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MULTI-STAGE TRAVELING WAVE THERMOACOUSTICS IN PRACTICE

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Recent developments of multi-stage traveling wave feedback thermoacoustic systems haves demonstrated that compactness of thermoacoustic systems, defined as the ratio of net output power over internal system volume, can be reduced significantly as compared with the commonly used standing wave/torus geometry. This volume reduction, up to a factor of 5, together with the high conversion efficiency and the low onset temperatures of 45ºC will definitely accelerate the introduction of thermoacoustic energy conversion towards practical, full scale applications. In multi-stage traveling wave systems mutual interaction between the stages and acoustic matching is crucial. The design and simulation of multi-stage traveling wave system is therefore complicated. This holds also for the way how useful acoustic output power could be extracted from this kind of devices. In particular, in case of a heat powered heat pump an advanced matching strategy is required to cope with the different temperature gradients in the various stages. Unless the more complicated simulation and design, the practical implementation differs not substantial from previous designs and is still straight forward using heat exchangers, regenerators and tubing. This, and the large freedom of implementation and possibility of up-scaling in power levels of thermoacoustic devices, will be elucidated on the basis of a few past and current projects. Based on the multi-stage concept a pilot of 100 kW thermoacoustic Power (TAP) generator was build an tested, converting part of the flue gas at 160ºC from a paper manufacturing plant into electricity. Results of this pilot will be detailed and reported. Other developments in this field are prototypes of a heat powered cooling system as add-on for vacuum tube collector systems and CHP systems.

Introduction

Since the early days of thermoacoustics, research en development had its focus on the thermo-dynamic process in the regenerator and heat exchangers. Thanks to this effort, nowadays the thermoacoustic process in itself is well understood and many publications can be found reporting thermo acoustic engines and heat pumps showing exegetic efficiencies over 40%.

However, overall or integral system performance, defined as the ratio between acoustic power delivered to a useful load and engine thermal input power is still far from that. In most experiments published, at least about one third of the net engine output power is dissipated in the acoustic circuitry or resonator and therefore is not available to the load, consequently degrading the overall performance proportionally.

Most promising and commercial interesting field of applications for market introduction of thermoacoustic systems is utilizing low temperature differences from solar vacuum tube collectors or waste heat in the range 70-200 °C. Unfortunately, just at these relatively low input temperatures high acoustic loss even more affect the overall system performance.

Understanding the acoustic loss and power transfer mechanisms had resulted in the concept of multi-stage traveling wave thermoacoustics this will be addressed in chapter 1 in which the result of a loss analysis and ranking of commonly used acoustic resonance and feedback circuits is given.

In chapter 2 details and measurements of two successful implementations of this approach will be presented.

1. Multi-stage traveling wave thermoacoustic engines

Thermoacoustic power gain is given by the ratio between the absolute regenerator out- and input temperatures. An option to increase thermoacoustic power gain at medium and low operating temperatures is to cascade multiple thermoacoustic units or cores[1] [1,2]. In order to get benefits of using multiple regenerator units in series, proper acoustic conditions (high and real impedance) in all connected regenerator units should be maintained. Unfortunately, in the classic bypass or torus geometry with standing wave resonator [3,4] this condition is hard to get in more than two regenerator units at the same time.

This limitation doesn't exist in a traveling-wave feedback circuit because of the preferred acoustic conditions are present by default and can be set per regenerator units individually by adapting the length and diameter of the connecting tube sections and increasing the regenerator cross-sectional area relative to the feedback tube diameter [5]. In theory an arbitrary number of regenerator units (with increasing cross-sectional area in the propagation direction) can be connected in series this way. Consequence of this approach is that each regenerator units and connecting tube section is different in size which is inconvenient from the production point of view.

A "special case" however, in which all regenerator units and connecting tube sections are identical, is when four regenerator units are placed on a mutual distance of ¼ λ. In that case reflections due to impedance anomalies tend to compensate[2] each other. If in addition an acoustic load is added per stage the device is acoustically symmetric and therefore will be "self-matching" requiring no adjustment or tuning at all. Recently, such a novel 4-stage "self-matching" traveling-wave engine is developed and experimentally validated [5,6].

Based on the promising results so far, this traveling-wave 4-stage configuration will be the bases for further deployment and commercialization of low temperature thermoacoustic engines for waste heat recovery and solar heat powered cooling systems.

[1] regenerator clamped between the in- and output heat exchanger
[2] Similar to the well-known ¼ λ transformer applied in microwave and antireflection coatings in laser optics.

1.1 The thermoacoustic core

In traveling-wave feedback configurations pressure and velocity amplitude are nearly in phase in the regenerator by default. Reduction of viscous losses, is obtained by enlarging the regenerator cross-sectional with respect to the feedback tube diameter. Doing so the volume flow rate, and with that acoustic power, is not altered but local velocity in the regenerator is reduced proportionally. The associated change in cross-sectional area will introduce some minor losses [7], but these losses are found to be less than the acoustic dissipation in the inertance, compliance and T-junction is standing wave geometries. The requirements for regenerator units in traveling-wave feedback geometries doesn't differ much from those for the usual bypass or torus based geometries[3] and will not further be addressed here.

Emphasis in this document is on acoustic loss in the acoustic resonance and feedback circuitry which has turned out to be the major issue in the design of useful integral thermoacoustic systems.

1.2 The acoustic resonance and feedback circuit

The importance of the acoustic circuitry was recognised in the European FP7 project "Thermoacoustic Technology for Energy Applications" and therefore one of the tasks was to quantify and analyse the losses in high amplitude acoustic circuitry [8].

Beside creating a high and real impedance in the regenerator(s), the main function of the acoustic resonance and feedback circuit is to transfer acoustic power from the thermoacoustic engine to the acoustic load. Key parameter for this function is the "coupling efficiency" defined by the ratio between the acoustic power absorbed by an acoustic load (e.g. heat pump or alternator) and the acoustic power delivered by the thermoacoustic engine

$$\eta_{Coupling} = \frac{P_{ac\_Load}}{P_{ac\_Source}} = 1 - \frac{P_{ac\_res}}{P_{ac\_Source}}$$

In order to make this analysis independent of the engine or heat pump implementation[4] the regenerator unit of the engine is or heat pump is taken out and replaced by an equivalent acoustic source at the position of the cold hex of the engine and by an equivalent load at the position of the input hex of the heat pump or at the position of the alternator. After re-assignment of the system components in this document the following definition of acoustic loss is used for the various resonators and feedback circuits.

Acoustic loss in the resonance and feedback circuitry is defined as the amount of acoustic power needed to maintain, in absence of a regenerator unit, the pressure amplitude at the initial position of the engine cold hex minus acoustic power delivered to the equivalent load.

As known, acoustic loss in the resonance and feedback circuitry is due to one or more of the following loss mechanisms [3,9], thermal boundary loss, viscous boundary loss, turbulent loss and minor losses. Thermal boundary layer loss is caused by periodic irreversible heat transfer through the boundary layer from and to the wall during (acoustic) compression and expansion. Viscous boundary layer loss is due to periodic shear stress between the back and forward moving gas and the wall. Turbulent loss and minor losses are not typical acoustic phenomena but occurs in any high velocity flow as is known from fluid dynamics and aerodynamics. Dissipation due to turbulence at high amplitude could become proportional with velocity to the power of 2.8. This means that at increasing amplitude acoustic loss grows faster than acoustic power which is proportional to velocity squared. At increasing amplitude this loss term becomes increasingly dominant and ultimately most of the engine output (source) power is dissipated in the resonator itself and is no longer available to the load.

[3] Small thermal time constant ($\omega\tau < 0.1$) and low viscous loss ($R << \rho.c$)
[4] There is no inertance and compliance in traveling wave feedback systems

1.2.1 Implementation of acoustic circuits

Acoustic resonators can be classified as standing-wave or Helmholtz type resonators, as acousto-mechanical resonators and as traveling wave or loop resonators. Next section gives the associated loss and coupling efficiency for typical operating conditions. Values are for helium at 4 MPa, 5% drive ratio (at the load) and a frequency of 120 Hz. Transferred acoustic power from source to load is kept at 300 W by adjusting the (real) load impedance. Source and load position are denoted in the figures by S and L.

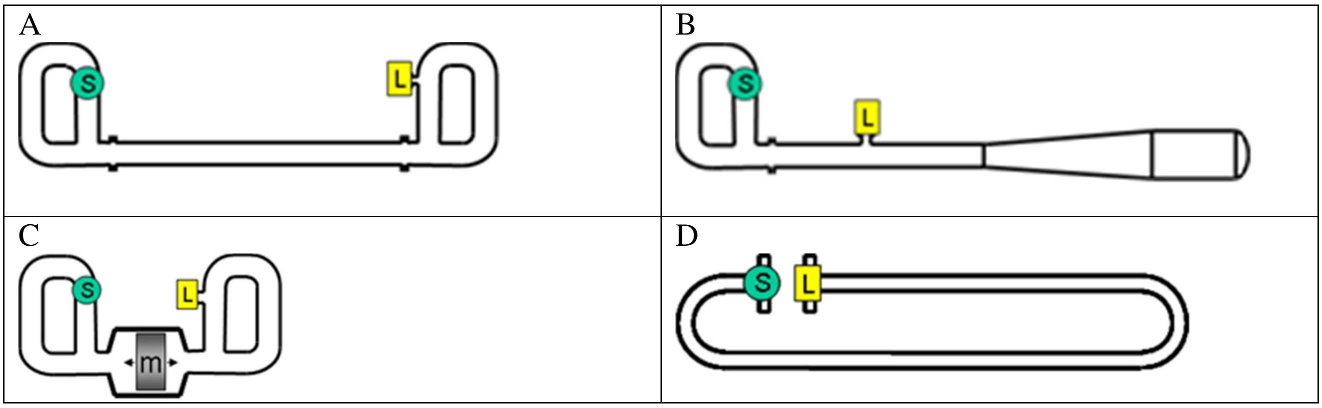

Figure 1 Geometry of the ½ λ resonator (a), the ¼ λ resonator (b), the acousto-mechanical resonator (c) and the traveling wave feedback loop (d)

Standing wave or Helmholtz like resonators (a,b). In this resonator type an acoustic wave is traveling back and forward yielding an interference pattern with maximum pressure amplitude et the ends and maximum velocity amplitude in the middle. Note that the volumes represents the total engine internal volume (inertance, compliance etc.). As mentioned, in a standing wave type resonator the local pressure amplitude is the result of two interfering traveling waves. Due to this interference, local pressure and velocity amplitude could be nearly twice the amplitude of the initial wave resulting in high local acoustic losses[5]. At the same time net transferred power to the load is the difference in power between forward and reverse wave and could be even zero (for reflection =1), while acoustic losses are still present.

Acousto-mechanical resonator (c) . In the acousto-mechanical resonator the mid-section gas column is replaced by a physical mass with such a value and dimensions that with the same end volumes (gas springs) the resonance frequency is still 120 Hz.

Traveling wave feedback (d). In this configuration, the load is connected to the equivalent acoustic source by a one wavelength long (feedback) tube. Characteristics for such a traveling wave section are an almost constant amplitude over the length while phase raises monotonically from zero to 2π at one wavelength distance. Precondition for maintaining near traveling waves is that reflections (reverse propagating waves) are avoided or minimized by terminating each section or loop by its characteristic impedance ($Z_0 = \rho.c.A_0^{-1}$). To get the correct feedback (phase = 2.π), the acoustic length of a traveling wave loop or ring resonator should be equal to λ at the oscillation frequency..

1.2.2 Ranking

Table 1 summarizes the results for the various resonance and feedback configurations. In addition to the losses also the internal gas volume of the acoustic circuit is listed. This gas volume is related to the physical size and compactness of the final integrated system.

[5] viscous loss could be proportional with $v^{2.8}$

Table 1 ***Data for 300 W load power at 5% drive ratio.***

Configuration	Total loss [W	$\eta_{Coupling}$	internal gas volume [dm^3]
Standing wave			
½ λ resonator	94	**0.69**	21.4
¼ λ resonator	57	**0.81**	28.0
Mechanical	37*	**0.88**	6.3
Travelling wave	40	**0.87**	1.6

* without clearance seal losses

The mechanical resonator seems superior in terms of loses but in practice clearance seal losses and piston alignment issues are found to be severe.

From the acoustic circuits the traveling wave option has lowest losses but, even more important is that for the same acoustic power transferred (in this case 300 W) the total internal gas volume is nearly one order of magnitude less than for the standing wave resonators potentially yielding a much more compact integral systems at the same time reducing constructive (cost) and safety requirements.

2. Practical implementation

This chapter addresses recent developments on low input temperature integral systems based on the traveling wave multi-stage concept

2.1 The THATEA low temperature integral system

One of the objectives of this project was to design, build and test an integral system of a low temperature thermoacoustic engine driving a thermoacoustic refrigerator. Both the engine and refrigerator should demonstrate a performance of 40% of the maximum attainable Carnot efficiency.

In this chapter only the overall integral system results are presented. Construction details of the multistage engine and refrigerator can be found in [10]. The working gas is helium at 2.7 MPa (26 barg) and frequency is 95 Hz.

Performance of the integral system is measured at three different engine input temperatures. The (local) pressure amplitude or drive ratio at the refrigerator stage is proportional with the engine input temperature. Table 2 shows the results for three engine input temperatures and the lowest cold hex temperature obtained after the system becomes thermally stable.

Table 2 Performance of the WP6 integrated system measured at increasing engine input temperature

Engine					
T_{H_E}	Hot hex input temperature	°C	169	211	239
T_{C_E}	Cold hex input temperature	°C	12	13.2	13
Q_E	Thermal input power	W	1041	1300	1728
Q_{stat}	Static heat loss	W	235	296	340
T_{H_reg}	Regenerator high temperature	°C	138	178	199
T_{C_reg}	Regenerator low temperature	°C	32.1	38.8	47
P_{ac1}	Acoustic power at refrigerator input (#1)		134	192	274
P_{ac2}	Acoustic power at engine input (#2)	W	73.0	91.4	121
W_{fb}	Acoustic loss feedback	W	21.4	30.8	44
W_{out_E}	Acoustic output power ($P_{ac1} - P_{ac2} + ¾ .W_{fb}$)	W	76.6	124	187
η_{T_E}	Thermal efficiency (W_{out_E} / Q_E)	-	0.10	0.14	0.15

η_{2_E}	Exegetic efficiency relative to T_{H_E}	-	**0.29**	**0.34**	**0.35**
$\eta_{2\_E\_reg}$	Exegetic efficiency relative to T_{H_reg}	-	**0.42**	**0.48**	**0.50**
Refrigerator					
dr	Drive ratio at cold hex	%	1.33	1.53	1.78
W_{in_R}	Acoustic input power ($P_{ac1} - P_{ac2} - ¼.W_{fb}$)	W	55.2	93.4	143
T_{c_R}	Cold hex temperature	°C	-33.7	-40.5	-45.5
Q_{C_R}	Net cooling power	W	78.2	95.1	95.4
T_{H_R}	After refrigerator temperature	°C	19.2	24.2	18.8
Q_{H_R}	Heat rejected	W	135	182	253
COP	(Q_{C_R} / W_{in_R})	-	1.42	1.02	0.67
η_{2_R}	Exegetic efficiency relative to T_{C_R}	-	**0.32**	**0.29**	**0.19**

The performance of the engine is strongly affected by the temperature drop across the low cost heat exchangers. Between the input temperature difference applied and the actual regenerator temperature difference there is a temperature drop of (239-199) + (47-13) = 74ºC. The last row of the engine section gives the efficiency without this temperature drop. Better heat exchangers could halve the temperature drop and in that case efficiency will be > 40%. Within the (input) temperature limits of the engine the refrigerator drive ratio was limited causing parasitic heat load to the cold hex to be non-neglectible.

Based on this concept a prototype of a solar cooler is under construction for use in combination with vacuum tube solar collectors.

2.2 Thermo Acoustic power (TAP)

Converting industrial waste heat into electricity is recognised as one of the short term techno-economic feasible applications of thermoacoustic energy conversion. In the framework of a Dutch SBIR programme, a pilot of such a system is developed, built and installed at the premises of a paper manufacturer.

The aim was to prove the economic feasibility of the TAP and to prove the scalability of thermoacoustics from lab to industrial power levels. In this pilot the TAP was designed for converting 100 kW of thermal power of flue gas at 150-160ºC into 10 kW electricity with an exegetic efficiency of > 40%. Basically it is also a 4-stage traveling wave feedback system using helium at a mean pressure of 750 kPa as working gas..

The housing is assembled from four pressure vessel (1.3m x 0.65 m∅) mutually connected by two straight and two bended feedback tubes each with an (equal acoustic) length of about 1.5 m and an internal diameter of 0.20m∅.

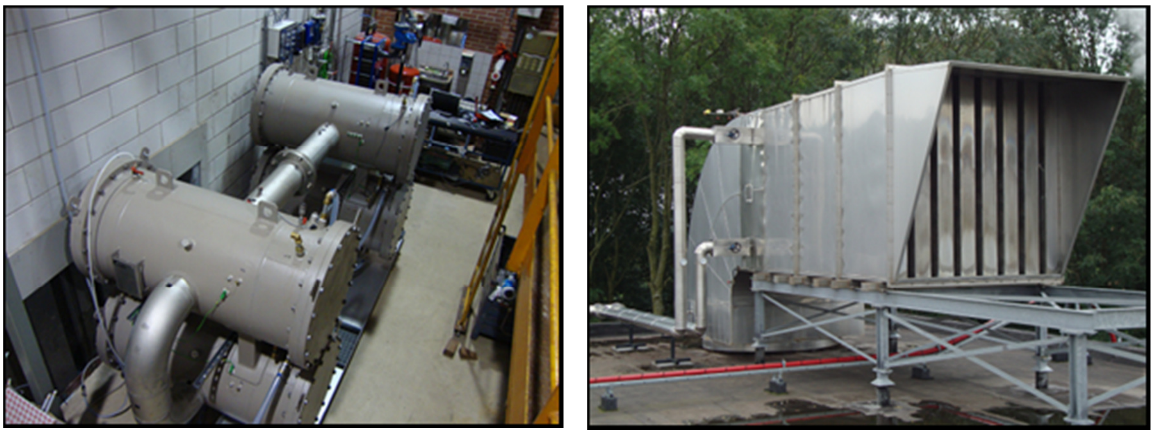

Figure 2. The 4-stage 100 kW_T TAP and the flue gas exhaust (3m x 3m) with halfway the high temperature circuit heat exchanger

The regenerator and heat exchangers are positioned traverse in the pressure vessels. Each of the regenerators measures 950 x 500 x 15 mm assembled as a stack of 84 sheets stainless steel gauze with a wire diameter of 90μm and a volume porosity of 74%.

The regenerator is clamped between two identical aluminium brazed finned tube heat exchangers with block size is 950 x 500 x 25.4 mm. The 86 tubes are provided with 9 mm high louvered fins at a pitch of 2.5 mm.

Waste heat is extracted from the production process by a commercial available heat exchanger (2.6 m x 2.1 m x 0.25m) inserted in the exhaust of the STEG. Then heat is transferred from hex at the roof down to an intermediate hex close to the TAP. From this intermediate hex thermal oil is used to transfer heat to the high temperature hex's of the TAP inside each vessel. The low temperature hex's of the TAP are connected to a water storage tank. This way, heat rejected from the TAP is used for pre-heating the production process water.

Part of the acoustic loop power is converted into electricity by linear alternators. For this purpose, each vessel contains two 1.25 kW linear alternators, operating in opposite phase, mounted in the open space in front of the cold hex's. Each alternator is mounted in its own sealed box allowing the 120 mm∅ power piston to respond on the pressure variations in the vessel. The clearance seal gap between piston and cylinder is 70μm. Maximum stroke is 40 mm.

For the travelling wave multi-stage configuration the acoustic impedance at the pistons of the linear alternators needs to be real in order to extract maximum power at minimum pressure amplitude. Real acoustic impedance means that the mechanical resonance of the alternators should be close to the acoustic oscillation frequency set by the feedback loop length.

Initially the TAP and alternators was designed for running at 70-80 Hz. In the end however, the high moving mass (magnet + springs) limits the mechanical resonance frequency of the linear alternators to about 40 Hz. This mismatch dramatically reduce the load to the engine and from that the amount of acoustic power that could be extracted.

For that reason, lack of appropriate load by alternators, the thermoacoustic performance of the TAP is measured in an alternative way, by using one of the four engine stages as an artificial acoustic load. This is done by disconnecting the high temperature hex of this stage from the heat source. Net acoustic output power delivered by the remaining three engine stages in that case is the difference between the acoustic power measured at the in- and output of the disconnected stage. In this configuration the three engine stages are converting 20 kW waste heat into 1.64 kW acoustic output power dissipated by the fourth stage[6]. At an input temperature of 99°C and heat rejection at 20°C this corresponds with 38% efficiency relative to the Carnot factor. Details of these measurements will be presented at the conference.

This is an encouraging result because it proves that thermoacoustic engines can be scaled from lab size up to power levels in real applications. The measured values for a 3-stage engine at these low power levels (relative to the design values) are found to agree well with the simulations[7]. The 1.64 kW output power is reached with helium at a mean pressure of 750 kPa and at only 1.7% drive ratio. Simulation for the initial 4-stage engine running at a drive ratio of 5% shows that for an input temperature of 140 °C the acoustic output power available for the alternators will be about 11 kW.

2.3 Issues left

Reduction of the temperature drop across the heat exchangers becomes more important now. In both, the small and large power, integral system presented here, the total temperature drop across the heat exchangers is in the order of 40 ºC which is a not neglectible part of the available input temperatures from waste heat or solar heat (e.g. 160ºC)..

[6] Act as thermoacoustic heat pump. Acoustic load by viscous loss and temperature lift

[7] Surprisingly it was found that simulation results for large systems are more accurate than for small ones

Another issue specific related to the TAP is that we found that it will be hard to scale up linear alternators above 10 kW, both for mechanical and economic reasons. An alternative of first converting the acoustic power into rotation and using standard generators is under study

3. Conclusions

- At low and medium input temperatures, the overall performance of integral systems is dominated by the losses in the acoustic circuitry rather than by losses in the thermoacoustic core.
- Traveling-wave feedback is found to have relatively low losses, but even more important, for the same acoustic power levels the internal gas volume of this concept is more than a factor of 5 less as for the classic standing wave geometries so significantly increasing the power density of thermoacoustic systems.
- Low acoustic loss in the traveling-wave multistage concept has yield absolute onset temperatures as low as 45ºC which is an essential requirement for utilizing waste and solar heat
- Up scaling in power over at least two orders of magnitude up to 100 kW and integrating a thermoacoustic system in an industrial process is demonstrated.
- The improved overall performance and scalability of the traveling-wave multistage concept will bring market introduction upcoming.

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