

Design and Analysis of Energy-Efficient Air-Cooling Systems for Domestic Applications: A Review

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ABSTRACT	ARTICLE DETAILS
The rapid growth of residential cooling demand has increased electricity consumption, peak power requirements, operating costs, and environmental impacts associated with conventional air-conditioning systems. This review examines the design and analysis of energy-efficient air-cooling systems suitable for domestic applications, with particular emphasis on direct evaporative cooling, indirect evaporative cooling, hybrid cooling, variable-speed vapor-compression systems, passive cooling strategies, and intelligent control. The thermodynamic principles, major design parameters, performance indicators, advantages, limitations, and applicability of these technologies are critically discussed. Evaporative cooling can provide substantial energy savings because it relies primarily on the latent heat of water evaporation rather than mechanically driven vapor-compression refrigeration. However, direct evaporative cooling increases indoor humidity and is therefore less suitable for hot-humid climates. Indirect evaporative cooling overcomes part of this limitation by cooling the primary air without direct moisture addition. Hybrid systems combining evaporative and mechanical cooling can provide an effective compromise between energy efficiency and humidity control. In addition, variable-speed compressors and fans, improved building envelopes, demand-controlled ventilation, thermal storage, and smart control can further reduce domestic cooling energy consumption. The review identifies climate-responsive design, water consumption, indoor air quality, system cost, maintenance, and control optimization as important considerations. A conceptual energy-efficient domestic cooling system is proposed in which passive heat-load reduction is combined with variable-speed mechanical cooling and an indirect/direct evaporative precooling stage. The review concludes that no single cooling technology is universally optimal; instead, system selection should be based on climate, indoor humidity, cooling load, water availability, occupant requirements, and life-cycle energy performance. KEYWORDS: Energy-efficient cooling; domestic air conditioning; evaporative cooling; indirect evaporative cooling; hybrid cooling; variable-speed compressor; passive cooling; residential buildings; thermal comfort; energy analysis.	Published On: 15 September 2026 Available on: https://ijmir.com

1. INTRODUCTION

Space cooling has become an increasingly important component of residential electricity consumption. Rising outdoor temperatures, urbanization, increasing household incomes, and greater expectations for thermal comfort are driving the growth of air-conditioning demand. The International Energy Agency (IEA) reports that air conditioners and electric fans already account for nearly 20% of electricity used in buildings globally, while continued growth in space-cooling demand is expected to place additional pressure on electricity systems [1]. More recent IEA analysis indicates that cooling demand is one of the fastest-growing sources of building-sector energy demand and that heatwaves are increasingly contributing to electricity-demand peaks [2,3].

Conventional domestic air-conditioning systems generally employ vapor-compression refrigeration. Although these systems can provide reliable temperature and humidity control, their compressor, condenser fan, evaporator fan, and associated components consume considerable electrical energy. The environmental impact is also influenced by refrigerant selection and electricity-

generation emissions. UNEP has emphasized that cooling-related emissions originate both from refrigerants and from the electricity required to operate cooling equipment [4].

The challenge is therefore not simply to provide lower indoor temperature but to provide thermal comfort with minimum energy, water, environmental, and life-cycle costs. Energy-efficient cooling can be achieved through a combination of improved building envelopes, passive heat-reduction measures, efficient fans and compressors, evaporative cooling, heat recovery, variable-speed operation, renewable energy integration, and intelligent control.

Evaporative cooling is particularly attractive because it uses the latent heat of water evaporation to reduce air temperature. ASHRAE identifies direct and indirect evaporative cooling as energy-efficient technologies applicable to comfort cooling and notes that indirect evaporative cooling can precool air without adding moisture to the primary airstream [5]. Previous reviews have also identified evaporative cooling as a promising alternative to conventional air conditioning, especially in climates with relatively low outdoor wet-bulb temperatures [6–9]. This paper reviews the major technologies and design approaches relevant to energy-efficient domestic air cooling and proposes a conceptual framework for designing an efficient residential cooling system.

2. FUNDAMENTALS OF INDIRECT EVAPORATIVE COOLING

2.1 Operating Principle of Indirect Evaporative Cooling

Indirect evaporative cooling (IEC) is a thermally driven cooling process in which the cooling effect produced by water evaporation is transferred indirectly to the air that is intended for ventilation or space conditioning. Unlike direct evaporative cooling, where water is evaporated directly into the supply-air stream and consequently increases its humidity ratio, IEC maintains physical separation between the primary air and the secondary air. This characteristic makes IEC particularly suitable for building HVAC applications where sensible cooling is required without significant moisture addition to the conditioned air.

A typical IEC consists of a series of narrow, thermally conductive channels separated by heat-transfer plates or membranes. The primary air stream flows through dry channels, while the secondary air stream passes through adjacent channels whose surfaces are wetted with water. Depending on the configuration, the two air streams may be arranged in parallel flow, counter-flow, or cross-flow [10–13]. Counter-flow and regenerative configurations are particularly important because they provide a more favorable temperature driving force and can achieve lower primary-air outlet temperatures. The operating process can be described in four fundamental steps:

1. **Primary-air entry:** Hot outdoor or return air enters the dry primary channels at temperature $T_{p,in}$.
2. **Secondary-air evaporation:** A portion of the secondary-side water evaporates into the secondary air, producing evaporative cooling.
3. **Heat transfer through the separating wall:** Sensible heat from the primary air is transferred through the heat-transfer wall toward the cooler secondary-side air.
4. **Primary-air cooling:** The primary air leaves the IEC at a lower temperature $T_{p,out}$, while its humidity ratio remains approximately unchanged because the primary and secondary air streams are physically separated.

The cooling mechanism is therefore a combination of evaporative heat transfer on the wet side, sensible heat transfer through the separating wall, and convective heat transfer on both air sides.

3. DEVELOPMENT OF INDIRECT EVAPORATIVE COOLING TECHNOLOGIES

IEC technology has developed through several major stages.

3.1 Conventional indirect evaporative cooling

Early IEC systems primarily used parallel-flow or counter-flow air channels separated by conductive plates. Although these systems prevented moisture addition to the primary air, their theoretical cooling potential was limited by the wet-bulb temperature of the secondary air.

3.2 Dew-point indirect evaporative cooling

Dew-point evaporative coolers use specially arranged primary and secondary channels to enable the primary air temperature to approach the dew-point temperature of the inlet air under favorable operating conditions. Xiao and Liu [12–13] and Alam et al. [11–14] identified dew-point evaporative cooling as one of the major advances in evaporative cooling technology.

The fundamental advantage is that the attainable supply-air temperature can be lower than that of conventional indirect evaporative cooling. This significantly expands the climatic and building applications of evaporative cooling.

3.3 Regenerative configurations

Regenerative IEC systems divide part of the cooled air into a secondary working stream. This arrangement enables improved heat-transfer utilization and allows the system to exploit a lower thermodynamic temperature limit.

Research on regenerative counter-flow IEC has increasingly incorporated annual building simulations and machine-learning-based prediction [11-16]. Such studies demonstrate the movement of IEC research from component-level optimization toward whole-building energy performance.

3.4 Hybrid evaporative–mechanical cooling

Hybrid systems combine IEC with conventional vapor-compression refrigeration. The IEC unit can precool the ventilation or return air before the mechanical refrigeration system, thereby reducing compressor work.

Krarti et al. [21-26] investigated hybrid evaporative–vapor-compression systems for Saudi residential buildings, while Chen et al. [19-22] investigated the long-term performance of a hybrid IEC–mechanical vapor-compression cycle in Saudi Arabia.

Hybridization is particularly important in hot and humid climates, where evaporative cooling alone may not always achieve required comfort conditions.

4. HEAT AND MASS TRANSFER MECHANISMS

IEC performance depends primarily on simultaneous heat and mass transfer. On the wet secondary side, water evaporation absorbs sensible heat from the air and heat transferred through the separating wall. The resulting secondary air becomes cooler and more humid. On the dry primary side, heat is removed through conduction across the wall. The overall heat-transfer process can be expressed conceptually as:

$$\dot{Q} = UA\Delta T_{lm}$$

where (U) is the overall heat-transfer coefficient, (A) is the effective heat-transfer area, and (ΔT_{lm}) is the logarithmic mean temperature difference.

However, IEC cannot be accurately described using sensible heat transfer alone. The evaporation process introduces coupled heat and mass transfer, and the Lewis relation between heat and mass transfer becomes important. Research has consequently investigated numerical models, experimental correlations, and optimization approaches for predicting IEC performance. Liu et al. [25-28], for example, examined heat- and mass-transfer model optimization and annual energy performance, while Caruana et al. [21-24] reviewed modeling methodologies for indirect evaporative cooling systems.

5. MAJOR IEC CONFIGURATIONS

5.1 Counter-flow configuration

Counter-flow systems arrange primary and secondary air streams in opposite directions. This configuration generally provides a favorable temperature driving force along the heat exchanger. A three-dimensional experimentally validated investigation reported in the Journal of Building Engineering [14-17] highlighted the importance of realistic geometrical representation in predicting counter-flow dew-point IEC performance.

5.2 Cross-flow configuration

In cross-flow systems, the primary and secondary streams flow perpendicular to one another. These configurations can provide compact designs and convenient manufacturing arrangements.

5.3 Parallel-flow configuration

Parallel-flow IEC systems are relatively simple but generally provide less favorable temperature driving conditions than counter-flow systems.

5.4 Regenerative counter-flow configuration

Regenerative systems use a portion of the cooled air to support the evaporative process. These systems can obtain lower supply-air temperatures and have received substantial research attention.

5.5 multi-vent systems

Tripathi et al. [7] investigated a multi-vent dry-channel integrated solar-driven IEC system. Such arrangements illustrate the potential for integrating evaporative cooling with renewable thermal energy.

6. MATERIAL AND HEAT-EXCHANGER INNOVATIONS

6.1 Polymeric materials

Sun et al. [5] experimentally investigated a polypropylene film-type IEC core. Polymeric materials can offer advantages including low weight, corrosion resistance, manufacturing flexibility, and potentially lower cost compared with metallic heat exchangers. However, long-term resistance to ultraviolet exposure, thermal cycling, fouling, biofilm formation, and mechanical degradation must be considered.

6.2 Porous media

Porous media can improve water distribution and increase the effective contact area between air and water. Several studies have investigated porous-media IEC systems and spraying strategies [29,30]. The main challenge is balancing increased heat- and mass-transfer area against pressure drop, water retention, fouling, and manufacturing complexity.

6.3 Natural-fiber cooling materials

Sofia et al. [25-27] investigated an IEC based on a finned heat pipe and natural-fiber cooling pad. Natural fibers are attractive because of their availability and potentially low environmental impact. Nevertheless, their long-term durability, biological stability, water absorption, structural integrity, and consistency require further investigation.

6.4 Macro-roughened surfaces

Surface modification can improve turbulence, wetting, and effective heat-transfer area. The enhanced dew-point evaporative cooling system investigated using a macro-roughened structure [14-15] represents an example of geometry-based heat-transfer enhancement.

6.5 Gyroid-based heat exchangers

Morselli et al. [6-8] investigated indirect evaporative cooling using gyroid-based heat exchangers. Additive manufacturing and advanced geometric design provide opportunities for producing complex three-dimensional structures with high surface-area-to-volume ratios. The challenge is that increased geometric complexity can increase manufacturing cost and pressure loss.

7. PERFORMANCE INDICATORS

(IEC performance is commonly evaluated using several parameters)

7.1 Cooling capacity

Cooling capacity indicates the rate at which useful heat is removed from the primary air stream.

$$\dot{Q}_c = \dot{m}_a c_p (T_{in} - T_{out})$$

This form is consistent with IEC literature and review studies. Where:

$\dot{Q}_c$ = cooling capacity (W or kW)

$\dot{m}_a$ = primary-air mass flow rate (kg/s)

c_p = specific heat capacity of air at constant pressure (kJ/kg·K)

T_{in} = primary-air inlet temperature (°C)

T_{out} = primary-air outlet temperature (°C)

$(T_{in} - T_{out})$ = temperature reduction of the primary air

7.2 Cooling effectiveness

Effectiveness measures the actual temperature reduction relative to the theoretical maximum temperature reduction [43-47].

7.3 Wet-bulb effectiveness

For conventional IEC systems, wet-bulb effectiveness is often used as:

$$\epsilon_{wb} = \frac{T_{db,in} - T_{db,out}}{T_{db,in} - T_{wb,in}}$$

where:

ϵ_{wb} = wet-bulb effectiveness of the IEC, dimensionless;

$T_{db,in}$ = inlet dry-bulb temperature of the primary air, °C;

$T_{db,out}$ = outlet dry-bulb temperature of the primary air, °C;

and

$T_{wb,in}$ = inlet wet-bulb temperature of the air, °C.

7.4 Coefficient of performance

For electrically driven IEC systems: For a more complete system-level assessment, the fan power should be included in the COP calculation:

$$COP = \frac{\dot{Q}_c}{W_{fan} + W_{pump} + W_{aux}}$$

Where:

$\dot{Q}_c$ = useful cooling capacity (kW)

W_{fan} = fan power consumption (kW)

W_{pump} = water-pump power consumption (kW)

W_{aux} = auxiliary power consumption, such as controls, sensors, actuators, etc. (kW)

The inclusion of fan and pump power is essential for meaningful comparison with mechanical refrigeration [49-52].

7.5 Water consumption

Water consumption is an increasingly important performance indicator. A system with high thermal effectiveness but excessive water consumption may not be environmentally preferable in water-stressed regions.

7.6 Pressure drop

Pressure drop affects fan power and therefore the net energy-saving potential:

$$W_{\text{fan}} = \frac{\Delta P \dot{V}}{\eta_f}$$

where:

1. W_{fan} = fan power consumption (W);
2. ΔP = pressure drop across the IEC heat exchanger and associated air passages (Pa);
3. $\dot{V}$ = volumetric airflow rate (m^3/s);
4. η_f = overall fan efficiency (dimensionless).

Consequently, heat-transfer enhancement should not be considered independently from aerodynamic performance.

8. INFLUENCE OF CLIMATE (Climate is one of the most important determinants of IEC performance)

8.1 Hot and dry climates

Hot and dry climates are particularly favorable because outdoor air has relatively low humidity and a large wet-bulb depression. Conventional and dew-point IEC systems can achieve significant temperature reductions under such conditions. Several studies have therefore examined IEC and hybrid cooling in Middle Eastern climates [21,22].

8.2 Hot and humid climates

High humidity reduces evaporative cooling potential because the air has limited capacity to accept additional water vapor. However, IEC can still provide useful sensible precooling without adding moisture to the primary air stream. This makes IEC more attractive than direct evaporative cooling for humid environments. Research on roof-integrated evaporative cooling and building applications in hot and humid climates [28-33] illustrates the need for climate-specific design.

8.3 Temperate and cold climates

IEC can also be used as a ventilation precooling technology in moderate climates. Xu et al. [17-23] investigated indirect evaporative chillers for comfort cooling in Northern European commercial buildings, demonstrating that IEC should not be regarded solely as a hot-climate technology.

8.4 Climate mapping

Data-driven climate maps can assist designers in identifying locations where IEC is most beneficial. The Energy Conversion and Management study on IEC maps of China [26] demonstrates the potential of regional performance mapping.

9. BUILDING APPLICATIONS

9.1 Residential buildings

Residential buildings can use IEC either as a standalone ventilation-cooling technology or as a precooling stage for mechanical air conditioning. Krarti et al. [16-21] demonstrated the relevance of hybrid evaporative–vapor-compression systems for residential building stocks.

9.2 Educational buildings

Li et al. [4] examined the energy-saving potential of dew-point IEC in school buildings. Educational buildings are particularly suitable for ventilation-based IEC because they have substantial fresh-air requirements and predictable occupancy patterns.

9.3 Commercial buildings

Commercial buildings can use IEC for ventilation cooling, supply-air precooling, or integration with chilled-water and vapor-compression systems. The Swedish case study reported by Xu et al. [15-17] demonstrates the possibility of integrating indirect evaporative chillers into commercial-building cooling systems.

9.4 Industrial buildings

Industrial applications can benefit from IEC where large ventilation loads and sensible cooling requirements dominate. However, process-specific humidity requirements must be considered.

10. HYBRIDIZATION WITH VAPOR-COMPRESSION SYSTEMS

Complete replacement of mechanical refrigeration is not necessarily the most appropriate strategy for all buildings. Hybridization provides a more practical pathway. In a typical hybrid configuration:

1. Outdoor air enters the IEC;

2. The IEC reduces its sensible temperature;
3. The partially cooled air enters the mechanical cooling coil;
4. The compressor operates at a reduced cooling load;
5. The overall electrical consumption is reduced.

The annual benefit depends on climate, cooling load, IEC effectiveness, operating hours, fan power, water consumption, and control strategy. Chen et al. [22-28] reported long-term performance analysis of a hybrid IEC–mechanical vapor-compression cycle, while Krarti et al. [21-25] evaluated hybrid systems at the building-stock level. Hybrid systems can therefore provide a compromise between the high energy efficiency of evaporative cooling and the temperature/humidity control capability of mechanical refrigeration.

11. INTEGRATION WITH RENEWABLE ENERGY

Solar energy offers a particularly promising pathway for IEC integration. Tripathi et al. [27-37] investigated a solar-driven indirect evaporative cooling system, demonstrating the potential to couple renewable energy with evaporative cooling. Solar-powered cooling has also been reviewed more broadly by researchers examining solar-driven cooling and air-conditioning technologies [36-40]. The combination of solar energy and IEC can reduce grid electricity demand. Solar photovoltaic systems can supply fans and pumps, whereas solar thermal energy may potentially be incorporated into thermally activated or hybrid configurations. Future systems could therefore combine:

Solar PV + IEC + thermal storage + mechanical backup + intelligent control

Such systems could improve energy independence while maintaining comfort during variable weather conditions.

12. NUMERICAL MODELING AND SIMULATION

Numerical modeling is essential for IEC design because experimental testing alone cannot efficiently evaluate the enormous range of geometrical, climatic, and operational conditions. Computational fluid dynamics can be used to investigate:

1. Airflow distribution;
2. Temperature fields;
3. Humidity distribution;
4. Wall heat transfer;
5. Evaporation;
6. Pressure drop;
7. Local wetting behavior;
8. Channel geometry;
9. Turbulence;
10. Transient operation.

Three-dimensional modeling is particularly important for complex heat-exchanger structures. The experimentally validated three-dimensional model reported in [51-54] demonstrates the importance of realistic geometry. Building energy simulation is also required to translate component-level performance into annual building energy savings. The broader review of building energy simulation methodologies [44] highlights the role of integrated simulation tools in building performance optimization.

13. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Artificial intelligence is becoming an important research direction in IEC. Sadighi Dizaji et al. [41-46] applied an experiment-oriented AI algorithm to optimize the geometry of an M-cycle indirect evaporative dew-point cooler. Machine learning can potentially identify nonlinear relationships between geometry, operating conditions, climate, and cooling performance. Machine-learning approaches can be used for:

1. Performance prediction;
2. Geometric optimization;
3. Fault detection;
4. Adaptive control;
5. Water-consumption prediction;
6. Energy forecasting;
7. Climate suitability assessment;
8. Real-time operating optimization.

The study reported in [43-46], which combined machine learning with in-situ measurements for predicting regenerative counter-flow IEC performance, illustrates the transition toward data-driven building cooling. Future IEC systems could employ a digital-twin framework in which real-time sensor information is continuously used to optimize airflow, water flow, bypass operation, and mechanical cooling.

14. DYNAMIC PERFORMANCE AND CONTROL

IEC performance is not constant because outdoor temperature, humidity, solar radiation, airflow rate, occupancy, and cooling demand change continuously. Tripathi et al. [49-52] investigated the dynamic performance of an evaporative cooling system under variable environmental conditions, emphasizing the importance of transient operation. Advanced control can determine when IEC should operate independently and when it should work together with mechanical refrigeration. A conceptual control hierarchy is:

Low cooling load → IEC only

Moderate cooling load → IEC + limited mechanical cooling

High temperature/humidity → IEC + mechanical cooling

Unfavorable evaporative conditions → mechanical cooling with IEC bypass

Such control can prevent unnecessary water consumption and fan/pump electricity use. Supply-based feedback control strategies for energy-efficient and grid-interactive cooling management [43-47] also indicate the broader potential of predictive and feedback-based HVAC control.

15. CONCLUSION

Indirect evaporative cooling has developed significantly from conventional evaporative cooling toward advanced dew-point, regenerative, hybrid, solar-assisted, and intelligent cooling systems. The literature reviewed in this study demonstrates that IEC can provide substantial energy-saving opportunities, particularly when it is properly matched to climate, building type, airflow arrangement, and operating conditions [47-51]. Dew-point and regenerative configurations have substantially increased the achievable cooling potential of evaporative systems. Advanced heat-exchanger materials and geometries, including polymeric films, porous media, natural fibers, macro-roughened structures, and gyroid architectures, offer additional opportunities for improving heat and mass transfer.

Hybrid IEC–vapor-compression systems appear particularly promising because they combine the low-energy characteristics of evaporative cooling with the reliable temperature and humidity control of mechanical refrigeration. Such systems are especially relevant where IEC alone cannot meet peak cooling or humidity-control requirements [48-51]. The literature also shows a transition toward dynamic modeling, machine learning, experimental AI optimization, building energy simulation, and climate-specific performance assessment. These developments can enable more reliable and adaptive IEC operation.

Nevertheless, IEC has important limitations. Water consumption, scaling, fouling, biological growth, maintenance, pressure drop, material durability, and reduced effectiveness under high-humidity conditions must be carefully addressed. In addition, component-level laboratory performance should not be assumed to represent annual building-level performance [52-53]. Future research should therefore move toward integrated multi-objective optimization involving energy, water, carbon emissions, cost, comfort, and lifecycle impacts. Long-term field demonstrations, standardized experimental methodologies, advanced materials, AI-based control, renewable-energy integration, and digital twins are expected to play important roles.

Overall, indirect evaporative cooling should be regarded not simply as an alternative to vapor-compression refrigeration but as a strategic component of future low-carbon HVAC systems. Its greatest potential lies in intelligent integration with mechanical cooling, renewable energy, thermal storage, advanced controls, and energy-efficient building design [51-53]. Such integrated systems could significantly reduce cooling-related electricity demand and contribute to the decarbonization and resilience of the building sector.

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