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A review of ductless mini split HVAC system

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Review article

A review of ductless mini split HVAC system

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ABSTRACT

Although a conventional ducted system is the HVAC system used by most of the household in the United States, the ductless mini split system is gaining popularity in the market. The ductless mini split heat pump system consists of an outdoor unit that provides hot or cold refrigerant into a house to one or more wall- or ceiling-mounted indoor fan units. Ductless mini splits can have several advantages over conventional systems including improved thermal comfort, performance, and energy saving. There have been several studies and research in the field of ductless mini splits to learn about the advantages and disadvantages of the system and determine its market potential. Future research and progress in the field require an in-depth understanding of the current state and challenges of the research done about the system. Therefore, the purpose of this paper is to identify the research and studies performed using ductless heat pumps and to quantify them based on their research focus within the topic. So, by performing a comprehensive literature review of the current state of research in the field of ductless mini splits, we have presented an overview of the methodology used and the results obtained by several researchers. In this paper, a reference guide is created to classify the papers based on the topic. The literature is classified into four main topics: performance, thermal comfort, energy savings, and market potential, and then summarized based on the topic. Moreover, the reference guide is also used to distinguish simulations from field evaluations.

Contents

1. Introduction

Most US residences use the conventional ducted HVAC system to deliver cooling and heating to condition the spaces in a home. The conventional ducted system consists of a network of ducts with a blower that delivers conditioned air to different indoor spaces (Roth et al., 2006). Today, most of the HVAC systems in Asia and Europe are ductless, and such systems are gaining popularity in the US market as well. The ductless mini split heat pump system consists of an outdoor unit that provides hot or cold refrigerant into a house to one or more various wall- or ceiling-mounted indoor fan units. The indoor units contain a fan that blows air over the refrigerant-filled heat exchanger, and hot or cold air is distributed throughout the room (Ashley et al., 2020). Ductless heat pumps (DHP) use inverter technology that allows

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Nomenclature

AHRI	Air Conditioning, Heating, and Refrigeration Institute
ASHP	Air Source Heat Pump
COP	Coefficient of Performance
DHP	Ductless Heat Pump
EER	Energy Efficiency Ratio
EEV	Electronic Expansion Valves
ER	Electric Resistance
FXO	Fixed Orifice
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HSPF	Heating Season Performance Factor
HVAC	Heating, Ventilating and Air Conditioning
MSHP	Mini Split Heat Pump
NEEA	Northwest Energy Efficiency Alliance
PNNL	Pacific Northwest National Laboratory
POE	Polyolester Oils
SEER	Seasonal Energy Efficiency Ratio
TXV	Thermostatic Expansion Valve
VBBD	Variable-Base Degree-Day
VCHP	Variable Capacity Heat Pump

them to operate at continuous variable partial load conditions to maximize their efficiency and energy savings.

A DHP can have several advantages over conventional systems. DHP systems do not require any ductwork; thus, no ducts must be added to spaces that did not have them before (Pang et al., 2019; Ce et al., 2018). This makes DHP suitable for retrofit applications as well. Since the ductless mini split system does not require ductwork, so the loss of energy via duct leakage is also minimized. Unlike central systems, DHP can be easily zoned by installing multiple indoor units, which can be independently controlled. This can minimize energy waste and improve thermal comfort simultaneously.

Types of Ductless Air Conditioning Systems

Different types of ductless mini split systems are available in the market. The most common types of ductless air conditioning used are the wall mounted mini split and ceiling mounted cassette ductless mini split. Wall mounted mini split air conditioners consist of the indoor unit being mounted high up on the wall, while the outdoor unit is placed outside, and the two systems are connected via refrigerant pipes. Ceiling mounted cassette units work on the same principle as the wall mounted systems. Ceiling mounted systems are also used in places where aesthetics is an issue. The thermal comfort from the wall mounted units may not be satisfactory for occupants in large rooms, so ceiling cassette units can provide better performance in such areas.

Another type of air conditioner in the mini-split air conditioning is concealed ducted mini-split heat pump, which offers a more aesthetically better option for homeowners. This system uses ducts to supply the conditioned air to spaces and also uses separate ducts for return air. This system also has an outdoor unit and an indoor unit which is typically installed in the attic of the house. This type of system hides the bulky components and allows installers to place the grill opening in "typical" ducted locations. These systems are also called "short-run ducted mini-split, mini-duct, or slim-duct" systems (Ce et al., 2018). These systems are advantageous in terms of energy savings as well. Ce et al. (2018) conducted research to evaluate the energy savings potential of the ducted mini split system by using a EnergyPlus model. The result showed that the ducted mini split system saved up to 34% of the energy in comparison to the traditional system.

Despite the significant progress of research and study in the field of DHPs in HVAC systems, little effort has been made to comprehensively review past studies and to integrate them quantitatively and qualitatively. Since the market for ductless mini splits is increasing every year, it is necessary to provide a comprehensive review of the studies performed in the field. Therefore, the purpose of this paper is to identify the research and studies performed using DHPs and to quantify them based on their research focus within the topic. The paper summarizes the research conducted and published in several journals. This paper also summarizes information about research done by national labs and universities in the topic. In this study, the papers are classified based on their research focus based on four main topics: performance, thermal comfort, energy savings, and market study. Table 1 acts as a reference to this literature review and divides the literature into their respective categories.

Table 1 is also used to distinguish field evaluations from simulations. Although most researchers have used lab homes or residential houses to conduct experiments, some researchers have used computer software to evaluate the performance and energy savings of DHPs. Pang et al. (2019) used an EnergyPlus model to measure the energy savings potential of DHP systems when they are installed in existing buildings with pre-existing HVAC equipment. Cheung and Braun (2014) used a model in the literature to simulate the performance of a variable-speed DHP system and compared the results to ducted residential heat pumps. Holloway (2013) compared the performance of different heat pump systems using a building energy simulation tool called TRNSYS. Lubliner et al. (2016) used BEopt Version 2.02 to estimate the typical space-heating and total annual energy use for seven homes equipped with DHPs and electric resistance heaters and compared the results obtained from the two systems. Ce et al. (2018) also used the BEopt model to compare the performance of ducted mini splits and ductless mini splits.

2. Performance

Mini split heat pump (MSHP) technologies utilize variable speed compressors and fans allowing for a reduction in cycling losses, improve part-load control, and enhanced humidity control (Winkler, 2011). This can make the measurement of the performance of the DHP systems difficult. Measurement of power consumed, and load delivered are needed to calculate the performance of the systems. Several researchers have used the coefficient of performance (COP) as a measure of performance of the heat pumps, while others have used Heating Seasonal Performance Factors (HSPF) and Seasonal Energy Efficiency Ratio (SEER) to evaluate the efficiency of the heat pumps. The performance of the ductless mini splits depends on the three main factors: compressor, refrigerant, and pipe dimensions.

2.1. Compressor

Compressor speed is dictated by its type between digital scroll compressor and inverter driven compressor. Digital scroll compressor operates at full speed with an unloader mechanism that opens the scrolling components thus creating zero pressure and temperature differential. The speed and partial load conditions are determined based on the average time of open and closed positions. Inverter driven compressors are the same scroll mechanism without any separation where the speed of the scrolling

Table 1
Ductless mini split reference chart.

Reference	Performance			Thermal comfort	Energy savings	Type of analysis		Interaction with existing systems			Market potential and cost	
	Compressor	Refrigerant	Pipe length			Field evaluation	Simulation	Electric baseboard	Window AC	Central system	Cost	Retrofit
Roth et al. (2006)					×							
Ashley et al. (2020)				×	×	×				×		
Pang et al. (2019)				×	×		×	×	×	×		
Ce et al. (2018)					×		×					
Cheung and Braun (2014)	×	×					×					
Holloway (2013)			×				×					
Lubliner et al. (2016)					×	×	×	×			×	
Winkler (2011)	×					×						
Hu and Yang (2005)	×											
Tu et al. (2011)	×											
St-Onge et al. (2018)	×						×					
Xia et al. (2002)	×											
Zhang et al. (2011)	×											
Atas et al. (2017)	×											
Lin and Yeh (2009)	×											
Choi and Kim (2003)	×											
Meng et al. (2015)	×											
Tu et al. (2016)	×											
Kegel et al. (2017)	×											
Sager et al. (2018)	×											
Sethi et al. (2015)		×										
Shen et al. (2016)		×										
Mota-Babilonia et al. (2017)		×										
Amarnath and Blatt (2008)		×										
Sencan et al. (2006)		×										

(*continued on next page*)

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Table 1 (*continued*).

Reference	Performance			Thermal comfort	Energy savings	Type of analysis		Interaction with existing systems			Market potential and cost	
	Compressor	Refrigerant	Pipe length			Field evaluation	Simulation	Electric baseboard	Window AC	Central system	Cost	Retrofit
Rothfleisch and Didion (1993)		×										
Abdelaziz et al. (2015)		×										
Minor and Yokozeki (2004)		×										
Pham and Rajendran (2012)		×										
Shen et al. (2022)		×										
Minamida et al. (2018)		×	×									
Yan et al. (2012)			×									
Pan et al. (2014)			×									
Ashrae Standard 55 (2010)				×								
Ueno and Loomis (2015)				×		×						
Rudd et al. (2013)				×								
Roth et al. (2013)				×		×						
Sutherland et al. (2016)				×	×	×					×	
Herk (2017)				×		×						
Christensen et al. (2011)				×		×						
Withers (2018)				×		×						
Martin et al. (2018)				×		×						
Withers (2016)				×		×						
Storm et al. (2012)					×	×						
Bugbee and Swift (2013)					×	×		×				
Korn et al. (2016)					×	×						
Breton et al. (2019)					×		×					
Schoenbauer et al. (2018)					×	×				×		
Janssen et al. (2020)					×	×						
Logsdon and Larson (2016)					×	×						
Jackson and Walczyk (2019)					×	×					×	

(*continued on next page*)

Table 1 (*continued*).

Reference	Performance			Thermal comfort	Energy savings	Type of analysis		Interaction with existing systems			Market potential and cost	
	Compressor	Refrigerant	Pipe length			Field evaluation	Simulation	Electric baseboard	Window AC	Central system	Cost	Retrofit
Proctor (2016)					×	×						
Anon (2014)					×	×						
Webb et al. (2018)					×	×					×	
Dentz et al. (2014)											×	×
Ductless Mini-Split Heat Pump Cost Study (2018)											×	
Faesy et al. (2014)											×	×
Kolwey and Geller (2018)					×					×	×	×
Emera Maine Heat Pump Pilot Program (2014)											×	
High Efficiency Heat Pumps (2016)											×	
Lapsa et al. (2017)											×	
Residential Heating (2013)											×	
Hlavinka et al. (2016)											×	
Baylon and Geraghty (2009)					×	×						×
Encotope Inc (2010)					×	×						
Fenaughty et al. (2017)												×

path is controlled usually by a frequency driver that controls motor speed.

Cheung and Braun (2014) compared the ductless system to a traditional system with a thermostatic expansion valve (TXV) and another one with a fixed orifice with an accumulator (FXO) and showed that the efficiency of the system increases when using a digital scroll compressor instead of single stage. Hu and Yang (2005) also experimented with traditional and digital scroll compressor and further proved the benefits of a digital scroll compressor. The part load conditions that can be supplied from a digital scroll compressor range from 17% to 100% where traditional compressor systems ranges from 48% to 104%. The system developed by Hu and Yang (2005) also had a broader range of capacity output than that of a variable frequency control system. Tu et al. (2011) experimented with a dual compressor system with a digital scroll compressor and single speed compressor where voids of operation were filled in for part load scenarios until 100% output was required where both systems operated in conjunction to ease drop-off as heat load dissipated near the end of the day. In their performance analysis conducted by St-Onge et al. (2018) with a ductless variable speed system showed that COP of a DHP generally decreases at higher compressor speeds and lower outdoor temperatures. Xia et al. (2002) introduced a methodology for a multi-compressor system set up for heat recovery operation that further highlighted bands of higher efficiency where part load operation surpasses single speed operations. However, the tests performed by Xia et al. (2002) in their methodology were performed in "cooling all" mode and without accounting for the latent load. Zhang et al. (2011) also experimented with a single speed compressor and a digital scroll compressor to evaluate performance where the pulse width modulation dictates how well efficiencies can be measured as digital scroll operation metrics are based on time averaging. In their study, Zhang et al. (2011) also accounted for the influencing factors of the cooling capacity of the system such as outdoor air temperature, indoor air temperature, solar radiation intensity, and inner heat sources.

Atas et al. (2017) evaluated a system operated by an inverter driven compressor initially set to a static 50 Hz with target temperatures and pressures produced identical between testing scenarios that indicated control was acceptable for loosening the static compressor speed limitation to a truer part load condition test. The succession was validation of the developed logic controller that produced a minimum COP of 2.24 in the worst conditions. Lin and Yeh (2009) experimented with a 0 Hz to 100 Hz inverter driven compressor alongside 480-step electronic expansion valves (EEV) and positioned the EEV to control individually dependent on-demand capacity. Lin and Yeh (2009) conducted their study with all evaporators in operation throughout the control process, however, issues can occur whenever a mode switching is done to run a single evaporator. Directly switching one control strategy to another could lead to discomfort for the users in the rooms.

Choi and Kim (2003) experimented with two evaporators and an inverter driven compressor. Testing conditions locked compressor speed while having separate but constant EEV position to monitor cooling capacity provided from a certain speed and orifice opening. Superheat ran rampant without any level of control but was expected as demand was not being filtered through controlling components. With the controlled indoor unit, superheat and the sub-cool temperature was between 4 °C–10 °C and between 4 °C–7 °C, respectively. In addition, Choi and Kim (2003) conducted the tests with varying indoor loads, EEV opening, and compressor speed. Meng et al. (2015) included solenoid valves in addition to EEVs to help with startup operation for system pressure. This was mainly in use for a predetermined oil management phase where the compressor starts up for a short time if it has been on below 35 Hz for longer than 60 min. This is a safety precaution and the remaining testing included outdoor condenser modifications that netted small data. Tu et al. (2016) further investigated multi-compressor systems where inverter driven exceeded digital scroll in the partial load conditions for this type of testing under a large band of efficiency variations and noise level considerations. The noise test results from Tu et al. (2016) showed that the noise value rises with an increase in the running frequency. The determining point where each compressor begins and ends operation is where this system holds the most value in energy efficiencies and performance.

The performance of ductless systems was also measured using the ductless Air Source Heat Pumps (ASHP) in the cold climate regions. In their study, Kegel et al. (2017) tested a ductless cold climate air source heat pump with a variable speed compressor in an environmental test chamber capable of inducing a wide range of heat pump operating conditions. Preliminary testing showed that the non-ducted system was capable of efficiently meeting space heating loads down to −25 °C. However, the researchers of Kegel et al. (2017) do not quantitatively analyze the performance of the ductless heat pump. Although, it was noted in the research that the measured heat output of the heat pump did not match the manufacturer-derived performance, highlighting the need for more testing and improved published performance curves. In a similar study, Sager et al. (2018) tested with ductless ASHP system with a rated heating and cooling capacity of 4.0 kW at 8.3 °C and 3.5 kW at 35 °C, respectively. The tests were completed by varying the outdoor temperature and indoor load in climate-controlled test facilities, so the effects of climate and indoor load were also considered. The results showed that the ductless ASHP was able to operate at very low outdoor temperatures below the manufacturer-rated temperature of −25 °C. The inverter-driven compressor also showed the ability to modulate its frequency at different outdoor temperatures and heating loads. The test also showed that the COP of the system increases as the compressor speed reduces.

2.2. Refrigerants

The performance of the heat pumps depend upon several factors such as refrigerant, type of compressor, type of heat exchangers, and expansion devices. Refrigerants are not only chosen based on their performance and thermodynamic properties but also based on environmental and nonhazardous properties. Owing to its good thermodynamic properties, hydrochlorofluorocarbon (HCFC) R22 was widely used as the working fluid in air conditioning and heat pump systems during most of the 20th century (Sethi et al., 2015; Mota-Babilonia et al., 2017). The application of the Montreal Protocol in developed countries phased out this ozone-depleting fluid in newly developed systems. Currently, new air conditioning systems in Europe, the USA, and other developed countries use the chlorine-free hydrofluorocarbon (HFC) R410A. R22 and R410A, which have been identified as greenhouse gases, contribute largely to climate change when leaked from vapor compression systems (Mota-Babilonia et al., 2017). R-410A has a Global warming potential (GWP) of 2088, and R-22 has a GWP of 1810, which is thousands of times higher than natural refrigerants like CO2 (Shen et al., 2016). In recent years, R410A has become more common for residential HVAC systems (Amarnath and Blatt, 2008).

In their study, Cheung and Braun (2014) investigated heating mode with different types of expansion valves for ductless systems using R-410A through a TXV or an FXO primarily used in single speed systems and then compared to variable speed systems. COP and efficiencies of heat production, heat transfer, degradations, and second law efficiency are measured and reported for the systems each kept at 2.2 kg of R410A. Sencan et al.

(2006) recorded COP of refrigerants from the first and second law of thermodynamics analysis with R-134a, R-407C, and R-410A. Results showed R-410A has lower efficiency compared to the other refrigerants. In addition to the evaluation of the efficiency of the refrigerants, Sencan et al. also found that condenser and evaporator temperatures have strong effects on the COP of the system. Rothfleisch and Didion (1993) conducted an experiment with a ductless mini split system to compare the performance of R22 and a mixture of 34% R32/66% R134a by weight. Unlike other studies, Rothfleisch and Didion (1993) experimented with both single-phase and two-phase refrigerant entering the low-pressure side of the liquid–suction heat exchanger. The results showed that the combination of this system and test procedure penalized the mixture performance by causing it to have a performance 18.9% lower than R22. Abdelaziz et al. (2015) conducted an experiment to develop an understanding of the performance of low-GWP alternative refrigerants to HCFC and HFC refrigerants in mini-split air conditioners under high-ambient-temperature conditions using R-410A as the baseline. The results demonstrated that there was a significant improvement in the performance of the alternatives over that of the baseline, in terms of both COP and cooling capacity. The study further suggested that DR-55 and HPR-2A had higher COPs than the baseline and matched the capacity of the baseline at both the hot and extreme test conditions. R-447A and ARM-71a had lower cooling capacity than the baseline at all ambient conditions.

Minor and Yokozeki (2004) examined the system performance of a ductless split heat-pump unit (2.5 kW) with a rotary compressor, designed for R-22 and tested with R-407C. The system was tested with several polyolester oils (POE) as lubricants. The results showed that the different POE lubricants used with R407C do not affect the compressor behavior and that some other system effects must be responsible for variations in capacity and energy efficiency. However, the causes for variations in capacity and energy efficiency were not discussed.

Although it has been available for many years, pure R32 has not been used in air conditioning systems because manufacturers have preferred R410A. Compared to R410A, R32 offers the disadvantages of being classified as a flammable fluid and higher compressor discharge pressures (Mota-Babilonia et al., 2017). Although R32 provides advantages such as lower refrigerant cost than R410A and better performance at higher ambient temperatures, the flammability of R32 makes manufacturers favor R410A (Pham and Rajendran, 2012). In their study, Shen et al. (2022) evaluated the performance of a two-speed scroll compressor with low-GWP R452B and R454B and compared the results with R410A. The results showed that, although the performance of the low-GWP refrigerants was comparable to the R410A, the R452B and R454B showed overheating issues at low ambient heating conditions. Results from Shen et al. also highlighted an issue in compressor or lubricant oil overheating risks due to the use of R452B and R454B. In another study, Minamida et al. (2018) experimented with a mini split system with a capacity of 7.1 kW with R-452B, R454B, and R-32 refrigerants replacement for R410A. The results showed that the COP of R-452B and R-454B is less than that of R-32. Although the performance of R-452B, R-454B, and R-32 was comparable to R-410A, Minamida et al. (2018) do not take into consideration the flammability of R-32 refrigerant.

2.3. Pipe length

The refrigerant pipe dimensions are also an important aspect of the performance of ductless mini split systems. In the outdoor and indoor system, all liquid and vapor copper refrigerant lines must be individually insulated throughout the system. Refrigerant piping and wiring connections can be brought into the outdoor unit through openings provided in the front and side of the unit.

For the performance comparison of different heat pumps Holloway (2013) used a 25 ft refrigerant pipe that matches the AHRI rating tests which mandate a minimum refrigerant line-set length of 25 ft. However, line set lengths above 50 ft are common in most American homes. When vapor or two-phase refrigerant moves for long distances after throttling in the expansion valve, it may gain heat from the environment and experience large pressure drops before reaching the evaporator, leading to decreased system efficiency (Holloway, 2013). In the study conducted by Holloway, the lengths of the pipe were not accounted for the effect of line set length on mini-split unit performance. In most ductless system studies, researchers did not account for the refrigerant pipe lengths, however, Yan et al. (2012) conducted a study on the effects of refrigerant pipeline length on the operational performance of a dual-evaporator air conditioning system. Results suggested that the system's COP decreased with an increase in the refrigerant pipeline length. The results also suggested that the highest COP would be resulted in when the outdoor unit is located equally between the two indoor units and the lowest COP would be when the outdoor unit is located close to either of the indoor unit. In their study, Pan et al. (2014) suggested that the longer refrigerant pipes impose pressure drop that can affect system performance. Longer pipes exert more losses during the flow of the refrigerant, which directly affects the performance of the system. In addition, Pan et al. (2014) also concluded that optimum diameters of the refrigerant pipelines are independent of their lengths. In another study, Minamida et al. (2018) experimented with a pipeline length of 7.5 m for the mini split system and 25 m for the VRF system and found that the pressure loss of refrigerant is directly proportional to the pipeline length. The pressure losses can be recovered if the compressor rotation speed is increased, the mass flow rate increases, and the pressure loss in the gas pipes, especially on the low-pressure side of the system, increases (Minamida et al., 2018). However, Minamida et al. did not quantitatively evaluate the effects on the performance of the system due to the different pipe lengths.

Performance highlights:

- The efficiency of the system increases when using a digital scroll compressor instead of single stage compressor.
- R-410A is current common refrigerant over the previous R-22 due to less ozone harmfulness.
- The COP of mini split system decreases with an increase in the refrigerant pipeline length.
- Mini split heat pumps have higher SEER and HSPF compared to single-speed and dual-speed systems.
- Mini split heat pumps offer improved part-load control and enhanced humidity control.
- The variable-speed DHP system outperforms the conventional system mainly due to smaller fan power consumption.
- The COPs of DHPs can vary depending on the climate and can be either more or less than the conventional systems.

3. Thermal comfort

ASHRAE 55 (Ashrae Standard 55, 2010) defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment". Indoor temperature and humidity are the main factors taken into consideration for the evaluation of thermal comfort. The comfort zone is sufficiently comfortable if at least 80% of its occupants can be expected to not object to the ambient condition. The primary method used by the researchers to evaluate thermal comfort is to calculate the number of times the temperature exceeded or fall behind the setpoint temperature.

Experiments were conducted to determine whether the thermal comfort provided by mini split heat pump (MSHP) is equal or better than the conventional systems.

Pang et al. (2019) experimented to measure the energy savings potential of DHP systems when they are installed in existing buildings with pre-existing HVAC equipment like zonal electric baseboards and window AC units. An EnergyPlus model was created to represent a single-family home which was used for the analysis of energy consumption of the DHP system. The model was based on the floorplan of the PNNL Lab Homes, which are two identical manufactured homes located on the campus of the Pacific Northwest National Laboratory (PNNL), in Richland, WA. The experiment was done for two HVAC configurations: (1) a DHP in the living room with electric baseboards and window AC units in the bedrooms; and (2) the same setup as configuration #1, with the addition of air transfer grilles installed between the living room and the bedrooms. In their study, Pang et al. (2019) conducted a comprehensive study by using different operation scenarios and schedules. The data obtained from the experiment was used to determine the number of hours the temperature went above or below the ASHRAE 55 standard. From the results, the discomfort time increased by 23% and 1.8% for configuration 1 and configuration 2 respectively. Ashley also et al. (Ashley et al., 2020) reported on the MSHP experiment conducted at the PNNL Lab Homes to examine their energy savings and thermal comfort potential. To conduct the experiment, DHPs were installed in the PNNL Lab Homes. Central and zonal heating experiments were conducted to examine thermal comfort and energy savings. Like in the study conducted by Pang et al. (2019) and Ashley et al. (2020) also did a comprehensive study by testing for different scenarios and configurations. To measure the thermal comfort Ashley et al. (2020) used the data from sensors to count the number of hours the temperature was 5° above or below the setpoint temperature. The central heating experiment showed that the number of hours of temperature above or below the setpoint was 22 in the living room for the baseline home while the number was 16 for the experimental home. So, the DHPs demonstrated slightly better results for the thermal comfort experiment. The study conducted by Ashley et al. (2020) and Pang et al. (2019) used the ''discomfort time'' as the metric for evaluation, which is dependent on the room temperature, humidity. So, the studies do not account separately for the temperature and moisture control of the systems.

In their study, Ueno and Loomis (2015) evaluated the performance of MSHPs for a set of eight houses. Like the experiments conducted by Ashley et al. (2020) and Ueno and Loomis (2015) also used a temperature offset method to measure thermal performance. The number of hours the temperature exceeded the 4° offset limit was counted using the temperature sensors. The temperature was found to be within the limit between 19% and 73% for the winter experiment, and about 96% of the time during summer. So, the performance of the MSHP was better during the summer. In addition, Ueno and Loomis (2015) also measured the relative humidity by using the method called the humidity control metric used by Rudd et al. (2013) to calculate the number of hours with interior levels over 60%. The results showed that the relative humidity was above the 60% limit for about 13% to 23% of hours during the experiment. In a similar study, Roth et al. (2013) conducted field tests in two homes in Austin, Texas, from October 2011 to June 2012 to evaluate the comfort performance of MSHPs. The methods used for the experiment were hourly comfort analysis and daily mean temperature analysis. For the hourly comfort analysis, temperature and indoor relative humidity were acquired through real-time monitoring and the data was used to determine if the condition lay within the comfort zone. The daily mean temperature analysis method used the daily mean dry bulb temperature instead of the hourly temperature. Unlike similar studies, to analyze the performance of the systems, Roth et al. (2013) used the data when the system was considered ''in operation''. A system is considered in operation when the building is expected to have either heating or cooling loads. The data obtained was used to determine the percentage of time the temperature and relative humidity were within the ASHRAE comfort zone. The results showed that the temperature for the central system was within the comfort zone for an average of 74% of the time, and for the ductless split systems, it was 87%.

Lubliner et al. (2016) reported on the results of field testing and monitoring of MSHP hybrid heating systems in seven homes of a high-performance affordable housing community located in Pierce County, Washington. The study included analysis of DHP and electric resistance heaters and comparison between the results of different systems. Each home was equipped with a single air handling unit, 1-ton DHP with an HSPF of 12 and a SEER of 25. The accumulated data collected and the survey results from the occupants were used to determine the thermal comfort results. Results suggested that the living area temperatures were generally 68°–74°F and relative humidity in the houses were generally at comfortable levels—between 40% and 60%.

Sutherland et al. (2016) equipped inverter driven MSHP in central Florida homes with the goal of reducing space heating and cooling energy by decreasing the runtime of the existing central system. Two additional homes were equipped with high-efficiency, DHPs as complete central system replacements—a single ducted unit and a multi-split design. Results from Sutherland et al. (2016) showed that while significant cooling savings were measured, the multi-split installation suffered comfort issues. The mini split replacement, however, showed superior interior moisture control. Herk (2017) reported on a project that was created from a partnership between the U.S. Department of Energy, IBACOS, Inc., and a production builder of Imagine Homes, located in San Antonio, Texas. The primary purpose of this project was to evaluate the performance of a multi-head mini split heat pump system in maintaining uniform comfort in an occupied environment. Like in the experiments done in Ashley et al. (2020) and Ueno and Loomis (2015), a 2° temperature offset limit was used to measure thermal comfort. Results showed that temperatures and relative humidity levels were always not uniform. Temperatures frequently varied well beyond ±2°F from the thermostat reading. The relative humidity levels also varied significantly—in some cases, by as much as 20% relative humidity. Unlike other studies, Herk (2017) also compared the measured airflow values for each room at low, medium, and high fan speeds. In an experiment by Christensen et al. (2011) in Denver, MSHP showed a variance of 1.6 °C across the supply-side thermistor measurements, along with a variance of 3.0 °C across the return-side thermistor measurements. However, Christensen et al. (2011) did not include the temperature and humidity control of the system as a means of evaluating thermal comfort.

The moisture control capabilities of the mini split system have also been investigated by researchers. There are various factors that could impact relative humidity such as occupant variable loads, amount of mechanical ventilation, dehumidification performance of air conditioners, and occupant operation of equipment. Although many mini split systems have relative humidity control modes that improve moisture removal, these still need improvement and are not adequate to maintain indoor relative humidity below 60% without supplemental dehumidification (Withers, 2018). In their study for evaluating moisture control of variable capacity heat pumps, Martin et al. (2018) observed periods of increased indoor relative humidity in four homes solely cooled using mini and multi-split systems without supplemental dehumidification. The occupied homes exhibited indoor hourly average relative humidity exceeding 60% for a maximum period of the day. In another study, Withers (2016) conducted research in a house lab with a supplemental mini split system and ASHRAE 62.2 ventilation and found that a mini split system without supplemental dehumidifier resulted in average indoor relative humidity exceeding 60% between 4%–15% of the test hours.

Thermal comfort highlights:

- DHPs are more suited for hot climate regions as the discomfort time during mini split experiments was found to be higher in winter.
- Ductless mini split room temperatures can vary well beyond ±2°F from the thermostat reading and the relative humidity levels also can vary by as much as 20%.
- DHPs can show better thermal comfort results if used with pre-existing HVAC equipment such as conventional ducted systems or electric baseboards.
- The traditional system shows better moisture control compared to the mini split system.
- The mini split shows superior interior moisture control compared to the multi-split system.

4. Energy savings

A ductless heat pump can save energy in various ways. A DHP system typically uses an inverter-driven compressor, which can achieve very high efficiency. Many of the DHPs currently on the market have a SEER of 20 or above, while most central heat pump systems are rated at the minimum Federal standard of SEER 13 (Pang et al., 2019; Winkler, 2011). MSHPs have no ducts, so they avoid the energy losses associated with the ductwork of central forced air systems (Roth et al., 2006). Several researchers have completed field evaluations in different single and multi-family homes for the testing and measurement of energy savings using DHP.

Various field evaluations of MSHPs included using the heat pump in homes with pre-existing HVAC equipment. Authors of Storm et al. (2012) evaluated the Northwest Energy Efficiency Alliance NEEA launched a regional project intended to implement, demonstrate and evaluate energy savings and market acceptance of a new generation of MSHPs in existing residential homes with electric resistance zonal heating systems. A DHP was installed in the main living area of the houses for the evaluation process, and after conducting extensive laboratory analysis and field analysis, the energy savings were calculated for the homes that participated in the NEEA pilot project. Results showed that an average of 3887 kWh/year of energy was saved by the DHP systems during the period of analysis. Since the experiment was done in homes with preexisting equipment, savings were strongly determined by the amount of pre-existing electric heating. Results from the PNNL lab homes experiment by Pang et al. (2019) showed a significant amount of energy savings when a DHP is used with existing HVAC equipment. The HVAC energy consumption was reduced by 37.3% for configuration 1 and 7.5% for configuration 2 annually. The results of the heating experiment from Ashley et al. (2020) showed that MSHP system saved 22% to 45% energy during the central experiment. Zonal heating experiment savings ranged from 7% to 35%. Since the analysis done by Ashley et al. (2020) and Pang et al. (2019) involved energy savings in homes with preexisting equipment, the actual energy usage by the DHP system was not evaluated.

Although ductless mini splits are more suited in the summer season, several researchers also conducted an experiment on the energy savings of MSHPs in cold climate regions. Bugbee and Swift (2013) collected the data on an installed DHP in an apartment in central Connecticut and analyzed the results over two winters. The DHP was installed in an apartment with an electric resistance baseboard. In this study, the experiments were conducted for different cases involving baseboard, DHP, and for both DHP and baseboard heater used simultaneously. The energy savings for the analysis ranged from 31.3% to 40%. In their study, Sutherland et al. (2016) monitored 53 Florida homes equipped with MSHP for three years with detailed sub-metered data on heat pump energy use as well as temperatures and interior humidity conditions. Energy savings were analyzed and compared to the central air conditioning system. The results showed that the supplemental MSHP installations generated median energy savings of 33% (6.7 kWh/day) for space cooling and 59% (6.5 kWh/day) for heating. The experiment by Sutherland et al. also involved energy savings analysis for both mini split and multi-split systems. Korn et al. (2016) reported on Massachusetts and Rhode Island Program Administrators commissioned an experiment to evaluate MSHPs. The analysis was conducted for two winters of 2015 and 2016 and the summer of 2015. The team used statistical analysis and created graphs and box and whisker plots to conduct the energy analysis of the houses. The results showed energy savings between 54 kWh and 784kWh per year. In another study, Breton et al. (2019) conducted an analysis with an enhanced variable-capacity heat pump (VCHP) component model developed in TRNSYS and simulated a ductless VCHP with supplemental baseboard heating. The results showed savings between 28% and 37% energy savings compared to the traditional system.

Researchers also conducted studies on the energy savings potential of ductless ASHPs. Schoenbauer et al. (2018) analyzed the energy savings from ASHPs on the project sponsored by the Center for Energy and Environment. The results showed that ASHPs can save up to 56% of energy in cold-climate areas. Schoenbauer et al. (2018) conducted a study for two configurations: ductless ASHP as the existing heating systems backup, and using only the existing traditional system without ASHP, so the actual performance of the ductless ASHP was not highlighted. In another study, Janssen et al. (2020) evaluated the energy savings of ductless mini split ASHPs in the cold Canadian climate. Results from Janssen et al. (2020) showed that heating season energy savings were 19% to 32% of the total bill. In addition, Janssen et al. (2020) also used the mini split in the cooling mode and estimated from the results that the heat pumps consumed 5 times less energy than the window air conditioner.

Logsdon and Larson (2016) examined the energy use and savings of DHPs in a new, mid-rise multifamily building in Seattle. In contrast to other studies, Logsdon and Larson (2016) conducted comparisons between two groups of houses, one with DHP and the other without DHP. Of the 279 apartments in the complex, 93 had DHPs, and 186 did not. The analysis compared the energy use between the two groups using industry-standard temperature–energy regression techniques. Regressions were conducted using a change point analysis methodology, where average daily kWh is taken as a piecewise linear function of average outdoor temperature, with possible "elbows" for heating and cooling depending on whether the usage profile was correlated with cold outdoor temperatures, warm outdoor temperatures, or both. The analysis was conducted with bi-monthly bills of energy usage while using daily energy usage would result in much more accurate results. The results from the analysis showed that the average savings are estimated to be around 350 kWh/year. In another study, Jackson and Walczyk (2019) conducted research to determine the most cost-effective DHP installation scenarios and inform new residential offerings using empirical evidence. The primary research objective was to estimate the annual energy savings resulting from the installation of a DHP. The research was conducted for single-family and multifamily homes. The data from Utility Customer Information and the survey with the participating homes were used for the analysis of the project. In their study, Jackson and Walczyk (2019) also accounted for the effects of the weather by using cooling and heating degree days in energy savings evaluation. Results from Jackson and Walczyk (2019) showed 32.9% energy savings for the single-family homes and 18.8% energy savings for the multifamily homes compared to the conventional system.

The Central Valley Research Homes project established experimental conditions in four homes of different vintages in Stockton, California for ductless mini split and ductless multi-split (Proctor, 2016). The baseline cooling systems were conventional split system air conditioners operating at a single speed, and the baseline heating systems are electric resistance heaters. The mini split unit was expected to produce 66% energy savings compared to the resistance heaters. The actual savings was 44% for a seasonal COP of 1.77. The Multi-split unit was expected to save 72% compared to the resistance heaters. The actual savings was 56% with a seasonal COP of 2.29.

In another study, the Authors of Anon (2014) reported on the results of primary research conducted by Northeast Energy Efficiency partnerships to better determine the potential for energy savings and efficiency program support for MSHPs in the residential sector. Nine residential DHP installations were monitored with the cooperation of New Hampshire Electric Cooperative and their customers. The estimated savings for the DHPs on average was $832 compared to electric resistance heat as the baseline. The study conducted by authors of Anon (2014) had the DHPs sized for heating loads, and it proved difficult to identify periods when active cooling was taking place, and as a result, accurate cooling savings were not presented. Another study by NEEA (Webb et al., 2018) for the DHP initiative in single family homes reported an average of 22% in energy savings from DHP installations. The reported savings varied widely, from 5% to 45%, however, the reasons behind such variation were not illustrated in the paper.

The use of computer software to estimate the energy savings of DHPs was also done by some researchers. Lubliner et al. (2016) used BEopt Version 2.02 to estimate the typical space-heating and total annual energy use for seven homes in Pierce County, Washington. The analysis was conducted for both ERs and DHPs. Unlike other studies, Lubliner et al. (2016) used both experimental evaluation and computer simulation to compare the energy savings. The results from the BEopt model were compared to the home's actual energy use to evaluate the savings from using DHPs, and the results showed that the average modeled savings estimate was 2636 kWh/year/house and the average measured savings estimate was 3310 kWh/year/house.

Energy savings highlights:

- Mini splits have no ducts, so they avoid the energy losses associated with the ductwork of central forced air systems.
- DHP can be easily zoned by installing multiple indoor units and can be independently controlled which can minimize energy waste.
- Energy savings from ductless mini splits can be as high as 45%.
- A significant amount of energy can be saved if a ductless mini split system is used with the pre-existing HVAC equipment.
- DHPs can be more efficient in cold climate regions if used simultaneously with a baseboard heater.

5. Market potential and cost

Mini split heat pumps are gaining in popularity in the United States due to their high efficiency, straightforward installation, the capability to provide space heating and cooling, quietness, zoning ability, and more recently, high heating capacity even at very low outdoor temperatures (Dentz et al., 2014). The market for DHPs is growing 10%–30% every year and is expected to grow further (Sutherland et al., 2016). Despite the increase in the market for DHPs, the cost of installation has been a factor of concern for many households in the United States. Therefore, several researchers have tried to quantify the market potential and installation costs of MSHPs.

5.1. Cost and potential

The cost of MSHPs can be dependent on the size of the system required. The MSHP market is largely clustered around a few capacity levels. These capacity levels tend to match with fractions of a cooling ton, such as 0.75 ton (9 kBtu/h), 1 ton (12 kBtu/h) and, so on Ductless Mini-Split Heat Pump Cost Study (2018). Researchers have used data from different experiments and surveys from contractors and installers to determine the market potential of MSHPs.

Lubliner et al. (2016) conducted an economic analysis to compare the life cycle cost between an all-ER system and DHP/ER hybrid system. The analysis was done with the Office of Financial Management assumptions, which included a 20% down payment, a nominal interest rate of 4.54%, and general inflation of 2.87% with 15-year and 30-year mortgage terms. The baseline all-ER zonal heated home life cycle net present value cost was approximately $22,757, and the DHP/ER hybrid heating system life cycle net present value cost was $19,067. The estimated net present value benefit of a DHP/ER hybrid heating system was estimated to be $3690. In another study, Sutherland et al. (2016) used the average full retail cost for equipment, materials, and labor for each of the ten supplemental MSHP installations was about $3900, in line with $3500–$4000 installed costs reported by Faesy et al. (2014) to perform the cost analysis and calculate the payback period of installation of MSHPs. The analysis showed that the median annual HVAC energy savings translate into about $285 saved per year (2375 kWh/year and $0.12/kWh), which yields a simple payback in about 14 years and an annual rate of return of 7.3%.

In their study, Kolwey and Geller (2018) analyzed whether heat pumps can be cost-effective and reduce energy consumption compared to heating with gas furnaces, in homes that also have central AC. Based on the cost estimates, the difference in the installed cost of the heat pump compared to the gas furnace/AC alternative ranges from $2800 savings in Denver to $4100 savings in Las Vegas. Also, it was estimated that the lifetime cost savings for heat pumps in the retrofit scenarios range from a savings of 6 percent in Phoenix to a loss of 30 percent in Denver. Jackson and Walczyk (2019) conducted a cost analysis for the installation of DHPs for single-family and multifamily applications. The analysis was done using the data from phone and web-based surveys. The survey showed that the cost per DHP was between $5511 and $6697.

The NEEA launched the Northwest Ductless Heat Pump Project as a pilot to demonstrate the viability of inverter-driven ductless heat pumps to displace electric resistance heat in existing Northwest homes. NEEA (Webb et al., 2018) reported that since 2008, an estimated 162,333 DHPs have been installed in the region. In their study, NEEA (Webb et al., 2018) also reported that the average total cost to install a single-zone DHP system including labor and equipment costs before any rebates or credits were applied was roughly $4200 in 2018.

Although DHPs are not cost-effective in many scenarios, several heat pump companies and utility providers have offered different rebate programs to promote the installation of heat pumps.

Several programs offer incentives to different single and multi-family homes for the installation of DHPs. The Massachusetts Residential Heating and Cooling Program offered rebates for the installation of high-efficiency MSHP systems. The authors of Ductless Mini-Split Heat Pump Cost Study (2018) evaluated the energy-efficiency related total and incremental costs of single-family home installations of MSHP systems rebated through the Massachusetts Residential Heating and Cooling program. The data sources for the analysis of the project were the HVAC, retail prices gathered by web scraping, and a sample of scanned invoices for system installations. The study considered the costs of installing MSHP systems in a retrofit scenario and a replacement scenario. The contractor survey data indicated that the total cost of a retrofit installation is about $75 higher than the total cost of a replacement installation.

The Emera Maine Heat Pump Pilot Program provided $600 rebates and optional on-bill financing for qualifying DHPs installed in residential homes and small commercial buildings of Emera Maine. EMI Consulting (Emera Maine Heat Pump Pilot Program, 2014) reported on the results of an evaluation completed on the Heat Pump Pilot Program. The research team collected and analyzed data from the qualifying participants and heat pump distributors. Results from household surveys showed that the participants saved on average $622 in heating costs after the installation of DHPs (Emera Maine Heat Pump Pilot Program, 2014). The data from distributors showed that the market share of energy-efficient heat pumps sold in Maine increased from 50% to 64% over the year. In Maine, $500 rebates were also available toward the installation of DHPs that provide a single or first zone of heating for a home between 2013 and 2016. An additional rebate of $250 was available for DHP installations that provide a second zone of heating (High Efficiency Heat Pumps, 2016; Lapsa et al., 2017). Connecticut Light and Power (Residential Heating, 2013) also offered a rebate of $500 or $1000 for residential customers who purchase and install a ductless split heat pump as the primary heat source for a unit. The rebate amount varies by efficiency standards. The system must be Energy Star qualified and have a heating efficiency of HSPF of 10 or greater. Customers receiving the $500 rebate must have a system of at least 14 SEER, 11.5 EER, and 8.2 HSPF.

In their study, Hlavinka et al. (2016) investigated the effects of utility-provided rebates and expenditures and forecasted the number of installations of DHP in the Pacific Northwest region of the United States. Using a statistical model for analysis it was predicted that the cost per outdoor unit is $4435 and the maximum market potential by the end of 2018 is 1,658,148.

5.2. Retrofit

Ductless mini splits are also commonly used in retrofitting applications in homes. In such applications, MSHPs work as a supplemental application with the existing system. In heating-dominated climates MSHPs are typically used as supplemental retrofit installations, providing the primary source of heating to the areas that are most used (Lubliner et al., 2016; Faesy et al., 2014). Buildings most suitable for MSHP retrofits are those with high-cost heating fuel such as liquefied petroleum gas, fuel oil, and, especially, electric resistance. Buildings with natural gas services are less suitable (Faesy et al., 2014).

Baylon and Geraghty (2009) reported on a Bonneville Power Administration sponsored small pilot project aimed at demonstrating the feasibility of using DHP technology as a retrofit for residential zonal electric heating. The analysis used a "variable-base degree-day" (VBDD) methodology to evaluate the electric bills and develop baseline energy requirements and the space heating usage before the installation of the DHP system. VBDD is a regression procedure used on sub-metered data to calculate space heat energy use estimates. The total estimate for average per-site savings in space-conditioning consumption was 4204 kWh/year. The analysis was followed up by Encotope Inc. (Encotope Inc, 2010) to calculate energy savings for a new period of analysis, and the saving was found to be 4400 kWh/year. In a similar study, Roth et al. (2013) conducted a cost analysis for retrofitting a MSHP unit to an existing home with a central system. Capital costs from Mitsubishi Electric and costs from Foundation Communities were used for the analysis. The analysis showed that the cost for central air conditioning retrofit was $6308 while the cost for MSHP retrofit was $6963. In another study, Fenaughty et al. (2017) conducted a field evaluation with Florida Power and Light for different energy efficiency retrofit applications in 56 homes. The results from mini split application showed cooling energy savings of 33% and heating energy savings of 59%. The heat pump retrofit study by Kolwey and Geller (2018) study showed that ductless heat pumps reduce source energy consumption in the retrofit scenarios by an average of 13 percent across five cities in the United States.

Dentz et al. (2014) analyzed MSHP retrofit feasibility for a variety of multifamily building types and characteristics. Energy use and economics were estimated for an MSHP retrofit in place of oil, natural gas, conventional through-the-wall heat pump, and electric resistance heat in New York City and Boston. MSHP demonstrated up to 30% annualized energy savings compared to the conventional systems. Dentz et al. (2014) also analyzed various issues regarding MSHP multifamily retrofits. MSHP retrofit in multifamily homes can face several issues: (1) technical barriers such as placement and location of the outdoor compressor unit and its proximity to the indoor evaporator unit; (2) Building code compliance may limit where outdoor compressors may be placed; (3) Extensive electrical work may be needed to install the indoor evaporator units; (4) Ensuring the adequate distribution of conditioned air from MSHPs can be an issue; (5) Initial investment (Dentz et al., 2014).

Market potential and cost highlights:

- The market for ductless heat pumps in the United States is growing 10%–30% every year.
- The cost of installation of DHPs can range from $3500 to $6697 depending on the manufacturer and the location.
- Several heat pump manufacturers and utility providers have offered different rebate programs to promote the installation of heat pumps.
- Provision of rebates and incentives to families encourages the installation of much more efficient systems.
- In heating-dominated climates MSHPs are typically used as supplemental retrofit installations, providing the primary source of heating.
- MSHP retrofit in multifamily homes can face several issues such as technical barriers such as placement of the outdoor compressor, building code compliance, need for extensive electrical work, and initial investment.

6. Conclusions

In this study, an evaluation of the research done in the field of ductless heat pumps was done and presented in a summarized manner. The existing literature of the research conducted was thoroughly evaluated and presented in systematic order. The literature were classified into different categories based on their research focus within the topic. The literature was classified into four main topics: performance, thermal comfort, energy savings, and market potential. The methodology used by the researchers and their findings were summarized in the paper. According to our assessments, mini splits can have various advantages over conventional systems. The SEER and HSPF of the mini split systems were found to be higher than the conventional ducted systems in most of the research conducted. However, the COPs of the DHPs can be either higher or lower than the conventional systems depending on the building type, equipment, and climate. DHPs can show better thermal comfort results if used with pre-existing HVAC equipment such as conventional ducted systems or electric baseboards in cold climate regions. Also, DHPs are more suited for hot climate regions. Ductless mini splits can also save a considerable amount of energy. Mini splits have no ducts, so they avoid the energy losses associated with the ductwork of central forced air systems. The energy savings from ductless mini splits can be as high as 45% compared to the conventional ducted systems. Although ductless mini splits are mostly used in Asia in Europe, it is gaining market in the United States as well. The market for heat pumps is growing 10%–30% every year and is expected to grow further.

CRediT authorship contribution statement

Manoj Bhandari: Literature review and writing. **Nelson Fumo:** Defining the content, Reviewing, Formatting.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: As Nelson Fumo, a co-author on this paper, is the Editor-in-Chief of Energy Reports, he was blinded to this paper during review, and the paper was independently handled by Dr. Jose Luis Rodriguez as a Senior Editor.

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