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Research paper

Trends in best-in-class energy-efficient technologies for room air conditioners

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ABSTRACT

Improving the efficiency of room air conditioners (RACs) could provide significant energy and associated emissions savings, particularly in emerging economies with hot climates where the cooling demand is expected to increase dramatically. To help accelerate efficiency improvements, this study identifies "best-in-class" high-efficiency RAC components and products. The findings show that manufacturers tend to minimize manufacturing costs by using RAC designs that are readily available or standardized to their production, and they share components across various models. High-efficiency RAC models use advanced compressor technologies optimized at a low frequency, large heat exchangers with thermodynamically effective materials and designs, highly efficient direct current fan motors, advanced metering devices, and smart sensors for temperature and humidity control. Recently RAC manufacturers have been improving seasonal efficiency – better reflecting part-load operation – especially via variable-speed (inverter) drives for compressor motors. Recent highest-efficiency RAC models use low global warming potential (GWP) refrigerants, having transitioned from conventional high-GWP refrigerants, in regions where RACs that use these low-GWP refrigerants are commercially available. Recently demonstrated innovative technologies show trends toward smart hybrid designs, evaporative cooling, and solid-state materials beyond the conventional vapor-compression technology. This information could help policymakers improve their RAC market-transformation programs to align with the most-efficient global technology.

1. Introduction

The International Energy Agency (IEA) estimates that space cooling applications were responsible for about 1 billion metric tons of CO_2 emissions and nearly 8.5% of total final electricity consumption worldwide in 2019 (International Energy Agency, 2020). Without major efficiency improvements to cooling equipment, the IEA estimates electricity demand for cooling in buildings could increase by up to 50% globally by 2030. In addition, worldwide energy demand from air conditioners (ACs) is expected to increase threefold by 2050, and emissions are expected to increase from 1135 million tons of CO_2 ($MtCO_2$) in 2016 to 2070 $MtCO_2$ in 2050. Simultaneously, in accordance with the Kigali Amendment to the Montreal Protocol (adopted in 2016, came into force 2019), the space cooling equipment industry is transitioning to low global warming potential (GWP) refrigerants. Article5 (A5) Parties, which are countries that consume and produce less than 0.3 kg/year of ozone-depleting substances per capita, to the Montreal Protocol are scheduled to begin their transition to lower GWP refrigerants beginning in 2024, while the transition to lower GWP refrigerants is already underway in non-A5 countries, led also by the European Union (EU) F-gas regulations. In order to take advantage of this disruptive transition and address the aforementioned estimated future impacts from space cooling equipment, innovation to improve the energy efficiency of space cooling equipment is of paramount importance in the next few years from the time of this writing. The Kigali Cooling Efficiency Program identifies cooling efficiency in the built environment as one of six high-impact opportunities to enhance economic output and increase job creation, via appropriate policies, after the COVID 19 pandemic (Kigali Cooling Efficiency Program, 2020). Catalyzing innovation in the efficiency of space cooling equipment will be a key part of this effort and will require a thorough understanding of the current "best-in-class" high-efficiency AC components and products. Separately, energy-efficiency policies typically can reduce national energy use at the lowest cost. Such policies can accelerate the adoption of highly efficient appliances and equipment to save energy, lower consumer electricity costs, shave peak load, improve air quality, and reduce greenhouse gas emissions (International Energy Agency, 2020; Kigali Cooling Efficiency Program, 2020).

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Designing effective energy-efficiency policies also requires information about the efficiency potential of target products. Although efficiency information is generally available for high-efficiency products, information about underlying, typically proprietary technologies is limited. Without this component-level detail, it is difficult to estimate the "technical potential" for efficiency improvement for a particular end use, defined here as the maximum efficiency improvement via technology diffusion that is technologically feasible. Technical potential differs from market potential, defined here as the changes in energy efficiency that might be expected under predicted market conditions based on market demand and expected future trends in product development and efficiency standards (Sathaye and Phadke, 2010). Because energy efficiency is limited by factors (often referred to as market failures) related to markets, policies, and other influences that inhibit technology diffusion, some technologically feasible products might not be used widely. As a result, policymakers are less able to address key questions related to the national energy savings possible through widespread adoption of the most-efficient feasible technologies as well as the technologies or design features that could enable those savings. Room air conditioners (RACs) are one product type for which efficiency improvements could provide significant energy savings. In 2018, the Government of India and Rocky Mountain Institute launched the Global Cooling Prize (Global Cooling Prize, 2021), an international innovation competition to develop super-efficient and climate-friendly residential cooling solutions for homes. The Global Cooling Prize target was set at a climate impact (including indirect emissions from energy consumption) of five-times lower than the market average. This efficiency improvement will be particularly important for emerging economies with hot climates where air conditioning use is expected to increase dramatically (Park and Shah, 2017; Shah et al., 2017). Because large global manufacturers account for a significant share of RAC markets in most regions, effectively designed energy-efficiency policies can facilitate global diffusion of high-efficiency products. Park et al. (2019) identify the need to better understand unrealized opportunities for improving RAC energy efficiency, adopting low GWP refrigerants, and reducing prices; this includes taking further advantage of non-energy or co-benefits associated with high-efficiency RACs.

In this article, we focus on efficiency technologies in ductless split ("mini-split") systems, which are currently available or are expected to be available commercially in the near future, for two reasons; mini-splits constitute about 77% of RACs used today worldwide, and technological improvements in mini-split systems would also be applicable to other types of ACs, with a few exceptions (International Energy Agency, 2018a).

To help meet this need for detailed RAC information both to catalyze innovation as well as to better characterize the efficiency potential, this study identifies "best-in-class" high-efficiency RAC components and products – which are also known as "max tech", "best-on-market", or "best available" technologies – with a focus on residential and light commercial applications. Advanced technologies and design strategies used in commercially available high-efficiency RACs are documented, including those that use low-GWP refrigerants. Technologies and strategies that have been demonstrated but not yet commercialized are documented as well. However, this study does not focus on technologies that are in an early stage of research and development (R&D). The results can be used to inform technology investment choices as well as the design of market-transformation policies that maximize RAC technical potential.

2. Methods and data

This study focuses on the technical potential of best-in-class ductless split RAC systems used for residential and light commercial applications. Ductless split RAC systems are common in the residential and commercial sectors almost everywhere except in the United States (U.S.), where ducted systems currently dominate but the market share of "mini-split" (ductless) systems has been increasing gradually (Park and Shah, 2017).

The study analyzes several economies – Australia, China, the EU, India, Indonesia, Japan, South Korea, and the U.S. – which account for about 70% of the global RAC market (The Japan Refrigeration and Air Conditioning Industry Association (JRAIA), 2019). The RAC efficiency metric used across all economies is the energy efficiency ratio (EER), defined by International Organization for Standardization (ISO) 5151 as follows: total cooling capacity (CC) divided by the device's effective power input under any set of rating conditions. In addition, region-specific seasonal efficiency metrics are used: seasonal energy efficiency ratio (SEER) for China, the EU, India, and the U.S.; cooling seasonal performance factor (CSPF) for Japan; and annual performance factor (APF) for heat pumps in China and Japan.

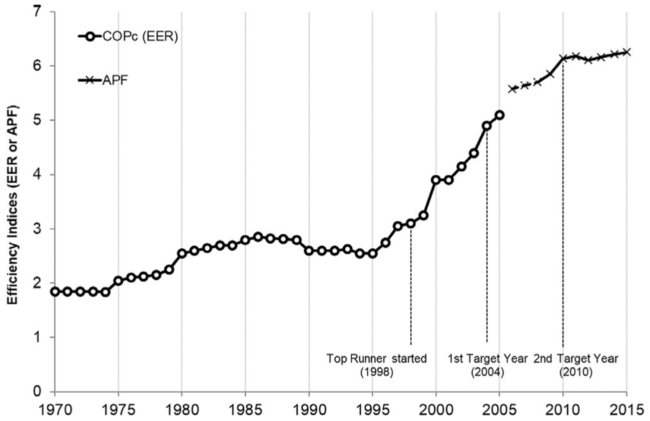
Collection of the study data proceeded through an intensive and thorough process from the following sources:

(1) Databases including the Lawrence Berkeley National Laboratory International Database of Efficient Appliances (Gerke et al., 2017); country/region-specific databases including the Energy Conservation Center Japan, the Australian Equipment Energy Efficiency program, the U.S. Air-Conditioning, Heating and Refrigeration Institute, and Eurovent; and the Topten China and Topten EU websites, which provide information on the best-performing appliances and equipment, including RACs.
(2) Review of literature and recent technical reports. For example, Park and Shah (2017) explored RAC products, including the highest-efficiency RAC models, available primarily in several economies – the U.S., China, India, Europe, South Korea, and Japan – plus developing economies in Southeast Asia. Shah et al. (2013) identified potential RAC efficiency improvements and their incremental costs, and they estimated potential total energy savings on a worldwide basis and country-specific basis. Desroches and Garbesi (2011) analyzed the energy savings and design characteristics of products considered the best on the market, products considered the best engineered, and emerging technologies in R&D for appliances and equipment.
(3) Review of product catalogs publicly available and web searches. RAC manufacturers provide product catalogs with technical specifications and sometimes additional documentation (e.g., service manuals, engineering data, technical data books) with detailed information.
(4) Consultation and interviews with industry and academic experts.
(5) Review of technologies selected as finalists for the Global Cooling Prize. Solutions eligible for this prize must have a climate impact (related to both energy and refrigerant use) at least five times lower than the baseline RAC impact and an installed cost to consumers not more than double the baseline RAC cost when manufactured at a scale of 100,000 units.

3. Results and discussion

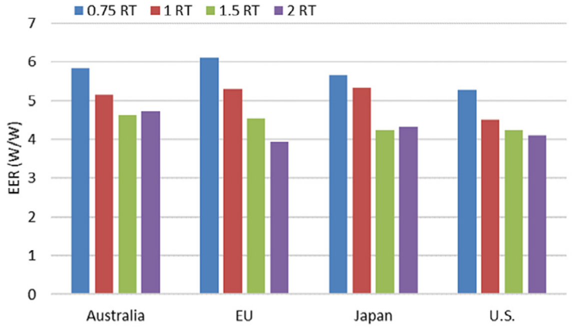
3.1. Trends in efficiency improvement and recent high-efficiency RACs

RAC manufacturers continue to research and develop advanced technologies to improve performance and reduce system

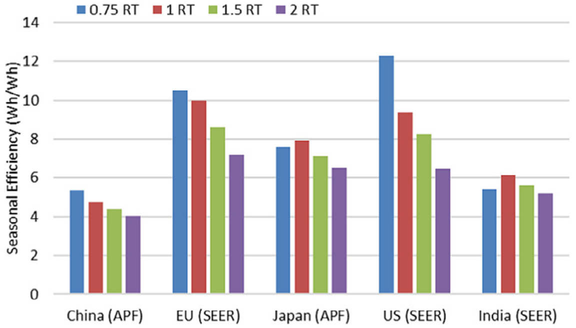


Authors' work based on the database of products registered in Japan's Top Runner Program and [15]. For RAC energy-efficiency metrics, Japan initially used COPs for cooling and heating; however, for the second target year (2010), Japan modified test methods and replaced the COP metric with APF to reflect actual outdoor temperature changes and corresponding indoor thermal loads.

Fig. 1. RAC efficiency trends in Japan. Authors' work based on the database of products registered in Japan's Top Runner Program and Kimura (2010). For RAC energy-efficiency metrics, Japan initially used COPs for cooling and heating; however, for the second target year (2010), Japan modified test methods and replaced the COP metric with APF to reflect actual outdoor temperature changes and corresponding indoor thermal loads.



(a) Efficiency of the highest-EER RAC models in four economies



(b) Efficiency of the highest seasonal efficiency RAC models in five economies

EER data are not available from China and India databases.

SEER and APF values are based on regional efficiency metrics and are not directly comparable across regions.

Fig. 2. Efficiency of highest-efficiency RACs in selected economies.

costs. For example, variable-speed (inverter) products that make RACs highly efficient already dominate mature RAC markets such as Australia, Europe, Japan, and the U.S. (Park and Shah, 2017). Along with this trend, seasonal efficiency metrics have been designed to estimate RAC performance based on part- and full-load operations under local climatic conditions. These metrics are intended to better represent product efficiency over a year of operation. As a result, manufacturers seem to have shifted their focus to improving seasonal efficiency that better reflects part-load efficiency, rather than improving full-load efficiency only as has been done historically in the industry (Richard, 2013). Although some regional RAC seasonal efficiency metrics are consistent with each other, others differ primarily owing to the outside temperature profiles used to aggregate steady-state and cyclic ratings into a seasonal efficiency value, as well as the ways of evaluating performance at part-load operation in each metric (Park and Shah, 2017). The performance of high-efficiency RACs tends to be optimized for region-specific test standards, but this is outside the scope of this paper.

Trends in RAC efficiency are shown in Fig. 1, given as coefficient of performance for cooling (COP_c, i.e., EER, a full-load efficiency at an outdoor dry bulb temperature of 35 °C) and annual performance factor (APF, a seasonal efficiency) in Japan. Yoshida (2017) describes Japan's historical efficiency improvement by technology development; for example, highly efficient direct current (DC) motors were mainly developed between 2007 and 2010 (achieving APF 5 or greater), and high-efficiency compressors were developed after 2012 (achieving APF 6 or greater) (Yoshida, 2017). The Japanese Top Runner program employs a unique approach: The Top Runner efficiency target is established by the market's most efficient product at the time of standard setting. Still, this program provides insight into how best-in-class technologies can be effectively promoted by policy design.

Park and Shah (2017) find that energy-efficient models available in several economies are produced by various global manufacturers. The highest-efficiency RACs are typically available in small sizes, particularly products with CCs of 0.75-refrigeration tons (RT; 2.5–2.6 kW) or less. In India, larger-capacity units (1.5 RT) are more popular, and 1-RT models have the highest efficiency. The efficiency of the highest-efficiency RACs currently available worldwide ranges from 5.0–6.5 in EER (Park and Shah, 2017; International Energy Agency, 2018b). However, the highest-EER RAC models do not necessarily achieve the highest seasonal efficiencies. Fig. 2 shows the highest-efficiency RACs by EER or seasonal efficiency available in several economies.

Manufacturers tend to standardize RAC designs and share components across various RAC models to minimize manufacturing costs, mainly because commercially available products have already been proven for performance and reliability in the market. Under this approach, manufacturers first standardize the design of outdoor units by CC, and then they do the same for indoor units. When a manufacturer targets RAC specifications for a given market, it identifies optimal combinations from readily available designs of indoor and outdoor units. The next step is to identify optimal levels of performance in key components, such as compressors and fan motors. Major RAC manufacturers optimize compressor efficiency when a unit is operated at variable frequency, resulting in a higher efficiency at a lower frequency. Fig. 3 shows examples of rated EER and compressor frequency by model and CC of selected RAC models produced by a global manufacturer in Europe and the U.S. Many RAC models in a product family tend to share the same compressor and cabinets, whose size is related to the heat exchanger size.

The following subsections analyze how five categories of energy-efficient technologies are implemented in commercially available high-efficiency (including highest-efficiency) RAC models:

1. Compressors and inverters
2. Heat exchangers
3. Motors and fans

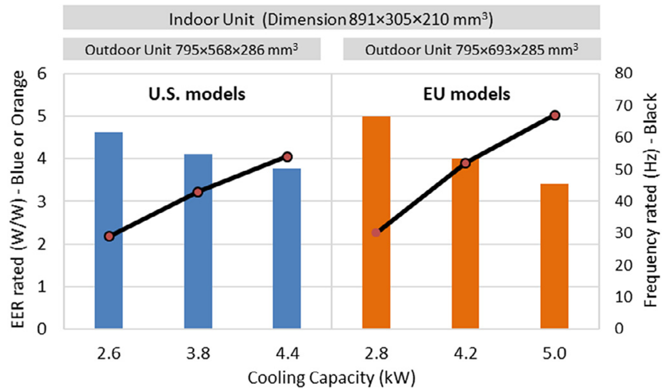
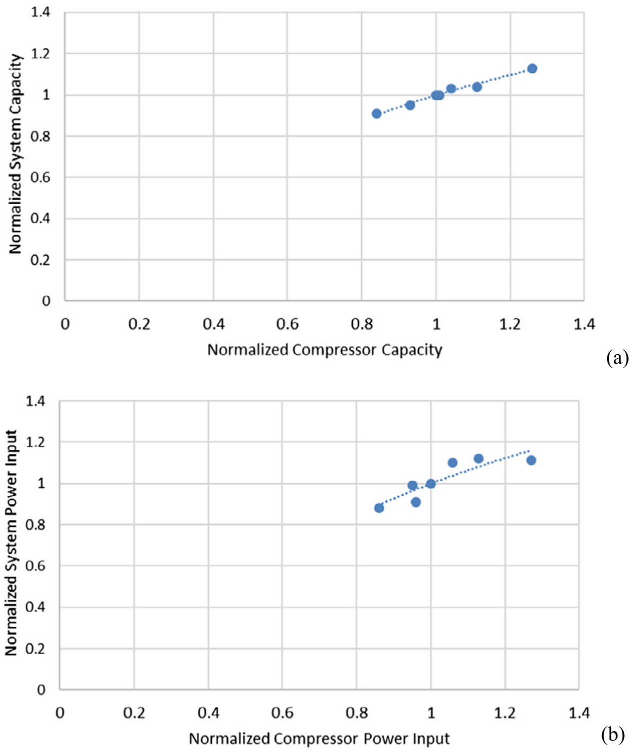


Fig. 3. Rated EER and frequency of selected RACs in the EU and U.S.



The baseline system that achieves EER 3.46 is represented by (normalized compressor capacity, normalized system capacity) = (1, 1) in (a) and (normalized compressor power input, normalized system power input) = (1, 1) in (b).
Source: [17]

Fig. 4. Typical relationship between compressor and system capacity and power input for 1.5-RT units. The baseline system that achieves EER 3.46 is represented by (normalized compressor capacity, normalized system capacity) = (1, 1) in (a) and (normalized compressor power input, normalized system power input) = (1, 1) in (b).
Source: Korea Refrigeration and Air-conditioning Assessment Center (KRAAC) (2017).

(4) Refrigerants
(5) Metering devices and smart sensors

The final subsection discusses advanced technologies that have yet to be commercialized.

3.2. Compressors and inverters

The compressor is the most essential part of RAC systems based on a vapor-compression refrigeration cycle – which constitute most of the RACs sold today – and improving compressor efficiency is key to improving RAC efficiency. Manufacturers improve compressor efficiency by either increasing CC or reducing power consumption. According to test and simulation data from the Korea Refrigeration and Air-conditioning Assessment Center (KRAAC) for 1.5-RT RACs and components, improving the compressor capacity and power input of nominal 1.5-RT RACs by 27% and 26%, compared to the baseline system that achieves EER 3.46, improves RAC system capacity and power input by about 13% and 11%, respectively (Fig. 4). Based on these relationships, a 35% improvement in compressor efficiency (by increasing capacity 15% and reducing power input 15%), compared to the baseline system that achieves EER 3.46, is estimated to improve RAC system efficiency by 14% (to EER 3.94).

Compressor innovations include mechanical methods to reduce the compressor's volumetric capacity; the load of the constant-speed motor is reduced by reducing the quantity of refrigerant that experiences compression. Another approach involves varying the speed of the compressor's motor using motor-control electronics called inverters, variable-speed drives, or variable-frequency drives (EMERSON, 2014). Variable-speed systems that modulate refrigerant flow by varying the compressor motor's speed enhance RAC seasonal efficiency, because performance improves at reduced refrigerant flow rates (i.e., part-load operation), compared to RACs that cycle on and off. Improving inverter efficiency enables manufacturers to optimize compressor efficiency when the compressor is operated across a wide range of frequencies.

Use of high-efficiency DC motors has increased the operating range of variable-speed compressors, and these compressors have become more efficient, especially via reduced friction losses and minimized leakage between the high- and low-pressure sides (Shah et al., 2013; Yoshida, 2017; Energy Conservation Center Japan (ECCJ), 2006). Rotary compressors are one of the most common types of compressors in RACs. Twin rotary compression has also increased compressor efficiency. For example, Daikin, based in Japan, has developed swing compressors that combine a vane and roller to minimize friction and refrigerant leakage (Zhang and Qin, 2015; Masusa et al., 1996). Gree, based in China, has developed rotary two-stage inverter compressors with vapor injection, which can work normally under extreme temperatures without increasing power consumption. Gree's improved two-stage vapor-injection technology has a variable-speed triple-cylinder rotary compressor, which the company says reduces refrigerant leakage and improves compressor efficiency (Luo et al., 2014; Huang et al., 2016).

Multi-pole DC motors provide higher efficiency and higher torque per unit of volume and weight. For example, using a 6-pole motor rather than a typical 4-pole motor boosts efficiency, mainly because the volume of the motor can be decreased by as much as 30%, and losses from the motor can be decreased by as much as 20% (Shah et al., 2013). Recent energy-efficient RACs use an 8-pole DC motor in the compressor. Other technologies are being developed to improve DC motor efficiency further. For example, using a neodymium magnet provides higher efficiency, because its magnetic flux density is higher, and it replaces the conventional motor's ferrite element (Shah et al., 2013; Energy Conservation Center Japan (ECCJ), 2006). Other design options include improving geometry for the coil winding, which reduces copper losses, and using thin silicon steel plates (e.g., Panasonic's R2 rotary compressor) or laminated steel sheets to limit iron losses (Shah et al., 2013). Table 1 shows high-efficiency technologies and the efficiency of final RAC products, based on manufacturer information.

Table 1
Examples of high-efficiency compressor technologies by manufacturer.

Manufacturer	Rated CC (kW) and EER (W/W) of final RAC products	Compressor technologies, per manufacturer information
Daikin	CC 2.5–5.0 EER 4.6–6.1	Swing (hermetic) Neodymium magnet DC motor
Panasonic	CC 2.5–3.5 EER 4.4–5.8	Rotary (hermetic) Brushless DC motor (8 poles)
LG	CC 2.5–5.0 EER 4.1–5.3	Twin rotary Brushless DC motor
Samsung	CC 2.5–3.5 EER 4.2–5.1	Twin rotary Brushless DC motor (8 poles)
Gree	CC 2.6–5.2 EER 4.7–5.4	Rotary two-stage Brushless DC motor (8 poles)

3.3. *Heat exchangers*

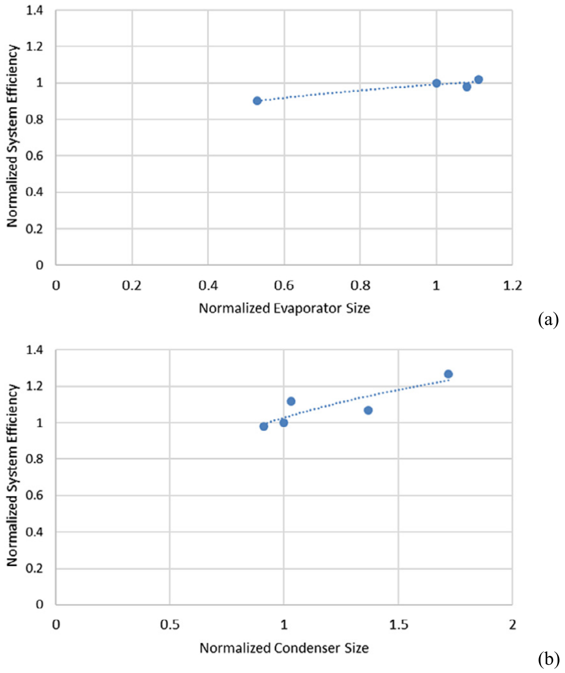
Enlarging the coil frontal area, the number of tubing rows in the coils, or both enables compressors to operate more efficiently owing to the larger heat-transfer area. For example, increasing the heat-transfer area by 80% is estimated to achieve a 35% increase in the efficiency of the RAC unit (not accounting for the fans) (Shah et al., 2013; Energy Conservation Center Japan (ECCJ), 2006). According to test and simulation data from KRAAC for 1.5-RT RACs and various components, increasing evaporator (indoor unit) size by 11% and condenser (outdoor unit) size by 72% improves RAC system efficiency by about 2% and 27%, respectively (Fig. 5). In addition, further increasing the heat-transfer area requires improving compressor efficiency to improve overall system efficiency. Based on this information, combining 50% and 100% increases in evaporator and condenser sizes, respectively, with a 15% improvement in compressor capacity improves RAC system efficiency by about 30% (to EER 4.75) compared to the baseline system.

However, increasing the heat-transfer area may increase the amount of materials (e.g., copper, aluminum) used in tubes, fins, and housings, and it usually raises the amount of refrigerant charge. It is also challenging to fit more heat-exchanger coils into an RAC cabinet. In addition, the higher air flow associated with higher heat-transfer efficiency increases noise (Shah et al., 2013; Energy Conservation Center Japan (ECCJ), 2006).

Heat-transfer performance can also be improved via heat-exchanger design. Copper tube and aluminum fin coil is the most common design for RACs. There has been widespread use of fin-and-tube heat exchangers across various applications. Residential products commonly use heat exchangers with tubes of 7.0 mm in diameter, and some high-efficiency RACs have tubes with diameters of 5.0 mm or less (Kim and Kim, 2015). For example, Daikin's FTXZ_N/RXZ_N series, which includes its best-performing models, uses a fin tube with different diameters (4 mm front and 6.35 mm back) using R32 refrigerant. Although a smaller-diameter tube can increase heat-transfer performance, coils with 5-mm diameter tubes are harder to manufacture owing to the material softness, and they are not as common in typical RACs.

Heat-transfer rates are higher for cooling fin patterns with louvered and variegated surfaces rather than smooth surfaces (e.g., using optimized slit fins in place of plain fins improved RAC efficiency by about 10%), hence various fin patterns have been developed to maintain good heat transfer while reducing noise and production costs (Erbay and Doğan, 2017). Fin surface and tube inside-surface heat-transfer enhancement are common practices. Table 2 shows examples of fin types used in high-efficiency RAC models.

Designing heat exchangers for high-efficiency RAC systems requires optimization of system-level performances tradeoffs. Normally, a larger (higher-capacity) heat exchanger results in higher system efficiency. However, using an evaporator coil that is too large could increase the evaporator temperature and hinder the system's dehumidification capability. Heat-exchanger size is also typically constrained by the size of the cabinet. A higher heat-transfer capacity can be achieved by a tighter heat-exchanger design, such as one with greater fin density. However, increasing fin density reduces the air pressure, so more power from the fan motor is needed to transport an equivalent air volume.



The baseline system that achieves EER 3.46 is represented by (normalized evaporator size, normalized system efficiency) = (1, 1) in (a), and (normalized condenser size, normalized system efficiency) = (1, 1) in (b).
Source: [17]

Fig. 5. Typical relationship between heat-exchanger size and RAC system efficiency for 1.5-RT units. The baseline system that achieves EER 3.46 is represented by (normalized evaporator size, normalized system efficiency) = (1, 1) in (a), and (normalized condenser size, normalized system efficiency) = (1, 1) in (b).
Source: Korea Refrigeration and Air-conditioning Assessment Center (KRAAC) (2017).

Table 2
Examples of fin types used in high-efficiency RAC models.

Manufacturer	Rated CC (kW) and EER (W/W) of final RAC products	Specifications, per manufacturer information
Daikin	CC 2.5–5.0 EER 4.6–6.1	- Indoor unit: multi-slit fin, tube (4 mm front, 6.35 mm back) - Outdoor unit: corrugated fin
Panasonic	CC 2.5–3.5 EER 4.4–5.8	- Indoor unit: slit fin - Outdoor unit: corrugated fin
LG	CC 2.5–3.5 EER 4.1–4.8	- Indoor unit: louver fin, tube (7 mm) - Outdoor unit: louver fin

3.4. *Motors and fans*

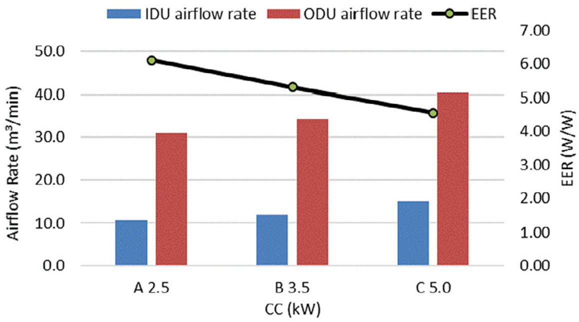
RACs typically have condenser and evaporator blower fans, which are driven by variable-speed electrical motors that adjust the airflow rate as required. The same efficiency approaches discussed in Section 3.2 for compressor motors also apply to fan motors, such as increasing the number of poles in DC motors and using rare-earth magnets (Shah et al., 2013; Energy Conservation Center Japan (ECCJ), 2006). Based on test and simulation data from KRAAC, combining a 35% improvement in compressor efficiency (15% capacity increase, 15% power input reduction), 50% and 100% increases in evaporator and condenser sizes, respectively, and a 35% improvement in all electrical and electronic devices improves RAC system efficiency by about 50% (to EER 5.24), compared to the baseline 1.5-RT RAC system that achieves EER 3.46 (Korea Refrigeration and Air-conditioning Assessment Center (KRAAC), 2017).

Manufacturers improve fan designs by reducing noise and power demand from the fan motors and thus increasing overall efficiency. Specifically, given a constant cabinet size, higher CC requires a greater compressor frequency, leading to a higher airflow rate set by the fans. Compressor frequency and airflow rates can be adjusted to meet a target efficiency level, varying by CC. For larger-capacity units, manufacturers can also use larger housings (i.e., larger heat exchangers), higher airflow rates, and compressors with higher power output. Noise rises when air flow is higher, resulting in a potential tradeoff between increased heat-transfer efficiency and increased noise (Shah et al., 2013; Energy Conservation Center Japan (ECCJ), 2006). Fig. 6 illustrates the complex tradeoff between efficiency, cooling capacity, airflow rates, cabinet sizes, and compressor motor electric output by showing examples of various RAC design options. In Fig. 6a, the three models have a constant cabinet size and compressor motor electric power output, resulting in lower efficiency for larger-CC models. However, airflow rate increases with increasing CC, which compensates for the decreased efficiency. In Fig. 6b, the three models have a constant cabinet size, while the largest-CC model (F) has higher compressor motor output and airflow rates compared with the other models. In Fig. 6c, the two larger-CC models (I and J) have larger cabinets, higher compressor motor outputs, and higher airflow rates compared with the other two models (G and H).

3.5. Refrigerants

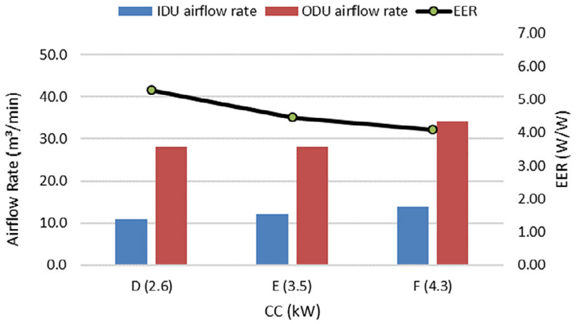
In accordance with the Montreal Protocol, RAC refrigerants have changed several times with the goal of improving safety and performance while reducing environmental impacts. To minimize negative tradeoffs and leverage opportunities for better performance, RACs that use refrigerant alternatives must be re-optimized for the specific alternatives used. Manufacturers must balance thermodynamic performance (e.g., capacity, temperature, efficiency), safety conditions (e.g., pressure, toxicity, flammability), compatibility with system materials, availability, cost, and environmental impact (Goetzler et al., 2016). Typically, single component replacement refrigerants for R-410A are flammable. R-32 has a higher capacity and COP than R-410A, but is flammable, has a higher GWP and a discharge temperature approximately 20 °C higher than that of R-410A. Fortunately, refrigerant blends offer additional possibilities that are non-flammable, typically including R-32 as a significant component (Xu et al., 2017; Chen and Yu, 2008; Tu and Liang, 2011; Piao et al., 2012; Xu et al., 2013). A recent review analyzed the new refrigerant mixtures alternatives developed from 2015 to date as alternatives to R-410A (Heredia-Aricapa et al., 2020).

Until 2012, most RAC manufacturers transitioned from R-22 to R-410A. Since then, Japanese manufacturers have begun transitioning from R-410A to R-32. Top-tier Chinese manufacturers produce R-32 RACs and have also developed R-290 RACs, completing retrofits of production lines. The Indian manufacturer Godrej leapfrogged R-410A and is transitioning directly from R-22 to R-290 (Park and Shah, 2017). The highest-efficiency RACs are being developed with low-GWP refrigerants. For example, some manufacturers' high-efficiency R-32 RAC models use a heat-exchanger tube with diameter reduced from 6 to 4 mm or from 7 to 5 mm to improve efficiency.



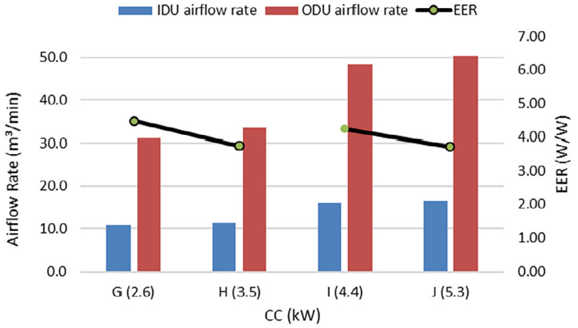
(a)

Model	IDU cabinet [m^3]	ODU cabinet [m^3]	Compressor motor output [W]
A	0.088	0.165	1,100
B			
C			



(b)

Model	IDU cabinet [m^3]	ODU cabinet [m^3]	Compressor motor output [W]
D	0.075	0.142	850
E			
F			1,000



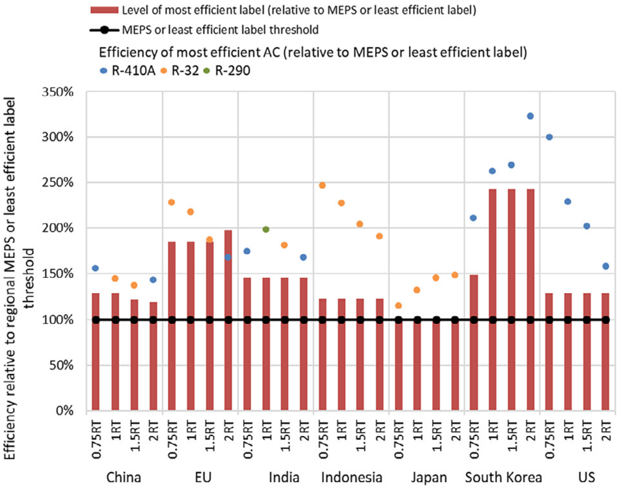
(c)

Model	IDU cabinet [m^3]	ODU cabinet [m^3]	Compressor motor output [W]
G	0.051	0.120	750
H			
I	0.089	0.182	1,100
J			

IDU = indoor unit, ODU = outdoor unit

Fig. 6. Examples of airflow rates, cabinet sizes, and compressor motor outputs for RACs produced by two manufacturers.

In addition, laboratory tests indicate that the efficiency performance of low-GWP refrigerants, including R-32 and R-290, is at least as good as the performance of R-410A and R-22 (Erbay and Doğan, 2017; Goetzler et al., 2016; Abdelaziz and Shrestha, 2016; Abdelaziz et al., 2015; OTS (Optimized Thermal Systems, Inc.), 2016). In some regions, the most-efficient RAC models use



Source: Updated from [5]. For example, the blue dot and red bar at "US (0.75RT)" mean that the efficiencies of the most-efficient U.S. RAC (12.3 W/W) and the most-efficient label (ENERGY STAR) requirement (5.27 W/W) are 3 times (300%) and 1.29 times (129%) as high as the U.S. MEPS (4.1 W/W), for 0.75-RT units.

Fig. 7. Efficiency of most-efficient RAC models – and refrigerants used in those models – relative to MEPS or least-efficient labels, by region. For example, the blue dot and red bar at "US (0.75RT)" mean that the efficiencies of the most-efficient U.S. RAC (12.3 W/W) and the most-efficient label (ENERGY STAR) requirement (5.27 W/W) are 3 times (300%) and 1.29 times (129%) as high as the U.S. MEPS (4.1 W/W), for 0.75-RT units.
Source: Updated from Park and Shah (2017).

low-GWP refrigerants (Park and Shah, 2017). In South Korea and the U.S., where mildly flammable refrigerants (e.g., R-32) and flammable refrigerants (e.g., R-290) cannot be sold on the market, the most-efficient RAC (ductless split) models still use non-ozone-depleting but high-GWP R-410A. In the EU, Japan, and Indonesia, the most-efficient models generally use low-GWP R-32. In China, the most-efficient models use R-410A or low-GWP R-32. In India, the most-efficient models use low-GWP R-32 or R-290, or high-GWP R-410A. Fig. 7 shows efficiencies of the most-efficient models relative to minimum energy performance standards (MEPS) or least-efficient labels, by region. Regardless of refrigerant type in terms of GWP, RACs are available in these regions that surpass the highest efficiency levels recognized by labeling programs.

Research and development efforts are still underway on potential low-GWP refrigerants that have attractive efficiency and risk features; these encompass refrigerants with decreased flammability, such as R-452B (a blend of R-125, R-1234yf, and R-32) and R-466A (a blend of R-32, R-125, and CF-31), and natural refrigerants such as hydrocarbons, including R-290 (Park and Shah, 2017; Honeywell Refrigerants, 2019).

3.6. *Metering devices and smart sensors*

Metering devices control refrigerant flow. Common RAC metering devices include those based on a capillary tube, fixed orifice, thermal expansion valve, or electronic expansion valve. The thermal expansion and electronic expansion valves provide the most accurate control. However, thermal expansion valves cannot control the wide range of refrigerant flows required by variable-speed RACs; electronic expansion valves with well-designed control algorithms better serve those flow requirements.

Occupancy sensors reduce energy use by switching off electrical devices when affected areas are vacant or inactive for prolonged periods. Smart sensors with advanced control algorithms are being developed, for example, using integrated device sensors and intelligent home sensor networks to predict occupancy patterns and save energy (Gerke et al., 2017). One manufacturer has developed RACs with integrated infrared sensors, which detect occupant locations as well as floor and wall temperatures to create a database of thermographic data. The intelligent sensor processors optimize these inputs to save energy while the comfort of occupants is preserved. When people are in the room, the airflow regulation for efficient operation is thought to reduce electricity consumption by up to 40%. When the room is unoccupied, the system switches to an energy-saving mode that further reduces energy use by 10% (Shah et al., 2013; Japan for Sustainability (JFS), 2007).

Energy efficiency can also be improved via optimization of the method for maintaining an adequately low evaporating temperature to provide dehumidification. The most common approach in the U.S. is to operate the evaporation cycle continuously at a low enough temperature to provide dehumidification. In contrast, a two-stage approach is common in Japan, which allows a higher-efficiency, high-temperature cycle of sensible cooling to alternate with a lower-temperature dehumidification cycle through addition of a second, dedicated expansion valve (Shah et al., 2013). The winning technologies of the Global Cooling Prize also optimized their dehumidification operation through smart controls to the specific conditions required under the Prize criteria (i.e., at or below 27 °C and 60% relative humidity) with very little overcooling and much higher energy efficiency as compared with the baseline unit (Kalanki et al., 2021).

3.7. *Advanced technologies yet to be commercialized*

Policy can help researchers and manufacturers overcome barriers to achieving higher RAC efficiency and using low-GWP refrigerants by supporting exploration of technical and economic potential, helping small manufacturers build R&D capacity, forming collaborations with global manufacturers, or establishing other approaches aimed at technology transfer and capacity building (Park et al., 2019). In November 2019, the Global Cooling Prize narrowed 139 applicant teams, representing 31 countries, to eight finalists composed of established global RAC manufacturers, technology startups, and other organizations (Global Cooling Prize, 2021; Kalanki et al., 2021). The technologies employed across these teams indicate several emerging RAC design trends, which are described briefly here.

Evaporative cooling designs. Some applicants used the latent heat of evaporation to lower the outdoor unit's intake air temperature via control technology that sprays water around the air intake at high ambient temperatures and cooling loads. Other applicants reduces the air temperature without adding humidity by using a hybrid solution that integrates membrane technologies with an evaporative cooling system to cool without using any refrigerant.

Smart hybrid designs. Some applicants optimized indoor cooling using smart operation in multiple modes of vapor-compression refrigeration, direct evaporative cooling, and ventilation depending on outside weather conditions. Hybrid designs included features compatible with renewable energy systems: integrating a solar photovoltaic panel into the outdoor unit or employing DC electrical components.

Solid-state materials. Some applicants used solid-state barocaloric cooling technology, which uses plastic crystals to eliminate the need for conventional vapor-compression technology. These solid organic materials behave like commonly used refrigerants; the process of applying and releasing pressure results in solid-to-solid phase changes in the crystals and large thermal changes due to molecular reconfiguration. The plastic crystals are purportedly widely available, low cost, and non-toxic. Recent research has also explored magnetocaloric materials which generate a temperature difference when exposed to a strong magnetic field (Kitanovski, 2020). However, both barocaloric and magnetocaloric technologies are still in an early stage and need further research and development in order to be deployed in commercially available cooling applications such as air-conditioning.

Thermally-driven technologies. These technologies include recent research on liquid desiccants and membrane desiccants which dehumidify incoming air using the desiccant (which is then regenerated using heat) (Chen et al., 2020). Smart hybrid systems may include combinations of such desiccant technology. However, desiccant dehumidification technology is also apparently at an early stage and not yet mature enough to compete on cost terms with dehumidification by overcooling using conventional vapor compression systems. As the cooling market grows faster in hot and humid regions of the world that use cooling systems for both cooling and dehumidification, these technologies as well as hybrid systems that use both vapor compression and desiccants are likely to become increasingly commercially viable. However, this will require better energy efficiency metrics and test procedures that capture this improvement in performance adequately.

4. Summary

By documenting best-in-class technologies and design strategies for ductless split RACs (focusing on residential and light commercial applications), this paper can help support design of market-transformation programs to accelerate development and deployment of high-efficiency products. The following are our key findings:

- To minimize manufacturing costs, manufacturers tend to use RAC designs that are readily available (or standardized to their production) and share components across various RAC models that they produce.
- Historically, RAC efficiency improvements focused on full-load operation. More recently, manufacturers have been improving seasonal efficiency, which better reflects part-load operation.
- RAC seasonal efficiency is enhanced as performance improves at reduced refrigerant flow rates (i.e., under part-load operation), compared to RACs that cycle on and off at full speed. Variable-speed (inverter) technology greatly improves seasonal efficiency, matching capacity with load under most conditions and eliminating the losses associated with RACs that cycle on and off at full speed.
- High-efficiency RAC models use advanced compressor technologies optimized at a low frequency, large heat exchangers with thermodynamically effective materials and designs including reduced-diameter tubes, highly efficient DC fan motors, advanced metering devices, and smart sensors for temperature and humidity control.
- Recent highest-efficiency RAC models use the low-GWP refrigerants R-32 and R-290, having transitioned from the conventional R-410A, depending on regional standards. When adopting a new refrigerant, manufacturers balance performance and safety with materials considerations, cost, and environmental impact, to achieve comparable or better performance in relation to conventional refrigerants.
- Advanced technologies yet to be commercialized include evaporative cooling, smart hybrid designs (with vapor compression, evaporative cooling, and renewable energy compatibility), and solid-state materials that do not require the conventional vapor-compression and refrigerant technologies.

CRediT authorship contribution statement

Nihar Shah: Supervision, Conceptualization, Methodology, Writing - review & editing. **Won Young Park:** Project administration, Investigation, Methodology, Visualization, Writing - original draft. **Chao Ding:** Investigation, Resources, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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