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Review article

Review on the technological advancement of Stirling cycle heat pumps

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ABSTRACT

This review paper provides a detailed examination of the technological developments in Stirling cycle heat pumps, highlighting their development, advances, and possible applications. Stirling cycle devices can operate as a heat engine, a heat pump, and a refrigeration system. Stirling heat pumps and refrigeration are the reverse processes of Stirling engines. Additionally, this study provides an outline of the Stirling heat pump machine and the findings that have been conducted in this field. The review starts with an overview of the general working principles, configurations, and drive mechanisms, as well as research results on the heat pump application. In addition, the current research addresses and highlights several modeling and optimization strategies for enhancing the Stirling cycle heat pump's performance for different classifications of Stirling heat pumps.

1. Introduction

The total demand for energy rises as technologies and industry advance, which mostly results in environmental degradation and pollution. Currently, most technologies are making efforts to build green power and improve the utilization of current energy more effectively to tackle these problems.

The building sector has a substantial impact on energy usage and the release of greenhouse gases (GHG), especially in residential areas. In the European Union (EU), the residential area contributes to 25.4% of total energy use and 20% of greenhouse gas emission (Bee et al., 2018; Rinaldi et al., 2021). A significant portion of these environmental concerns are due to the power source that the buildings use fuel and hydrochlorofluorocarbon (HCFC) refrigerants in the heat pump or refrigeration systems. The building industry, specifically the residential sector, uses the majority of its energy for space and water heating applications, see Fig. 2. This shows heating technologies should be shifted toward novel technologies such as Stirling cycle heat pump, which mitigate the environmental effects.

A heat pump is one alternative that can utilize existing energy more efficiently. A heat pump is a system that delivers heat from a low-temperature region to a heat high-temperature region. The amount of heat generated by a heat pump exceeds the energy it uses, making it different and more efficient than other types of heaters like combustion heaters or electric heaters. This is because it requires work to pump heat energy from low temperatures regions, and then convert it into heat energy. Subsequently, both of them transferred together to the high-temperature source. These factors led to the development of various types of heat pumps, including chemical heat pumps, adsorption heat pumps, steam-driven jet heat pumps, and vapor compression heat pumps. These pumps are mostly used in a variety of industries, including drying, evaporation, distillation, waste heat recovery, air conditioning, and water heating.

The heat pumps mentioned above, especially vapor compression heat pumps, can use existing energy more effectively. They also have weaknesses because of their working fluid, which can lead to environmental problems, including thickness reduction of the ozone layer and increasing greenhouse effect. In addition, it needs a working fluid whose critical temperature exceeds the temperature heat sink and whose freezing point is considerably less than the temperature heat source. Due to this fact, the Montreal and Kyoto Protocols, which limit the use of CFC, HCFC, Halon, PFC, HFC, and SF6, were signed in 1987 and 1997, respectively (Getie, 2021). The engineering community is looking for alternatives to other forms of heat pumps in addition to performance improvement because of energy challenges and climate change (Cavallini et al., 2005; Getie, 2021; Liu et al., 2018). Therefore, developing a heat pump to refrain from the requirement of such operating fluids will be vital in the future.

Robert Stirling in 1816 invented a closed thermodynamic Stirling cycle device used as an engine that transforms heat energy into mechanical energy (Urieli and Berchowitz, 1984). Beale reported that these cycle devices could be used as an engine and heat pump (Beale, 1971). The device used as a refrigerator or heat pump, which is the reverse process of the Stirling engine, was first developed in 1832 (Kohler, 1968). Thus, in this review, the term Stirling cycle devices primarily refers to the Stirling cycle heat pumps.

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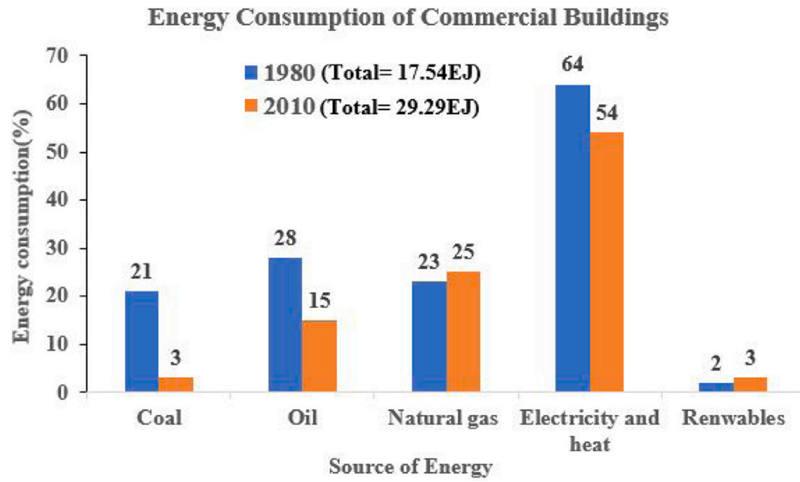

Fig. 1. World total final buildings' energy consumption (International Energy Agency Office of Energy Technology and R&D and Group of Eight (Organization), 2006).

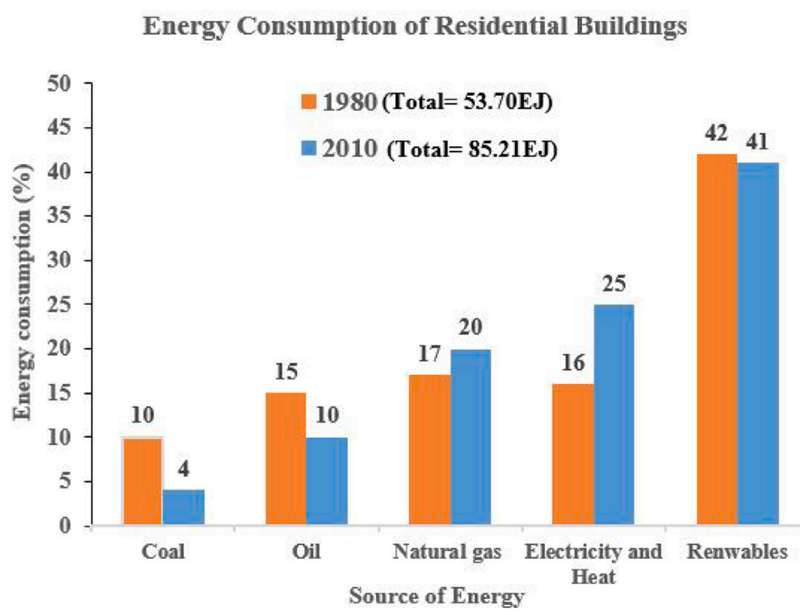

Fig. 2. World total final buildings' energy consumption (International Energy Agency Office of Energy Technology and R&D and Group of Eight (Organization), 2006).

Table 1
Energy consumption in EU households (2020).
Source: Eurostat.

Domain	Energy consumption
Space heating	62.8%
Water heating	15.1%
Lighting and appliances	14.5%
Cooking	6.1%
Space cooling	0.4%
Other	1%

The primary focus of this study is on Stirling heat pump technologies that utilize environmentally friendly gases, such as hydrogen, helium, nitrogen, and air, as refrigerants. In a certain situation, these devices have the potential to serve as an alternative to the current vapor-compression heat pump systems (Haywood et al., 2002) (see Fig. 1).

Extensive studies have been carried out on Stirling devices, particularly focusing on engines and cryocoolers in past years. The findings indicate significant advancements in efficiency and performance for both engines and cryocoolers, with ongoing improvements and considerations for broader applications. While significant emphasis has been given to engines and cryocoolers, relatively little attention has been directed towards the development of heat pump works on the Stirling cycle.

There is a significant prospect for research on Stirling cycle heat pumps as a result of environmental concerns. The goal of this review paper is to give a summary of the technological developments and research that have been made in the area of Stirling heat pumps.

Heat pumps are an efficient heating technology as compared to combustion and electrical heaters. The market for heat pumps has grown significantly globally, greater than twice in some countries in a year (Rosenow et al., 2022). Therefore, governmental encouragement is required to increase efforts for heat pump technology and accomplish goals related to climate change.

European Union set a goal to reduce greenhouse gas emissions by 80–95% in 2050 due to the high cost of fuel and global warming. This scenario changes the researchers to search for another technology for heating applications to meet the 2050 agenda of the European Union (net-zero pathway). In 2020, One hundred seventy-seven million heat pump were installed globally according to the International Energy

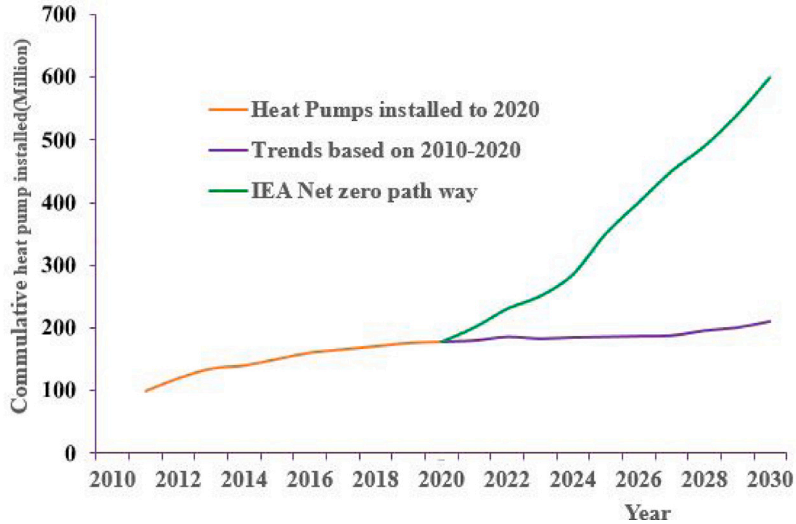

Fig. 3. Global sales of heat pump (Rosenow et al., 2022).

Agency (IEA) and the demand for heat pump increased especially in the coldest region, see Fig. 3.

The demand of high-temperature heat pumps (HTHP) and very high-temperature heat pumps (VHTHP) in the range of 90–160 °C increased in paper metal, food, paper, and chemical industries (Arpagaus et al., 2018). Research findings showed that when comparing the life cycle costs of all these technologies, Stirling-cycle-based heat pumps give more economic benefits than fossil fuel, biofuel-fired conventional boilers (Khan et al., 2023). Therefore, the Stirling heat pump is one solution for heating applications in the future to meet the 2050 of the European Union agenda.

2. Principal and classification of Stirling heat pumps

Stirling cycle is the most well-known thermodynamic cycle, which is used in engines, heat pumps, and refrigerators cycles.

A Stirling heat pump is a device that delivers heat energy from a low-temperature region to a higher-temperature region using the Stirling cycle, as a thermodynamic cycle. It has variable compression and expansion spaces, regenerator, working fluid, displacer, piston, and driving mechanisms. Since the Stirling cycle machine has a regenerator, it is classified as a regenerative thermal machine. The power piston compressed and expanded the working fluid in an enclosed system. The gas is moved back and forth by the displacer between the heat ejector/warm space and heat absorber/cold space. Heat extracted from low-temperature region and rejected to a higher-temperature region for the heating system, see Fig. 4. In the expansion process, heat is absorbed from an external source (such as lake, river, or waste heat) and in the compression process, heat is rejected from the heater. The P-V diagram, which represents the process, states that work must be delivered to the system in an amount equal to the area on the diagram in an ideal cycle, see Fig. 5.

There are four different thermodynamic processes that make up an ideal Stirling heat pump cycle.

Process 1-2 (Isothermal compression): The working fluid/refrigerant is compressed isothermally by the piston in a hot region. Heat is rejected to the hot region through the hot heat exchanger since the pressure and temperature of the refrigerant increase.

Process 2-3 (constant volume heat rejection): Piston or both piston and displacer move simultaneously to transfer the refrigerant to the cold region of the heat pump. The temperature of the gas is lowered to that of the cold region as it passes through the regenerator due to heat rejection from the refrigerant to the regenerator, and heat is stored in the regenerator.

Process 3-4 (isothermal expansion) : In the expansion space, the refrigerant expands isothermally. Heat is absorbed in the cold region through the cold heat exchanger as the temperature and pressure of the working fluid decreases.

Process 4-1 (constant volume heat addition): Piston or both piston and displacer move simultaneously to transfer the refrigerant to the hot region of the heat pump. The pressure and temperature of the gas is increased to that of the hot region as it passes through the regenerator due to heat rejection from the regenerator to the refrigerant, and then the process repeats.

The actual Stirling heat pump's pressure versus volume diagram differs from the ideal heat pump cycle, see Fig. 6. Configuration, drive mechanisms, and irreversibility variables influence the sinusoidal variation of the working volume of the majority of actual Stirling machines.

2.1. Classification and driving mechanism of Stirling heat pump

Stirling heat pumps are classified in different ways in accordance with the different machine configurations and driving mechanisms. The cylinder, working fluid, piston, displacer, driving mechanisms, regenerator, and heat exchanges are the fundamental components of a Stirling cycle devices (Ramos, 2015).

Stirling's machines are mainly classified on three categories, see Fig. 7. Stirling heat pumps can be classified into two kinds (single-acting and double-acting) based on their method of operation. Single-acting has one piston and one cylinder, which may be housed in the same or different cylinders. But double-acting Stirling heat pumps essentially consist of two or more pistons (Féniès et al., 2015; Formosa et al., 2014; Wu et al., 2014). There are three different kinds of Stirling heat pumps, based on how the piston, compression, and expansion spaces are arranged: Gamma, Beta, and Alpha. According to driving mechanisms: kinetic, thermoacoustic, and free piston or gas type.

The kinetic, thermoacoustic, and free piston classification systems are the most frequently employed at the various heat pumps, which are addressed in this review.

2.2. Cylinder arrangement or configuration

There are three different kinds of Stirling heat pumps, based on how the piston, displacer, compression, and expansion spaces are arranged, called the Alpha, Beta, and Gamma arrangements or configurations (Kirkley, 1962; Urieli and Berchowitz, 1984). Low, medium, and high-temperature differences between the source and sink heat

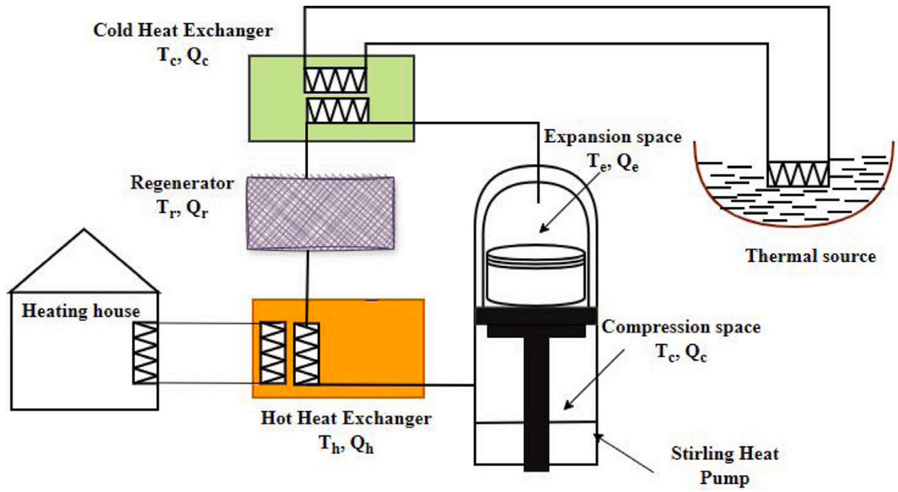

Fig. 4. Working diagram of Stirling Heat pump (Walker et al., 1982).

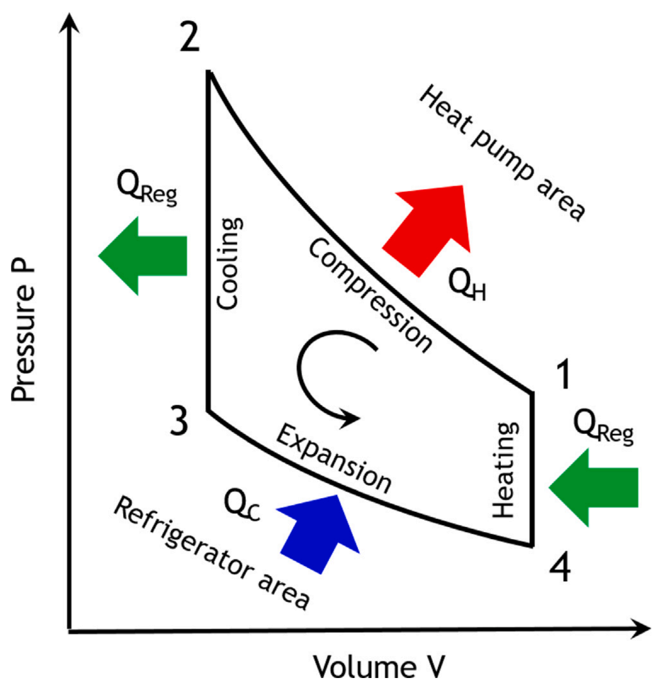

Fig. 5. Pressure versus volume diagram of the ideal Stirling heat pump cycle.

exchangers of the Stirling machines are typically regarded as being below 100 °C , 200 °C–400 °C , and above 400 °C , respectively (Chen et al., 2023). The working pressure also increases with temperature difference.

Alpha Stirling heat pump: A heater, regenerator, and cooler are connected in sequence with two pistons in different cylinders (Ahmed et al., 2017; McFarlane, 2014), see Fig. 8. A displacer is not employed in this arrangement. To keep the working fluid at a comparatively higher pressure, the contact space between the two pistons and the cylinder must be sealed. To heat or cool the working fluid at constant volumes, the two pistons are set up regularly to travel in the same direction. Stirling machines with an alpha arrangement have proved to be more appropriate for applications involving medium and high-temperature (Egas and Clucas, 2018). Furthermore, reports claimed that Alpha type arrangement are inappropriate for applications involving low-temperature differences (Altin et al., 2018).

Beta Stirling heat pump : The power piston and displacer of this Stirling heat pump are both enclosed inside a single cylinder (Hachem et al., 2017, 2015), see Fig. 9. The major responsibility of the displacer is to move the working fluid between the compression and expansion spaces through a network of heat exchangers. The earliest version of the Stirling machine was a Beta design, as can be seen in the patent drawing from 1816. This type of heat pump can be utilized efficiently for applications with low to high-temperature differences depending on the drive mechanism. Crank drives were preferred from low to medium temperatures, and rhombic drive mechanisms were more appropriate from medium to high-temperature difference (Batooei and Keshavarz, 2018).

Gamma Stirling heat pump: This heat pump has the same piston and displacer arrangement as the beta type, but the power piston and the displacer are set up in different cylinders (Batooei and Keshavarz, 2018), see Fig. 10. This type of heat pump is suitable for low-temperature applications (Egas and Clucas, 2018).

2.3. Driving mechanisms

To facilitate proper movement of the working fluid, there are different types of driving systems for Stirling heat pumps. The most common driving systems are categorized as free-piston, thermoacoustic, and kinetic types.

Kinetic-drive: The mechanical piston of Stirling heat pumps are moved through a variety of kinetic-drive systems, such as rhombic, swash-plate, Ross-yoke, and crank slider (Wang et al., 2016), see Fig. 11. The Stirling heat pump's most popular drive is the crank-slider system. Single cylinder beta type Stirling heat pumps operating at high pressures frequently employ the rhombic drive. The swash-plate drive is typically used for automotive four cylinders double-acting Stirling engines. Ross-yoke drives are typically seen in smaller Stirling heat pumps. Regardless of the configurations, all kinematic Stirling machines have a number of important engineering design issues that could limit their application. Mechanical friction could be one problem (Getie, 2021) (see Fig. 12).

Free-piston drive(FPSH): There are no crankshafts or other complex linkages in this heat pump. By using the clearing seal instead of the contact seal between the cylinder and piston, mechanical wear was reduced significantly (Wang et al., 2021). In this type of machine, the crank mechanism is removed and substituted by metallic springs and gas springs since the mechanical pistons have no mechanical linkages, see Fig. 13.

Thermoacoustic/Pulse tube drive: Due to the friction in the moving parts, the moving displacer in the aforementioned two heat pumps

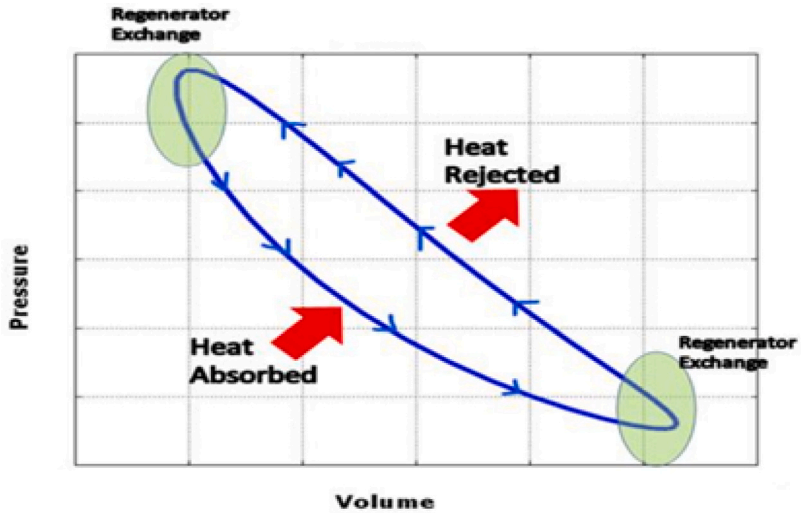

Fig. 6. Pressure versus volume diagram of the Actual heat pump cycle (Kowalski et al., 2022).

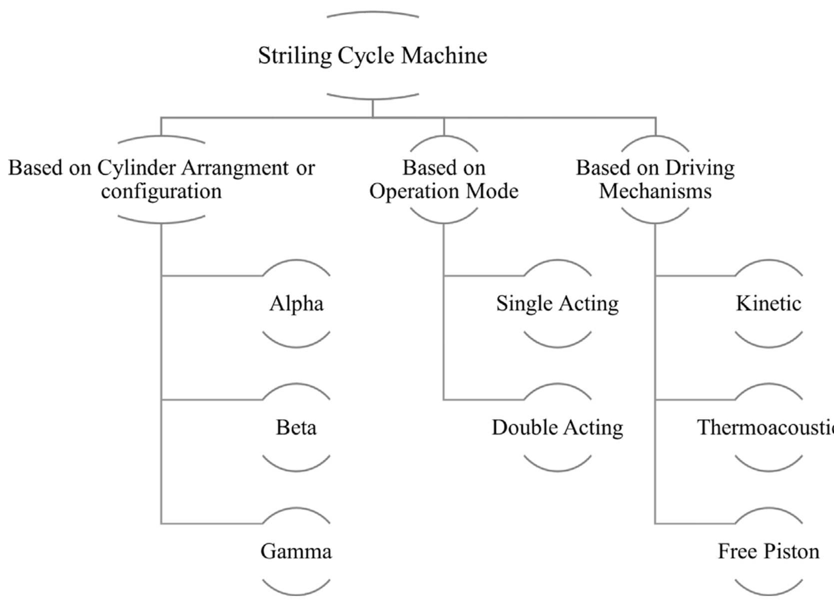

Fig. 7. Classification of Stirling cycle devices (Ahmed et al., 2020).

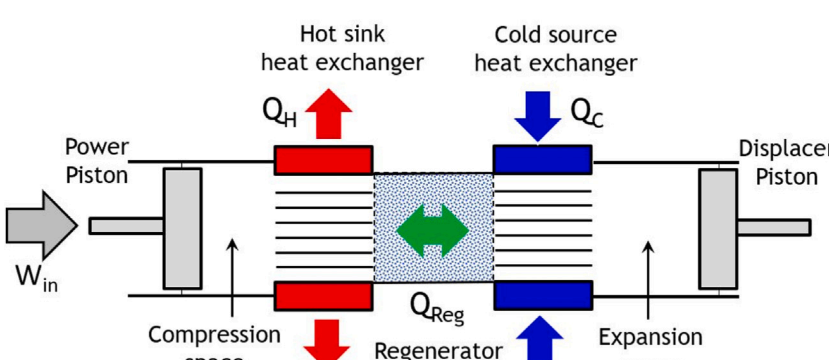

Fig. 8. Alpha Stirling heat pump.

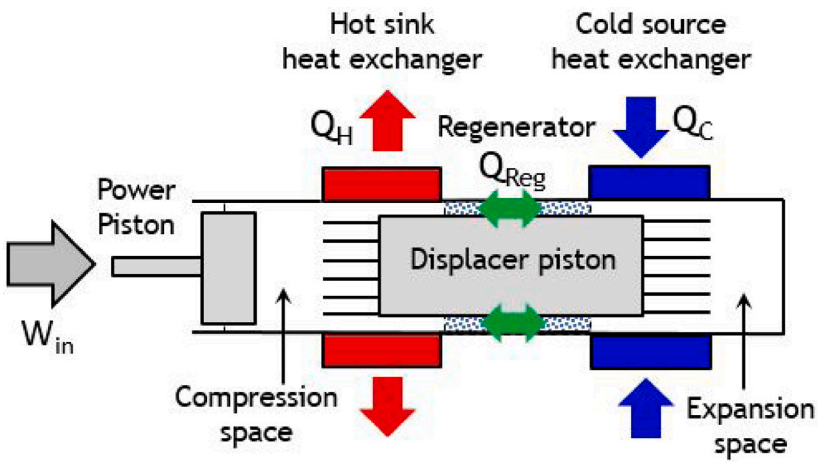

Fig. 9. Beta Stirling heat pump.

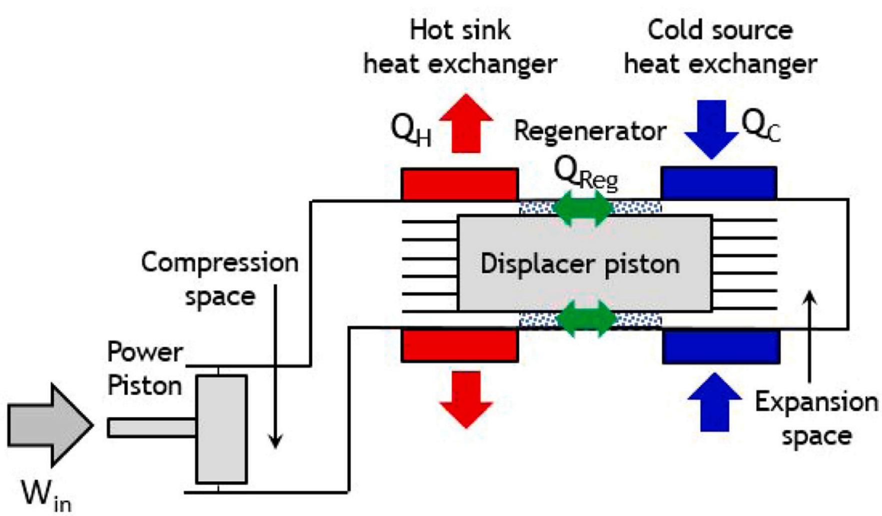

Fig. 10. Gamma Stirling heat pump.

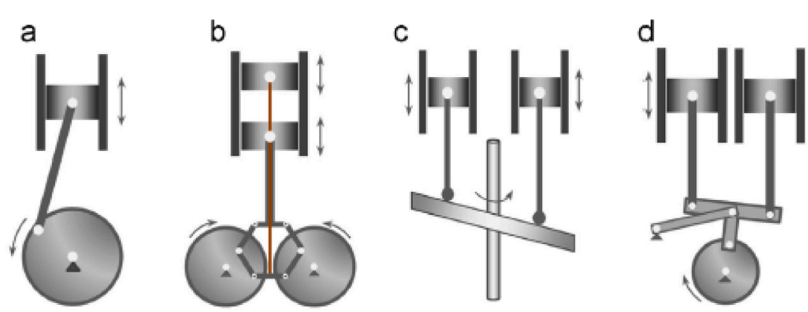

Fig. 11. Kinetic drive mechanisms used for Stirling machines: (a) crank-slider drive; (b) rhombic drive; (c) swash-plate drive; and (d) Ross-yoke drive (Wang et al., 2016).

has constraints. shuttle heat loss and linear heat conduction loss are caused by the displacer's vibration, leading to the short lifespan of the machine. The mechanical displacer is removed and substituted with a pulse tube in a thermoacoustic heat pump, see Fig. 14. Pulse tube action is a term used to describe the heating caused by the oscillating gas flow within the tube. This heat pump works by first creating an acoustic wave in the compressible fluid, which then travels through the waveguide. The oscillatory fluid and regenerator interact to produce the heat pumping effect, which moves heat within fluid boundary layers in the path of wave propagation (Chen et al., 2022). Oscillating flow over the aperture serves as a displacer to divide the heating and cooling areas. Merkli and Thomann (1975) made the initial discovery of the thermoacoustic heat pumping phenomenon in a standing wave

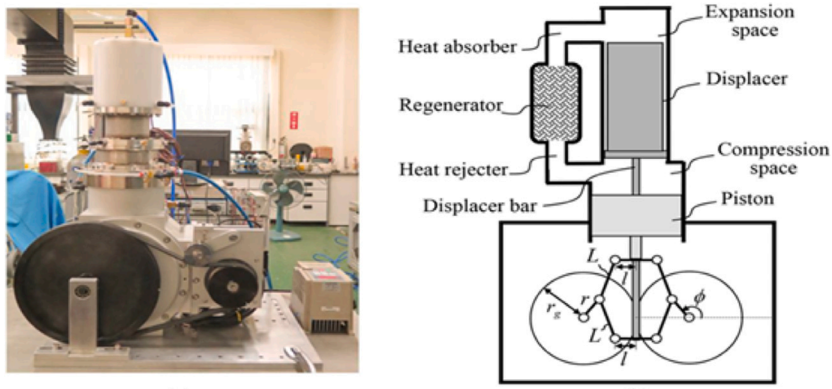

Fig. 12. Rhombic driven Stirling heat pump (Cheng et al., 2020).

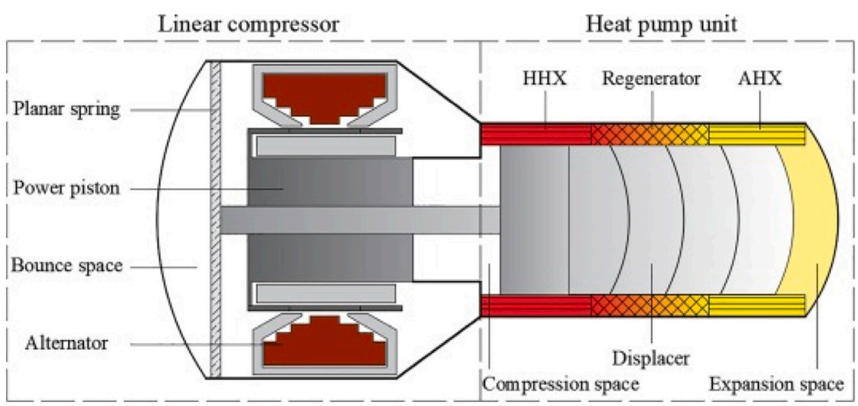

Fig. 13. Free piston heat pump (Wang et al., 2021).

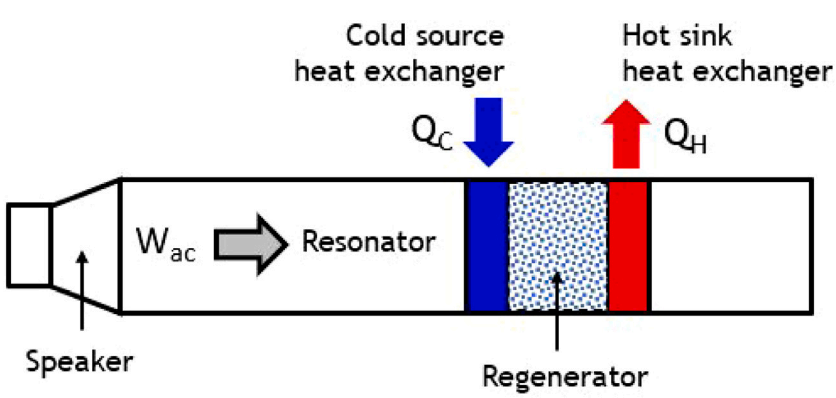

Fig. 14. Thermoacoustic heat pump.

thermoacoustic refrigerator powered through a moving piston in 1975.

In general, the kinetic type of Stirling heat pump has advantages over the thermoacoustic and free piston Stirling heat pumps due to its high performance, long reliability, and flexibility.

3. Thermodynamics modeling techniques

The development of the thermal model adopted for the Stirling heat pump is similar to the Stirling engine. Researchers are always attempting to create a realistic model and optimization methods to enhance Stirling cycle devices' performance. This endeavor led to the development of several thermal models, which are shown below in chronological order, and he parameters used in this research are based on previous research and applied to a number of Stirling cycle machine models (Ahmed et al., 2020; Chen and Griffin, 1983; Martini, 1983) (see Fig. 15).

3.1. Zero-order modeling

The model's main goal is to establish a mathematical relationship and conduct a basic analysis to determine the effectiveness and power output of Stirling cycle machines. The mathematical formulation to determine the engine's power output was initially set out by Beale (1969). West (1986) verified the expression made by Beal and suggested a modified expression This modeling approach provides a rapid overview of the performance, but cannot be applied to construct a new device or calculate its power output and work input.

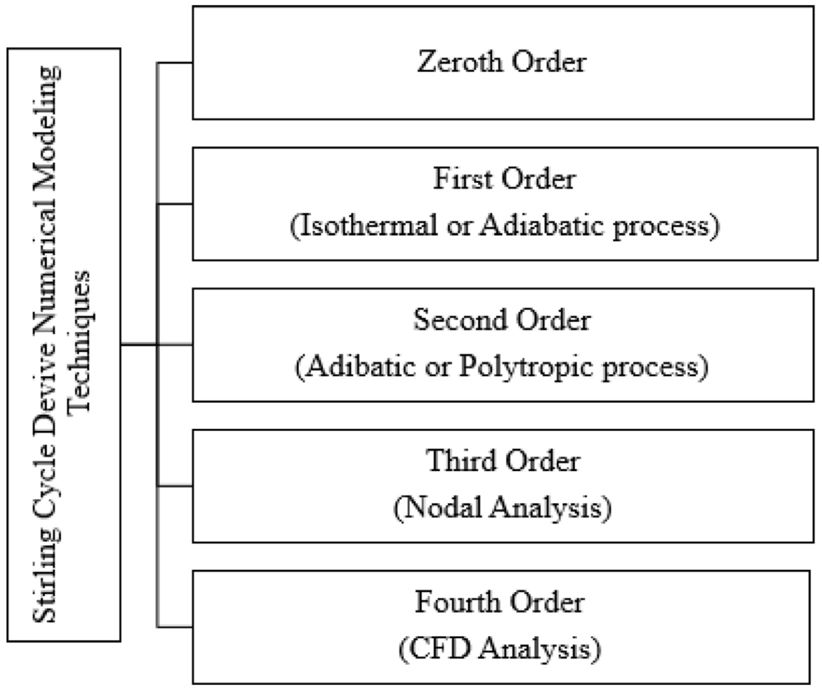

Fig. 15. Modeling of Stirling cycle devices (Ahmed et al., 2020).

3.2. First-order modeling

This model relies on isothermal assumption assessment, and the Schmidt hypothesis was developed by Gustave Schmidt in 1871 (Urieli and Berchowitz, 1984). In addition, it is assumed that the expansion and cooler sections are at constant source temperatures, while the compression and heater areas are assumed to be at constant sink temperatures.

Although it gives a simple way to calculate the machine's overall size, power output, and work input, it is not a very effective tool for comprehensive Stirling cycle machine design. The computation starts by carrying out an ideal loss-free analysis (no thermal and power loss), and the braking power output is determined using a straightforward correlation factor. The performance values predicted by this analysis diverge greatly from experimental values due to the ideal nature of the analysis, so it is advised that those who would like to consider the possibility of Stirling devices.

3.3. Second-order modeling

This model is a modification of the first-order analysis, with the compression and expansion spaces being either adiabatic or polytropic rather than isothermal and including the thermal and power losses depending on the type of second-order model (Chen and Griffin, 1983). Then, to achieve the predicted net performance, various losses were deducted from the heat engine's basic power output and added to the heat pump's work input. The primary enhancement of this method over first-order modeling is the identification and quantification of power and heat losses.

This model approach can be further subdivided into adiabatic and polytropic processes based on heat transfer between the gas area and cylinder in the simplified cycle analysis (Ahmed et al., 2020).

In comparison to third-order models, second-order models typically can accurately incorporate all dimensions and operational variables without resorting to the more time-consuming computer simulation procedures. There is no proof that current third-order analyses are better than second-order approaches because the ideas used in second-order analyses give adequate accuracy with a rapid response, which makes them acceptable for rapid design phases and optimization studies (Chen and Griffin, 1983).

3.4. Third order modeling

This approach, known as the nodal analysis method, begins with the development of a differential equation that demonstrates the concepts of momentum, energy, and mass conservation as well as the equation of state (Martini, 1983). The domain is divided into various control volume analyses to numerically solve these equations because they are too complex for an analytical approach.

In comparison to second-order models, this analysis requires substantially more calculation time and money to compute fluid flows and temperatures inside the machine that are not practicable to measure.

3.5. Fourth-order modeling

This modeling techniques use 3D or CFD analysis. It is very useful for analyzing the flow pattern, and heat transfer of the machine's operating fluid (Ahmed et al., 2020).

This modeling method is very outstanding since it enables the creation of a real-time computer simulation of the machine as compared to zero- or one-dimensional models. This enables in careful studying how machine performance is affected by geometric and operational characteristics for the optimization, but it needs much computational time.

4. Review of the Stirling heat pump development

Stirling heat pump machines are divided into different categories depending on their driving mechanisms. In this part, the paper shows detailed overview of research and developments of different categories of the Stirling cycle heat pump as follows:

4.1. Thermo-acoustic heat pump

In thermo-acoustic, acoustic waves interact with a regenerator that has a significantly larger heat capacity than the medium through which the sound wave travels. It performs as an engine when the temperature difference changes into the acoustic wave, or it acts as a heat

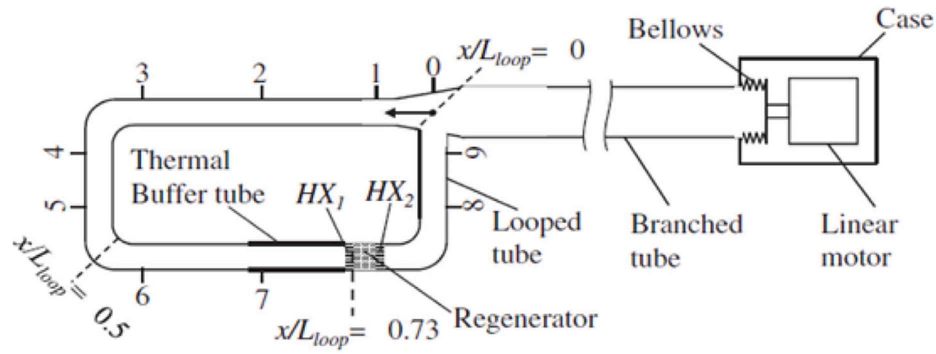

Fig. 16. Schematic representation of the test device (Bassem et al., 2011).

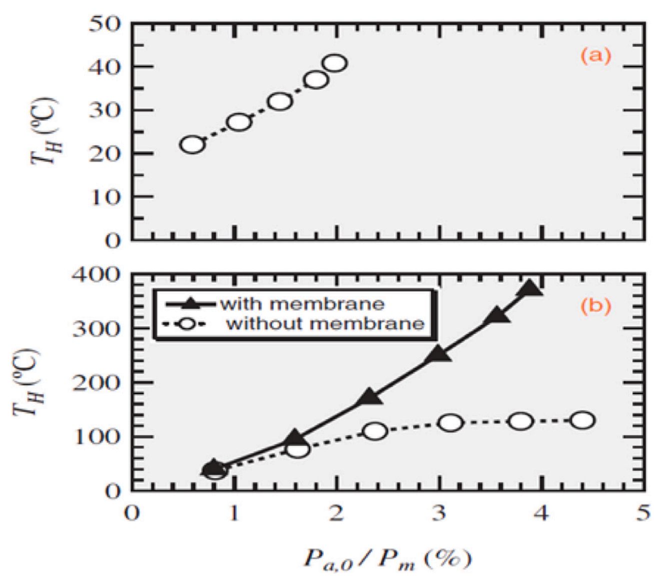

Fig. 17. Hot temperature as a function of driving pressure ratio for (a) air as working fluid and (b) nitrogen as working fluid (Bassem et al., 2011).

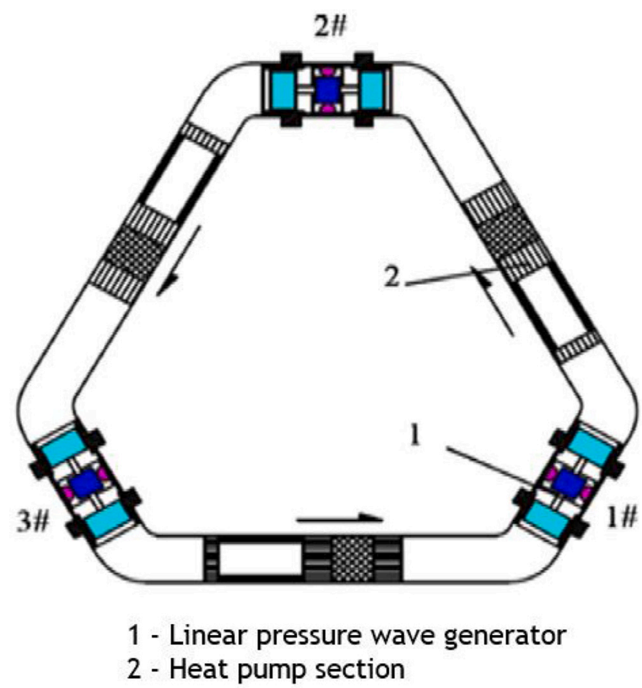

Fig. 18. Traveling-wave thermoacoustic heat pump (Yang et al., 2014).

pump or refrigerator when the thermo-acoustic wave changed into a temperature difference.

Thermo-acoustic heat pump (TAHP) can be utilized for either heating or cooling applications. Merkli and Thomann (1975) found the thermo-acoustic heat pumping phenomenon in a standing-wave thermo-acoustic system powered by a moving piston in 1975. Later, Hofler (1986), Swift (1988), and Wheatley et al. (1983b) carried out a number of standing-wave TAR experimental experiments and estimated TAR efficiency using the linear thermo-acoustic theory. In 2002, Yazaki et al. (2002) constructed the first traveling-wave thermo acoustic refrigerator prototype, which showed a lower onset temperature than its standing-wave counterpart. Following his study, De Blok (2008), Luo et al. (2006), Tijani et al. (2002) made significant advancements in the development of traveling-wave TARs

The integral system, which consists of resonator, engine, and heat pump, was built, and tested by Tijani and Spoelstra (2012). They were employing DeltaEc software for design and optimization. Based on the experiment's findings, the heat pump produces 200 W at 80 °C at a drive ratio of 3.5% and 250 W at 60 °C at a drive ratio of 3.6%. The performance in two scenarios is roughly 40% of Carnot efficiencies.

Bassem et al. (2011) demonstrated the impact of heating performance by using nitrogen gas and air as a working fluid by building a thermo-acoustic heat pump. It consists of a branched tube, a looped tube consisting of regenerator, and an acoustic driver. Furthermore, they investigated how the looped tube's acoustic impedance was distributed, see Fig. 17. The heat pump in the study served as a heater by maintaining the temperature of the cold side of the regenerator at ambient levels. It produced a hot temperature of 370 °C at 0.5 MPa nitrogen and the driving pressure ratio of 4% (P(a,o) = 20 kPa). When 0.1 MPa air is used as the working fluid, the working gas temperature at the hot heat exchanger increases from 25 to 41 °C (see Fig. 16).

In their study, Yang et al. (2014) constructed a heat pump with three linear pressure wave producers that are connected to three heat pumps in a single closed loop to demonstrate the simulation result. A thermal buffer tube, regenerator, ambient heat exchanger, hot-end heat exchanger, cold-end heat exchanger, and connecting tubes are all components of each heat pump segment, see Fig. 18. Theoretical computations were conducted at different hot end temperatures of 120 and 150 °C as well as different waste-heat temperatures of 40 and 70 °C. Based on the computations, it can be concluded that this system has a high relative Carnot efficiency of 50–60%.

Yang et al. (2022) developed a thermo-acoustic-based heat driven for both cooling and heating applications. It used cooler core units and two thermoacoustic engine to boost efficiency, and they used SAGE software for optimization, see Fig. 19. The test showed that cooling powers between 0.61 and 3.89 kW and performance coefficients between 0.08 and 0.30 when the system used as a refrigerator. These findings were attained by using a 10 MPa pressure, a 300 °C high

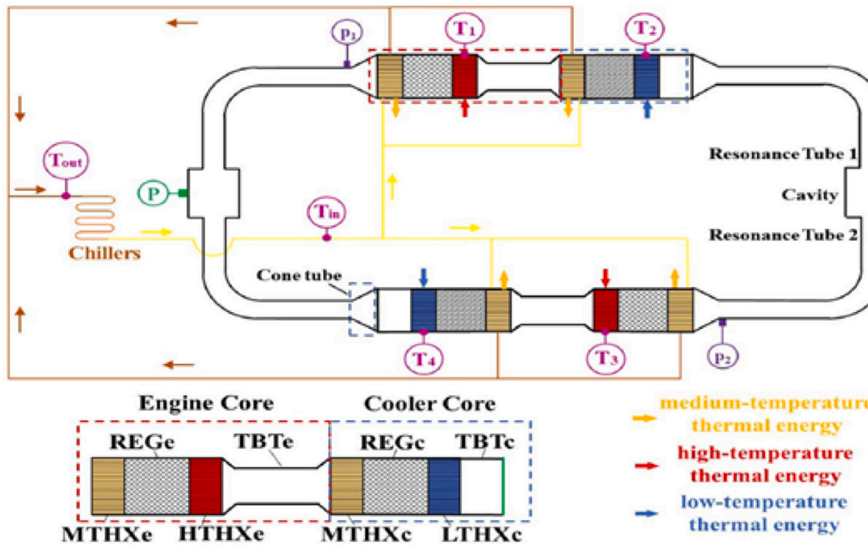

Fig. 19. Thermoacoustic HDCCH system (Yang et al., 2022).

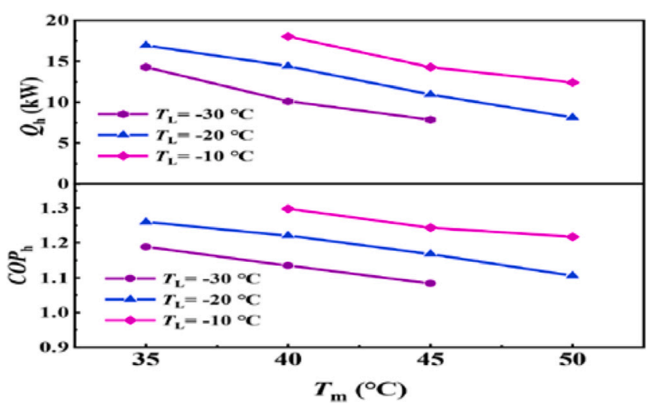

Fig. 20. Influences of medium temperature T_m on the heating power Q_h and COP of the thermo-acoustic HDCCH system working as a heat pump (Yang et al., 2022).

temperature, a 45 °C medium temperature, and a −30 °C to −5 °C low temperature range. When the system was used as a heat pump, it was found that heating powers of 7.85 kW and 14.3 kW, respectively, could be obtained at low temperatures of −30 °C and −10 °C. These outcomes, which were attained at a medium temperature of 45 °C , matched performance coefficients of 1.08 and 1.24, respectively (see Fig. 20).

Traveling-wave TARs or TAHPs have made tremendous progress after two to three decades of study to the point of practical commercial application. By utilizing sunlight thermal energy, Sound Energy Ltd (Yu, 2022) in the Netherlands has created thermo-acoustic cooler device for comfort conditions. The initial test was implemented effectively in Saudi. However, there are still a number of scientific barriers preventing the widespread implementation of such pumps, such as the sophistication of the structure. A former one that has a straightforward design known as an acoustic resonator has been investigated by Biwa et al. (2005) and Chen et al. (2019, 2020). However, the heat pumping efficiency of these devices is frequently relatively low due to the irreversibility induced by inadequate heat exchange between the oscillating fluid and stack (Wheatley et al., 1983). The energy conversion efficiency of conventional traveling wave thermo-acoustic heat pump or refrigeration is improved by the use of a looped pipe that promotes traveling waves (Xu et al., 2020; Yu et al., 2012; Zhang et al., 2016). However, the loop adds to the sophistication of the structure, requires more area, and raises the cost of construction as compared to the resonator. To increase the compactness and heat-pumping capability of the system, it is crucial to build a novel topology.

Poignand et al. (2011, 2013) proposed two acoustic driver concepts in 2011 to address the aforementioned difficulties. A co-axial, compact device was built that offered versatility and compactness as compared to earlier thermo-acoustic devices.

In, 2016 Widyaparaga et al. (2020, 2016) study examined A thermo-acoustic heat pump powered by two loudspeakers. According to the experimental results, it is possible to change or even reverse the heat-pumping direction along the regenerator by modifying the loudspeakers' magnitude and phase difference.

Abd El-Rahman et al. (2020) built a TAR powered by two pistons and a rotating motor in 2020. The temperature difference created by the TAR, which ran at 42 Hz, was 27 °K. A thermo-acoustic refrigerator with a larger cooling capacity that is similar to Poignand's concept was recently produced by Ramadan et al. (2021).

The operating processes of two acoustic driver thermo-acoustic heat pump were examined in Chen et al. (2022) study from both the thermodynamic and acoustic angles, see Fig. 21. The acoustic properties, temperature, and the impacts of acoustic drivers on heat pump and acoustic fields within the heat pump are theoretically studied.

Hu et al. (2024) studied thermo-acoustic heat pump heating technology that utilizes medium/low-grade heat source. Under normal home heating conditions, numerical investigations were carried out, including performance analysis, evaluation of exergy loss, and axial distribution of important factors. The suggested thermoacoustic heat pump, with a heating temperature of 300 °C and a heat-sink temperature of 55 °C , achieves a heating capacity of 5.7 kW and a coefficient of performance of 1.4, based on the results.

In conclusion, prior research demonstrated that the two acoustic driver approach can improve the compactness of thermo-acoustic heat pumps. Additionally, the most effective configuration in recent developments of thermo-acoustic heat pumps has been identified as the coupling of three linear pressure wave generators, each coupled with a heat pump, into a single closed loop. Table 1 shows summarized literature and research development on thermo-acoustic heat pump (see Table 2).

4.2. Review of kinetic driven Stirling heat pump

kinetic configuration requires linkages between the mechanical power inlet, the piston and the displacer. To ensure proper movement of the working gas, there are different kinetic drive mechanisms

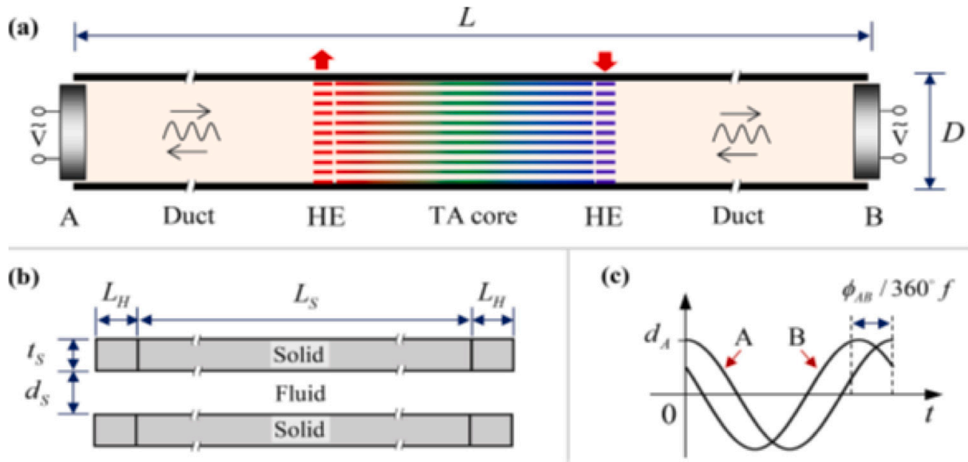

Fig. 21. (a) Schematic of the dual-acoustic-driver TAHP. HE and TA core stand for heat exchanger and thermoacoustic core. A and B are two acoustic drivers. (b) Two adjacent plates. (c) Displacements of the two acoustic drivers (Yang et al., 2022).

Table 2
Summary of review on thermoacoustic Stirling heat pump.

Authors	Methods of research	Working fluid	Source and sink temperature	Electric input, real COP, Carnot COP	Findings
Chen et al. (2022)	Theoretical	N/A	N/A	N/A	Examined the operation of a thermo-acoustic heat pump, which has the benefit of being compact that is powered by two sound drivers.
Tijani and Spoelstra (2012)	Experimental	Helium	10 °C and 80 °C	117 W, 0.5, 1.14	At 3.6% drive ratio and 60 °C, the heat pump generates 250 W, and at a drive ratio of 3.5% and 80 °C, the heat pump generates 200 W.
Yang et al. (2022)	Experimental	Helium	−10 °C, 45 °C	N/A, 1.24, N/A	Used SAGE software to obtain good optimization for heat-driven combined cooling and heating system, which employed dual thermo-acoustic engine and cooled cores to increase effectiveness.
Bassem et al. (2011)	Experimental	Air and Nitrogen	25 °C, 370 °C for nitrogen and 25 °C, 45 °C for air	N/A	Nitrogen at 0.5 MPa and driving pressure of 4%, it generates 370 °C. The working fluid temperature rises from 25–41 °C at 0.1 MPa of air.
Yang et al. (2014)	Theoretical	Helium	Waste heat (40–70 °C), 120–150 °C	1.4 kW, 2.99, 4.8	Developed a heat pump with three linear wave generators connected in a closed loop with three heat pumps. Each heat pump segment produces 1038.7 W of heating power and 713.44 W of heat absorption power.

employed such as Ross-yoke drives, swash plates, crank-sliders, rhombic, etc. This literature part focuses only on the common driving mechanisms in the development of Stirling heat pump technologies.

Rix (1988) studied the initial investigation on the feasibility of Ross Yoke Stirling cycle heat pump. A prototype was built by converting an SM1 engine into a heat pump, and it has been tested utilizing two hot oil circuits for exchanging heat and helium as the refrigerant through a broad range of heat supply temperatures and temperature lift. This first test has a weakness since it has a low coefficient of performance, below unity. Although the machine's coefficient of performance was too low, research shows that operation at large temperature lifts

Later a Rix (1989) study, a heat pump could be utilized to recover industrial waste heat. A net COP of 3.5 should be reached for a device that transforms 100 °C waste heat into 200 °C usable heat. The increased performance of the heat pump has been obtained by increasing the heat exchange rate between the refrigerant and oil through the appropriate design finned heat exchanger.

Tyagi et al. (2004) developed the finite time thermodynamics method to undertake a parametric evaluation of thermo-economic optimization for Stirling heat pumps. The study demonstrated the impact of a variety of parameters, including source and sink temperatures, heat capacitance, and the effectiveness of heat exchangers, and economic parameters. They demonstrated that, both from a thermodynamic and economic perspective, the economic parameter and the regeneration side effectiveness were found to have a larger influence than the other parameters. Once more, it has been discovered that for improved cycle performance, the inlet temperature on the source side reservoir should be slightly higher.

Cheng et al. (2020) constructed a 1-kW Beta type with rhombic driving system to test the thermodynamic model that was built to forecast the performance of water heating applications. Their finding showed that it can generate 904 W of rejected heat, and 417 W of absorbed heat by using helium as a refrigerant at 5 bar and 1000 rpm. After running for 15 min, the temperature of the output water at the heat rejection outlet drops from 25–19 °C, while the temperature of the outlet water at the heat absorber outlet rises from 25–38 °C, see Fig. 22.

Easa et al. (2022) conducted research on the effectiveness of gamma-type Stirling water dispensers for domestic water cooling and heating applications. The theoretical result reported that Stirling water dispensers of the gamma type were improved by using twin-wavy plate heat exchangers of various diameters rather than shell and tube heat exchangers. To achieve Schmitt's target, a numerical model is developed. The water cooler produces 4 kW and 1.4 kW of heating and cooling load.

Kowalski et al. (2022) studied 10 kW water-to-water cycle Stirling heat pump and modeled by using modified Schmidt's and the theoretical models demonstrated that the heat pump has a heating performance of 3.96–6.69. Its heating capacity reduces as the temperature difference rises, while the electric heating power rises as the difference temperature rises, see Fig. 23 (see Table 3).

Table 3
Summary of review on kinetic Stirling heat pump.

Authors	Methods of research	Working fluid	Source and sink temperature	Electric input, real COP, Carnot COP	Findings
Rix (1988)	Experimental	Helium	75 °C, 250 °C	N/A, <1, 1.43	The experiment was built by converting a Stirling engine into a heat pump, and it was put through extensive testing at various heat supply and temperature lift levels. Its initial investigation led to very poor performance.
Rix (1989)	Experimental	Helium	Waste heat 100 °C, 200 °C	N/A	Improve the performance through proper finned heat exchanger design. The heat pump converts 100 °C waste heat to 200 °C.
Cheng et al. (2020)	Experimental	Helium	25 °C, 38 °C	N/A, 1.775, N/A	At 1000 rpm, 5 bar and 1 liter per minute, it generates 904 W of rejected heat, 417 W of absorbed heat and 38 °C of warm water.
Easa et al. (2022)	Theoretical	Helium	N/A	N/A	The water dispenser designed by using wavey-plate heat exchangers, which raise the heating and cooling loads by 37% and 19% respectively. This heat exchanger increased performance by approximately 22%.
Tyagi et al. (2004)	Theoretical	N/A	N/A	N/A	The effectiveness of regenerator as well as the economic parameters had a stronger impact on the analyzed variables of source and sink temperature, heat capacitance rate, effectiveness and economic parameter.
Kowalski et al. (2022)	Theoretical	N/A	15 °C–35 °C, 45 °C–90 °C	N/A, 3.69 6.69, N/A	The performance parameter was determined a cross a wide range of source temperature (15 °C–30 °C) and sink temperature of (45 °C–90 °C) for water-to-water cycle.

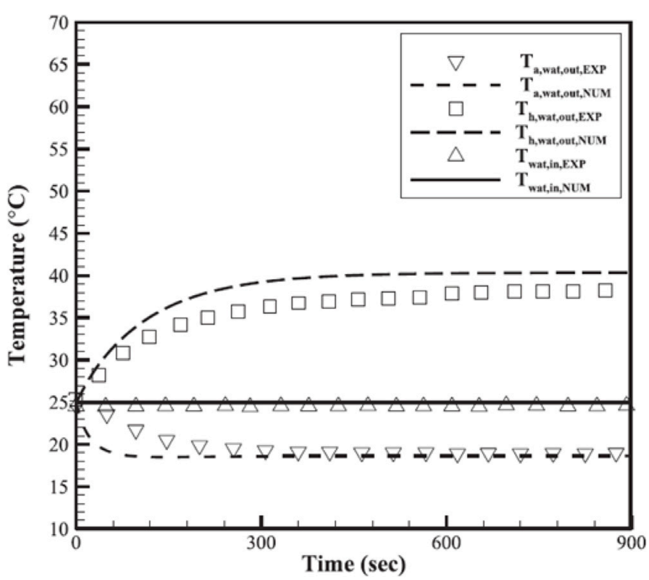

Fig. 22. The temperature variation of water at the inlet and outlet of the water jacket with respect to time (Cheng et al., 2020).

4.3. Review on free piston Stirling heat pump

Kinematic drives face several engineering challenges specifically in friction, while free piston drives provide less predictable motion of moving parts, that adversely influence the device's effectiveness. In this part, recent technologies in free-piston Stirling heat pumps has been reviewed, but there are few research papers for this heat pumps as compared with the other heat pumps.

Wang et al. (2021) conducted research on how temperature changes affected the efficiency of free piston Stirling heat pumps. An electrically powered free piston heat pump was created using the SAGE software. The analysis of the mathematical model demonstrated that at 40 °C of heating temperature, and −20 °C of ambient temperature, 2409 W of heating capacity could be produced with a 1 kW power input. They also showed that the significant gas wall temperature variation in the heat exchanger is one of the key reasons for the comparatively poor performance of such heat pumps (see Fig. 24).

Afterward, they also studied the performance of free-piston Stirling heat pumps with a circumferential temperature variation in the hot heat exchanger and showed numerically the effect of such temperature variation (Wang et al., 2022).

Dai et al. (2024) study involved the design, construction, and testing of a two-kilowatt free-piston Stirling heat pump prototype that is able to operate in temperatures between −20 and 10 °C. Their study carried out both experimental and numerical investigations. Based on experimental data, the prototype achieved a heating capacity of 2253 W with a corresponding COP of 2.76 at a hot-end temperature of 45 °C and an outside ambient temperature of 0 °C.

Wang et al. (2023) study presented a novel multi-unit, heat-powered, double-acting free-piston Stirling heat pump system. The system makes it simple to modify the acoustic field by simply changing the number of units utilized. A small-diameter piston rod that reduces damping losses connects the Stirling engine and Stirling heat pump, substantially boosting the efficiency of acoustic power transmission and simplifying the system design.

Sun et al. (2024) proposed an integrated combined cooling, heating, and power (CCHP) machine based on Stirling free-piston configuration. The conventional CCHP system has bulky structure, complexity of operation, and high initial investment cost. This novel integrated system can cool, heat, and produce power without any additional devices. The system can save 39% of energy consumption when compared to traditional independent energy-supplying systems when providing the same cooling and heating capacity and electricity under typical working conditions. The prototype can obtain 0.26, 1.28 of cooling and heating coefficient of performance, respectively.

5. Conclusion and perspectives

The development of heat pumps using the Stirling cycle has given less attention than cryocoolers and engines. Therefore, in this paper, a detailed literature review of research efforts done in the development of Stirling heat pump has been performed. In light of the reviewed literature, the subsequent conclusions are summarized:

- The construction industry, particularly the residential, significantly raises energy consumption and emissions of greenhouse gases.

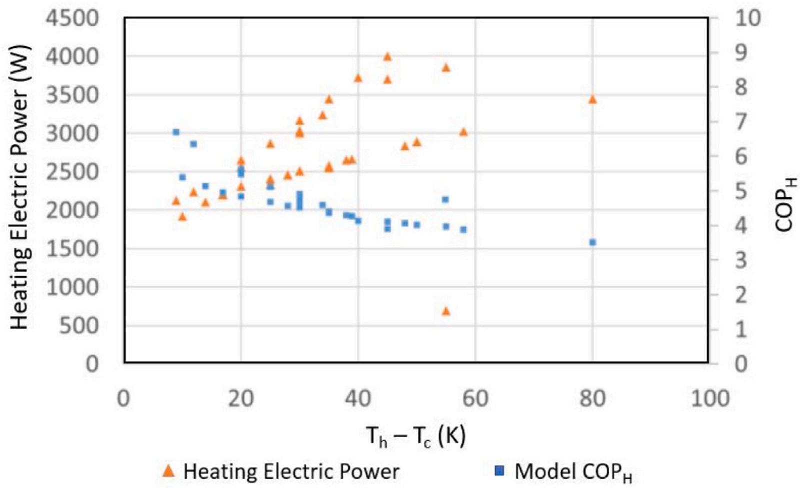

Fig. 23. Chart of heating electric power and COP as a function of temperature difference (Kowalski et al., 2022).

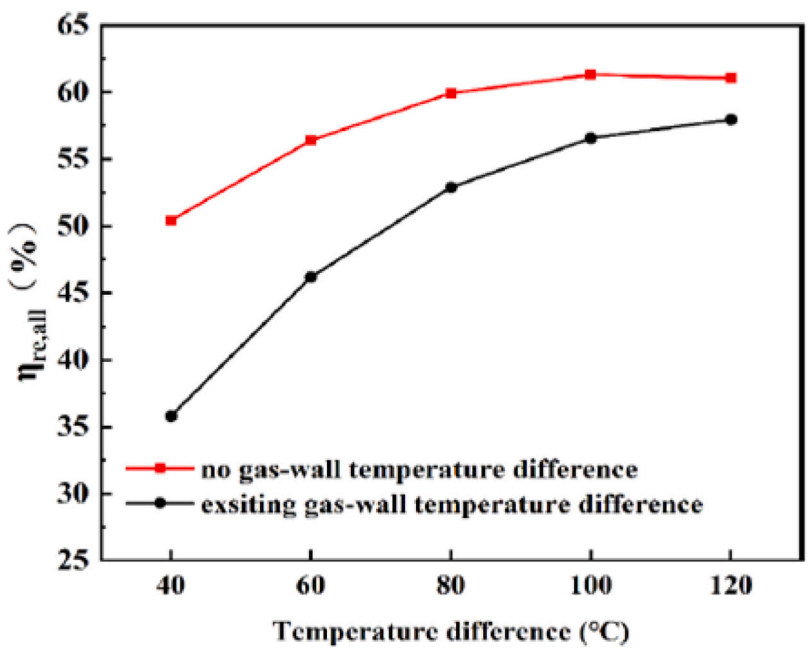

Fig. 24. The effect of gas wall temperature variation in heat exchangers on relative Carnot efficiency of the whole system (Wang et al., 2021).

- Even though vapor compression cycle type of heat pump has high performance, it needs a working fluid whose critical temperature is higher than the heat sink's temperature and whose freezing point is considerably lower than the heat source's temperature. In addition, the refrigerant or the working fluid are the cause for global warming and the use of a neutral gas such as nitrogen or helium could be a possible solution.
- In the thermo-acoustic heat pump, nitrogen is the best working fluid as compared to the atmospheric air and the membrane attached to motor also increases of heat pump's effectiveness. According to studies, the dual acoustic driver approach can increase compactness, but the most efficiency is achieved when three linear pressure wave-generators are linked with three heat pumps into a single closed loop.
- Several studies have been done on the kinetic, thermo-acoustic, and free piston types of heat pumps, and the research showed that the kinetic Stirling heat pumps have the greatest heating performance, particularly for water-to-water cycles and thermo-acoustic heat pumps increase the life span. However, the researchers did not properly verify the Stirling heat pump configuration that should have provided better performance.
- The three heat exchangers (cold, hot and regenerator) had the highest effect on the effectiveness of Stirling heat pump, but most research focuses on cold and hot heat exchanger optimization not in regenerator optimization in the case of heat pump.
- Currently, most researchers use isothermal and adiabatic thermodynamic models and validate them by changing the existing heat engine into heat pump. This may not have the highest performance because of different geometry and design parameters in the optimized design procedure, and researchers should improve current thermodynamic models for forecasting the performance of Stirling heat pumps.

There is a potential heating application for Stirling cycles heat pumps, but it still suffers from a number of challenges and the research done on the Stirling heat pump is limited. Therefore, future research must be carried out on Stirling heat pump for heating applications by selection of proper configuration, suitable working fluid, appropriate thermodynamic model, compactness to reduce the cost and efficient control system.

CRediT authorship contribution statement

Temesgen Assefa Minale: Writing – original draft. **François Lanzetta:** Writing – review & editing, Supervision. **Sylvie Bégot:** Writing – review & editing, Supervision. **Muluken Z. Getie:** Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

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Research ethics

We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

IRB approval was obtained (required for studies and series of 3 or more cases)

Written consent to publish potentially identifying information, such as details or the case and photographs, was obtained from the patient(s) or their legal guardian(s).

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