-volume ratio. This allows for much more compact evaporator designs.

Challenge: Smaller channels increase flow resistance. Excessive pressure drop (ΔP) forces the compressor to work harder, potentially offsetting any thermal benefits.

Micro-finned Tubes: Internal grooves (typically 0.1–0.3 mm deep) use capillary action to draw liquid refrigerant up onto fin tips. This supports annular flow, where a thin liquid film covers the entire inner wall, greatly enhancing boiling heat transfer.

Turbulators (Twisted Tapes & Coiled Wires): Inserted into the tube, these force the refrigerant into a spiral motion. Centrifugal forces push denser liquid toward the walls—promoting evaporation—while vapor remains in the center.

Performance: Though capable of increasing heat transfer by 20–40%, they are seldom used in small domestic refrigerators because the added pressure drop overloads compact compressors.

Comparison of Passive Techniques

Table -1: Comparison of Passive Techniques

Technique	Primary Benefit	Major Constraint	Technique	Primary Benefit
Louvered Fins	High h enhancement	Dust accumulation (clogging)	Louvered Fins	High h enhancement
Vortex Generators	Excellent mixing	Complex manufacturing	Vortex Generators	Excellent mixing

4. NANOFLUIDS AND NANO-REFRIGERANTS

Dispersing nanoparticles (1–100 nm) into standard refrigerants or lubricants creates advanced fluids with improved thermal and physical properties.

4.1 Thermal and Lubrication Mechanisms

The improvement goes beyond simple conductivity—it involves molecular-level interactions:

Brownian Motion: Nanoparticles constantly move at random, generating tiny convective currents within the fluid. This micro-scale stirring enhances heat distribution beyond what mechanical means can achieve.

Thermal Conductivity (k): Metals and metal oxides conduct heat far better than liquid refrigerants. Even minimal nanoparticle concentrations form effective "thermal bridges" in the fluid.

Boundary Layer Disruption: Particles physically interfere with the formation of thick, insulating thermal layers near tube walls, facilitating faster heat transfer.

Tribological Benefits (Nanolubricants): When mixed with compressor oil, nanoparticles act like microscopic ball bearings. They fill surface imperfections on moving parts such as pistons and cylinders, reducing friction ( ) and lowering operating temperatures.

4.2 Performance Summary

Effectiveness depends heavily on particle concentration and compatibility with the base fluid.

Nanoparticle	**Base Fluid**	**Concentration**	**COP Improvement**	**Key Outcome**
Al_2O_3	R134a	0.1 vol%	**10.5%**	Improved heat transfer in evaporator.
TiO_2	R600a	0.5 wt%	**12.2%**	Reduced compressor energy consumption.
CNTs (Carbon Nanotubes)	R134a	0.8 wt%	**14.3%**	Superior thermal conductivity gain.
Graphene	R600a	0.05 wt%	**18.0%**	Exceptional lubrication and heat flux.

5. PHASE CHANGE MATERIAL (PCM) INTEGRATION

PCMs utilize latent heat—the large energy exchange involved in changing physical state (e.g., solid to liquid)—to store or release thermal energy efficiently.

5.1 Evaporator Integration

Materials like paraffin waxes or eutectic salts are commonly placed in a casing around the evaporator.

- **Thermal Inertia:** While the compressor runs, it cools and solidifies the PCM. During off cycles, the PCM gradually melts, absorbing heat from the refrigerated compartment.
- **Reduced Cycling:** By extending cooling duration, PCMs minimize frequent compressor starts and stops (short-cycling), which waste energy and accelerate wear.
- **Stability:** Acts as a thermal buffer, dampening temperature spikes when the door is opened and warm air enters

5.2 Condenser Integration

Placing PCM on the hot side allows it to absorb excess heat during peak operation.

- **Sub-cooling:** The PCM cools the refrigerant below its saturation point. Each 1°C of sub-cooling generally increases cooling capacity by about 1%.
- **Lower Condensing Pressure:** By absorbing transient heat peaks, the PCM stabilizes and reduces condensing pressure. This lowers the pressure ratio (P_{cond}/P_{evap}), significantly decreasing compressor workload.

5.3 Overall Impact

Incorporating PCMs shifts the system’s energy demand from fluctuating peaks to a steadier profile.

- **Energy Savings:** Daily electricity use drops by 7–12%.
- **COP Gains:** Efficiency improves by 10–20%, mainly due to reduced compressor load and more effective heat rejection.

6. DISCUSSION AND CHALLENGES

The integration of passive HTE techniques presents a balance between thermal gain and mechanical constraints.

Geometry Optimization: As observed in the experimental results, not all modifications are beneficial. The square-notched tube resulted in a lower COP (1.58) than the plain tube (1.74), likely due to excessive pressure drop and the creation of stagnant "dead zones" in the flow. Conversely, the U-notched profile optimizes the trade-off by disrupting the boundary layer without causing significant flow resistance.

Nanofluid Stability: While Al_2O_3 and CuO nanoparticles show potential for 20–40% heat transfer improvement, their long-term stability remains a challenge. Particle agglomeration and sedimentation can lead to clogging in capillary tubes or increased wear on the compressor.

Economic Feasibility: The manufacturing cost of notched tubes and the high price of graphene-based nanolubricants are significant barriers. For consumer acceptance, the payback period through energy savings must be optimized to within 3–5 years.

7. CONCLUSION

This review and experimental analysis demonstrate that passive heat transfer enhancement is a viable and cost-effective method for improving domestic refrigerator efficiency. The following conclusions are drawn:

Geometric Impact: Evaporator tube geometry significantly influences the VCRC performance. The U-notched profile is the most effective modification, providing a COP improvement of approximately 14% over standard plain tubes.

Technique Synergy: The most practical route toward high-efficiency systems involves a compound approach—combining optimized tube geometries (like U-notches) with advanced nanolubricants or PCMs for thermal stability.

Future Direction: Future research should prioritize the long-term durability of these modifications and the development of scalable manufacturing processes for notched tubing to ensure these enhancements are commercially viable for the next generation of eco-friendly refrigeration systems.

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