Low operating temperature integral thermo acoustic devices for solar cooling and waste heat recovery

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Utilizing low temperature differences from solar vacuum tube collectors or waste heat in the range 70-200 °C seems to be the most promising field of applications for thermo acoustic systems.

At these reduced temperatures overall system performance is increasingly affected by the ratio between amplified (useful) power and acoustic power in the resonance circuitry.

Well known is that this ratio can be improved by deploying multiple regenerator units (hex-reg-hex).

However, in commonly used torus or coaxial bypass configurations the correct timing (real and high acoustic impedance) is hardly to realize inside more than two regenerator units (soft spot).

Acoustic losses in the standing wave resonator together with a high regenerator impedance account for another fundamental limitation because of the relatively low transferred and loop power at a given pressure amplitude.

Therefore a novel acoustic geometry will be presented in which a near real impedance can be maintained in even more than two regenerator units and in which acoustic feedback is performed by a near traveling wave.

This approach improves the overall performance of low operating temperature thermo acoustic systems.

1   Introduction

Now a days "traveling wave" thermo acoustic energy conversion is recognized as highly efficient. The well known torus configuration [1] has reached an efficiency of 41% of the Carnot factor at a high operating temperature of 725 °C. From market introduction point of view at these elevated temperatures thermo acoustics has to compete with more mature devices like (free piston) Stirling engines and probably little space is left here for introducing this emerging technology.

Introduction of thermo acoustics therefore is expected to be in the field of utilizing solar and waste heat and for applications not feasible with conventional technology for practical or economic reasons.

In general, operating temperature for these potential applications will be in the range of 70 °C for solar and industrial waste heat, up to 400 °C for exhaust gas of a CHP system (thermo acoustic tri-generation).

In this document the impact of medium and low operating temperature on system level will be detailed and a novel acoustic geometry more adapted for low operating temperature engines is presented.

2   Limitations in torus or bypass geometry

The main parameter to be optimized for integral systems (engine plus heat pump) is de ratio between engine net output power, which is actually the amplified fraction of loop power, and acoustic losses in the resonator / housing.

Acoustic power through the regenerator unit or loop power depends on its cross-sectional area (A_0), amplitude (p_a) squared, and impedance (Z_{reg}). This impedance in its turn is the result of acoustic interaction between timing circuitry like a torus [1] or bypass [2] and flow resistance in both regenerator and heat exchangers.

In order to limit the impact of viscous losses in the regenerator it is common practice is to set[1] the absolute value of the regenerator impedance to 10-20 times the gas characteristic impedance ($\rho.c$).

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1 by adjusting torus or bypass circuitry

As a result acoustic power through the regenerator, the so called loop power equals

$$P_{ac\_loop} = \frac{A_0 . p_a^2}{2 . \mathrm{Re}[n.\rho.c]} \qquad (1)$$

In which n is the complex impedance enhancement factor set by the bypass or torus circuitry.

For an ideal thermo acoustic heat engine acoustic output power equals loop power times T_{Hot} / T_{Ccold} -1.

Acoustic loss per m^2 tube wall of the acoustic (resonator) circuitry due to thermal and viscous boundary layers is well known [1,3] and is proportional to total inner wall surface and local amplitude squared.

At small amplitude (laminar flow) both output power and acoustic loss are proportional tot amplitude squared so the ratio between output power and acoustic loss depends from geometric and system parameters only. As an example, for an ideal thermo acoustic engine coupled to a 3 m long resonator with i.d.100 mm and filled with air at 100 kPa the relation between operating temperature and the normalized ratio between acoustic loss and engine output power is given in Figure 1.
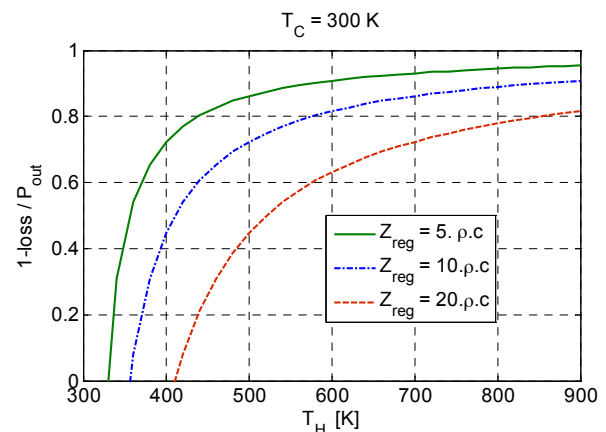

Figure 1 Impact of regenerator impedance on available output power in the small amplitude regime (dr < 1%).

The course of Figure 1 is typical for all standing wave like geometries with enhanced regenerator impedance and it clearly shows the heart of the matter for low operating temperature engines.

At abating operating temperatures (T_H) impact of a high regenerator impedance becomes more and more dominant.

According to Figure 1, an in other aspects, ideal engine, with its regenerator impedance set to 20 times $\rho.c$ could not even start below 410 K because acoustic loss in that case exceeds the engines net output power (gain times loop power). Note that high temperature engines ($T_H > 800$ K) and engines using electro-acoustic resonance [4] are much less sensitive to resonator loss and impedance setting (n) because of the high gain respectively slight wall surface.

The previous holds for onset and small amplitude conditions. At normal operating amplitude or drive ratio (5-10%) the impact of a high regenerator impedance becomes even more severe. Due to high local velocity amplitudes in the standing wave resonator acoustic loss finally becomes proportional to the amplitude raised to the power 2.8 while net engine output power remains proportional to the amplitude squared.

The ratio between output power and acoustic loss can be enhanced by increasing acoustic power gain deploying a serial sequence of regenerators as was proposed already by Ceperly [5]. This multi stage concept is experimental verified in a bypass configuration [6] but it was found that due to the short "soft spot" associated with the standing wave resonator the number of serial units to be effective is very limited and its is troublesome to reach the correct phase even in two regenerator units.

3 Hybrid geometry with traveling wave feed back

For low operating temperature engines the limitations outlined in the previous section requires an alteration of the acoustic geometry to avoid high local amplitudes and to allow multiple regenerator units. Thereby of course the next partially well known conditions has to be fulfilled

- absolute value of the regenerator impedance should be enhanced (reduced velocity) with respect to $\rho.c$
- phase between pressure and velocity in the regenerator should be close to zero or slightly negative
- in at least a part of the feedback loop a near travelling wave should be maintained

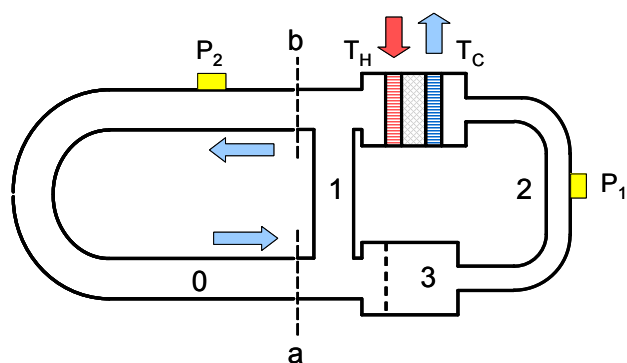An example of such a geometry is given in Figure 2

Figure 2 Alternative geometry with travelling wave feed back loop (not on scale).

The geometry depicted in Figure 2 actually is a bypass geometry [2] with the standing wave resonator replaced by a travelling wave feedback loop like [5]. In this configuration a heat pump can be placed in series with the engine or inserted in section 3 which also contains a membrane for streaming suppression.

Operation can be explained by splitting the configuration of Figure 2 at reference planes a and b and considering the section with regenerator and heat exchangers as an active acoustic 2-port as is depicted in Figure 3.
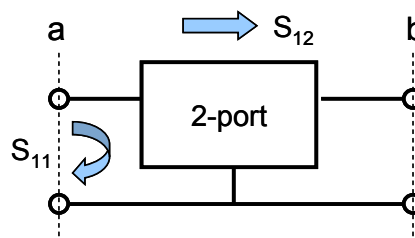

Figure 3 2-port representation with scattering(s) parameters of the regenerator, hex and bypass section.

Figure 3 shows the relevant[2] scattering parameters of this 2-port which are input reflection (s_{11}) and forward gain[3] (s_{12}). When output of the 2 port is feed back to the input port oscillation will occur if

- net forward power gain ≥ 1
- phase delay of the 2-port plus feed back loop is $2.\pi$ ($= \lambda$)

By tuning the length and diameters of bypass (section 1) and regenerator branch (section 2 and 3) the impedance at the input terminal (a) could be matched to the impedance of the feed back loop (0) or, the other way round, the diameter of the feed back loop can be adapted to match to the input impedance of the (active) 2-port

Both options result in a near travelling wave in the feedback loop which minimize the ratio between power loss and transferred or feedback power.

An example of the such a matched input impedance for a one stage engine is given in Figure 4.

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[2] A linear 2-port is described by four complex numbers per frequency

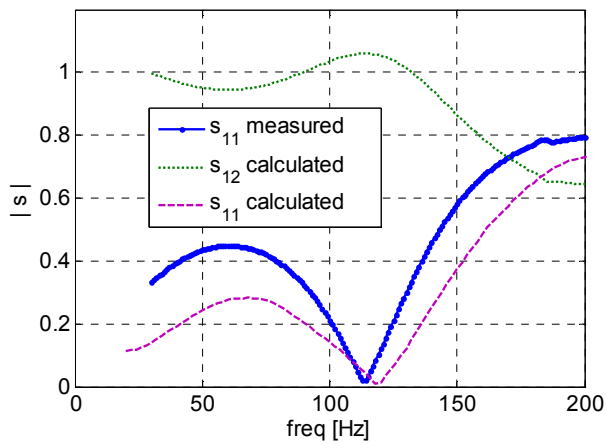[3] Forward power gain $|s_{12}|^2 \approx T_H / T_C$

Figure 4 Measured input reflection [7] and calculated input reflection and forward gain for a one-stage configuration.

Figure 4 shows that the regenerator-hex section represented by the two-port has a reflection minimum around 117 Hz while the forward gain here exceeds one. This means that oscillation could occur if the length of the feedback loop plus the acoustic length of the 2-port ($\approx 0.8\ \pi$) equals an integer multiple of $2.\pi$. Because reflection at this frequency is close to zero a near travelling wave will exist in the feedback loop.

The calculated regenerator impedance for the one-stage engine at cold and hot side is respectively $6.0\ \rho.c \angle\ -16°$ and $3.9\ \rho.c \angle\ -15°$ which are quite low values as compared with a typical bypass or torus configuration.

Note that gas velocity in the regenerator in addition is reduced by enlarging the cross-sectional area.

Other benefits of this hybrid configuration

- due to the relative low regenerator impedance the "soft spot" is much longer which allows for simple cascading two or more regenerator units (heat pump as well as second or third engine) in the same branch
- regenerator units of engine and heat pump share the same branch so only one membrane (or other provision) is needed for streaming suppression which besides can be mounted on a convenient position.
- opposite to the bypass or torus geometry regenerator impedance is hardly dependent of flow resistance allowing optimizing (means reducing) regenerator length and flow resistance without affecting timing (phase).

4   Experimental verification

In order to verify the benefits of the proposed hybrid configuration a two stage engine is build according tot the layout given in Figure 5
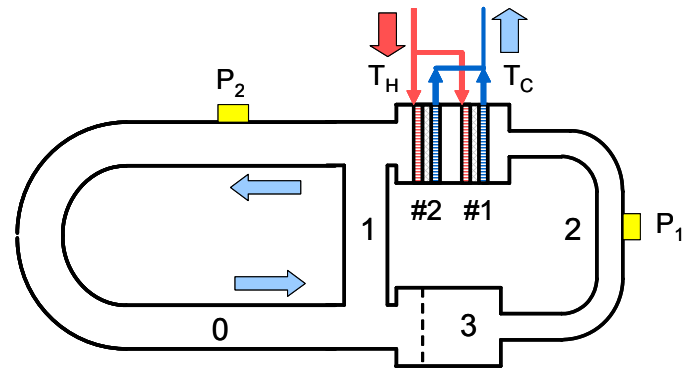

Figure 5 Layout of the two stage engine

The layout is similar to the one stage engine. Only a slight adaptation of the length of section 2 and 3 is required to get the input impedance matched again to the feedback loop. Details of the two stage engine are shown in Figure 6.
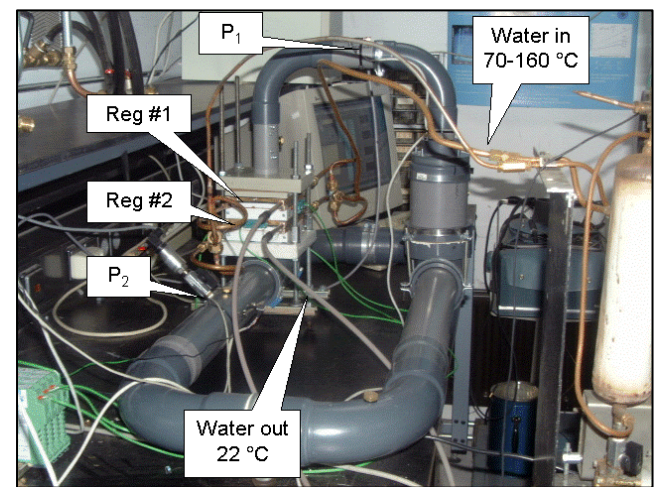

Figure 6 Experimental setup of the two stage engine.

The engine consist of two identical regenerator units ($A_0 = 0.012\ m^2$) spaced apart 30 mm. Both equipped with heat exchangers for heat supply at high temperature (T_H) and heat removal at low temperature (T_C). All heat exchangers are manufactured by soldering 3 screens copper gauze (75 μm wire diameter and porosity 80%) to 5 mm water tubes spaced 10 mm apart.

Regenerators are made from 12 screens stainless steel gauze having a wire diameter of 80 μm ($\approx \delta/3$) and a volume porosity of 73 % resulting in a normalized relaxation time ($\omega\tau$) of 0.09.

Heat exchangers and regenerator are clamped between spacers made from high temperature plastic. This sandwich construction   allows for easy changing the number of stages.

Feedback, bypass and regenerator branch are made from standard pvc tubing of respectively 75 mm and 50 mm. Section 3 is made from 110 mm pvc tube and holds also a membrane for streaming suppression.

Acoustic power is measured in the feedback loop at P_2 as well as in the regenerator loop at P_1 using the pressure gradient as a measure for the acoustic velocity. This method is common practice for acoustic intensity measurements into open air (e.g. Brüel & Kjær). Due to the small spacing

required between the sensors (≈ 60 mm) acoustic power can be measured in short sections. Acoustic power measurements this way are less sensitive to diameter changes or other irregularities as compared with the two microphone method.

To stay close to the final applications the setup is powered by a dedicated gas fired water heater which can heat water up to 160 °C (10 bar). Process heat is removed to a car radiator placed outside the building.

To check for timing, in- and output impedance of the setup is calculated and found to be 6.1.ρ.c ∠ -29.9° and 4.9.ρ.c ∠ -25.3° for regenerator unit #1 and 5.3.ρ.c ∠ -10.6° and 4.1.ρ.c ∠ -4.7° for unit #2 which indicate near optimal timing conditions in both units.

Most important requirement for a low temperature engine is a low onset temperature. Another relevant parameter is the increase of required temperature with acoustic power through the regenerator which should be minimal. The measured results for the two stage engine are given in Figure 7.
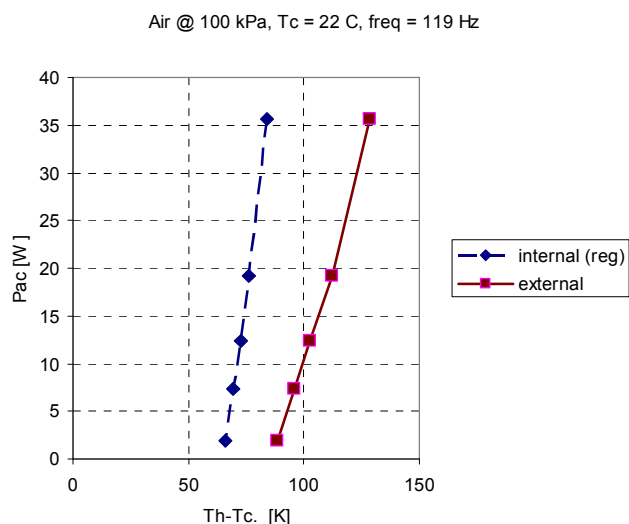

Figure 7 Measured acoustic regenerator input power (P_1) versus the internal (across the regenerator) and external applied temperature difference.

Figure 7 shows an external applied onset temperature difference of 85 K. The average regenerator temperature difference at onset is 65 K. The steep slope of the "power / ΔT" curve indicate little turbulence even at relative high acoustic power levels for air at atmospheric pressure.

The growing difference between temperature across the regenerator and the external applied temperature difference is due to the limited heat transfer of the heat exchangers. Note that the slope of both curves become steeper at rising power due to the increasing heat transfer rate in regenerator (ωτ) as well as in the heat exchangers.

At an external water temperature of 150 °C (ΔT_{ext} = 128 K) acoustic power measured at the input of the first regenerator (P_1) is 35 W which is close to the calculated value of 36.6 W. The measured acoustic power in the feedback loop (P_2) equals 78 W. Pressure amplitude in the feedback loop at P_2 is 3480 Pa. For a tube diameter of 75 mm this corresponds with an acoustic impedance of 343 N.s.m^{-3} which is close to the characteristic value for air at 98 kPa (ρ.c ≈ 400 N.s.m^{-3})

confirming the presence of a near travelling wave in this section.

5   Integral system

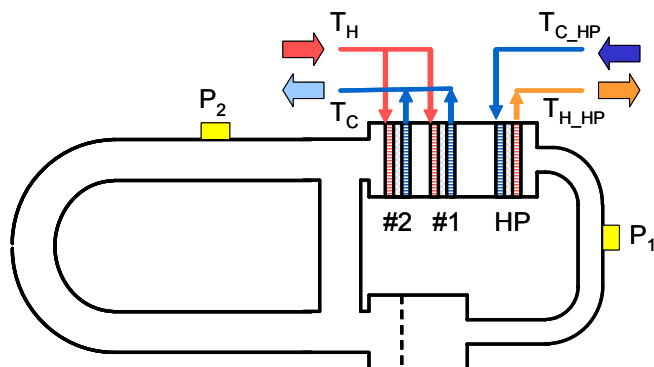The layout of an integral system based on the hybrid configuration is given in Figure 8.

Figure 8 Integral system build up of a two stage engine plus heat pump

The heat pump (HP) is placed at the input of the engine (at #1). Screens and heat exchangers are the same as used in the engine except for the regenerator length which is doubled using 24 screens. Note that opposite to the torus or bypass configurations the cold side of the heat pump now "looks" to the ambient temperature heat exchanger instead of to the heated side. This will significantly reduce the unwanted heat load of the cold side of the heat pump.

After some adaptation of the section lengths 2 and 3, reflection (s_{11}) is minimized similar to Figure 4. The calculated values of the associated in- and output impedances for each regenerator unit are given in Figure 9.
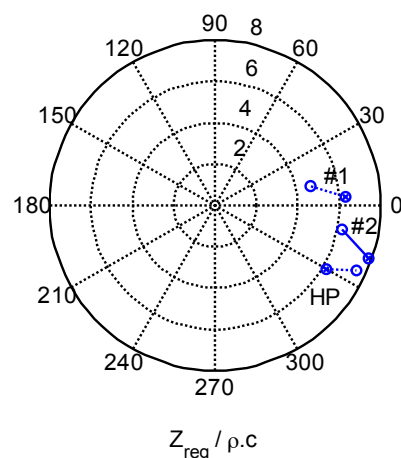

Figure 9 Calculated in- and output impedance for engine #1, engine #2 and the heat pump (⊗ denotes input impedance)

Figure 9 shows a phase for all regenerator units within +15° and -30°. This confirms that within the hybrid configuration a correct phase can be maintained in multiple regenerator units.

The absolute value of the impedance in each regenerator unit is still quite low as compared with the bypass configuration which is an unconditional stipulation for minimizing the ratio between acoustic los and output power

Unfortunately lack of time causes that at the time of writing this paper (April 2008) the heat pump was not implemented yet.

However, experimental and simulation results so far in lowering both acoustic loss an operating temperature are encouraging and in line with theory.

Final results and detailed measurements on a hybrid low operating temperature integral system including heat pump will be presented at the conference and can be found at that time on www.aster-thermoacoustics.com .

6   Conclusions so far

- In standing wave type resonators high acoustic loss as compared to amplified loop power has turned out to be a fundamental limitation at low operating temperature and high regenerator impedance.

- An alternative hybrid configuration more adapted for low operating temperatures is proposed which actually combines the bypass geometry with a low loss travelling wave feed back loop.

- A low external applied onset temperature is demonstrated and the steep curve of acoustic power versus operating temperature indicate for low acoustic loss.

- The proposed hybrid configuration allows for simple cascading multiple regenerator units including heat pump and needs only one membrane or other provision for streaming suppression which besides can be mounted on a convenient position.

Acknowledgement

References

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