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# Developing more efficient travelling-wave thermo-acoustic refrigerators: A review

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ABSTRACT

The use of hazardous refrigerants in current refrigeration systems and their impact on environment have spurred much research into alternative technologies. Thermo-acoustic refrigeration is considered as one of the potential solution to the current search for environmental friendlier technology because of the absence of harmful refrigerants in the system. To date, most of the studies focus on the applicability of the technology toward a global agenda of a sustainable future. This paper summarizes recent development with regards to the designing and the performance of highly efficient traveling-wave thermo-acoustic refrigerators. Past studies discussing devices outputs namely the lowest temperature achieved, the cooling power and the coefficient of performance of travelling-wave refrigerators, are described. The review looks at the performance and the geometrical configuration of devices developed by previous researchers. A summary of the optimization targets and the outcomes achieved is described. It appears that most studies undertaken so far rely heavily on parametric approach, with single parameter being investigated while the others are kept constant during the optimization process. This opens the door for further use of advanced optimization techniques able to deal with parameters varying simultaneously, together with conflicting objectives, in order to identify global optimal solutions potentially more effective.

## Introduction

Future researches related to sustainable development would have to incorporate two main issues namely the environment-protection and the energy-saving. The current urgency to replace chlorofluorocarbon (known as CFC) refrigeration because of the seriousness of the ozone depletion potential and global warming potential problems open ways for alternative cooling technologies [1]. Thermo-acoustic cooling systems are drawing attention of researchers as next-generation of eco-systems because of the possibility to reuse and to transform energy such as solar energy and waste heat, making the devices highly rated with respect to their energy-saving potential. In thermo-acoustic refrigerator, inert gases are generally used as working medium; hence, these environmentally-friendly gases are expected to mitigate issues related to the environment. In addition, thermo-acoustic systems can be driven thermally or electrically. The former are powered by heat energy while the latter are driven by compressor. Thermally-driven thermo-acoustic systems are being developed for cryogenic and room temperature cooling. While the aim of cryogenic thermo-acoustic cooling is to reach the lowest possible temperature, the room-temperature thermo-acoustic cooling seeks to achieve the highest efficiency. Most of the worldwide attention are turned to the latter because of its relatively huge commercial likelihood to provide a substitute for CFC refrigeration.

The fundamental of thermodynamic heat pump is the basis of the operation of thermo-acoustic refrigeration. Hence, acoustic work is necessary to transfer heat from low to high temperature reservoir. The oscillation of the working fluid next to the solid walls, at resonant frequency, induces significant cooling effect as heat is driven from one end of the solid wall to the other. At relatively high pressure and with a suitable geometrical configuration of the solid structure (called stack or regenerator) within the oscillating working fluid particles, considerable amount of cooling can be induced as suggested by Reid and Swift [2], Tijani et al. [3], Guédra et al. [4], Tartibu [5] and Babu and Sherjin [6] just to name few. A recent study conducted by Hao et al. [7] demonstrates the existence of heat-induced, self-amplifying thermo-acoustic oscillations in solids theoretically and numerically.

There is two types of thermo-acoustic systems. Travelling-wave thermo-acoustic refrigerators which are generally large and standing-wave thermo-acoustic refrigerators which are generally more compact. Although the general principle of standing-wave and travelling-wave system is the same, the acoustic wave in travelling-wave system actually travels through a loop as shown in Fig. 1. Nowadays, thermo-acoustic travelling-wave energy conversion is described as relatively more efficient. The increase in efficiency observed in travelling-wave system is attributed to the phasing similarity between the pressure and the velocity curves of the acoustic wave [8]. While the phase angle between the pressure and the velocity curves is evaluated to be 90° in standing-wave system, these two curves are in phase in travelling-wave system [9]. Therefore, there is a more efficient transfer of heat energy in travelling-wave system resulting in an increase of the potential

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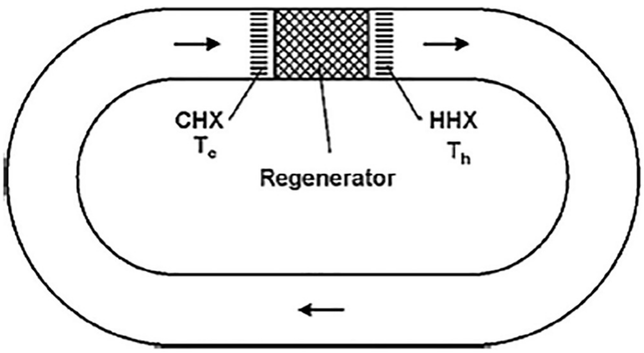


**Fig. 1.** Schematic of a thermo-acoustic system (adapted from Ref. [13]).

overall efficiency of the device. The coefficient of performance of a standard vapor compression refrigerator ranges between 2 and 6, based on the working fluid [10]. The coefficient of performance of typical standing-wave thermo-acoustic system is between 1 and 1.2 [11,12]. Development of efficient traveling-wave thermo-acoustic refrigerators is helping to make the technology more competitive and widen its range to many industrial applications.

The development of highly efficient sustainable refrigerators has never been more crucial as today when we are witnessing energy source depletion and global concerns with regards to the degradation of the environment. There is no review on the development of highly efficient thermo-acoustic refrigerators with an emphasis on the geometrical configuration of the system possibly due to the developmental stage of the devices as well as the relatively smaller community of researchers actively involved in this field. The "infancy" of the technology, the lack of comprehensive description of current advances in the development of highly efficient thermo-acoustic systems and the cost required in order to venture into this area should not discourage future researchers. There is a need to explore alternative solutions for a sustainable future. Therefore, this paper presents an overview of recent studies conducted on highly efficient thermo-acoustic refrigeration systems. This study focus mainly on the geometrical configuration of the travelling-wave thermo-acoustic systems and their corresponding performance. Most of the previous work related to the analysis and optimization of thermo-acoustic devices suggest that there is a strong link between the devices geometry and their overall performance. In the midst of a multitude of geometrical configuration and a diversity of approach used to develop travelling-wave devices, it is necessary to make an inventory of current models, highlight interesting features that have proven to be beneficial to the devices and point out insightful details that could potentially contribute to the development of more efficient devices. Hence, a discussion on diverse findings have been undertaken in this paper. An overview of diverse travelling-wave devices geometrical configuration and performance have been reported in tabulated format. This will assist future researchers to quickly spot areas where efforts could be invested with respect to the development of highly efficient thermo-acoustic refrigerators.

## General review

### *Single/multi-stage thermo-acoustic systems*

A heat-driven thermo-acoustic cooler was designed by Wheatley et al. [14] in 1989. In spite of the fact that the cooler was simple to build and had no moving parts, the total efficiency of the device was poor (in the range of 5–10%) with a relatively smaller cooling temperature span. The direction of propagation in most standing-wave component is opposite to the temperature gradient in the thermo-acoustic engine's stack. This explains the substantial decrease of efficiency of thermo-acoustic engine because the standing-wave component consumes acoustic energy [15]. Although the efficiency of the engine was enhanced by Hofler [16] in 1999, by adjusting the contribution of the travelling-wave component in heat-driven thermo-acoustic cooler, the regenerators of that device was still working in standing-wave mode. The relatively low efficiency was attributed to the intrinsically irreversible thermodynamic cycle of the thermo-acoustic conversion in standing-wave mode. A loop tube with two regenerators was proposed by Ueda et al. [17] in 2004. Their study has pointed out that the possibility to achieve reversibility in thermo-acoustic engine and thermo-acoustic refrigerator.

The concept of a looped travelling-wave thermo-acoustic refrigerator containing one engine stage and one refrigerator stage in a closed loop was also investigated by Yazaki et al. [18]. The low efficiency of their devices was ascribed to the use of a stack (with its higher hydraulic radius) instead of a regenerator, the viscous dissipation within the stack and the difficulty to achieve a near travelling acoustic field with the layout arrangement of the engine and refrigerator considered. An attempt to address the latter issue experimentally was undertaken by Hotta et al. [19]. Interestingly, the lowest cooling temperature was achieved when phase angle between the velocity and the velocity was far away from 0°. Jin et al. [20] studied a looped travelling-wave thermo-acoustic refrigerator with one thermo-acoustic engine stage and one thermo-acoustic refrigerator stage. These two components were connected by two resonators with lengths of respectively $3/4\,\lambda$ and $1/4\lambda$ ($\lambda$ is the wavelength of the sound-wave that propagate within the looped configuration) as shown in Fig. 2. The refrigerator stage consist of a regenerator (REG) positioned in between a cold heat exchanger (CHX) and an ambient heat exchanger (AHX) while in the engine stage, the CHX is replaced with a hot heat exchanger (HHX). The thermal buffer tubes (TBT), the resonators and the secondary heat exchangers interconnects the two stages. The numerical simulation conducted with DeltaEC (Design Environment for Low-amplitude Thermo-Acoustic Energy Conversion) indicates a refrigeration temperature of $-3$ °C, an overall performance above approximatively 40% and the Carnot coefficient of performance of 13% with an input heat of 210–250 °C. This multi-stage travelling-wave thermo-acoustic configuration, inspired by De Blok et al. [21,22], was able to achieve higher efficiency and could be driven at low heating temperature by enlarging the thermo-acoustic core locally and by rearranging the thermo-acoustic core in the loop.

The recent interest in multi-stage travelling-wave thermo-acoustic

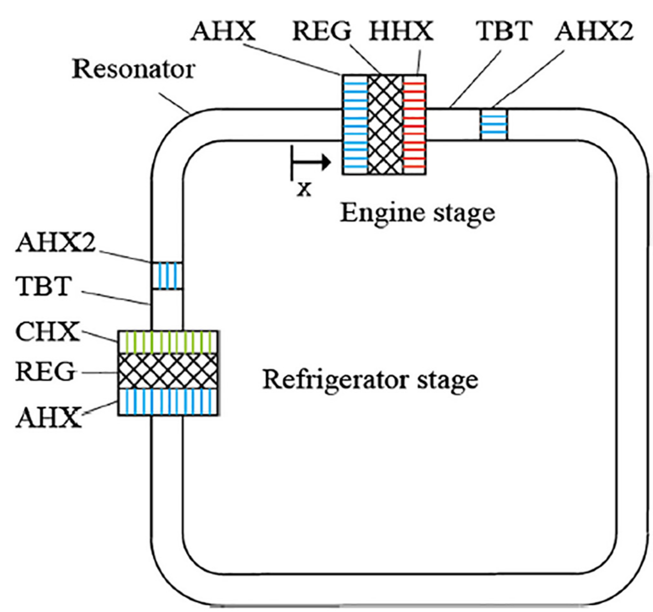


**Fig. 2.** Schematic diagram of a two-stage travelling-wave thermo-acoustic refrigerator (adapted from Ref. [20]).

devices is due to the relatively lower onset temperature and the reduced acoustic power losses. The development of thermo-acoustic engine driven by a low onset temperature and able to achieve a high efficiency is essential for any practical application. There is evidence of several experimental prototypes that have used waste heat [21–23], making this concept suitable for heat recovery applications. The coupling of multi-stage thermo-acoustic heat engine with refrigerator has been the focus of many studies [21,24]. Multiple regenerator units connected in series are beneficial if the acoustic conditions (high and real impedance) is maintained. In travelling-wave arrangement, the preferred acoustic conditions is closely related to the length and diameter of the mutual tube sections and the size of the regenerator cross-section relative to the tube diameter [25]. It appears that if the mutual distance in between the regenerator units is ¼ λ, the reflections due to the impedance anomalies compensate each other resulting in "self-matching" of the four stage engine analyzed by De Blok [25]. Interestingly, replacing one-stage engine unit, in De Blok four stage engine, with one-stage refrigerator units results in more loads and leads to higher onset temperature in the three-stage engine coupling system [24]. The engine-refrigerator coupling has been analyzed in depth by Zhang et al. [24]. An investigation into the fundamental theory and operation mechanism of multi-stage thermo-acoustic systems was conducted. A small scale thermo-acoustic refrigerator driven by a three stage travelling-wave thermo-acoustic engine (Fig. 3) was designed using the DeltaEC code. Resonators (ducts) with smaller cross-sectional area were used to connect the four thermo-acoustic units. The influence of the onset temperature on the performance of the thermo-acoustic system reveals that an increase of the heating temperature from 165 °C to 195 °C result in a decrease of the corresponding refrigeration temperature from 20 °C to 5 °C.

Travelling-wave thermo-acoustic engine have a potential to amplify acoustic power when a travelling-wave passes through the channel of regenerator subjected to an axial temperature gradient. The ratio of the high temperature end to the cold temperature end of the regenerator determines the gain of the engine [26]. Some previous studies [27,28] have used the efficiency of the regenerator and the dissipation in the duct as indicators of the performance of travelling-wave thermo-acoustic engine. These indicators depends on the geometrical configuration of the regenerator in a refrigerator namely the position, the length, and the flow channel radius. To maximize the coefficient of performance for the entire refrigerator, there is a need to optimize values of both efficiency (maximum) and the dissipation in the duct

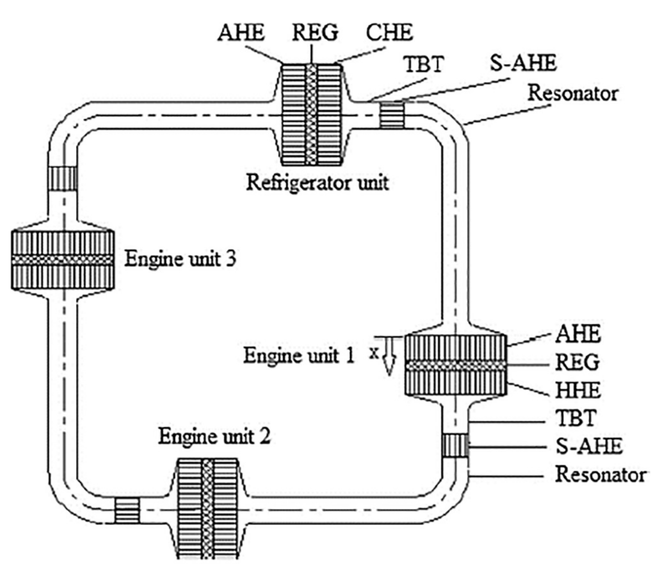


**Fig. 3.** Schematic diagram of a three-stage thermo-acoustic engine driven refrigerator (Adapted from Ref. [24]).

(minimum). The looped tube length proposed by Yazaki et al. [9] reduces the dissipation in the duct because of the traveling-wave it produces. High efficiency and low dissipation coexist if higher acoustic impedance could be achieved locally at the regenerator's location within the thermo-acoustic device with looped tube. The enlargement of the regenerator cross-sectional area relatively to the cross-sectional area of the duct meets the requirement for high efficiency and low dissipation in the duct [29,30]. Senga and Hasegawa [26] have designed and built a prototype of a loop-type cascade travelling-wave thermo-acoustic engine with four regenerators. Their study reveal the benefit of the enlargement of the cross-sectional area of the regenerator section and the duct diameter with regards to the acoustic impedance at the regenerator position, the traveling field in ducts and the amplification of the acoustic power. This study pointed out the difficulty to reach acoustic power amplification corresponding to the number of stage (as suggested in Ref. [31]) because of the acoustic load inserted in the looped tube.

In a four-stage thermo-acoustic engine, the stage number (or the number of units) has an impact on the onset temperature and the efficiency of regenerator. The study conducted by Zhang and Chang [30] suggests that when the temperature difference across the regenerator is over 80 K, in the four-stage travelling-wave thermo-acoustic engine considered in their study, the number of stage is not directly proportional to the acoustic power generated and the efficiency of regenerator. It appears that the higher the number of stage is, the lower acoustic power generated and the efficiency of heat engine will be and vice versa. Larger number of stage results in lower onset temperature difference as discussed in previous section [21,22]. It is therefore necessary to select the number of stage carefully in order to reach a compromise between the minimum working temperature required and the system performance. Biwa et al. [32] have investigated experimentally the extent to which the critical temperature ratio (ratio of the high and cold temperature end of the regenerator) can be reduced in order to start a thermo-acoustic engine. They have considered a thermo-acoustic Stirling engine consisting of a looped tube and a branch resonator. Although many researchers [9,17,33–37] have reported a critical temperature ratio of 1.6, Biwa et al. [32] study has demonstrated that the lowest critical temperature ratio attainable in a thermo-acoustic engine doesn't have to be fixed at this value. A decrease of the critical temperature ratio from 1.76 to 1.19 is reported using five differentially heated regenerators.

In order to address the issue related to the lower performance exhibited by a three-stage thermo-acoustic engine driven refrigerator, Luo et al. [38] propose the use of two thermo-acoustic engines (TAE) and one thermo-acoustic refrigerator (TAR) in a closed-loop configuration (Fig. 4). This system consists of a main ambient heat exchanger (MAHX), a regenerator (REG), a high-temperature exchanger (HHX) in TAE or a cold heat exchanger (CHX) in TAR, thermal buffer tube (TBT), and a secondary ambient heat exchanger (SAHX). This study pointed out that the middle engine, in a three-stage thermo-acoustic engine, has a tendency to be in pressure trough and volumetric speed peak, resulting in a high acoustic losses [28]. Hence, the absence of this extra-phase shifter (resonator tube portion between engines) in the system makes the locations of each thermo-acoustic core critical in order to achieve self-matching between thermo-acoustic engines and refrigerator. Although an overall exergy efficiency of 15.5% is reported, this study suggest the possibility to improve the efficiency of this system by setting different TAE structure through geometrical optimization.

The thermal efficiency of travelling-wave thermo-acoustic engine with looped configuration is significantly affected by the thermal loss carried by the streaming known as Gedeon streaming. Gedeon streaming generally appears in an oscillating flow when there is loop [39]. Considered as a time average mass flow, Gedeon streaming can carry heat from the hot end of the regenerator and deliver it to its cold end (or to the thermal buffer tube). With respect to thermo-acoustic engines, part of the heat absorbed from the thermal source, will be

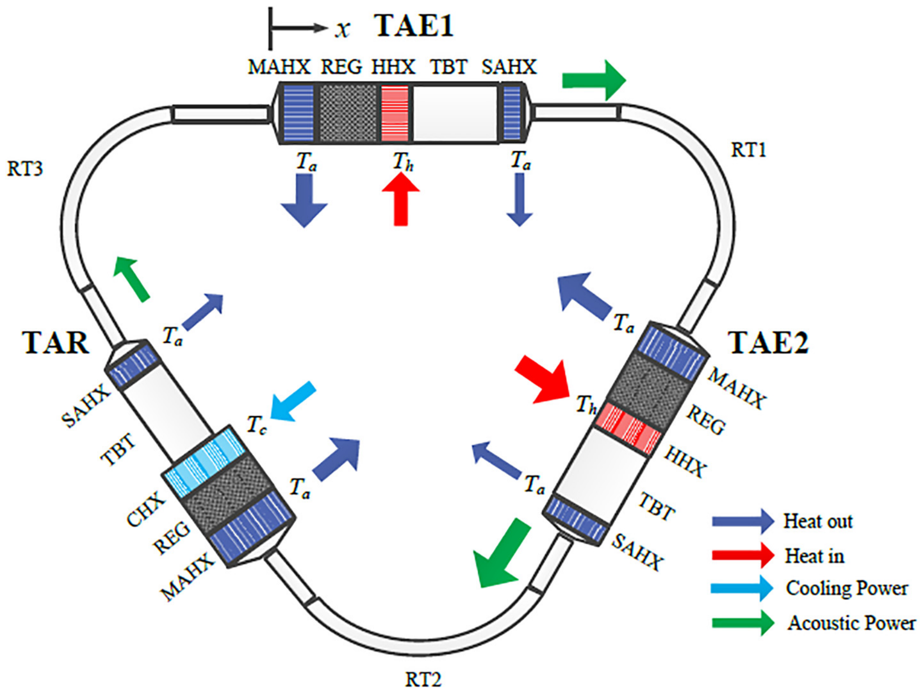


**Fig. 4.** Schematic diagram of a two-stage thermo-acoustic engine driven refrigerator (Adapted from Ref. [38]).

carried and delivered to the cold end and ultimately the surrounding, by the Gedeon streaming, without participating in the thermo-acoustic thermal conversion process [40]. This heat, carried by Gedeon streaming, is considered as a thermal loss in many previous studies [43–47]. When it comes to thermo-acoustic refrigerators, part of the refrigeration capacity is mitigated through the heat delivered by Gedeon streaming to the cold end, resulting in a loss of the refrigeration capacity [46]. These two thermal losses, caused by Gedeon streaming, have been identified as the main cause of the decrease of thermal efficiency in thermo-acoustic engines and thermo-acoustic refrigerators. Tang et al. [40] have investigated the mechanism behind the effect of Gedeon streaming on the thermal efficiency of the four stage travelling-wave thermo-acoustic engines numerically. Their results reveal the potentiality of a four-stage travelling-wave thermo-acoustic engine to achieve a promising thermal efficiency of 12.6%, corresponding to a Carnot efficiency of 35.7% when the thermal source temperature is 180 °C. However, a dramatic decrease of the thermal efficiency because of the occurrence of Gedeon streaming implies that the suppression of this streaming is indispensable. Hydrodynamically asymmetric component (such as jet pump and check valve) and elastic diaphragm are some of the methods used to suppress Gedeon streaming [44]. The former can suppress DC flow completely only under certain conditions while the latter has been applied to thermo-acoustic refrigerators successfully [45]. An elastic membrane has been proposed in some studies, in order to suppress (or to eliminate) the Gedeon streaming [42,44,47,48] and to lead to a significant gain in pressure ratio and thermal efficiency of thermo-acoustic engine.

*Hybrid thermo-acoustic systems*

New thermo-acoustic engine configuration has the potential to achieve higher efficiency. Travelling-wave thermo-acoustic resonators are superior to standing-wave thermo-acoustic resonators because of their lower acoustic loss. A hybrid configuration thermo-acoustic engine made of two stages was proposed by De Blok [23]. Each stage consist of a hot heat exchanger (HHX), a regenerator (REG) and an ambient heat exchanger (AHX). In addition, the system comprises a feedback pipe, a bypass pipe, an inertance tube and a compliance (Fig. 5). A looped-tube with a bypass pipe using air as the working gas can achieve an onset temperature difference as low as 65 °C [23]. Comprehensive numerical simulations were conducted by Al-Kayiem and Yu [49] using DeltaEC software. An engine performance of 46.5% of the Carnot efficiency and a cooler performance of 39.6% of Carnot coefficient of performance are reported. This study reveals the dependence between the regenerator length in the engine unit and the engine efficiency. A longer length results in a smaller temperature gradient, hence a lower power production. However, a shorter length leads to a higher conductive heat loss through the regenerator. Hence, a compromise is necessary. This study pointed out the sensitivity of the dimensions of the bypass and inertance tube with respect to the achievement of the right phase and impedance within the engine unit, the cooler unit and the feedback pipe. Similarly, the study conducted by Hu et al. [50] suggest that the inertance tube has usually a relatively smaller cross-sectional area and a longer length, resulting in a significant phase shifting. This hybrid configuration thermo-acoustic engine operates on the same principle as other existing travelling-wave thermo-acoustic engines apart from the design of the acoustic resonator. To improve the power density and thermal efficiency, Al-Kayiem and Yu [51] suggest a substantial increase of the regenerator length and the mean pressure.

In order to verify the effect of the acoustic load on the hybrid geometry with travelling-wave feedback, an acoustic load has been incorporated into the system by Al-Kayiem [52]. This new hybrid configuration, shown in Fig. 6, consists of two engines and two coolers. Each engine comprises an ambient heat exchanger (AHX), a regenerator (REG) and hot heat exchanger (HHX) while each coolers comprises an ambient heat exchanger (AHX), a regenerator (REG) and cold heat exchanger (CHX). In addition, there are two by-pass pipes, two inertances, two compliances, two thermal buffer tubes (TBTs), and two feedback pipes (FBPs). Through numerical analysis, an improvement of the efficiency from 6.8% (for system without acoustic load) to 20.3% (for the system with acoustic load) is reported. Hence, a hybrid two-stage engine with a by-pass configuration driving two coolers reduces significantly acoustic losses.

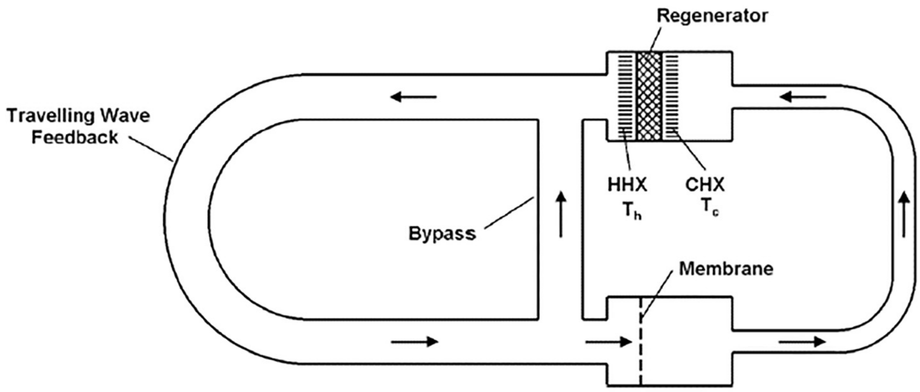


**Fig. 5.** Hybrid geometry with traveling-wave feedback (Adapted from Ref. [45]).

*Double loop thermo-acoustic systems*

The development of thermo-acoustic devices capable of achieving both high efficiency and low temperature oscillation is essential for practical application. The magnitude of the heat from industrial waste ranges from 400 K and 600 K. However, the magnitude of the critical onset temperature of thermo-acoustic engine is generally in the range of 600–1000 K [41]. The insertion of five regenerators in a loop tube combined with a branched tube, as described in the previous section could results in a drop of the critical onset temperature ratio of approximatively 1.19 [32]. In order for the thermo-acoustic engine to work at its highest thermal efficiency, a regenerator is located in a position corresponding to the peak of the real part of the acoustic impedance. This positioning is crucial in a multi-stage thermo-acoustic engine with multiple regenerators. A double-loop-type thermo-acoustic refrigerator driven by a multi-stage thermo-acoustic engine (Fig. 7) that enhance a low temperature oscillation and achieve higher efficiency was proposed by Hasegawa et al. [53]. Each units of the prime mover consist of an ambient heat exchanger, a hot heat exchanger and a thermally insulated regenerator. An oscillation at $\Delta T = 110.8$ K corresponding to a typical temperature of industrial waste heat and a Carnot coefficient of performance of 21% are reported. This numerical study demonstrates the potential of this multi-stage type to generate a low temperature oscillation while achieving high efficiency. An experimental investigation on a double-loop-type traveling-wave thermo-acoustic refrigerator driven by a multi-stage traveling-wave engine was conducted by Sharify and Hasegawa [54]. A minimum refrigeration temperature of −107.4 °C (corresponding to a hot temperature of 270 °C) and the maximum coefficient of performance of 0.029 (at −50 °C) was achieved. This study demonstrates that the positioning of multiple regenerators closer to what is described as “sweet spot” of the prime mover loop can potentially reduce the onset temperature of thermo-acoustic oscillations and improve its cooling performance.

*Single/double stage refrigerators*

Travelling-wave thermo-acoustic refrigerator are potentially high efficient as compare to standing-wave thermo-acoustic refrigerator [41,45,55,56]. This refrigerator generally consists of a looped tube couple to an acoustic driver and a regenerator installed in the looped

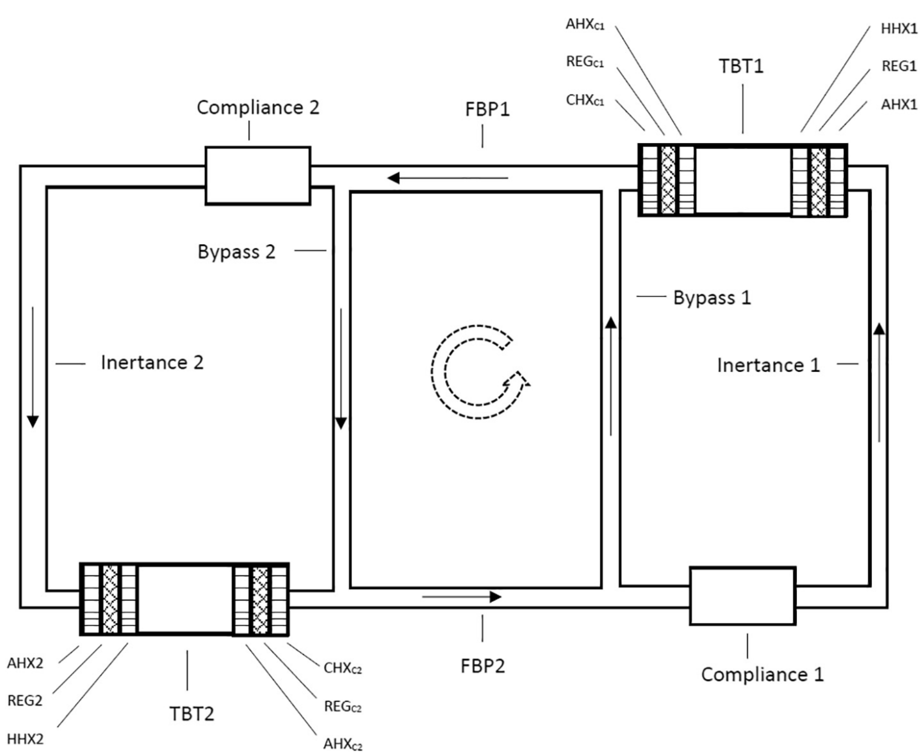


**Fig. 6.** Schematic diagram of a hybrid two-stage engine with a by-pass configuration driving two coolers (Adapted from Ref. [54]).

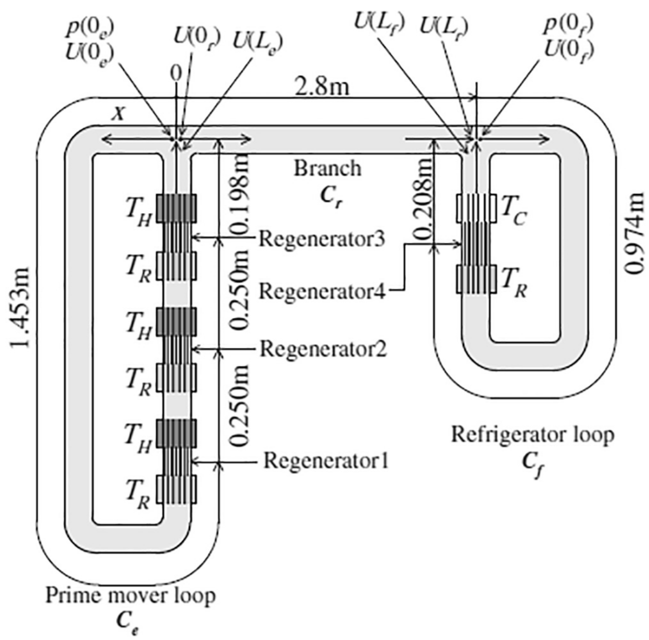


**Fig. 7.** Double-loop-type thermo-acoustic refrigerator driven by a multi-stage thermo-acoustic engine (Adapted from Ref. [53]).

tube (Fig. 8a). The numerical study conducted by Ueda et al. [27] have demonstrated the dependence between the parameters characterizing the regenerator (namely the regenerator's location, length and porosity) and the coefficient of performance of the refrigerator. A coefficient of performance exceeding 60% of the Carnot coefficient of performance is reported when the three factors are optimized simultaneously. Yu and Jaworski [13] have investigated travelling-wave thermo-acoustic engines. This work provide clarity on the relationship between the flow resistance, the acoustic impedance and the geometrical configuration of regenerators with regards to the power produced. While a higher impedance for travelling-wave thermo-acoustic engine leads to a decrease of the acoustic power output of the engine, a low impedance results in the degradation of its the thermodynamic efficiency [13]. The flow resistance of the regenerator plays a crucial role in the determination of its impedance. When the regenerators parameters (porosity, channel dimensions, materials etc.) are similar, the regenerator with low resistance will achieve a better performance. In practice, the reduction of the regenerator's resistance is achieved by making the regenerator shorter and increasing its cross-sectional area. The geometrical configuration of the torus tube of travelling-wave thermo-acoustic refrigerators is the reason behind their relatively low acoustic impedance [57]. The numerical study conducted by Yahya et al. [58] demonstrates that the addition of a second stage (Fig. 8b) can improve the acoustic impedance and contribute to the achievement of the required acoustic impedance phase, resulting in a relatively higher cooling power, better coefficient of performance and good overall efficiency of the system through the inertance and the compliance (Fig. 8b). An increase of the overall efficiency of 125%, with the temperature difference between the cold and ambient heat exchanger of 25 K corresponding to a cooling power of 447 W, is reported. In order to enable the electrical to acoustic power conversion, linear motors or loudspeakers can be used as acoustic drivers in thermo-acoustic devices. A travelling-wave thermo-acoustic refrigerator consisting of a linear motor, a branched tube and looped tube having a regenerator was designed and constructed by Bassem et al. [59]. A minimum temperature of 232 K and a Carnot coefficient of performance of 20% at 265 K corresponding to optimum values of the regenerator radius and position are reported.

*Looped tube travelling-wave thermo-acoustic refrigerator driven by standing-wave engine*

As part of the European project called THATEA (Thermoacoustic Technology for Energy Applications), a travelling-wave thermo-acoustic refrigerator driven by a standing-wave thermo-acoustic engine capable of achieving 40% of the maximum theoretical Carnot coefficient of performance was investigated by Pierens et al. [60]. The experimental set-up consisting of a Brayton thermo-acoustic engine (as a replacement of loudspeakers or linear motors mention in the previous section) driving a travelling-wave refrigerator is shown in Fig. 9. A coefficient of performance relative to Carnot of 30% corresponding to a cooling power of 210 W at 233 K is reported. The code CRISTA [61] was used to perform a numerical investigation of the design. This study reveals that placing an insert in the inertance (or inductance) is beneficial to the increase of the cooling power and counterproductive to the energy conversion efficiency. As a way of improving this refrigerator performance, a new buffer shape combined with moving membrane together with inserts in the inductance were explored experimentally [62]. Although this new study has confirmed that inserts in the inductance achieve better coupling between the thermo-acoustic engine and travelling-wave thermo-acoustic refrigerator and more cooling power, no significant change of the refrigerator performance has been observed from this new investigation. Interestingly, Luo et al. [63] have designed and studied a travelling-wave thermo-acoustic refrigerator coupled to a standing-wave thermo-acoustic engine. This system could operates at room temperature. This study reported a cooling capacity of 30 W at −20 °C and 100 W at 0 °C with the production of frost by the refrigerator. At the most efficient point (through the optimization of the resonator length), a cooling power of 80 W corresponding to −20 °C was achieved.

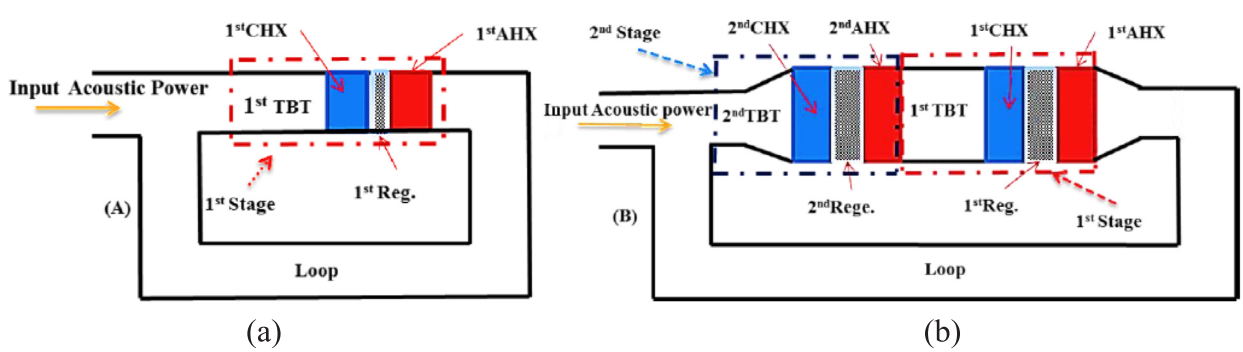


**Fig. 8.** (a) One stage travelling-wave thermo-acoustic refrigerator with constant cross-section (b) Two stage travelling-wave thermo-acoustic refrigerator with two acoustic drivers (1S123M & 1S123DX) (Adapted from Ref. [58]).

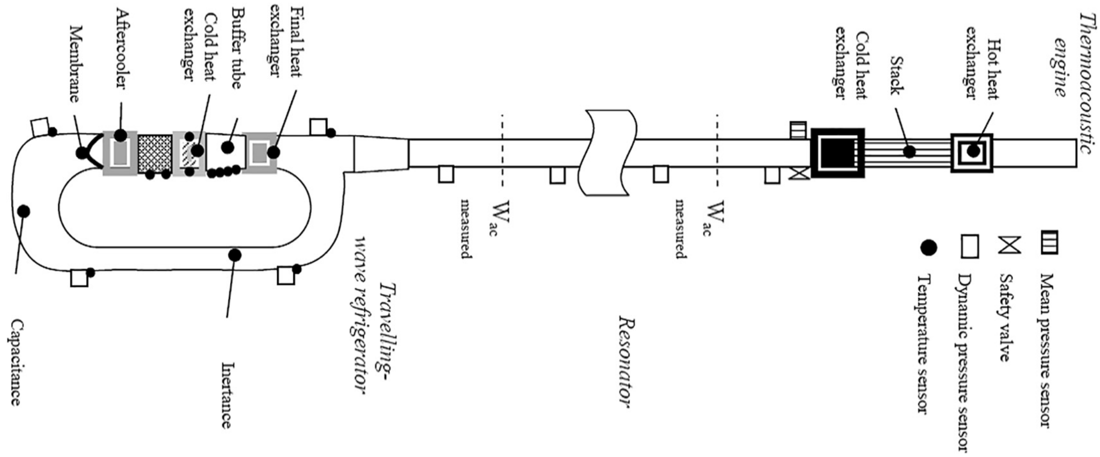


**Fig. 9.** Brayton thermo-acoustic engine driving a travelling-wave refrigerator (Adapted from Ref. [62]).

*Thermo-acoustic Stirling configuration*

The development of traveling-wave thermo-acoustic engine capable of converting heat into acoustic power with an efficiency of 41% of the Carnot efficiency, reported by Backhaus et al. in 1999 [42,43] was a major breakthrough in the development of travelling-wave thermo-acoustic engine. This is attributed to the positioning of the looped tube at the pressure antinode of a quarter-wavelength standing-wave resonator. A thermo-acoustic Stirling-engine consisting of ambient heat exchangers (AHX1 and AHX2), a regenerator (REG), a hot heat exchanger (HHX), a thermal buffer tube (TBT) and a feedback tube (L) was designed by Tijani and Spoelstra [43]. This torus-shaped section was attached to a quarter-wavelength acoustic resonator (Fig. 10). An acoustic power of 280 W corresponding to a thermal efficiency of 32% (or 49% of Carnot efficiency) are reported. The reason behind this higher efficiency with respect to Backhaus et al. [42,43] design, can be summarized as follows:

- Higher power density and lower thermo-viscous losses in the boundary layers have been achieved by increasing the pressure and frequency;
- Heat transfer between the medium gas and the ambient heat exchanger (and subsequently performance) has been improved through the use of smaller channels for the heat exchanger (AHX1);
- Lower viscous losses has been achieved by making the hydraulic radius of the regenerator five times smaller than the thermal penetration depth;
- Good heat transfer from the hot heat exchanger (HHX) to the medium gas is ensured through the generation of a maximal thermal power into the HHX block;
- Good thermal insulation between the hot heat exchanger (HHX) and the ambient heat exchanger (AHX2) by making the thermal buffer tube 10 times longer than the peak to peak displacement of the medium gas at high acoustic amplitude;
- Acoustic losses are minimizes by making use of a feedback tube with constant diameter, ensuring that internal surface of the tube are smooth and bends are made gentle;
- Higher performance is achieved by ensuring that the velocity lags the pressure by 30° at the ambient side of the regenerator and leads the pressure by 30° at the cold side of the regenerator [64];
- Gedeon streaming is suppressed by placing an elastic membrane just above the AHX1 [39,42];
- Jet-streaming is reduced in the thermal buffer zone by placing flow straighteners in the thermal buffer tube.

A thermo-acoustic-Stirling heat engine has been proposed as a driving source for a thermo-acoustic-Stirling refrigerator (Fig. 11) in the study conducted by Luo et al. [65]. The main structure parameters of

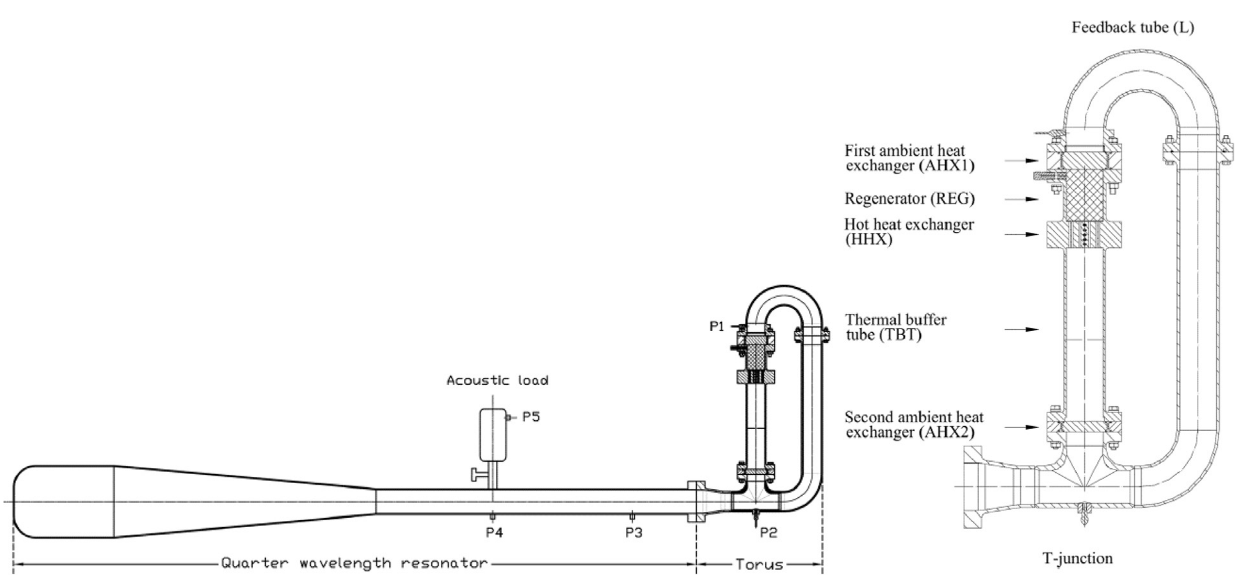


**Fig. 10.** Schematic of a thermo-acoustic Stirling-engine (Adapted from Ref. [43]).

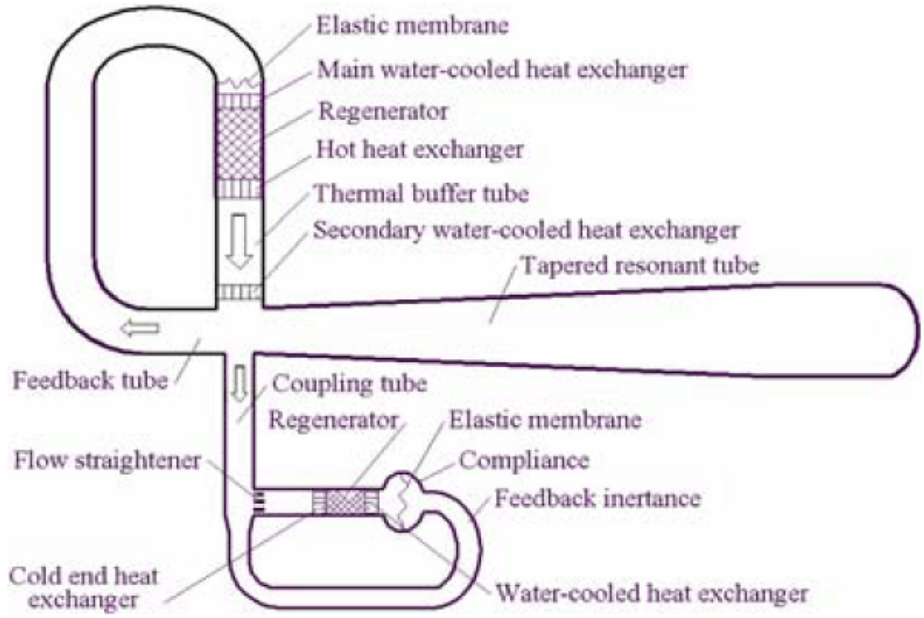


**Fig. 11.** Thermo-acoustic-Stirling refrigerator driven by thermo-acoustic-Stirling heat engine (Adapted from Ref. [65]).

the traveling-wave thermo-acoustic engine consists of a main ambient heat exchanger, a regenerator, a high temperature heat exchanger, a thermal buffer tube, a secondary ambient heat exchanger and an inertance tube. The traveling-wave thermo-acoustic refrigerator is made of a cold end heat exchanger, a regenerator, an ambient heat exchanger, a thermal buffer tube, a compliance cavity and an inertance tube. This experimental investigation revealed the occurrence of DC-flow in the two travelling-wave systems resulting a significant drop in performance of the two subsystems. The provision of two elastic membranes (Fig. 11) was meant to suppress the DC-flow. A no-load temperature of −65 °C, a cooling capacity of 270 W and 405 W corresponding respectively to −20 °C and 0 °C have been reported. Although similar investigation from the same author is reported in a different study [66] and closely related results are reported, this second study pointed out one important aspect required in order to achieve higher efficiency operations for both the thermo-acoustic Stirling heat engine and thermo-acoustic Stirling refrigerator. This study reveals that the phase angle between the pressure wave and velocity wave passing through the regenerator of the thermo-acoustic Stirling engine and the thermo-acoustic Stirling refrigerator must be kept under 40°. This could be achieved by optimizing the thermo-acoustic Stirling refrigerator dimensions or operating parameters based on the thermo-acoustic Stirling engine. The inertance tube of the thermo-acoustic Stirling refrigerator shown in Fig. 11 was substituted by an inertial mass in the study conducted by Yu et al. [55]. This inertial mass is made of a piece of flexible membrane sandwiched by two thin metal pieces and small bolts. This assembly suppress the Gedeon stream in the travelling-wave loop and make the elastic membrane placed nearby the ambient heat exchanger unnecessary. Maximum cooling powers of 340 W and 469 W corresponding to cold end temperature of −20 °C and 0 °C and total coefficient of performance of 0.16 and 0.216 respectively are reported.

**Summary on previous work on travelling-wave systems**

In line with the development of thermo-acoustic systems, this section provides an overview of some high efficient thermo-acoustic coolers developed recently. The energy required to drive the device, the minimum temperature (or cooling power) achieved and the geometrical configuration of the devices are highlighted in tabulated format (Table 1).

**Optimization scheme**

The insufficient cooling capacity of thermo-acoustic systems remain one of the main hindrance to their practical realization. This challenge is closely related to the heat-sound energy conversion in such systems. In some recent interesting studies, it has been suggested that this cooling capacity can be improved by setting a phase adjuster within the looped tube [67]. An improvement of the sound intensity as large as 30 times by inserting a phase adjuster is reported. The acoustic fields used in thermo-acoustic systems are closely related to the resonance frequency and temperature ratio at regenerators' ends. Although the reduction of the cross-section with the phase adjuster results in great dissipation of energy, resonance mode control through phase adjuster has demonstrated better cooling potential [68]. The experimental investigation conducted by Inoue et al. [68] reports a cooling point of 13.9 °C for a system without phase adjuster and about 4 °C with phase adjuster from about 20 °C ambient temperature, under similar condition. There is definitely room for improvement for the current thermo-acoustic systems. With the purpose of reaching higher performance from travelling-wave thermo-acoustic systems, there have been a number of optimization schemes. The coefficient of performance of these thermo-acoustic refrigeration systems has improved significantly in comparison to the standing-wave counterparts [69]. The reported studies relies extensively on parametric studies either numerically or/and experimentally. In general, the optimized parameters are associated with local minimum/maximum of the objective function(s), the achievement of the lowest temperature, the temperature difference across the regenerators, the lowest onset temperature, the improvement of the thermal-to-acoustic-to-cooling conversion and the performance (COP). Table 2 lists the outcomes of past researches, the parameters optimized and the methodology used in order to improve the performance of the thermo-acoustic systems.

The use of optimization is currently very limited in the designing of travelling-wave thermo-acoustic systems. The development of travelling-wave thermo-acoustic systems should benefit from the advancement made in the designing of standing-wave thermo-acoustic systems because of the similarities with regards to the refrigeration goal. During the recent years, they have been significant increase of studies aimed at addressing the limitation of parametric studies who could only produce locally optimal solutions (as opposed to global optimal solutions) and were unable to solve the compromise (trade-off) observed (e.g. distinct

**Table 1**
Geometrical description and performance of previous work on travelling-wave systems.

| Authors | Method | Heating temperature/power | Refrigeration t° achieved/cooling power | Overall performance /Carnot COP | System description | | |
|---|---|---|---|---|---|---|---|
| | | | | | Regenerator material | Resonator material | Working fluid |
| Jin et al. [20] | Numerical (DeltaEC) | 210–250 °C | −3°C | 0.4/13% | A looped travelling-wave thermo-acoustic refrigerator with one thermo-acoustic engine stage and one thermo-acoustic refrigerator stage | | |
| | | | | | stainless-steel gauze | PVC tubing | Helium |
| Zhang et al. [24] | Numerical (DeltaEC) | 165 °C<br>175 °C<br>185 °C<br>195 °C | 20 °C<br>15 °C<br>10 °C<br>5 °C | 25.9%<br>27.2%<br>28.5%<br>28.8% | A multi-stage travelling-wave thermo-acoustic engine driven refrigerator with four thermo-acoustic units evenly distributed within a looped tube resonator. | | |
| | | | | | – | – | Helium |
| Yazaki et al. [18] | Experimental | 230 W heating power380 W heating power | −27 °C<br>−11 °C | –<br>– | Acoustic cooler using Stirling cycles executed by a traveling-wave | | |
| | | | | | Honeycomb ceramics | Pyrex glass tube | 86% helium, 14% argon |
| Inoue et al. [68] | Experimental | 300 W heating power | 4 °C with Phase adjuster and 5.6 °C with Expander Phase Adjuster | – | A looped tube like thermo-acoustic system including two energy converting components called prime mover and heat pump. | | |
| | | | | | Honeycomb ceramic | Stainless steel | Air |
| Sakamoto et al. [76] | Experimental | 360 W heater power 600 °C | Minimum temperature 18.4 °C | – | A loop-tube-type thermo-acoustic cooling system | | |
| | | | | | Honeycomb ceramic | stainless steel | Air |
| | | | | | Honeycomb ceramic | stainless steel | Air |
| Kang et al. [47] | Experimental | 300 W heating power | −30 °C and cooling power of 40 W at 0 °C | Overall performance of 13% at 0 °C | Heat-driven thermo-acoustic cooler system | | |
| | | | | | Stainless steel screens | – | Helium |
| Hasegawa et al. [53] | Numerical | Temperature difference ΔT = 110.8 K | – | 21%. | A double-loop-type thermo-acoustic refrigerator driven by a multi-stage thermo-acoustic engine | | |
| | | | | | – | – | Helium |
| Bassem et al. [59] | Experimental | Linear motor | 232 K | 20% at 265 K | A looped tube traveling-wave thermo-acoustic refrigerator | | |
| | | | | | Stainless steel meshes | Stainless steel | |
| Luo et al. [65] | Experimental | 2.2 kW heating power | −65 °C Cooling capacity of 270 W at −20 °C 405 W at 0 °C | – | Thermo-acoustic-Stirling refrigerator driven by a thermo-acoustic-Stirling heat engine | | |
| | | | | | Stainless steel screens | stainless steel | Helium |
| Luo et al. [66] | Experimental | 2.2 kW heating input | −64.4 °C Cooling power of 250 W at −22.1 °C | – | Thermo-acoustic-Stirling refrigerator driven by a thermo-acoustic-Stirling heat engine | | |
| | | | | | Stainless steel screens | Stainless steel | Helium |
| Yu and Al-Kayiem [28] | Numerical | – | 0 °C | 15–17% | A three-stage traveling-wave thermo-acoustic engine driving a single-stage traveling-wave thermo-acoustic cooler | | |
| | | | | | – | – | Helium |
| Al-Kayiem and Yu [49] | Numerical | 1480 W heating power | −19 °C 639 W of heat at −19 °C | Engine: 46.5% Refrigerator: 39.6% | A hybrid configuration travelling-wave thermo-acoustic engine driven cooler | | |
| | | | | | Stainless steel screens | – | Nitrogen |
| Kang et al. [77] | Numerical/ experimental | 2500 W heating power | Cooling power of 282 W at 0 °C | $\eta_{(SWTAE)}$: 26.2%,$\eta_{(TWTAE)}$: 34.3% and $COP_{(TWTAC)}$:2.67 | It consists of a standing-wave thermo-acoustic engine (SWTAE), a travelling-wave thermo-acoustic engine (TWTAE) and a travelling-wave thermo-acoustic cooler (TWTAC) in series. | | |
| | | | | | Stainless steel screens | Stainless steel | Helium |
| Xu et al. [78] | Numerical | 850 K | 77 K cooling power of 7.75 W | 11.78% | A pulse tube cryocooler (PTC) driven by a three-stage traveling-wave thermo-acoustic heat engine | | |
| | | | | | Stainless steel screen | – | Helium |
| Sharify, and Hasegawa [54] | Experimental | 90 °C<br>270 °C | −42.3 °C<br>−107.4 °C | 0.029 at −50 °C | A double-loop-type traveling-wave thermo-acoustic refrigerator driven by a multi-stage traveling-wave Engine | | |
| | | | | | Stainless steel mesh | Stainless steel | Helium & argon |
| Pierens et al. [60] | *Experimental* | 7–2 kW heating power | Cooling power of 210 W | 30% | A travelling-wave thermo-acoustic refrigerator, driven by a Brayton thermo-acoustic engine | | |
| | | | | | Stainless steel screens | Stainless steel | Helium |
| Yahya et al. [58] | Numerical | – | Cooling power of 447 W corresponding to a COP of 3 | – | Two-stage, twin acoustic driver looped tube thermo-acoustic refrigerator | | |
| | | | | | Stainless steel screens | – | Helium |
| Ren et al. [79] | Experimental/ theoretical | 468 W acoustic power (experimental)<br>382 W (theoretical) | 135 K at no load | 38.7% | A traveling-wave thermo-acoustic cryocooler | | |
| | | | | | Stainless steel screens | Stainless tube | – |
| Pierens et al. [62] | Experimental | 7 kW heating power at 700 °C | 210 W cooling power at 233 K | 30% of Carnot COP | A travelling-wave thermo-acoustic refrigerator driven by a standing-wave thermo-acoustic engine | | |
| | | | | | Stainless steel screens | Stainless steel | Helium |

(*continued on next page*)

**Table 1** (*continued*)

| Authors | Method | Heating temperature/power | Refrigeration t° achieved/cooling power | Overall performance /Carnot COP | System description | | |
|---|---|---|---|---|---|---|---|
| | | | | | Regenerator material | Resonator material | Working fluid |
| Al-Kayiem and Yu [51] | Numerical | 260 °C heat input of 1100.7 W | Cooling power of 232.4 W at −19.1 °C | 27% | A travelling-wave thermo-acoustic engine with a bypass configuration used as a thermally driven thermo-acoustic refrigerator | | |
| | | | | | Stainless steel meshes | – | Air |
| Hotta et al. [19] | Experimental | 270 W heating power | Cooling of 18.2 °C to 0 °C | – | A loop-tube-type thermo-acoustic cooling system uses heat energy as a power source | | |
| | | | | | – | – | Air, argon, mixture of argon and Helium |
| Yu et al. [55] | Experimental | 1750 W to 2400 W heating power | Cooling powers of 340 W and 469 W at −20 °C and 0 °C respectively | Corresponds to a total COP of 0.16 and 0.216 | A traveling-wave thermo-acoustic refrigerators driven by a traveling-wave thermo-acoustic engine | | |
| | | | | | Stainless steel screens and copper screens | – | Helium |
| Ueda et al. [27] | Numerical | Use of acoustic driver | – | 60% | A traveling-wave thermo-acoustic refrigerator | | |
| | | | | | Stacked screens | – | Helium |
| Jaworski and Mao [80] | Experimental | 2.5 kW of heating power | −20 °C and Cooling load of 133 W | COP of 2.06 | A thermo-acoustic engine powered by burning biomass | | |
| | | | | | Stainless steel screens | Steel pipe | Air |
| Luo et al. [38] | Numerical (DeltaEC) | 22.2 kW heating power at 923 K | Cooling power of 1410 W at 110 K | 15.5% | One thermo-acoustic refrigerator driven by two stage engine | | |
| | | | | | Stainless steel gauze | PVC pipes | Helium |
| Al Kayiem [52] | Numerical (DeltaEC) | 2240 W heating input at 223 °C 3851 W heating power at 535 °C | 708 W of cooling power at −36 °C 1200.5 W cooling power at 188 °C | 40% of Carnot COP | Two-stage travelling-wave thermoacoustic engine with a by-pass configuration driving two coolers | | |
| | | | | | Stainless steel mesh screen | – | Nitrogen |

**Table 2**
Previous optimization work on travelling-wave thermo-acoustic systems.

| Authors | Optimization method | Optimization parameters | Outcomes |
|---|---|---|---|
| Jin et al. [20] | DELTAEC | Cooling temperature, heating temperature, average phase difference in the regenerator and average normalized acoustic impedance in the regenerator; | Improved Carnot coefficient of performance of the refrigerator stage and engine efficiency; |
| De Blok [21] | Experiment | Working fluid | Decreased onset temperature |
| Yazaki et al. [18] | Experiment | Regenerator position | Reduced temperature at the cold side of the regenerator |
| Ueda et al. [27] | Mathematical modelling (Rott equations) | Regenerator position, length and flow channel radius | Improved coefficient of performance |
| Hasegawa et al. [53] | Mathematical modelling (Rott equations) | Radii of regenerators channel, gas flow and regenerator lengths | Reduced viscous loss, improved efficiency of multi-stage thermo-acoustic engine |
| Bassem et al. [59] | Mathematical modelling (Rott equations) | Regenerator radius and position | Reduced cold temperature and improved Carnot coefficient of performance |
| Al-Kayiem and Yu [49] | DeltaEC | Inertance tube, bypass pipe and regenerators of engine and cooler | Increased power production, reduced conductive heat loss and improved engine efficiency |
| Zhang and Chang [30] | DeltaEC | Hydraulic radius of regenerator and ratio between thermal penetration depth and hydraulic radius (to be within 3–5) | Achieve balance between the thermal effect and viscous losses and Lower the onset temperature |
| Xu et al. [78] | DeltaEC | Inner diameter and length of all component and regenerator porosity of heat engine unit and pulse tube cryocooler | Improved Carnot COP |
| Ullah et al. [81] | Experimental | Center distance between the two regenerators (evaluated to be ≈ 52% of the total length of the looped tube) | Reduced onset temperature |
| Yahya et al. [58] | DeltaEC | Diameter and length of loop, inertance, thermal buffer tubes, heat exchangers and diameter/porosity of regenerators | Improved cooling load or COP |
| Ren et al. [79] | Mathematical equation (Rott theory) | Inertance tube length/diameter and volume of capacitive cavity | Optimized phase shifter and improved efficiency of refrigeration |
| Dhuchakallaya and Saechan [82] | Multivariable search method (DeltaEC) | Length and diameter of each section, thickness and porosity of heat exchangers and the hydraulic radius of the stack/regenerator | Improved efficiency |
| Yu and Jaworski [13] | Mathematical modelling (Linear acoustic theory) | Channel dimension in the regenerator and local impedance | Improved acoustic power output |
| Tourkov and Schaefer [83] | Experimental | Position of the regenerator | Improved heat-to-acoustic conversion efficiency |
| Al-Kayiem and Yu [51] | DeltaEC | Lengths of the regenerator, bypass pipe, phase shifting pipe, compliance volume and thermal buffer tube | Improved cooling performance |
| Hotta et al. [19] | Experiment | Heat pump position | Increased cooling temperature |
| Jaworski and Mao [80] | Experimental | Cross-section area of the regenerator, feedback/inertance tube, and hydraulic radius of the regenerator | Increased cooling load |

maximum cooling and maximum coefficient of performance in standing-wave thermo-acoustic refrigerator [5]) in many studies. The use of evolutionary algorithm, Nelder mead simplex method, response surface methodology and multi-objective optimization approach in order to produce global minimum/maximum have been implemented successfully in the designing of standing-wave thermo-acoustic systems recently [70–74]. This relatively new advanced optimization techniques (in the field of thermo-acoustic) offers the possibility to optimize many parameters simultaneously as desired, with objective functions that are possibly conflicting in their combined effect. That is the case in travelling-wave thermo-acoustic refrigerator with regards to:

- The compromise between high efficiency and high power output based on specific applications [58];
- The trade-off between the regenerators efficiency, the acoustic dissipation and the duct of a multi-stage system with respect to the sought improvement of performance of the entire refrigerator [26] and
- The overlooked interdependence between the geometrical parameters (length, diameter, position and porosity of components) describing travelling-wave systems that are normally treated independently in parametric approaches, just to name few.

Due to the proven capability of these new approaches in the designing and optimization of simple thermo-acoustic systems, it is expected the use of these advanced optimization techniques will continuously improve the performance of travelling-wave systems. In addition, a recent study has successfully implemented Artificial Neural Network as a new approach for the prediction of the performance of simple standing-wave thermo-acoustic refrigerators [75]. Like standing-wave devices, travelling-wave systems have significant amount of nonlinear parameters affecting their performance. These nonlinear mapping between the input and outputs parameters could be modelled using ANN in order to predict the performance of travelling-wave systems.

## Conclusion

This paper has reviewed recent researches related to the development of more efficient travelling-wave thermo-acoustic refrigerators. It is highlighting a number of geometrical configurations of travelling-wave thermo-acoustic systems, issues encountered in the developmental phase of these systems, recommendations made for further improvement and performance achieved. The numerical, experimental and theoretical studies conducted on travelling-wave systems can be summarized as follows:

- With respect to single/multi-stage thermo-acoustic systems: Multi-stage systems are able to achieve higher efficiency and could be driven at low heating temperature by enlarging the thermo-acoustic core locally and by rearranging the thermo-acoustic core in the loop. It appears that adopting a mutual distance in between the regenerator units of ¼ λ address the issues related to the matching of thermo-acoustic engines and refrigerators in a multi-stage arrangement. The influence of the onset temperature on the performance of the thermo-acoustic system reveals that an increase of the heat input result in a decrease of the corresponding refrigeration temperature. The enlargement of the cross-sectional area of the regenerator section relatively to the duct, in a looped tube travelling-wave arrangement, meets the requirement for high efficiency and low dissipation in the duct. It seems that the number of stage is inversely proportional to the magnitude of the acoustic power and the efficiency of heat engine and vice versa. However, the selection of the number of stage has to be done carefully in order to ensure that there is a compromise between the working temperature and the system performance. In order to suppress (or to eliminate) Gedeon streaming that contribute significantly to the thermal loss in a looped configuration, the use of elastic membrane have contributed favorably to the thermal efficiency of thermo-acoustic engine.

- With respect to hybrid thermo-acoustic systems: Previous researches have pointed out the sensitivity of the dimensions of the bypass and inertance tube in line with the achievement of the right phase and impedance within the engine unit, the cooler unit and the feedback pipe. In addition, it appears that in order to improve the power density and thermal efficiency, the length of the regenerator and the mean pressure within the systems have to be substantially large. Interestingly, it appears that a hybrid two-stage engine with a bypass configuration driving two coolers reduces significantly acoustic losses, resulting in an improvement of the efficiency.
- With respect to double loop thermo-acoustic systems: A double-loop-type thermo-acoustic refrigerator driven by a multi-stage thermo-acoustic engine is suitable in order to achieve a low temperature oscillation while enhancing the efficiency. The positioning of multiple regenerators closer to the “sweet spot” of the prime mover loop can potentially reduce the onset temperature of thermo-acoustic oscillations and improve its cooling performance.
- With respect to single/double stage refrigerators: There is a dependence between the parameters characterizing the regenerator (namely the regenerator’s location, length and porosity) and the coefficient of performance of the refrigerator. When the regenerators parameters (porosity, channel dimensions, materials etc.) are similar, the regenerator with low resistance exhibit a better performance. In practice, the reduction of the regenerator’s resistance is achieved by making the regenerator shorter and increasing its cross-sectional area. The addition of a second refrigerator stage can improve the acoustic impedance and contribute to the achievement of the required acoustic impedance phase, resulting in a higher cooling power, coefficient of performance and overall efficiency of the system through the inertance and the compliance.
- With respect to looped tube travelling-wave thermo-acoustic refrigerator driven by standing-wave engine: Previous studies reveal that placing an insert in the inertance (or inductance) is beneficial to the increase of the cooling power and counterproductive to the energy conversion efficiency. In addition, inserts in the inductance achieve better coupling between the thermo-acoustic engine and travelling-wave thermo-acoustic refrigerator and more cooling power.
- With respect to thermo-acoustic stirling configuration: There are a number of reasons behind higher efficiency of this configuration. In summary, the higher efficiency is attributed to the increase of the pressure and frequency, the use of heat exchanger with smaller porosity, the selection of regenerator having an hydraulic radius five times smaller than the thermal penetration depth, the use of thermal buffer tube 10 times longer than the peak to peak displacement of the medium gas at high acoustic amplitude, the use of feedback tube with constant diameter, the appropriate phasing between the pressure and velocity each sides of the regenerator and the use of elastic membrane and flow straighteners. It is recommended that the phase angle between the pressure wave and velocity wave passing through the regenerator of the thermo-acoustic Stirling engine and the thermo-acoustic Stirling refrigerator (in a thermo-acoustic-stirling refrigerator driven by thermo-acoustic-stirling heat engine) must be kept under 40°. This could be achieved by optimizing the thermo-acoustic stirling refrigerator dimensions or operating parameters based on the thermo-acoustic Stirling engine.

Although, they have been a fair amount of numerical/experimental optimization attempts that are undoubtedly providing guidance on parameters affecting the performance of travelling-wave thermo-acoustic systems, greatest opportunity for future work in the development of more efficient thermo-acoustic travelling-wave systems point toward the use of advanced optimization techniques for further improvement and understanding of the devices. Studies taking into account interdependence between design parameters in thermo-acoustic systems and studies providing guidance and clarity on trade-off/compromise in presence of conflicting objectives with regards to the performance of thermo-acoustic systems in order to identify global optimal solutions (inherently more efficient, in comparison with parametric studies mostly conducted in previous researches) will contribute significantly to the understanding and improvement of these systems efficiency.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2018.12.004.

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