



Research Paper

Overview and outlook of heat-driven oscillating systems for sustainable heating, cooling and power generation

Shunmin Zhu^{a,b,*}, Geng Chen^c, Zhibin Yu^d, Christos N. Markides^e^a State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China^b Department of Engineering, Durham University, Durham DH1 3LE, UK^c National Engineering Research Centre of Power Generation Control and Safety, School of Energy and Environment, Southeast University, Nanjing 210096, China^d Department of Mechanical and Aerospace Engineering, School of Engineering, University of Liverpool, Liverpool L69 3GH, UK^e Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK

ARTICLE INFO

Keywords:

Distributed energy systems

Stirling engine

Thermoacoustic cooling

Thermofluidic oscillator

Electric generator

Heat pump

ABSTRACT

As a class of promising micro- or small-scale energy conversion technologies, heat-driven oscillating systems have drawn growing attention in heating, cooling, and power generation, thanks to their high reliability and high efficiency, especially for the conversion of lower-grade heat in distributed power generation and cogeneration applications. Representative heat-driven oscillating systems include single-phase (e.g., Stirling cycle systems, thermoacoustic systems), and two-phase alternatives (e.g., thermofluidic oscillators, etc.). This vision article reviews the articles featured in the Special Issue 'Heat-Driven Oscillating Systems for Sustainable Heating, Cooling, and Power Generation', and summarises the state-of-the-art advances in various heat-driven oscillating systems for heating, cooling, and power generation applications, with an emphasis on Stirling-cycle and thermoacoustic systems, which are currently the most mature. Finally, challenges and prospects within this growing and important domain are identified.

1. Introduction, context and motivation

A growing need for the more efficient use of primary energy resources, energy security, and increasing environmental and sustainability concerns have given rise to a significant and urgent interest in developing advanced sustainable energy conversion systems [1–5]. The most mature technology for the conversion of thermal energy to work (mechanical, hydraulic, or electrical) is the Rankine cycle, which stands as the natural benchmark for any innovative technology aimed at distributed power generation when utilising heat sources up to ~700–800 °C [6]. At the lower end of this temperature range, up to ~300–400 °C, the use of water as the working fluid is typically replaced by a wide range of organic compounds in organic Rankine cycles (ORCs). Significant efforts have been made in recent decades to identify optimal fluids for ORC systems at different temperatures, scales and applications, including for direct power generation from a variety of waste heat [7,8] or renewable (e.g., geothermal or solar) heat [9,10] sources, as well as for cogeneration [11]. Advanced design approaches in this space integrate system optimisation with working fluid molecular

design methodologies [12–14]. ORC (and, in general steam-Rankine cycle) systems are an excellent technology in this space, yet they rely on components that are considered as having high engineering complexity and capital cost (e.g., turbines) [15], while requiring sustained maintenance to ensure performance.

In this context, heat-driven oscillating systems have been proposed as a potential alternative to the aforementioned systems in smaller-scale applications. Heat-driven oscillating systems represent a distinctive category of energy conversion technologies, in which sustained, high-intensity oscillations of thermodynamic variables, such as pressure, temperature, and volume, arise under a continuously maintained temperature gradient between external heat sources and sinks. Representative heat-driven oscillating systems include Stirling cycle systems [16], thermoacoustic systems [17], thermofluidic oscillators (TFOs) [18], etc. These heat-driven oscillating systems can convert thermal energy into mechanical work (in the form of reciprocating pistons or oscillatory fluids), which can be further utilised to produce electricity, pump heat, or produce a cooling effect. The most attractive advantages of these systems lie in the fact that they have no or few moving parts and seals, which results in high reliability and low maintenance costs.

* Corresponding author at: State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China.

E-mail address: zhushunmin@mail.ipc.ac.cn (S. Zhu).

<https://doi.org/10.1016/j.applthermaleng.2026.133305>

Received 4 June 2026; Received in revised form 19 August 2026; Accepted 13 September 2026

Available online 19 September 2026

1359-4311/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Nomenclature

Abbreviations

AHX	ambient-end heat exchanger
CHP	combined heat and power
CSP	concentrated solar power
FPSC	free-piston Stirling cryocooler
FPSE	free-piston Stirling engine
FPSG	free-piston Stirling generator
HHX	hot-end heat exchanger
ICE	internal combustion engine
KSE	kinematic Stirling engine
LM-TEG	liquid metal triboelectric generator
NCL	natural circulation loop
NFTEG	non-contact fibre-reinforced rotary triboelectric generator
ORC	organic Rankine cycle
TFO	thermofluidic oscillator
TRL	Technology Readiness Level

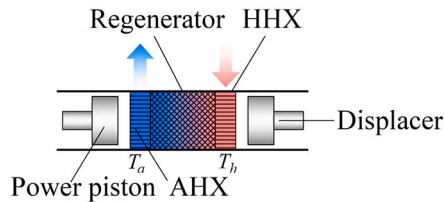


Fig. 1. Schematic of a Stirling engine. A regenerator filled with porous materials is sandwiched between an AHX (at a temperature T_a) and a HHX (at a temperature T_h). A power piston and a displacer reciprocate next to the AHX and the displacer piston, respectively. Gas parcels reciprocating in the regenerator experience a thermodynamic cycle consisting of compression, heat addition, expansion, and heat rejection, thereby enabling thermal energy supplied from an external source to be transformed into mechanical power.

Moreover, their capacity to utilize diverse heat sources, such as alternative fuels, solar energy, biomass, and nuclear energy, positions them as a promising solution to achieve sustainable heating, cooling, and

power generation.

This vision article is part of the special issue entitled ‘Heat-driven oscillating systems for sustainable heating, cooling, and power generation’. It summarises the state-of-the-art advances in various heat-driven oscillating systems for different applications, including low-grade heat recovery, solar heat utilisation, refrigeration and cryogenic engineering, and thermal energy harvesting, identifies the challenges, and prospects within this growing and important domain. The article is arranged as follows: [Section 2](#) introduces the latest progress of a range of heat-driven oscillating systems, with a particular focus on Stirling-cycle systems and thermoacoustic systems. [Section 3](#) provides the outlook and future challenges of different heat-driven oscillating systems.

2. Current research areas, trends and challenges

2.1. Stirling-cycle systems

Stirling-cycle systems are machines that operate based upon forward or reverse Stirling thermodynamic cycles, and these machines mainly include Stirling engines [19], Stirling refrigerators or cryocoolers [20], and Stirling heat pumps [21].

[Fig. 1](#) illustrates the schematic of a Stirling engine. It mainly includes, from left to right, a power piston, an ambient-end heat exchanger (AHX), a regenerator, a hot-end heat exchanger (HHX), and a displacer. According to whether there is a mechanical linkage between the power piston and the displacer, the Stirling engine can be divided into two types, i.e., the kinematic Stirling engine (KSE) and the free-piston Stirling engine (FPSE), as shown in [Fig. 2](#). The Stirling engine is an external combustion engine in which the working fluid undergoes the forward Stirling thermodynamic cycle [22]. Due to the external combustion nature, the Stirling engine can use a diverse variety of heat sources, including conventional fossil fuels [23,24], biomass [25], solar energy [26], and nuclear energy [27]. When using fossil fuels or biomass as fuel, in contrast to an internal combustion engine (ICE), the Stirling engine can easily achieve a very low emission level since the combustion takes place outside the engine, and it can be readily controlled [28]. Besides, the ideal thermal efficiency of a Stirling engine is equal to the Carnot efficiency. These advantages enable the Stirling engine to be a promising candidate for combined heat and power (CHP) systems, space nuclear power systems, concentrated solar power (CSP) systems, and underwater power supplies.

Both a Stirling refrigerator and a Stirling heat pump are based on the

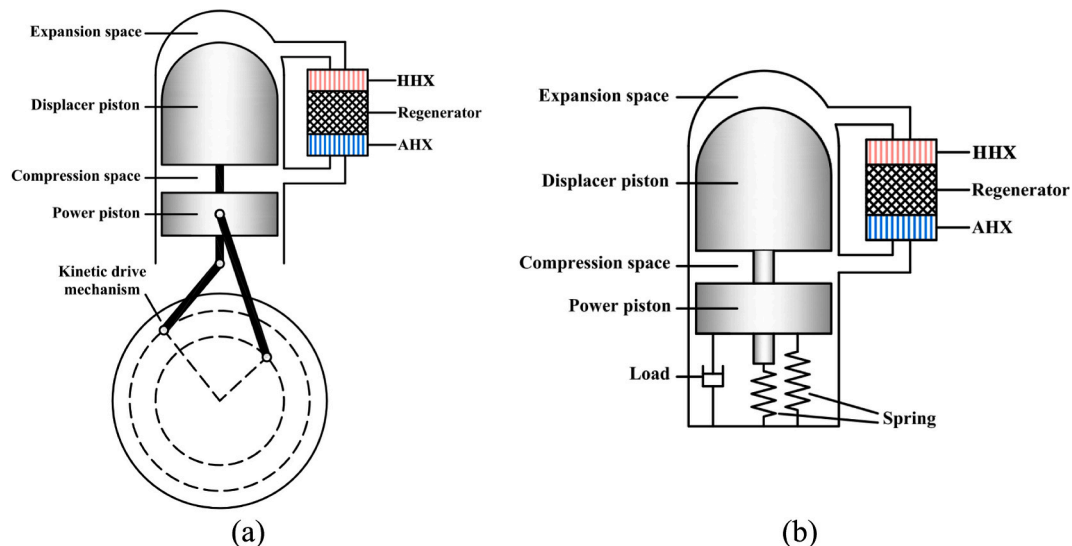


Fig. 2. Typical configurations of (a) KSE and (b) FPSE [28]. In the KSE, the power piston and the displacer piston are rigidly connected via a mechanical mechanism, while in the FPSE there is no mechanical linkage between the two pistons.

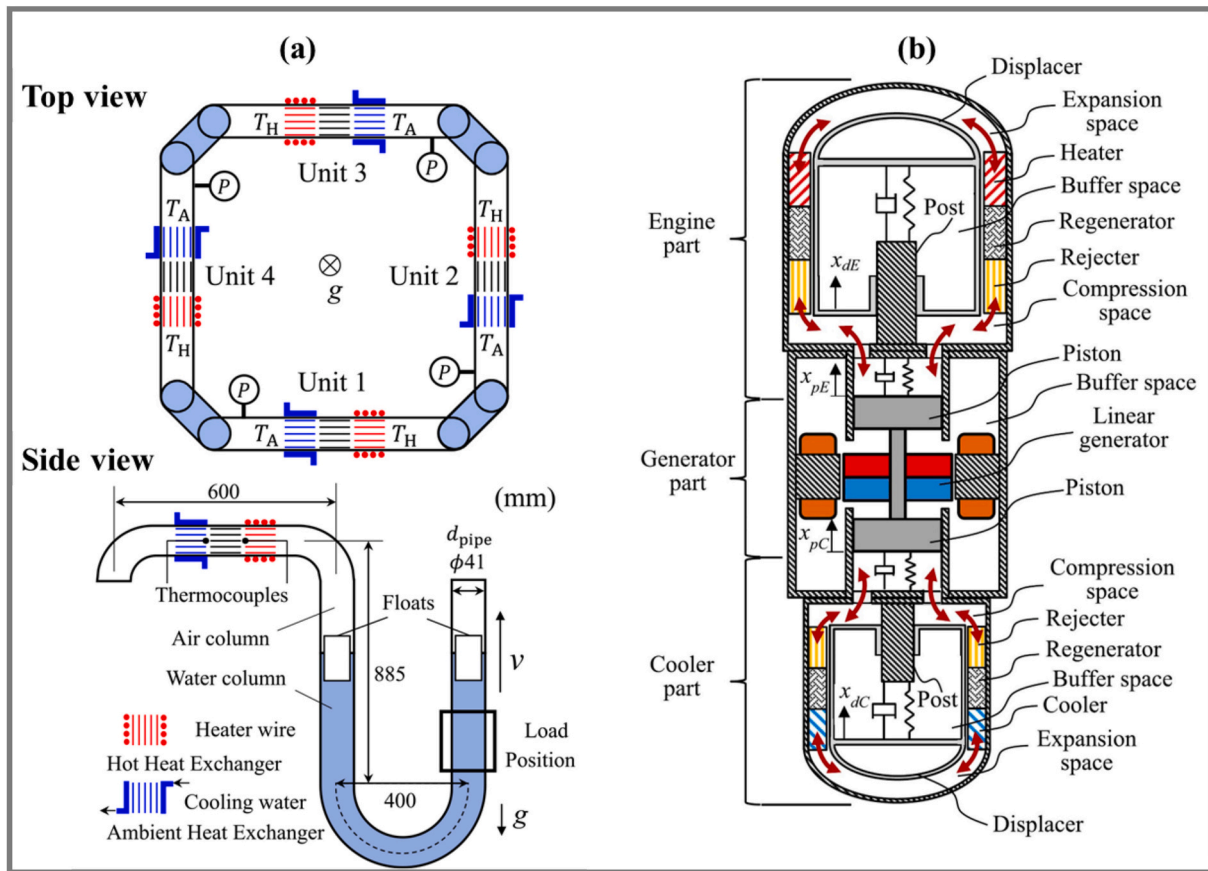


Fig. 3. Schematics of: (a) LPSE [45], and (b) free-piston Stirling heat-driven cooler [46]. The LPSE includes four identical units. Each unit comprises a U-tube section containing a liquid column and a gas column section. The free-piston Stirling heat-driven cooler includes three parts, i.e., the engine part, the cooler part, and the linear alternator part.

reverse Stirling cycle, and they use external input mechanical energy to pump heat from a low-temperature heat source to a high-temperature heat source [29]. Compared with vapour compression refrigeration technology, the Stirling refrigerator avoids the use of chlorofluorocarbon refrigerants and their effect on the environment, so it is an environmentally friendly refrigeration technology [30]. However, Stirling refrigerators have not received much attention in moderate temperature refrigeration applications till now [30], mainly because of the higher capital cost compared to vapour compression refrigeration technology. In contrast, they draw more attention in cryogenic temperature applications, such as high-temperature superconducting applications [31], gas liquefaction [32], space missions [33], night vision equipment [34], ultra-low temperature freezer [35], and similar.

Unlike vapour-compression heat pumps, the working fluid (generally helium) in a Stirling heat pump is a gas throughout the working process, and it does not undergo any phase change [36]. So, the Stirling heat pump will not be limited by either condensation or evaporation temperatures of the working fluid, and it has the advantage of wide temperature range adaptability [37]. Thanks to this advantage, Stirling heat pumps have recently attracted more and more attention, especially in building heating and hot water supply [38], as well as high-temperature industrial applications [39,40].

In this Special Issue, Zhou et al. [41] performed a performance analysis on an autonomous circulation miniature integrated nuclear reactor (ACMIR), which includes a free-piston Stirling generator (FPSG). The system employs an integrated nuclear reactor design. Compared with the scheme that integrates FPSGs with space nuclear reactors using heat pipes [42,43], the proposed concept is highly integrated and lightweight. A multi-physics coupling model of the ACMIR is developed,

and the model includes a sub-model for thermodynamic and dynamic characterisation of the FPSG. With the aid of the model, the performance of the ACMIR is evaluated under steady-state conditions and reactivity insertion accidents. The results indicate that under steady-state operation, the system could output 4.7 kW of electric power, and the ACMIR's total reactivity oscillation deviation is within ± 0.5 pcm.

Wong et al. [44] evaluated the performance of a γ -configuration Stirling engine under four different motion profiles of the displacer and power piston. They found that the proposed hybrid motion profile, in which the displacer's motion follows a non-sinusoidal rise-dwell-fall-dwell while the power piston employs sinusoidal motion, outperforms the other three considered motion profiles. This is because the hybrid motion profile introduces dwell periods in the displacer motion, which enables the working fluid to remain for a longer time at each heat exchanger. So, the heat transfer could be enhanced, and the output performance of the Stirling engine could be improved.

To meet rural electricity demands, Tomihira et al. [45] proposed using a liquid piston Stirling engine (LPSE) with four identical sub-units to drive a self-rectifying turbine, thus to produce electricity with a rotary electric generator. Fig. 3(a) gives the schematic of the LPSE. They explored the optimal combination approach between the LPSE and the turbine by testing with orifice plates, and they also considered more scenarios with the aid of numerical simulation, i.e., installing orifice plates in two adjacent LPSE sub-units or all four sub-units. When the pipe diameter increases to 200 mm, the proposed power generation system could achieve a thermal-to-electric efficiency of 7.9% in simulations, at a gas temperature ratio (T_H/T_A , T_H : heating temperature; T_A : ambient temperature) of 1.56. The corresponding relative Carnot efficiency is around 20%.

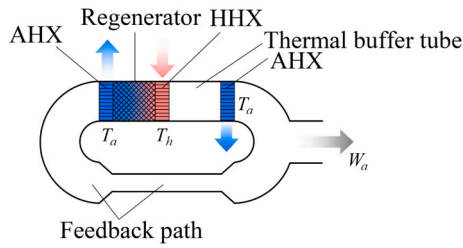


Fig. 4. Schematic of a (travelling-wave) thermoacoustic engine. The thermoacoustic engine has a looped tube, which includes an AHX (at a temperature T_a), a regenerator, a HHX (T_h), a thermal buffer tube, another AHX (T_a), and a feedback path. In comparison with Fig. 1, the two pistons are replaced by acoustic components. The gas parcels in the thermoacoustic engine undergo a similar thermodynamic cycle to that in a Stirling engine, and convert external heating power into acoustic power W_a .

Yang et al. [46] developed a free-piston Stirling heat-driven cooler, which integrates a FPSE with a free-piston Stirling cooler by using a linear alternator, as shown in Fig. 3(b). They developed a numerical model to evaluate the performance of the integrated system, and they also built a test rig to validate the accuracy of the model. In experiments, the test rig can reach 259 K when the heating temperature for the Stirling engine is 723 K. In addition, it can provide a cooling power of 60 W

with a COP of 0.107. In another study [47], the authors evaluated the performance of the developed system when it operates as a free-piston Stirling trigeneration system, and they found the numerical model's deviation is within 10%. During tests, the highest efficiency of the linear alternator is 4%, and the maximum cooling capacity of the trigeneration system is 50 W.

To meet the deep space power supply application, increasing the cold end temperature of an FPSG could reduce the volume and mass of the radiant panels effectively. Therefore, Liu et al. [48] explored the effects of cold end temperature on the performance of a 100-W FPSG prototype by a combination of numerical simulation and experiment, and they found that when the heating power remains constant, with the cold end temperature increases, the heat loss at the hot end rises linearly, and the thermal efficiency declines sharply. When the cold end temperature is around 500 K, and the hot end temperature 1060 K, the prototype was reported as capable of achieving a thermal-to-electrical efficiency of 26.8%.

The piston offset may deteriorate the performance of an FPSG. To address this, Yang et al. [49] proposed to use a conical orifice plate to inhibit piston offset. They first identified the internal structure of the conical orifice plate through numerical simulation, then they applied the conical orifice plate to an FPSG prototype to explore the effectiveness of the proposed inhibiting approach. The results indicate that the use of the conical orifice plate could significantly inhibit the piston offset without

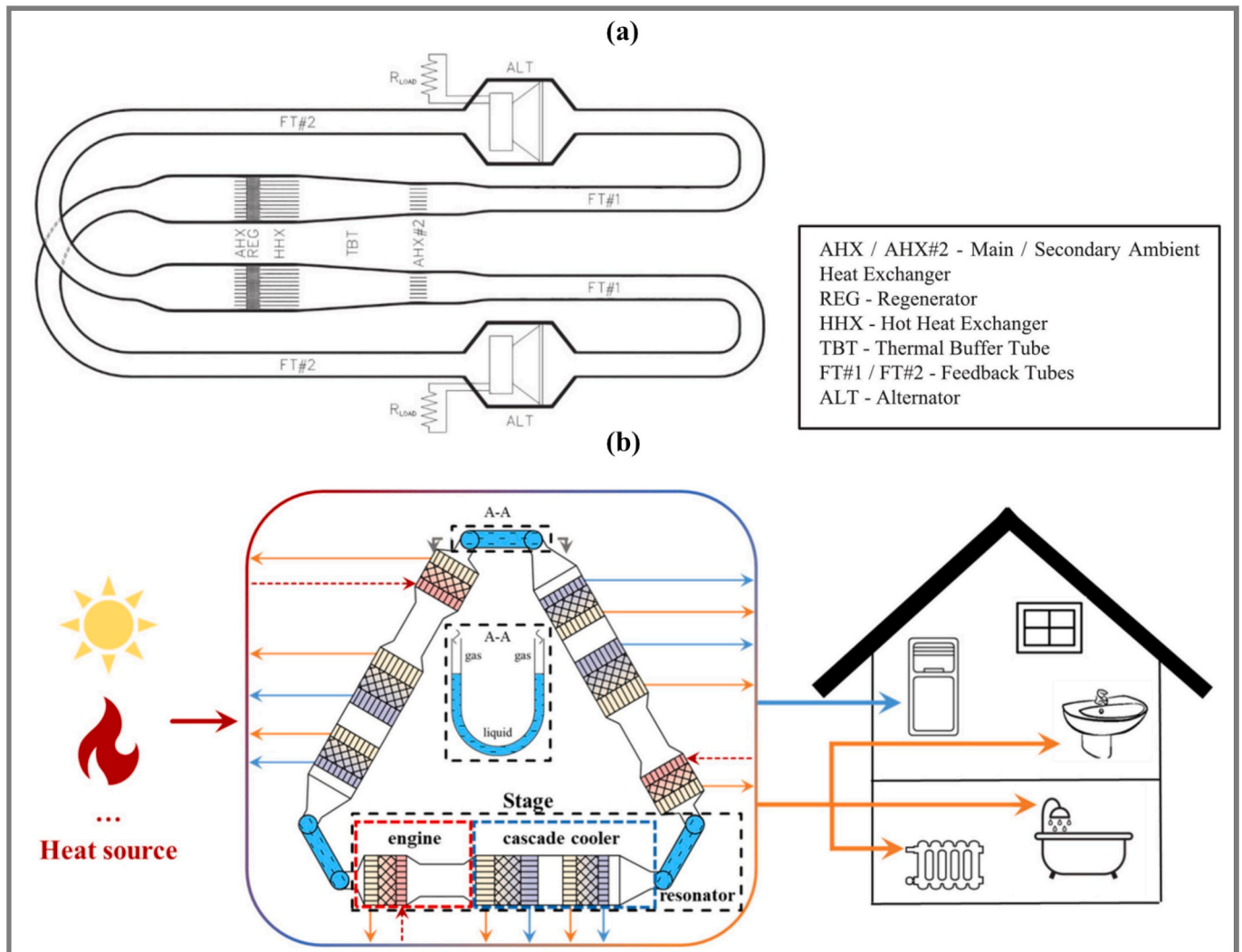


Fig. 5. Schematics of: (a) the two-stage looped thermoacoustic electric generator [63], and (b) the new heat-driven thermoacoustic refrigeration system [64]. The two-stage looped thermoacoustic electric generator includes two identical units, and each unit comprises a thermoacoustic engine and an alternator.

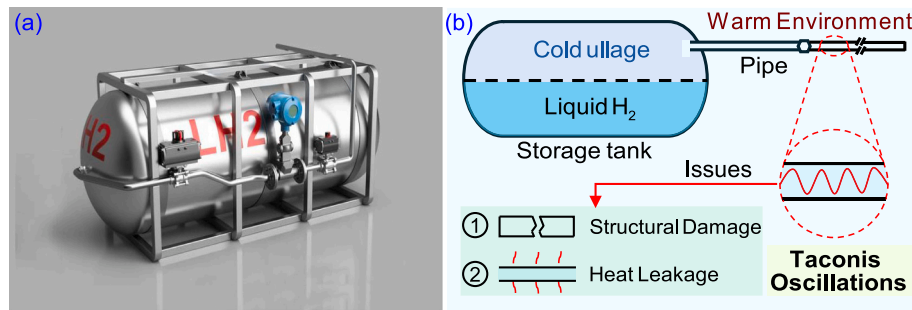


Fig. 6. Illustrations of a small-scale liquid hydrogen storage tank and possible Taconis oscillations within the cryogenic pipelines [68]. The significant temperature difference between the two ends of the cryogenic hydrogen pipe would lead to Taconis oscillations.

obviously sacrificing efficiency.

As a special heat-driven Stirling heat pump, Vuilleumier heat pumps have drawn much attention in recent years [50]. Yuan et al. [51] proposed to change the rod's diameter to regulate the capacity of Vuilleumier heat pumps, aiming to replace the conventional heating temperature regulation method. They compared the new method and the conventional method numerically, and found that a larger variation in capacity and a smaller reduction in COP could be achieved with the proposed regulation method than with the conventional regulation method.

The linear compressor is a key component of a free-piston Stirling cryocooler (FPSC) [52]. Xi et al. [53] developed a miniature moving magnet linear compressor prototype with a magnetic spring. The structural parameters of the linear compressor are specially optimised to improve the properties of the magnetic spring. Then they coupled it with a Stirling expander to form a FPSC, and the cryocooler achieves a cooling capacity of 1.35 W at 150 K, with a linear compressor efficiency of 82.7%.

In related work, Ma et al. [54] examined the influence of trace nitrogen concentrations ranging from 50 to 150 ppm on the performance of a Stirling-type pulse tube cryocooler operating at approximately 40 K. Their results revealed pronounced refrigeration-temperature oscillations over the range of 38–52 K, which were attributed to the presence of trace nitrogen. They also proposed a process of repeated nitrogen phase transitions at the cold end to explain the reason for temperature fluctuations.

2.2. Thermoacoustic systems

Thermoacoustic systems are machines that exploit the interaction between high-amplitude sound waves and heat to either generate power from heat (engines) or pump heat from a low-temperature heat source to a high-temperature heat source with sound (refrigerators/heat pumps) [55,56]. Fig. 4 gives the schematic of a travelling-wave thermoacoustic engine. Compared with conventional Stirling systems, thermoacoustic systems generally rely on a simpler mechanical architecture, as they require fewer moving components for operation [57,58]. This implies that thermoacoustic systems have higher reliability and longer lifespan. While the reduction in moving parts means some moving parts in conventional Stirling systems must be replaced by acoustic tubes in thermoacoustic systems, like the displacer in a Stirling engine, which is replaced by a feedback tube in a thermoacoustic-Stirling engine [57]. Therefore, the thermodynamic efficiency of thermoacoustic systems will be sacrificed to some extent since more power losses are usually associated with these acoustic tubes.

In this Special Issue, Ahmed et al. [59] explored the feasibility of using liquid metal triboelectric generators (LM-TEGs) as acoustic-to-electric conversion devices in a heat-driven thermoacoustic power generation system. They obtained charge and power densities of $388 \mu\text{C}/\text{m}^2$ and $1.7 \text{ W}/\text{m}^2$, respectively, on a developed acoustically-driven LM-TEG test rig. In another work, they considered using another type of

triboelectric generator—non-contact fibre-reinforced rotary triboelectric generator (NFTEG) [60], to achieve acoustic-to-electric conversion in heat-driven thermoacoustic power generation systems. In experiments, when CO_2 is used as the working gas of the acoustic-driven NFTEG system, and the drive frequency is 35 Hz, an electric power output of 1.46 W is obtained on the developed NFTEG prototype.

Guo et al. [61] performed fundamental research in which they analysed the onset and dynamic characteristics of a standing-wave thermoacoustic engine with general impedance boundaries, and they validated the developed model by using thermoacoustic instability experiments. Furthermore, they revealed how variations in geometric configuration and electrical parameters affect the initiation of thermoacoustic oscillations and the subsequent dynamic behavior of the engine.

Korobko et al. [62] also concentrated on the onset characteristics of standing-wave thermoacoustic engines. They found that a longitudinal temperature gradient in the thermoacoustic stack is not a sufficient condition for spontaneous thermoacoustic oscillations, while thermoconvective streams initiate spontaneous thermoacoustic oscillations, which has been proven in both experiments and CFD modelling. In addition, the dynamic characteristics of heaters affect the thermoacoustic engine's onset significantly.

To recover waste heat from an ICE, Baccoli et al. [63] designed a two-stage looped thermoacoustic electric generator (Fig. 5(a)) with the aid of DeltaEC software, and the designed generator could output 300 W electrical power at a hot temperature of 530 K. Then, they conducted a computational fluid dynamics analysis on the thermoacoustic electric generator by using OpenFOAM to consider the nonlinear thermo-fluid dynamics. Furthermore, the DeltaEC model is recalibrated by the CFD analysis results, and a good agreement has been achieved between the two different numerical methods.

Wang et al. [64] proposed a new cascade configuration for the cooler in a heat-driven thermoacoustic refrigeration system. The system includes three identical stages, and in each stage, they used a thermoacoustic engine to drive a cascade thermoacoustic cooler, with a gas-liquid resonator as the phase-shifter (Fig. 5(b)). They numerically compared the new cascade configuration with a conventional heat-driven thermoacoustic refrigeration system and found that under the identical temperature settings, the COP of the triple-cooler cascade system is 2.5 times that of the conventional system, showcasing significant potential for utilising high-temperature heat sources.

Zare et al. [65] studied the dynamics and performance of a diaphragm thermoacoustic Stirling oscillator using a combination of the describing function approach and a genetic algorithm. The obtained numerical results are compared with experimental results, and it is concluded that the proposed describing function method can accurately analyse the stable limit cycle and performance of diaphragm thermoacoustic Stirling oscillators.

While thermoacoustic oscillations can be deliberately exploited for energy conversion, their spontaneous occurrence is undesirable in combustors, burners, or cryogenic systems. In cryogenic systems, these

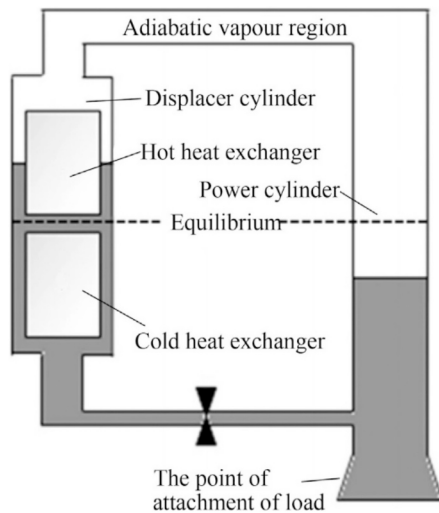


Fig. 7. Schematic of a two-phase TFO [80]. When the TFO operates, the working fluid experiences periodical evaporation and condensation between the hot-end and cold-end heat exchangers, which induces a sustained fluid oscillation.

oscillations, known as Taconis oscillations [66,67], can generate severe vibration issues in pipelines and increase heat leak to cryogenic vessels. Helmholtz resonators provide a passive means of suppressing such instabilities. On this basis, Gu et al. [68] performed a theoretical and numerical investigation on a coupled system that includes a cryogenic hydrogen tube and a Helmholtz resonator, as shown in Fig. 6. They explored the effects of the Helmholtz resonator's key geometric parameters on the acoustic performance of the coupled system. The results indicate that enlarging the Helmholtz resonator and putting the Helmholtz resonator close to the centre of the hydrogen tube could mitigate the Taconis oscillations effectively.

2.3. Other heat-driven oscillating systems

An interesting subset of heat-driven oscillating systems is a class of technologies referred to as TFOs [18,69], which are a class of thermodynamic heat converters that can utilize lower-grade external heat sources. TFOs include single-phase systems, such as Sondhauss tubes [70,71], standing-wave thermoacoustic engines [72], and the Fluidyne engine [73], amongst other, as well as two-phase alternatives. Two-phase TFO technologies (as shown in Fig. 7) are based on unsteady thermodynamic heat engine cycles, with periodic phase change undergone by organic working fluids [74,75]. Owing to the higher heat transfer coefficients of boiling and condensation, two-phase TFOs can be more power dense than their single-phase counterparts, and are well suited to the conversion of low-grade heat into hydraulic work for fluid pumping [76], pressurisation [77], or CHP applications [78]. Although these technologies, similar to all thermodynamic systems aimed at low-grade heat conversion, have inherently low efficiencies (limited by the low heat-source temperature), TFOs usually have no [18,69] or few [79] moving parts and dynamic seals. Therefore, the capital, operating and maintenance costs of these technologies are low, positioning them as suitable for distributed energy provision.

Natural circulation loops (NCLs) are a type of passive thermal management system that operates without mechanical pumps, using buoyancy-driven flow for heat transport [81]. Since NCLs operate without mechanical pumps, the risk of failure, as well as maintenance and operating costs, is reduced. So, they have shown promising prospects in energy applications, such as solar thermal systems, advanced nuclear reactors, geothermal power plants, electronics cooling systems, and so on. NCLs have also been employed in FPSCs for heat transport [82]. In this Special Issue, Hashemi-Tilehnoee et al. [83] contributed a

review paper, which summarises the latest research progress in NCLs, meanwhile recommending a future research roadmap in this field.

3. Outlook and future challenges

Stirling engines were invented as early as 1816 [84], and later, the innovation of the FPSE configuration made this technology more reliable and compact [85]. After around 210 years of development, nowadays, Stirling engines have been deployed in some specific application scenarios, such as CSP systems, CHP systems, and silent submarines. For these applications, the Technology Readiness Level (TRL) of the Stirling engine is between 7 and 9. It has great potential to be used in space nuclear reactor power systems in the near future, since the ground test results were promising [27]. Currently, for space nuclear reactor power systems, the TRL of Stirling engine is assessed to be 6 [86]. For CSP and CHP applications, currently, high capital costs act as the main barrier to widespread penetration of this technology, though they could achieve significant environmental and cost savings. For example, Stamford et al. [86] assessed the life-cycle environmental and economic impacts of Stirling engine CHP unit in the UK context, and they concluded that the life-cycle environmental and economic performance of Stirling engine CHP unit is inferior to that of conventional solutions, because of its low on-site efficiency. Therefore, reducing the capital costs of the Stirling engine while maintaining high on-site operational efficiency is a future trend of this technology [28,87]. Currently, typical output power of Stirling engine is from several W to several 100 kW, and multi-megawatt systems are under development for defence applications [88].

Besides, against the background of grid decarbonisation and carbon neutrality, using renewable energy sources (e.g., solar and biofuel) to power the Stirling engines, meanwhile integrating with thermal energy storage [89], could promote their wider applications. Some attempts to couple solar panels/collectors with Stirling engines for the provision of heating and electricity to households have been made in recent years [24,90,91]. However, the initial capital costs of such a hybrid system are high and the payback time is long at the current stage.

In contrast to Stirling engines, Stirling refrigerators, especially low-temperature ones, have found more practical applications in infrared detectors, optical and electronic devices, and superconducting equipment. Future research directions include further increasing the cryocoolers' lifespan and reliability, developing high-capacity Stirling cryocoolers for gas liquefaction [92], and with lower cooling temperatures for pre-cooling of sub-K cooling systems [93].

As for Stirling heat pumps, they have not received much attention until the recent decade [37], and this may be because of the ever-increasing need for carbon emission reduction worldwide. Khan et al. analysed the HighLift heat pump developed by Olvondo Technology using exergy analysis and life cycle assessment methods [40]. They found that with increased operating time, Stirling heat pump is more environmentally friendly than boilers using traditional energy sources, and can provide lower exergy losses. Currently, there are several demonstration applications of Stirling heat pumps in the industrial sector in Norway [94] and Sweden [40], while their capital costs remain high. So, this technology requires further inroads to reduce capital costs and operational costs. Besides, the integration of renewable energy (such as solar energy, wind energy, biomass energy, etc.) with Stirling heat pumps will be an important development trend since the use of renewable energy sources will lower the energy (generally fossil fuel or electricity from fossil fuel) consumption of Stirling heat pumps and gain energy-saving benefits [95].

In recent years, one-way oscillating flow cycle engines [96–98], coolers [99–101] and heat pumps [102] have been proposed, which are based on a thermodynamic cycle with two isochoric and two adiabatic processes. They have the potential to reduce the irreversibility in conventional Stirling cycle systems [103], while experimental validation is highly desired.

Thermoacoustic systems are a promising technology that can convert

Table 1

Summarize of maturity level, advantages and challenges of different heat-driven oscillating systems.

Heat-driven oscillating systems	Applications	Maturity level	Advantages	Challenges
Stirling-cycle systems	Engines/generators	Mature, commercially available	• High efficiency • High reliability (especially for free-piston ones) • Flexibility of fuel sources	• High capital costs • Stringent manufacturing requirements
	Refrigerators	Mature, commercially available	• High COP • High reliability (especially for free-piston ones) • Compact size	• Limited cooling capacity • With lower cooling temperature
	Heat pumps	• Kinematic ones: partly commercially available • Free-piston ones: prototypes, under R&D	• Wide temperature range adaptability • High COP • Compact size	• High capital costs • Stringent manufacturing requirements • Few demonstration applications
Thermoacoustic systems	Engines/generators	Prototypes, under R&D	• High reliability • Low capital costs	• Lower power density compared with Stirling systems • Low operational efficiency
	Refrigerators	Prototypes, under R&D	• High reliability • High COP • Low capital costs	• The coupling between the thermoacoustic refrigerator and hot/cold sources • Few demonstration applications
	Heat pumps	Prototypes, under R&D	• Wide temperature range adaptability • High COP • Low capital costs	• The coupling between the thermoacoustic heat pump and hot/cold sources • Few demonstration applications
Thermofluidic oscillators	Engine/pump	Prototypes, under R&D	Low capital, operating and maintenance costs	• Low thermal efficiency • Few demonstration applications

thermal energy into acoustic power or consume acoustic power to pump heat [104,105]. Their typical output power is from several W to several 100 kW, making them well-suited to micro- or small-scale, distributed energy systems. After miniaturisation, they can also be used to drive low-power electronics [58,106]. Ideally, the reliability of thermoacoustic systems is higher than that of Stirling systems, as thermoacoustic systems have fewer moving components. Accordingly, the manufacturing cost of thermoacoustic systems can be lower than that of Stirling systems. Some innovative designs, such as the thermoacoustic-Stirling configuration [57], multi-stage looped travelling-wave configuration [107], and the looped configuration with bypass tubes [108], may accelerate the real application of this technology. Until now, thermoacoustic engines, thermoacoustic refrigerators, or thermoacoustic heat pumps are not commercially mature yet and lack industrial demonstration. Therefore, more efforts are needed to improve operational efficiency and power density of thermoacoustic systems, and optimise the coupling between the thermoacoustic system and heat sources [109].

The aforementioned Stirling and thermoacoustic systems are based on single-phase cycles and usually do not feature phase change, whereas TFOs are two-phase cycles and involve periodic evaporation–condensation of the working fluid during heat-to-power conversion [74,110]. The reported thermal efficiency of TFOs was reported as reaching about 1.5% at an 80 °C heat source temperature, and it is expected that 5% is possible at scales of up to a few 100 W [69]. The proposal of advanced designs and configurations, the enhancement of thermal performance especially via the minimisation of parasitic unsteady thermal losses [72], and the use of novel working fluids or mixtures thereof selected to match the external heat source/sinks [70] will make this technology more competitive for the recovery and conversion of very low-grade heat sources. Table 1 summarises the maturity level, advantages and challenges of different heat-driven oscillating systems. A quantitative comparison between Stirling, thermoacoustic, and thermofluidic systems can be found in Ref. [111].

In summary, heat-driven oscillating systems are a type of unique but important energy conversion system. They are well-suited to micro- or small-scale, distributed energy system applications. Some of them already play significant roles in our daily lives, while some of them are still in the R&D stage (Stirling/thermoacoustic heat pumps are identified as the most promising technologies for near-term deployment and

commercialisation). Against the background of decarbonisation and carbon neutrality, with the efforts of peers from both academic and industrial sectors, it is expected that they will play a more important role in achieving the global carbon emission reduction target in the near future.

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.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Grant No. 52306031 and 52405096). The authors would like to thank Professor Giorgio Besagni for his efforts, all authors who submitted their manuscripts to this Special Issue. The guest editors would also like to thank the Editorial Board of *Applied Thermal Engineering* and all reviewers for their efforts and valuable comments in reviewing the selected articles and advising authors and editors. For the purpose of Open Access, the authors have applied a CC BY public copyright license to any Author Accepted Manuscript version arising from this submission.

Data availability

No data was used for the research described in the article.

References

- [1] M. Herrando, K. Wang, G. Huang, T. Otanicar, O.B. Mousa, R.A. Agathokleous, et al., A review of solar hybrid photovoltaic-thermal (PV-T) collectors and systems, *Prog. Energy Combust. Sci.* 97 (2023) 101072, <https://doi.org/10.1016/j.pecs.2023.101072>.
- [2] X. Ling, Y. Liang, M. Zhao, J. Shen, Y. Zhu, K. Ye, Multi-criteria parameter analysis and optimization of a combined cooling, heating, and power system based on SOFC/GT and S-CO₂/T-CO₂ cycle, *Appl. Therm. Eng.* 272 (2025) 126433, <https://doi.org/10.1016/j.applthermaleng.2025.126433>.
- [3] A.M. Daabo, S. Mahmoud, R.K. Al-Dadah, Development of small-scale axial turbine for solar powered Brayton cycle, in: 2016 International Conference for Students on Applied Engineering (ICSAE), 2016, pp. 170–175, <https://doi.org/10.1109/ICSAE.2016.7810182>.

- [4] K.H. Kumar, M.K. Karmakar, A.M. Daabo, B. Mondal, Optical efficiency and convective heat loss of a cylindrical-hemispherical receiver used in parabolic dish concentrator, *J. Therm. Anal. Calorim.* 149 (2024) 2481–2497, <https://doi.org/10.1007/s10973-023-12814-w>.
- [5] A.M. Daabo, S. Zubeer, H. Ismael, F. Mustafa, H. Hamzah, A. Basem, et al., A novel economic and technical dispatch model for household photovoltaic system considering energy storage system in “Duhok” City/Iraq as a case study, *J. Energy Storage* 94 (2024) 112440, <https://doi.org/10.1016/J.EST.2024.112440>.
- [6] C.N. Markides, Low-concentration solar-power systems based on organic Rankine cycles for distributed-scale applications: overview and further developments, *Front. Energy Res.* 3 (2015).
- [7] M.A. Chatzopoulou, S. Lecompte, M. De Paep, C.N. Markides, Off-design optimisation of organic Rankine cycle (ORC) engines with different heat exchangers and volumetric expanders in waste heat recovery applications, *Appl. Energy* 253 (2019) 113442, <https://doi.org/10.1016/J.APENERGY.2019.113442>.
- [8] M.A. Chatzopoulou, M. Simpson, P. Sapin, C.N. Markides, Off-design optimisation of organic Rankine cycle (ORC) engines with piston expanders for medium-scale combined heat and power applications, *Appl. Energy* 238 (2019) 1211–1236, <https://doi.org/10.1016/J.APENERGY.2018.12.086>.
- [9] A. Ramos, M.A. Chatzopoulou, J. Freeman, C.N. Markides, Optimisation of a high-efficiency solar-driven organic Rankine cycle for applications in the built environment, *Appl. Energy* 228 (2018) 755–765, <https://doi.org/10.1016/J.APENERGY.2018.06.059>.
- [10] J. Song, P. Loo, J. Teo, C.N. Markides, Thermo-economic optimization of organic Rankine cycle (ORC) systems for geothermal power generation: a comparative study of system configurations, *Front. Energy Res.* 8 (2020).
- [11] O.A. Oyewunmi, C.J.W. Kirmse, A.M. Pantaleo, C.N. Markides, Performance of working-fluid mixtures in ORC-CHP systems for different heat-demand segments and heat-recovery temperature levels, *Energy Convers. Manag.* 148 (2017) 1508–1524, <https://doi.org/10.1016/J.ENCONMAN.2017.05.078>.
- [12] L.M.T. van Kleef, O.A. Oyewunmi, C.N. Markides, Multi-objective thermo-economic optimization of organic Rankine cycle (ORC) power systems in waste-heat recovery applications using computer-aided molecular design techniques, *Appl. Energy* 251 (2019) 112513, <https://doi.org/10.1016/J.APENERGY.2019.01.071>.
- [13] M.T. White, O.A. Oyewunmi, M.A. Chatzopoulou, A.M. Pantaleo, A.J. Haslam, C. N. Markides, Computer-aided working-fluid design, thermodynamic optimisation and thermoeconomic assessment of ORC systems for waste-heat recovery, *Energy* 161 (2018) 1181–1198, <https://doi.org/10.1016/J.ENERGY.2018.07.098>.
- [14] C.N. Markides, A. Bardow, M. De Paep, C. De Servi, J. Groß, A.J. Haslam, et al., Working fluid and system optimisation of organic Rankine cycles via computer-aided molecular design: a review, *Prog. Energy Combust. Sci.* 107 (2025) 101201, <https://doi.org/10.1016/J.PECS.2024.101201>.
- [15] C. Jiang, S. Zhu, G. Yu, E. Luo, K. Li, Numerical and experimental investigations on a regenerative static thermomagnetic generator for low-grade thermal energy recovery, *Appl. Energy* 311 (2022) 118585, <https://doi.org/10.1016/J.APENERGY.2022.118585>.
- [16] K. Wang, S.R. Sanders, S. Dubey, F.H. Choo, F. Duan, Stirling cycle engines for recovering low and moderate temperature heat: a review, *Renew. Sust. Energy. Rev.* 62 (2016) 89–108, <https://doi.org/10.1016/J.RSER.2016.04.031>.
- [17] G. Chen, L. Tang, B. Mace, Z. Yu, Multi-physics coupling in thermoacoustic devices: a review, *Renew. Sust. Energy. Rev.* 146 (2021) 111170, <https://doi.org/10.1016/J.RSER.2021.111170>.
- [18] R. Solanki, A. Galindo, C.N. Markides, Dynamic modelling of a two-phase thermofluidic oscillator for efficient low grade heat utilization: effect of fluid inertia, *Appl. Energy* 89 (2012) 156–163, <https://doi.org/10.1016/J.APENERGY.2011.01.007>.
- [19] H. Wang, Y. Chen, E. Luo, H. Kang, S. Zhu, Study on the influence of real gas compressibility on the performance of free-piston Stirling engines, *Appl. Therm. Eng.* (2025), <https://doi.org/10.1016/j.applthermaleng.2025.128441>.
- [20] L. Wei, H. Sun, H. Ma, G. Yu, S. Zhu, W. Dai, et al., Upscaling of thermoacoustic-Stirling duplex cryocoolers based on resonance tube coupling, *IScience* 28 (2025).
- [21] G. Teng, L. Dai, R. Wang, J. Hu, Z. Wu, L. Zhang, et al., Experimental study of an efficient low-temperature thermoacoustic Stirling heat pump, *Int. J. Refrig.* 172 (2025) 17–26, <https://doi.org/10.1016/J.IJREFRIG.2025.01.005>.
- [22] H. Sun, G. Yu, D. Zhao, S. Zhu, W. Dai, E. Luo, Operating characteristics study of a dual-opposed free-piston Stirling generator, *Appl. Therm. Eng.* 249 (2024) 123387, <https://doi.org/10.1016/J.APPLTHERMALENG.2024.123387>.
- [23] M. Sheykhi, M. Mehregan, S. Ghorbani, A. Emamian, M.H. Kayhani, A.A. Delouei, et al., Simulation and performance optimization of a novel hybrid CCHP system based on the prime movers of internal combustion engine and Stirling engine, *Appl. Energy* 393 (2025) 126103.
- [24] D. Roy, S. Zhu, R. Wang, I. González-Pino, M. Herrando, C.N. Markides, et al., Techno-economic and environmental analyses of a solar-assisted Stirling engine cogeneration system for different dwelling types in the United Kingdom, *Energy Convers. Manag.* 302 (2024) 118160, <https://doi.org/10.1016/J.ENCONMAN.2024.118160>.
- [25] T. Schneider, D. Müller, J. Karl, A review of thermochemical biomass conversion combined with Stirling engines for the small-scale cogeneration of heat and power, *Renew. Sust. Energy. Rev.* 134 (2020) 110288, <https://doi.org/10.1016/J.RSER.2020.110288>.
- [26] S. Zhu, G. Yu, Y. Ma, Y. Cheng, Y. Wang, S. Yu, et al., A free-piston Stirling generator integrated with a parabolic trough collector for thermal-to-electric conversion of solar energy, *Appl. Energy* 242 (2019) 1248–1258.
- [27] P.R. McClure, D.I. Poston, M.A. Gibson, L.S. Mason, R.C. Robinson, Kilopower project: the KRUSTY fission power experiment and potential missions, *Nucl. Technol.* 206 (2020) S1–12, <https://doi.org/10.1080/00295450.2020.1722554>.
- [28] S. Zhu, G. Yu, K. Liang, W. Dai, E. Luo, A review of Stirling-engine-based combined heat and power technology, *Appl. Energy* 294 (2021) 116965, <https://doi.org/10.1016/J.APENERGY.2021.116965>.
- [29] S. Zhu, G. Yu, X. Li, W. Dai, E. Luo, Parametric study of a free-piston Stirling cryocooler capable of providing 350 W cooling power at 80 K, *Appl. Therm. Eng.* 174 (2020), <https://doi.org/10.1016/j.applthermaleng.2020.115101>.
- [30] M.Z. Getie, F. Lanzetta, S. Bégot, B.T. Admassu, A.A. Hassen, Reversed regenerative Stirling cycle machine for refrigeration application: a review, *Int. J. Refrig.* 118 (2020) 173–187, <https://doi.org/10.1016/J.IJREFRIG.2020.06.007>.
- [31] J. Park, J. Ko, H. Kim, Y. Hong, H. Yeom, S. In, et al., Experimental test of 4 kW-class Stirling cryocooler for superconducting cable cooling system, *IOP Conf. Ser.: Mater. Sci. Eng.* 502 (2019) 012140, <https://doi.org/10.1088/1757-899X/502/1/012140>.
- [32] J. Park, S. In, J. Ko, H. Kim, Y. Hong, H. Yeom, et al., Development and parametric study of a 1kW class free-piston Stirling cryocooler (FPSC) driven by a dual opposed linear compressor for LNG (re)liquefaction, *Int. J. Refrig.* 104 (2019) 113–122, <https://doi.org/10.1016/J.IJREFRIG.2019.05.008>.
- [33] B. Collaudin, N. Rando, Cryogenics in space: a review of the missions and of the technologies, *Cryogenics (Guildf)* 40 (2000) 797–819, [https://doi.org/10.1016/S0011-2275\(01\)00035-2](https://doi.org/10.1016/S0011-2275(01)00035-2).
- [34] R. Radebaugh, Cryocoolers: the state of the art and recent developments*, *J. Phys. Condens. Matter* 21 (2009) 164219, <https://doi.org/10.1088/0953-8984/21/16/164219>.
- [35] B. Hajagos, Life Cycle Assessment and Emission Reduction of Cascade and Stirling Ultra-Low Temperature Freezers, Eindhoven University of Technology, 2021.
- [36] R. Wang, J. Hu, Z. Jia, E. Luo, J. Xu, Y. Sun, Performance study of a free-piston Stirling heat pump with a circumferential temperature gradient in the heating heat exchanger, *Int. J. Refrig.* 146 (2023) 274–289, <https://doi.org/10.1016/J.IJREFRIG.2022.11.007>.
- [37] T.A. Minale, F. Lanzetta, S. Bégot, M.Z. Getie, Review on the technological advancement of Stirling cycle heat pumps, *Energy Rep.* 12 (2024) 3504–3518, <https://doi.org/10.1016/J.ENERGY.2024.09.028>.
- [38] L. Dai, K. Luo, Y. Sun, J. Hu, L. Zhang, Z. Wu, et al., A 2 kW-class free-piston Stirling heat pump prototype suitable for cold regions for domestic heating, *Int. J. Refrig.* 159 (2024) 112–123, <https://doi.org/10.1016/J.IJREFRIG.2023.12.030>.
- [39] N. Häggqvist, T.M. Tveit, R. Zevenhoven, Combining measurements and simulation for condition monitoring and performance optimization of an alpha-configuration double-acting high-temperature Stirling cycle-based heat pump, *Case Stud. Therm. Eng.* 47 (2023) 103066, <https://doi.org/10.1016/J.CSITE.2023.103066>.
- [40] U. Khan, R. Zevenhoven, L. Stougie, T.-M. Tveit, Prediction of Stirling-cycle-based heat pump performance and environmental footprint with exergy analysis and lca, *Energies (Basel)* 14 (2021) 8478.
- [41] T. Zhou, G. Jiao, X. Zhang, Y. Xia, K. Su, Y. Zhang, et al., Performance analysis of an integrated space nuclear reactor with Stirling engine based on multi-physics coupling, *Appl. Therm. Eng.* 277 (2025) 126943, <https://doi.org/10.1016/j.applthermaleng.2025.126943>.
- [42] H. Wang, Y. Chen, J. Luo, L. Zhang, H. Kang, E. Luo, et al., A novel high-power free-piston Stirling engine generator with integrated heat pipes for thermal-to-electric conversion of clean energy, *Energy* 314 (2025) 134218, <https://doi.org/10.1016/J.ENERGY.2024.134218>.
- [43] M.A. Gibson, D.I. Poston, P. McClure, T. Godfroy, J. Sanzi, M.H. Briggs, The Kilopower Reactor Using Stirling Technology (KRUSTY) nuclear ground test results and lessons learned, in: 2018 International Energy Conversion Engineering Conference, American Institute of Aeronautics and Astronautics, 2018, <https://doi.org/10.2514/6.2018-4973>.
- [44] H.M. Wong, R. Bahar, Y.S. Ong, Experimental evaluation of the displacer and working piston hybrid motion to improve the performance of a Stirling engine, *Appl. Therm. Eng.* 279 (2025) 127936, <https://doi.org/10.1016/j.applthermaleng.2025.127936>.
- [45] J. Tomihira, H. Kusudo, E. Shoji, T. Biwa, P. Murti, S. Okuhara, et al., Liquid piston Stirling engine loaded with self-rectifying turbine: equivalent load analysis with orifice plate, *Appl. Therm. Eng.* 278 (2025) 126937, <https://doi.org/10.1016/j.applthermaleng.2025.126937>.
- [46] H.-S. Yang, S.-Y. Kuan, M.A. Ali, Effect of dynamic characteristics on the performance of a free-piston Stirling heat-driven cooler, *Appl. Therm. Eng.* 274 (2025) 126795, <https://doi.org/10.1016/j.applthermaleng.2025.126795>.
- [47] H.-S. Yang, Y.-T. Lin, A complete model for free-piston Stirling trigeneration systems, *Appl. Therm. Eng.* 275 (2025) 126861, <https://doi.org/10.1016/j.applthermaleng.2025.126861>.
- [48] H. Liu, C. Chi, R. Li, M. Lin, J. Mou, K. Jiao, et al., Parameter study of a free piston Stirling generator under high cold-end-temperature condition, *Appl. Therm. Eng.* 274 (2025) 126695, <https://doi.org/10.1016/j.applthermaleng.2025.126695>.
- [49] M. Yang, H. Liu, Y. Yuan, X. Yu, C. Chi, M. Lin, et al., Research on piston offset inhibition method of free piston Stirling generator based on conical orifice plate, *Appl. Therm. Eng.* 267 (2025) 125695, <https://doi.org/10.1016/j.applthermaleng.2025.125695>.
- [50] G. Dogkas, E. Rogdakis, A review on Vuilleumier machines, *Therm. Sci. Eng. Prog.* 8 (2018) 340–354, <https://doi.org/10.1016/J.TSEP.2018.09.004>.
- [51] Z. Yuan, B. Luo, X. Su, J. Liu, R. Li, P. Zou, et al., Evaluation of methods for capacity regulation of Vuilleumier heat pump, *Appl. Therm. Eng.* 267 (2025) 125754, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.125754>.

- [52] S. Zhu, G. Yu, X. Li, M. Ying, C. Yan, W. Dai, et al., Acoustic field characteristics of a free-piston Stirling cryocooler with large cooling capacity at liquid nitrogen temperature, *Appl. Therm. Eng.* 147 (2019) 324–335, <https://doi.org/10.1016/J.APPLTHERMALENG.2018.10.096>.
- [53] Z. Xi, F. Xu, X. Zhang, Study of a miniature moving magnet linear compressor using magnetic spring, *Appl. Therm. Eng.* 262 (2025) 125235, <https://doi.org/10.1016/j.applthermaleng.2024.125235>.
- [54] J. Ma, H. Hui, Z. Jiang, P. Qu, X. Zhou, S. Liu, et al., Experimental study on the effect of trace nitrogen on pulse tube cryocooler in 40 K temperature range, *Appl. Therm. Eng.* 275 (2025) 126778, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126778>.
- [55] J. Wen, L. Zhang, H. Kang, S. Liu, K. Wang, Advances in the utilization and suppression of thermoacoustic effect: a review, *Int. J. Heat Mass Transf.* 231 (2024) 125758, <https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2024.125758>.
- [56] Artur J. Jaworski, Xiaolan Mao, Development of thermoacoustic devices for power generation and refrigeration, *Proc. Inst. Mech. Eng. A: J. Power Energy* 227 (2013) 762–782, <https://doi.org/10.1177/0957650913493622>.
- [57] S. Backhaus, G.W. Swift, A thermoacoustic Stirling heat engine, *Nature* 399 (1999) 335–338, <https://doi.org/10.1038/20624>.
- [58] T. Jin, J. Huang, Y. Feng, R. Yang, K. Tang, R. Radebaugh, Thermoacoustic prime movers and refrigerators: thermally powered engines without moving components, *Energy* 93 (2015) 828–853, <https://doi.org/10.1016/J.ENERGY.2015.09.005>.
- [59] F. Ahmed, J. Wang, R. Yang, G. Yu, S. Zhu, W. Tang, et al., Harnessing acoustic energy with liquid metal triboelectric nanogenerators: a promising approach for moving-parts-free power generation, *Appl. Therm. Eng.* 260 (2025) 125048, <https://doi.org/10.1016/J.APPLTHERMALENG.2024.125048>.
- [60] H. Chen, Y. Yang, J. Wang, Y. Shang, W. Tang, G. Yu, et al., An acoustic-driven high-power rotary triboelectric generator, *Appl. Therm. Eng.* 267 (2025) 125752, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.125752>.
- [61] F. Guo, J. Du, Y. Wang, Y. Liu, Self-sustained thermoacoustic oscillators with general impedance boundary: onset and dynamic behavior determination and theoretical-experimental validation, *Appl. Therm. Eng.* 271 (2025) 126338, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126338>.
- [62] V. Korobko, M. Radchenko, D. Mikielewicz, A. Radchenko, O. Moskovko, R. Radchenko, et al., Thermoacoustic engines for low-grade heat conversion into mechanical power: a study on oscillation initiation, *Appl. Therm. Eng.* 274 (2025) 126688, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126688>.
- [63] R. Baccoli, A. Di Meglio, A. Fenu, N. Massarotti, Design and performance of a ThermoAcoustic electric generator powered by waste-heat based on linear and nonlinear modelling, *Appl. Therm. Eng.* 276 (2025) 126938, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126938>.
- [64] B. Wang, J. Chi, Z. Wu, L. Xiao, L. Zhang, J. Hu, et al., A heat-driven thermoacoustic refrigeration system with cascade configuration of the cooler, *Appl. Therm. Eng.* 276 (2025) 126924, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126924>.
- [65] S. Zare, Z. Raeisi, R.A. Lashaki, M. Makki, N. Ghasemi, Evaluation of a thermoacoustic Stirling oscillator using a describing function and a genetic algorithm, *Appl. Therm. Eng.* 278 (2025) 127125, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.127125>.
- [66] M.P. Shenton, J.W. Leachman, K.I. Matveev, Investigating Taconis oscillations in a U-shaped tube with hydrogen and helium, *Cryogenics (Guildf)* 143 (2024) 103940, <https://doi.org/10.1016/J.CRYOGENICS.2024.103940>.
- [67] Y. Niu, L. Hu, Y. Liu, B. Gao, Asynchronous quenching in cryogenic thermoacoustic systems under active control, *Cryogenics (Guildf)* 153 (2026) 104260, <https://doi.org/10.1016/J.CRYOGENICS.2025.104260>.
- [68] L. Gu, L. Liu, Z. Li, L. Tang, Z. Yu, G. Chen, Suppression of Taconis oscillations in cryogenic hydrogen tubes using a Helmholtz resonator: theoretical modelling and numerical simulations, *Appl. Therm. Eng.* 274 (2025) 126687, <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126687>.
- [69] L. Grosu, M. Feidt, A.J. Jaworski, M. Ja'fari, C.N. Markides, Oscillatory flow power cycles, in: *Power Generation Technologies for Low-Temperature and Distributed Heat*, 2023, pp. 207–289, <https://doi.org/10.1016/B978-0-12-818022-8.00004-1>.
- [70] C. Sondhauss, Ueber die Schallschwingungen der Luft in erhitzten Glasröhren und in gedeckten Pfeifen von ungleicher Weite, *Ann. Phys.* 155 (1850) 1–34, <https://doi.org/10.1002/andp.18501550102>.
- [71] K.T. Feldman, Review of the literature on Sondhauss thermoacoustic phenomena, *J. Sound Vib.* 7 (1968) 71–82, [https://doi.org/10.1016/0022-460X\(68\)90158-2](https://doi.org/10.1016/0022-460X(68)90158-2).
- [72] P.H. Ceperley, A pistonless Stirling engine—the traveling wave heat engine, *J. Acoust. Soc. Am.* 66 (1979) 1508–1513, <https://doi.org/10.1121/1.383505>.
- [73] C.W. Stammers, The operation of the Fluidyne heat engine at low differential temperatures, *J. Sound Vib.* 63 (1979) 507–516, [https://doi.org/10.1016/0022-460X\(79\)90826-5](https://doi.org/10.1016/0022-460X(79)90826-5).
- [74] C.N. Markides, R. Solanki, A. Galindo, Working fluid selection for a two-phase thermofluidic oscillator: effect of thermodynamic properties, *Appl. Energy* 124 (2014) 167–185, <https://doi.org/10.1016/J.APENERGY.2014.02.042>.
- [75] O.A. Oyewunmi, C.J.W. Kirmse, A.J. Haslam, E.A. Müller, C.N. Markides, Working-fluid selection and performance investigation of a two-phase single-reciprocating-piston heat-conversion engine, *Appl. Energy* 186 (2017) 376–395, <https://doi.org/10.1016/J.APENERGY.2016.05.008>.
- [76] T. Smith, Power dense thermofluidic oscillators for high load applications, in: *2nd International Energy Conversion Engineering Conference*, American Institute of Aeronautics and Astronautics, 2004, <https://doi.org/10.2514/6.2004-5758>.
- [77] D. Yarger, M. Beck, R. Peterson, Experimental study of a mesoscale two-phase thermocompressor, in: *4th International Energy Conversion Engineering Conference and Exhibit (IECEC)*, American Institute of Aeronautics and Astronautics, 2006, <https://doi.org/10.2514/6.2006-4014>.
- [78] A.I. Taleb, M.A.G. Timmer, M.Y. El-Shazly, A. Samoilov, V.A. Kirillov, C. N. Markides, A single-reciprocating-piston two-phase thermofluidic prime-mover, *Energy* 104 (2016) 250–265, <https://doi.org/10.1016/J.ENERGY.2016.02.113>.
- [79] C.J.W. Kirmse, O.A. Oyewunmi, A.I. Taleb, A.J. Haslam, C.N. Markides, A two-phase single-reciprocating-piston heat conversion engine: non-linear dynamic modelling, *Appl. Energy* 186 (2017) 359–375, <https://doi.org/10.1016/J.APENERGY.2016.05.140>.
- [80] C.N. Markides, A. Osuolale, R. Solanki, G.B.V. Stan, Nonlinear heat transfer processes in a two-phase thermofluidic oscillator, *Appl. Energy* 104 (2013) 958–977, <https://doi.org/10.1016/J.APENERGY.2012.11.056>.
- [81] D.N. Basu, S. Bhattacharyya, P.K. Das, A review of modern advances in analyses and applications of single-phase natural circulation loop in nuclear thermal hydraulics, *Nucl. Eng. Des.* 280 (2014) 326–348, <https://doi.org/10.1016/J.NUCENGDES.2014.09.011>.
- [82] D. Berchowitz, A Personal History in the Development of the Modern Stirling Engine, ISEC International Stirling Engine Committee, 2018.
- [83] M. Hashemi-Tilehnoee, M. Misale, S.M. Seyyedi, E. Palomo del Barrio, A. Marchitto, S.S. Rahim Hosseini, et al., Overview of fundamental aspects of natural circulation loops, *Appl. Therm. Eng.* 276 (2025) 126936, <https://doi.org/10.1016/j.applthermaleng.2025.126936>.
- [84] Robert Stirling, Stirling Air Engine and the Heat Regenerator. 4081, 1816.
- [85] W.T. Beale, Free Piston Stirling Engines - Some Model Tests and Simulations, SAE Technical Paper 690230, 1969, <https://doi.org/10.4271/690230>.
- [86] Y. Lee, A. Guzik, A. Trebi-Ollennu, V. Jovovic, J.-P. Fleurial, J. Elliott, et al., Technology readiness assessment for Stirling power convertor, in: *Nuclear and Emerging Technologies for Space (NETS 2026)*, American Nuclear Society, Illinois, 2026, p. 331, <https://doi.org/10.13182/NETS26-10403>.
- [87] S. Zhu, K. Wang, I. González-Pino, J. Song, G. Yu, E. Luo, et al., Techno-economic analysis of a combined heat and power system integrating hybrid photovoltaic-thermal collectors, a Stirling engine and energy storage, *Energy Convers. Manag.* 284 (2023) 116968, <https://doi.org/10.1016/J.ENCONMAN.2023.116968>.
- [88] Hyliion Awarded \$41.7 Million U.S. Navy Contract to Scale Multi-Megawatt KARNØ Power Modules. <https://investorshyliion.com/news/news-details/2026/hyliion-awarded-41-7-million-u-s-navy-contract-to-scale-multi-megawatt-karno-power-modules/default.aspx>.
- [89] J.E. Rea, C.J. Oshman, M.L. Olsen, C.L. Hardin, G.C. Glatzmaier, N.P. Siegel, et al., Performance modeling and techno-economic analysis of a modular concentrated solar power tower with latent heat storage, *Appl. Energy* 217 (2018) 143–152, <https://doi.org/10.1016/J.APENERGY.2018.02.067>.
- [90] J.A. Auñón-Hidalgo, M. Sidrach-de-Cardona, F. Auñón-Rodríguez, Performance and CO2 emissions assessment of a novel combined solar photovoltaic and thermal, with a Stirling engine micro-CHP system for domestic environments, *Energy Convers. Manag.* 230 (2021) 113793, <https://doi.org/10.1016/J.ENCONMAN.2020.113793>.
- [91] J. Kotowicz, W. Uchman, Analysis of the integrated energy system in residential scale: photovoltaics, micro-cogeneration and electrical energy storage, *Energy* 227 (2021) 120469, <https://doi.org/10.1016/J.ENERGY.2021.120469>.
- [92] D. Sun, Y. Xu, Q. Shen, An efficient high cooling capacity Stirling cryocooler and its application for capturing boil-off methane from liquefied natural gas, *Int. J. Refrig.* 165 (2024) 425–433, <https://doi.org/10.1016/J.IJREFRIG.2024.06.013>.
- [93] C. Fang, X. Liu, L. Li, Y. Zhou, C. Pan, Progress on an 8 K gas-coupled three-stage Stirling pulse tube cryocooler, *Cryogenics (Guildf)* 146 (2025) 104018, <https://doi.org/10.1016/J.CRYOGENICS.2024.104018>.
- [94] A. Høeg, T.-M. Tveit, Low to very high temperature thermal energy recycling – 3 case studies, *E3S Web Conf.* (2021) 09001, <https://doi.org/10.1051/e3sconf/202131309001>.
- [95] S. Trevisan, B. Buchbjerg, A. Høeg, R. Guedez, Techno-economic comparative assessment of high-temperature heat pump architectures for industrial pumped thermal energy storage, *J. Eng. Gas Turbines Power* 147 (2024), <https://doi.org/10.1115/1.4066989>.
- [96] B. Luo, Q. Xiang, X. Su, S. Zhang, P. Yan, J. Liu, et al., A novel oscillating flow cycle engine with characteristics of temperature glide heat addition and no regenerator for low-grade heat utilization, *Appl. Therm. Eng.* 255 (2024) 124017, <https://doi.org/10.1016/J.APPLTHERMALENG.2024.124017>.
- [97] Y. Wang, B. Luo, J. Li, J. Fu, J. Liu, R. Li, A novel one-way oscillating flow cycle engine with characteristic of large temperature glide heat addition for low-grade heat utilization, *Therm. Sci. Eng. Prog.* 57 (2025) 103203, <https://doi.org/10.1016/J.TSEP.2024.103203>.
- [98] B. Luo, Q. Xiang, X. Su, S. Zhang, P. Yan, J. Liu, et al., A novel cycle engine for low-grade heat utilization: principle, conceptual design and thermodynamic analysis, *Energy* 301 (2024) 131634, <https://doi.org/10.1016/J.ENERGY.2024.131634>.
- [99] Y. He, B. Luo, Performance analysis of a novel oscillating flow cooler for sensible loads cooled from the ambient temperature, *Energy* 319 (2025) 135090, <https://doi.org/10.1016/J.ENERGY.2025.135090>.
- [100] B. Luo, X. Su, S. Zhang, P. Yan, J. Liu, R. Li, Analysis of a novel gas cycle cooler with large temperature glide for space cooling, *Energy* 326 (2025) 136294, <https://doi.org/10.1016/J.ENERGY.2025.136294>.
- [101] B. Luo, Y. Chen, K. Liu, J. Sun, H. Bi, Q. Xiang, et al., One-way oscillating flow cycle cooler: a promising technology for cooling and heating, *Appl. Therm. Eng.* 238 (2024) 122053, <https://doi.org/10.1016/J.APPLTHERMALENG.2023.122053>.

- [102] B. Luo, X. Su, S. Zhang, P. Yan, J. Liu, R. Li, Performance analysis of one-way oscillating flow cycle heat pump, *Appl. Therm. Eng.* 248 (2024) 123297, <https://doi.org/10.1016/J.APPLTHERMALENG.2024.123297>.
- [103] B. Luo, Q. Xiang, X. Su, C. Chen, Y. Li, One-way heat exchange regenerative cooler: principle, conceptual design and thermodynamic analysis, *Energy Convers. Manag.* 281 (2023) 116848, <https://doi.org/10.1016/J.ENCONMAN.2023.116848>.
- [104] G. Chen, L. Tang, B.R. Mace, Modelling and analysis of a thermoacoustic-piezoelectric energy harvester, *Appl. Therm. Eng.* 150 (2019) 532–544, <https://doi.org/10.1016/J.APPLTHERMALENG.2019.01.025>.
- [105] W. Sun, G. Chen, L. Tang, K.C. Aw, Mode switching between electric-driven thermoacoustic refrigerator and heat pump, *Energy* 317 (2025) 134607, <https://doi.org/10.1016/J.ENERGY.2025.134607>.
- [106] G. Chen, Y. Wang, S. Tao, J. Xu, L. Tang, J. Wang, et al., High-performance thermoacoustically driven triboelectric nanogenerator for autonomous wireless monitoring, *Cell Rep. Phys. Sci.* 7 (2026) 103214, <https://doi.org/10.1016/J.XCRP.2026.103214>.
- [107] K. de Blok, Novel 4-stage traveling wave thermoacoustic power generator, in: *ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting: Volume 2, Fora, ASMEDC*, 2010, pp. 73–79, <https://doi.org/10.1115/FEDSM-ICNMM2010-30527>.
- [108] L. Xiao, K. Luo, D. Zhao, Z. Wu, J. Xu, E. Luo, A highly efficient heat-driven thermoacoustic cooling system: detailed study, *Energy* 293 (2024) 130610, <https://doi.org/10.1016/J.ENERGY.2024.130610>.
- [109] T.W. Steiner, M. Hoy, K.B. Antonelli, M. Malekian, G.D.S. Archibald, T. Kanemaru, et al., High-efficiency natural gas fired 1 kWe thermoacoustic engine, *Appl. Therm. Eng.* 199 (2021) 117548, <https://doi.org/10.1016/J.APPLTHERMALENG.2021.117548>.
- [110] J. Tan, J. Luo, J. Huang, J. Wei, T. Jin, A closed two-phase thermofluidic oscillator with zeotropic mixtures for low-grade heat recovery, *Energy* 211 (2020) 118691, <https://doi.org/10.1016/J.ENERGY.2020.118691>.
- [111] K. Wang, C.N. Markides, Summary and future outlook, in: *Power Generation Technologies for Low-Temperature and Distributed Heat*, 2023, pp. 473–480, <https://doi.org/10.1016/B978-0-12-818022-8.00006-5>.