Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and
8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-30527

NOVEL 4-STAGE TRAVELING WAVE THERMOACOUSTIC POWER GENERATOR

Kees de Blok
Aster Thermoakoestische Systemen
Smeestraat 11, 8194LG Veessen
The Netherlands

ABSTRACT

Utilizing low temperature differences from solar vacuum tube collectors or waste heat in the range 70-200 °C seems to be the most promising and commercial interesting field of applications for thermoacoustic systems. Recently a novel 4-stage “self matching” traveling wave engine is developed and tested. Beside the low acoustic loss and compactness, due to traveling wave feedback, all components per stage are identical which is beneficial from (mass) production point of view. Based on this concept a 100 kW_T thermoacoustic power (TAP) generator is under construction. This project is carried out in the framework of phase two of the Dutch SBIR program. The 100 kW_T TAP will be installed at a paper manufacturing plant in the Netherlands for converting part of the flue gas at 150°C from the paper drying process into electricity. Emphasis in this project is on production and cost aspects lowering the investment per kW_e to a level competitive to ORC’s. After successful completion of this pilot, commercialization and delivery of 100kW to 1 MW thermoacoustic power generators for industrial waste heat recovery and as add-on for CHP systems is planned to begin in 2012. The same concept of the 4-stage traveling wave engine is also implemented in an atmospheric pressure operated thermoacoustic cooking device for developing countries which generate beside hot water up to 50 W electricity. Details, ongoing work and experimental results of these projects will be presented.

INTRODUCTION

Utilizing low temperature differences from solar vacuum tube collectors or waste heat in the range 70-200 °C seems to be the most promising and commercial interesting field of applications for thermoacoustic systems. Pre-requirement for successful applications is the development of thermoacoustic engines with onset temperatures far below the (waste heat) input temperature and a steep rise of acoustic loop power with the applied temperature difference. While optimizing heat exchangers and regenerator is important deployment of multi-stage configurations and reducing acoustic loss in the acoustic resonance and feedback circuitry are key issues in developing low operating temperature thermoacoustic devices.

Insertion of multiple regenerator units and reducing acoustic loss requires is hardly possible in the commonly used torus or bypass standing wave configuration. Therefore, in the first part of this paper, the design and use of traveling wave resonance and feedback circuits is briefly addressed.

In the second part of this paper background, design practice and different implementation examples of low operating temperature multi-stage traveling wave feedback thermoacoustic devices will be described as preparation for the pilot of a 100 kW_T Thermo Acoustic Power (TAP) generator. Because of this pilot is currently in progress, more details will be presented during the conference.

1 Acoustic resonance and feedback in thermo acoustic systems

Acoustic dissipation in the resonance and feedback circuit of a thermoacoustic system is found to be a dominant parameter in overall performance. While optimizing the TA process during the years has yield engine efficiencies of nearly 50% of the Carnot efficiency, the actual available power transferred to a useful load, such as a heat pump or linear generator, in general comes short of the net engine output power. Pertain to this is that all high efficiency standing wave engines reported in literature so far dissipate most of their output power into the resonator, leaving no more than half of the net output power available to a useful load like a linear alternator or heat pump.

1.1 Standing wave resonator

In a standing wave type resonator the local pressure and velocity amplitude is the result of two interfering traveling waves. Due to this interference local amplitude could be nearly twice the amplitude of the initial wave resulting in high local acoustic losses[1]. Actually, in a standing wave resonator the net transferred power to the load is the difference in power between forward and reverse wave. This transferred power could be small or even zero (reflection coefficient =1), while acoustic losses (due to the high amplitude) are still present yielding a very low coupling efficiency from engine to load defined as

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

In which P_{ac_source} is the net engine output power, P_{ac_loss} is the power dissipated in the resonator and P_{ac_load} is the useful system output power. Unfortunately this happens for the classic torus or bypass configuration which will terminate the standing wave resonator with a high acoustic impedance (10 to 20 times ρ.c) yielding a reflection coefficient close to one (otherwise there couldn't be a standing wave). As indicated in [1] this effect becomes more severe at abating operating temperatures (less gain) and will not only impede deployment of thermoacoustic engines on low solar or waste heat operating temperatures but it also reducing system performance of high temperature engines. A way out to reduce acoustic losses associated with the required acoustic feedback is to utilize (near) traveling waves resonance and feedback circuitries in stead.

1.2 Traveling wave feedback

In a traveling wave section, there is no reverse wave and consequently no interference. Characteristic for such a traveling wave section is 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 (backward waves) are avoided or minimized by terminating each section or loop by its characteristic impedance ($Z_0 = \rho.c.A_0^{-1}$). This will be addressed in the next chapters. To get the correct feedback (phase = 2.π), the acoustic length of a traveling wave loop or ring resonator should be equal to λ. An example of (partially) traveling wave feedback is given in [1].

In traveling wave configurations velocity reduction in the regenerator, required to reduce 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 proportional. The associated change in cross-sectional area will introduce some minor losses but with a proper rounding these losses are found to be less severe as the acoustic dissipation in a standing wave yielding a more efficient coupling between engine and load.

Traveling wave feedback is found not only to have less acoustic losses but even more important, this type of (loop) resonator has the option to insert an arbitrary number of regenerator units. By this means, acoustic gain could be increased in such a way that even at low engine input temperatures (< 150 °C) acoustic loop power could be kept limited to two or three times the net output power reducing proportionally the acoustic loss and enabling efficient operation at low temperatures.

While not directly related to the system performance, from application point of view, the space occupied by a thermoacoustic system could be a relevant issue. In general, dimensions of a thermoacoustic system are mainly definite by the size of the acoustic resonance and feedback circuitry. Simulation and experiments shows that for the same net acoustic output power the internal gas volume of an engine with traveling wave feedback loop is significantly less as compared with the classic standing wave type resonators. This is a practical feature allowing for building more compact integral systems and reduce constructive and safety requirements.

2 Multistage engines

Thermo acoustic power gain is given by the ratio between the absolute regenerator in- and output temperatures. A well known option to increase thermo acoustic power gain at low operating temperatures is to cascade multiple thermoacoustic units[2] [2,3]. In order to get benefits of using multiple regenerator units in series it is obvious that in all connected regenerator units the acoustic conditions (high and real impedance) should be maintained. Unfortunately, in the classic standing wave torus configurations this is hard to maintain in more than 2 regenerator units without adding additional loops or branches increasing the acoustic losses.

In a traveling wave feedback circuit the preferred acoustic condition in all regenerator units can be set individually by adapting the length and diameter of the mutual tube sections

---

[1] viscous loss could be proprtional with $v^{2.8}$

[2] regenerator clamped between the in- and output heat exchanger

and increasing the regenerator cross-sectional area relative to the feed back tube diameter [4]. When carefully dimensioned, 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 in general all regenerator units and mutual tube sections are different in size. A "special case" however, in which all regenerator units and mutual tube sections are identical, is when four regenerator units are placed on a mutual distance of ¼ λ.

2.1 Special case, the 4 stage engine

In case the mutual distance between the regenerator units is ¼ λ reflections due to impedance anomalies tends to compensate[3] each other. If in addition an acoustic load is added per stage the device is acoustically completely 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 by Aster. Based on the promising results so far this symmetric 4-stage configuration will be the base for further deployment and commercialization of low temperature thermoacoustic engines.

Before entering the pilot phase the concept is tested. in various test rigs which are described briefly in the next chapters each demonstrating one of the promising features of this concept.

3 Test rigs

In this chapter, details, ongoing work and experimental results on this novel concept are presented. All configurations are based on the same symmetric 4-stage configuration. Implementation however is completely different, illustrating the flexibility of the concept.

3.1 Atmospheric test rig

This section describes the design and experiments of an atmospheric test rig used to validate the symmetric 4-stage approach. The layout and implementation are given in Figure 1.

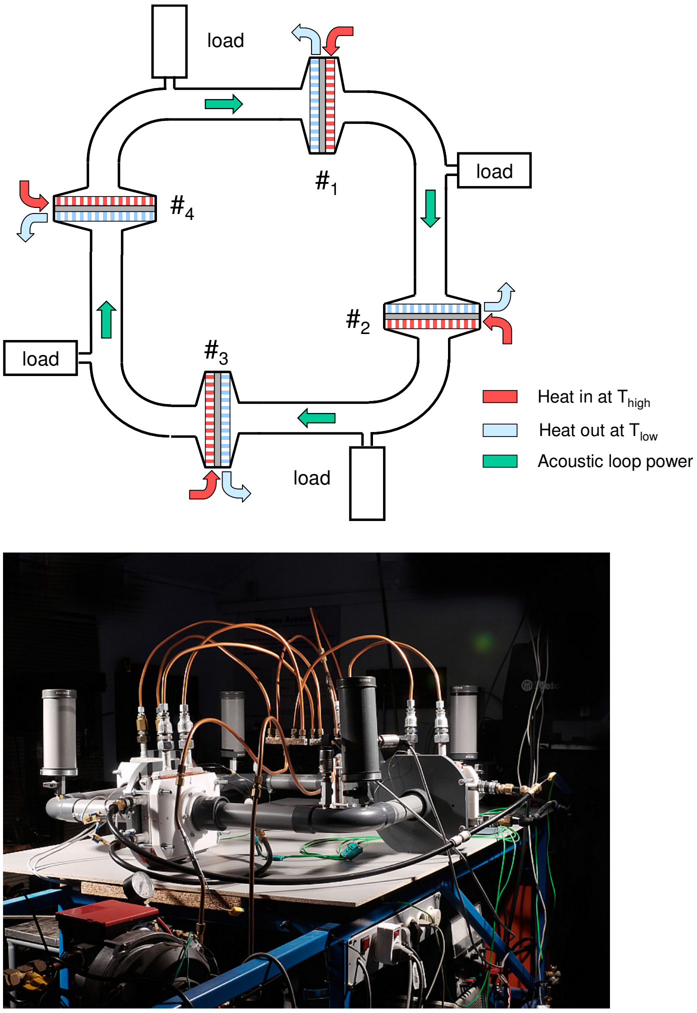


Figure 1 4-stage Atmospheric test rig

The regenerator units of the four stages are identical. Both hex's are car heater radiators with core size 150 x150 x 22 mm and equipped with louvered fins. The regenerator, clamped between both heat exchangers, measures also 150x150 mm and is made of 18 sheets stainless steel gauze with 80 µm wire diameter and a volume porosity of 70% yielding a normalized thermal time constant $(\omega\tau_t)$ less than 0.1 at the nominal pressure amplitude of 4000 Pa (4% drive ration). Regenerator temperatures are measured with 0.5 mm type K thermocouples positioned between the regenerator and both hex's. Static heat conduction between the hex is measured to be 0.85 $W.K^{-1}$.

Standard 50 mm pvc tubing (i.d. 43 mm) is used for the near travelling wave acoustic feedback sections. High temperature (180°C) plastic flanges and tubes are used at the hot heat exchanger side. Acoustic loop power is measured using the pressure gradient as a measure for the acoustic velocity. In

---

[3] Similar to the well known ¼ λ transformer appllied in microwave and anti reflection coatings in laser optics.

addition each stage is loaded with a dummy load for measuring the net acoustic output power

To stay close to the final applications the set-up is powered by hot water from a dedicated gas fired water heater able to heat water up to 160 °C (10 bar). Thermoacoustic process heat from the low temperature heat exchangers is removed at ambient temperature by a car radiator placed outside the building. The maximum temperature difference between the high and low temperature water circuits obtained this way is 130 K.

Figure 2 shows the measured performance for various acoustic loads

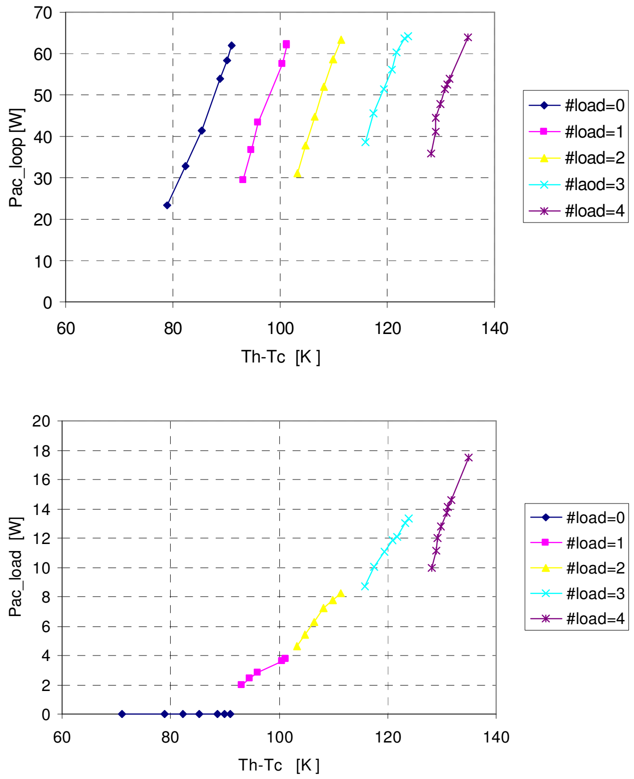


Figure 2 Acoustic loop power and output power versus applied water temperature difference for an increasing number of (dummy) loads

As can be seen from Figure 2 without any load (all valves closed) the onset temperature difference between in- and output water is about 70 K while the acoustic loop power reach more than 60 W at 90 K water temperature difference. It is obvious that there is no net acoustic output power in this case. This steep ΔP_{ac} / ΔT curve however indicate low acoustic loss. Subsequent measurements shows the effect of one by one opening the valves of the dummy loads.

As expected when opening more valves, more gain (higher temperature difference) is needed to compensate for the extraction of acoustic power. Remarkable is that the slope of the ΔP_{ac} / ΔT curve is unaltered indicating constant (load independent) acoustic loss. With all valves opened the total acoustic output power delivered to the four dummy loads is 18 W. This output power is obtained at a relatively low acoustic loop power (64W) confirming a high thermoacoustic gain as expected from multiple regenerator units. Because of this low acoustic loop power the acoustic losses are modest which is indicated by the steep ΔP_{ac} / ΔT curve.

At maximum load (18W) and temperature difference (132 K) total heat rejected from the four cold hex's is measured to be 656 W. Due to the short regenerator total static heat flow is 4*0.85*132 = 449 W leaving 207 W rejected by the thermoacoustic process[4].
Without static heat loss thermal efficiency of the 4-stage engine is 18 / (207+18) = 8 % corresponding with 27 % of the Carnotfactor which is conform the simulation for such a simple atmospheric air operated device running at low temperature. While due to the high static heat loss, this test rig has no practical use, at least it demonstrate the feasibility of the 4-stage concept.

3.2 Thermoacoustic cooking device

For the FACT foundation, Aster has implemented the concept of the 4-stage traveling wave engine into an atmospheric pressure operated thermoacoustic cooking device for developing countries. Beside hot water the device will deliver some electric power. The prototype of this extreme thin (50 mm) thermoacoustic engine is described here briefly to demonstrate another way of implementation. The basic configuration is depicted in Figure 3.

---

[4] This poor ratio between static and thermoacoustic heat flow is typical for atmospheric thermoacoustic devices. For pressurized systems impact of static heat loss becomes proportionally less.

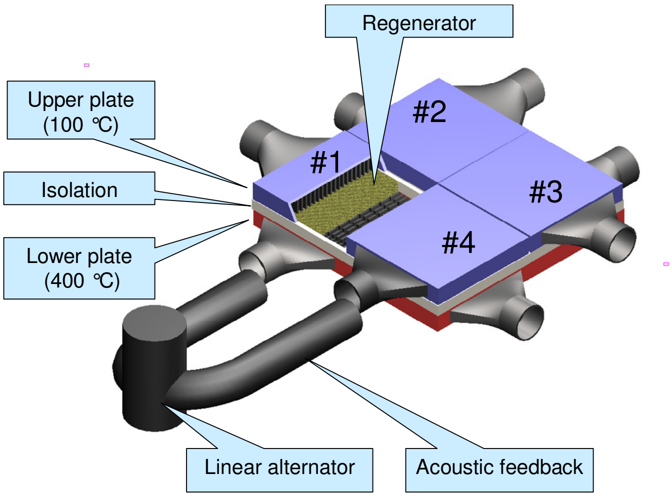
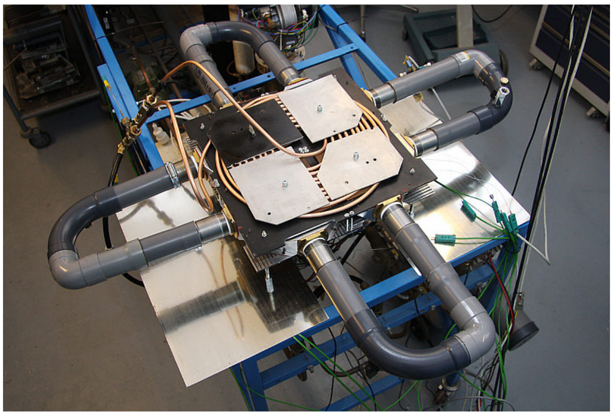


Figure 3 4-stage thermoacoustic cooking plate

The idea behind is to position the device between an arbitrary heat source (e.g. wood fire) and a water reservoir containing the heated water. Each regenerator unit consist of an aluminum upper and lower plate with internal fins acting as respectively cold and hot hex. Both plates are separated by a thermal isolation layer which also contains the regenerator. The regenerator is made of 35 sheets sheets stainless steel gauze with 80 µm wire diameter and a volume porosity of 70%. Regenerator temperatures are measured with 0.5 mm type K thermocouples positioned between the regenerator and both hex's. Static heat conduction of each regenerator is measured to be 0.24 $W.m^{-1}K^{-1}$

The acoustic in- and outputs of each regenerator unit are 90° rotated with respect to each other and mutually connected by 43 mm i.d. tubes (only one drawn). Balanced linear alternators are planned in one or more of these feedback tubes. Figure 4 shows the implementation of the extremely flat thermoacoustic engine. For measurement purposes the water reservoir is replaced by a spiralzed water tube



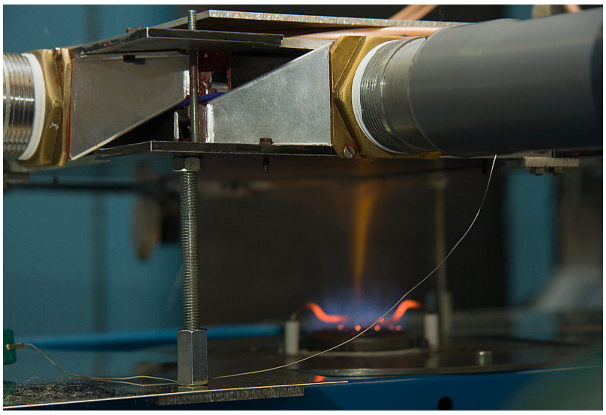


Figure 4 test set-up of the flat (50 mm) thermoacoustic engine with the water reservoir replaced by a spiral zed water tube

In Figure 4 the thermoacoustic cooking plate is shown without alternators. In a first test using a single cheap alternator the electric output was 5.4 W. Taking into account the bad acoustic to electric efficiency of the alternator (31%) the net acoustic engine output power was 17.6 W at an acoustic loop power of only 34 W. This high output relative to the acoustic loop power proves the high gain and low acoustic loss in spite of the numerous bends and diameter transitions. Work on this device is in progress and results will be updated during the conference.

3.3 4-stage thermoacoustic engine

Aster has introduced the four stage concept in the European THATEA project (THermoacoustic Technology for Energy Applications) as a solution for the low temperature integral system. One of the project targets is to realize an integral system of an low temperature (waste) heat driven thermoacoustic cooler demonstrating an exergetic efficiency of at least 40%. The project is ongoing and the engine section of the low temperature system is just assembled. The setup is shown in Figure 7

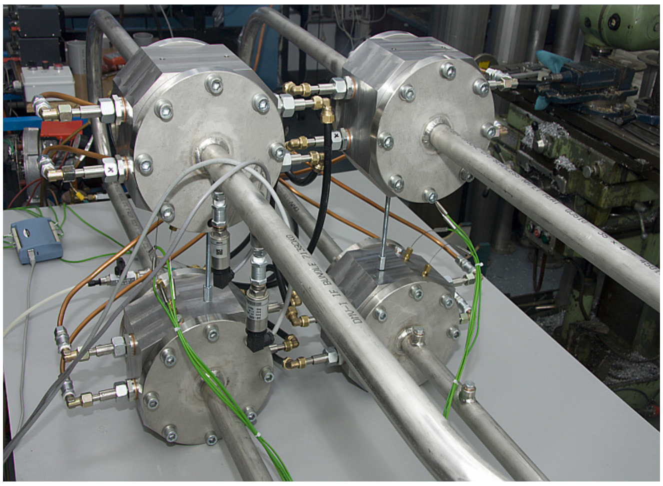


Figure 5 Pressurized 4 stage thermoacoustic engine

High and low temperature heat exchangers in each regenerator unit are aluminium brazed with block size 69x95x22 mm and equipped with louvered fins. The regenerator measures 69x95x10 mm and contains 75 sheets stainless steel gauze having 33 μm wire diameter and a volume porosity of 70%. Initially the construction and regenerator are designed for a mean pressure of 4 Mpa helium. However, due to mechanical restrictions of the hex's mean pressure (P_0) for the tests is currently limited to 2.5 Mpa.

Regenerator temperatures are measured with 0.5 mm type K thermocouples positioned between the regenerator and both hex's. Static heat conduction of each regenerator is measured to be 0.18 $W.m^{-1}K^{-1}$. The 1.7 m long feedback loops has inner diameter of 25 mm. The void volume between flanges and hex's is partially filled with plastic inserts fixed on the flanges providing also the proper rounding (r > 8 mm) for the diameter transitions. Total gas volume of the system is only 10.6 dm^3 which is only 1/6 of the internal gas volume of a torus type engine with standing wave resonator for the same engine output power. and frequency.

Typical figures to characterize a thermoacoustic engine are onset temperature and the slope of the acoustic loop power (P_{ac_loop}) versus temperature ($\Delta T=T_H-T_C$) curve. For the initial 4-stage engine this curve is given in Figure 6 for both helium and argon without any modification made to the rig.

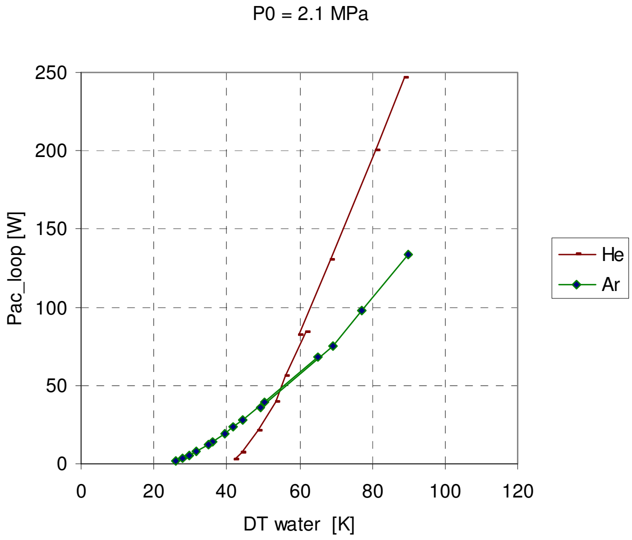


Figure 6 Acoustic loop power versus temperature differenence between the high and low temperature water circuits

Figure 6 shows that for argon the regenerator gauze used is quite optimal indicated by a record minimum onset temperature difference between the high and low temperature water circuits less than 30 K. At 90 K water temperature difference, acoustic loop power is 140 W at 3.4% drive ratio measured at the input of the regenerator units.

For helium at 2.1 Mpa the regenerator's are found quite dense ($\omega\tau < 0.08$) leading to a higher onset temperature of about 42 K. At 90 K water temperature difference acoustic loop power however is already raised up to 250 W at 2.5% drive ratio.

The more steep P_{ac_loop} / ΔT curve for helium indicate less acoustic losses due to lower effective Reynolds number in the feedback loops and a better heat transfer in the hex.

The high acoustic loop power found at low drive ratio is typical for traveling wave feedback. The steep ΔP_{ac} / ΔT curve for helium indicate low acoustic losses and shows that in principle there is enough margin to drive a useful load (cooler) at the proposed operating temperature of 200 °C (ΔT = 180K).

In order to measure real efficiency the rig will be equipped with four dummy loads. Results and details about final thermal and acoustic power levels and efficiency of the 4-stage engine will be presented at the conference.

3.4 Thermo Acoustic power generator (TAP)

Based on this traveling wave four stage concept, a 100 kW_T thermoacoustic power (TAP) generator is under construction now. This project is carried out in the framework of phase two of the Dutch SBIR program. The 100 kW TAP will be installed at a paper manufacturing plant in the Netherlands for converting part of the flue gas at 130-150°C from the paper drying process into electricity. Emphasis in this project is on production and cost aspects for lowering the investment per kW_e to a level competitive to ORC's. After successful completion of this pilot, commercialization and delivery of $100kW_T$ to 1 MW_T thermoacoustic power generators for industrial waste heat recovery and as add-on for CHP systems is planned to begin in 2012. An artist impression of the planned TAP is depicted in Figure 7.

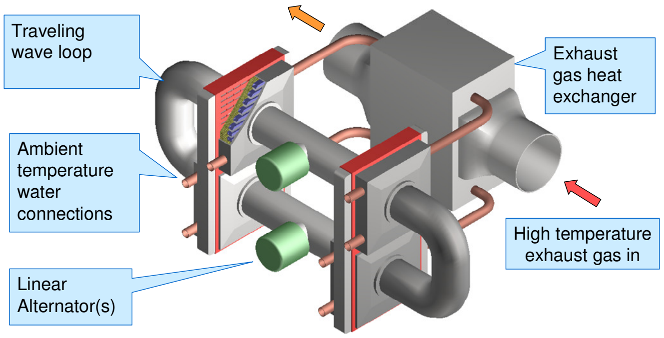


Figure 7 Thermo Acoustic Power unit (TAP)

The TAP consist of a 4-stage thermoacoustic engine. The TAP will use helium at 600 kPa as working gas. Effective regenerator and hex cross-sectional area is 0.6 m^2. Traveling wave feedback loops are used to connect the four regenerator units. Inner diameter of the feedback tubes is 209 mm. Planned oscillation frequency is 70-80 Hz. Because of the housing volume and looped construction the physical size of the 100 kW TAP will be about 3.5 m x 1.8 m x 1.2 m.

The TAP is powered by hot water (120-140 °C) coming from a commercial exhaust gas heat exchanger. Heat of the four low temperature hex's is rejected at ambient temperature (20-30°C). Four resonant balanced linear alternators will be used to convert engine acoustic output power into 10 kW electricity

Construction of the device is in progress and implementation details of the TAP will be presented during the conference and can be found at that time on www.aster-thermoacoustics.com .

4 Conclusions

The concept of a novel 4-stage traveling wave feedback thermoacoustic engine is presented and feasibility of the concept is demonstrated by a number of completely different implementation examples.
Acoustic losses in traveling wave feedback loops are found to be lower than in "classic" torus engines equipped with standing wave resonators. This is demonstrated in one of the rigs which shows a record minimum onset temperature less than 30 K between the high and low temperature water circuits.
Based on this 4-stage concept a 100 kW_T thermoacoustic power (TAP) generator is under construction. This TAP will be installed at a paper manufacturing plant in the Netherlands for converting part of the flue gas from the paper drying process into electricity.
The symmetric 4-stage configuration presented here will be the base for further deployment and commercialization of low temperature thermoacoustic engines for solar and waste heat recovery.

ACKNOWLEDGMENTS

Research on this concept is financially supported by:

- FACT Foundation for developing the thermoacoustic cooking device (www.fact-foundation.com)
- the EC within the SEVENTH FRAMEWORK PROGRAMME "THermoacoustic Technology for Energy Applications" (Grant Agreement no.: 226415, Thematic Priority: FP7-ENERGY-2008-FET, Acronym: THATEA)
- Dutch SBIR programme "verduurzaming warmte en koude in de industrie - fase 2", under contract number: SBIR 09313 for the pilot and pre commercialisation phase of the 100 kW Thermo Acoustic Power (TAP) unit.

REFERENCES

. [1] C.M. de Blok, "Low operating temperature integral thermo acoustic devices for solar cooling and waste heat recovery", Acoustics'08, Paris. PA15

[2] P.H.Ceperly. "Gain and efficiency of a short travelling wave heat engine". J.Acoust.Soc.Am. 77 No3, march 1985, 1239 - 1244.

[3] D.L. Gardner and G.W. Swift, A cascade thermoacoustic engine, J. Acoust. Soc. Am. 114 (2003), pp. 1905–1919.

[4] C.M. de Blok, "Multistage traveling wave thermoacoustic engine with distributed power extraction" PCT/NL 2010/050