Bi-directional turbines for converting acoustic wave power into electricity

Kees de BLOK[1], Pawel OWCZAREK[2], Maurice-Xavier FRANCOIS[3]

[1] Aster Thermoacoustics, Smeestraat 11, 8194LG Veessen, The Netherlands
[2] Future Energy Management, Weegschaalstr.45, 7521cc Enschede, The Netherlands
[3] Hekyom, 3, rue de la Croix Martre, 91120 Palaiseau, France

e-mail address of corresponding author: c.m.deblok@aster-thermoacoustics.com

Abstract

Converting acoustic power from thermoacoustic engines into electricity using resonant linear alternators is a common approach but has severe limitations in terms of cost and scalability. The paper will describe in detail the experiments and measurement results on various bi-directional turbines in high frequent acoustic flow fields and at elevated mean pressures. The conclusion from the experiments so far is that this type of turbine could be a cost effective, scalable and efficient device for converting acoustic wave energy into rotation and from there into electricity.

1. Introduction

Thermoacoustics is a key enabling technology for the conversion of heat into acoustic power. Nowadays thermoacoustics in itself is well understood and has proven to be a generic applicable and efficient conversion technology. For practical and economic viable applications however, two issues have to be solved in a practical and cost effective way. (1) heat to be converted need to be supplied at high or medium temperature and rejected at a lower temperature from the process with minimal temperature loss and (2) high acoustic (wave) power generated has to be converted into electricity. Focus of this paper is on the conversion of the generated acoustic power into electricity.

Converting acoustic power from thermoacoustic engines into electricity using resonant linear alternators is a common approach but has severe limitations in terms of cost and scalability. The increase of moving mass with increasing power finally sets a practical limit to the output power caused by the extreme periodic forces in the construction and the difficulty to maintain clearance seals (≈ 70 μm) stable over large stroke amplitudes.

Linear alternators make use of the pressure variation of the acoustic wave. There is however no physical reason why not using the periodic velocity component of the acoustic wave. A way to convert such a bi-directional flow into rotation is known from shore and off-shore electricity production plants based on an oscillating water column (OWC) [1,2,3]. In this type of power stations, waves force a water column in a chamber to go up and down. This chamber is connected to the open atmosphere and the periodic in- and outflow of air drives a bi-directional turbine of which the rotation direction is independent of the flow direction. In a thermoacoustic system similar periodic flow conditions exist, so in principle, bi-directional turbines can be deployed for conversion of acoustic wave motion as well.

In OWC plants, using air at atmospheric pressure, the reported conversion efficiency is in the range of 25 to 40%. This modest efficiency is because of the performance of (bi-directional) turbines depends on de density of the working fluid. Thermoacoustic engines, fortunately operate at elevated mean pressures up to 40 bar and the increased gas density will raise turbine efficiency up to 85%.

This makes bi-directional turbines a low cost and scalable candidate for converting the generated acoustic power into electricity. For testing and validating of this option a few bi-directional impulse turbines were are designed and build using 3-D rapid prototyping. In parallel, a numerical model was developed. From the results we could estimate the performance based on the pressure distribution on the blade and the measured performance.

The paper will describe in detail the experiments and measurement results on various bi-directional turbines in high frequent acoustic flow fields and at elevated mean pressures.

Results so far are encouraging. The conclusion from the experiments is that this type of turbine could be a cost effective, scalable and efficient device for converting acoustic wave energy into rotation and from there into electricity.

2. Description of the turbine under test

A bi-directional turbine consists of rotor with symmetric blade shape enclosed by two guide vane sets. The rotor is connected to a brushless electromotor used as generator. The dimensions and assembly is shown in Figure 1and Table 1.

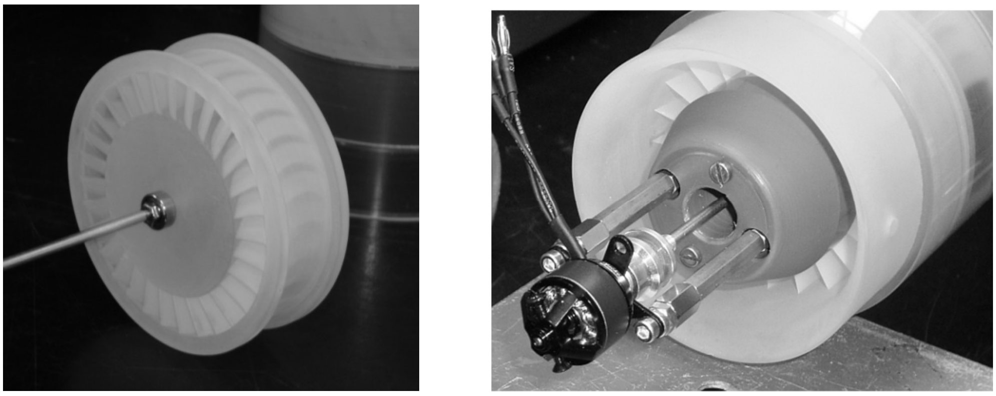

Figure 1 Rotor of the bi-directional turbine and the assemble with guide vanes and generator

Table 1 Dimensions of the turbine

Rotor diameter	84	mm
Blade height	6	mm
Blade chord	25	mm
Blade thickness	5.5	mm
Mutual space between blades	2.1	mm
Number of blades	31	

The generator is a brushless outer runner type A10-9L made by Hacker [4]. The output of the generator is connected to a set of 10W resistors which can be set to 1 to 5 Ω. Efficiency of this motor as generator is measured separately in order to be able to estimate the actual shaft power of the rotor

The acoustic source, generating the periodic flow, consist of a 12” 500W bass speaker with a maximum cone stroke of about 50mm p-p driven by a function generator and power amplifier. The 300 long coupling tube between speaker and turbine is equipped with a dpdx probe for measuring the acoustic power towards the turbine. Output power is measured by the electric power dissipated in the load resistor of the generator corrected for the known generator efficiency to yield the shaft power.

The mechanical turbine output power (P_m) at the rotor shaft is given by

$$P_m = To.\omega \qquad (1)$$

In which To is the torque and ω the rotational speed. Torque and rotational speed are both functions of gas velocity so output power is proportional with gas velocity squared. For thermoacoustic applications the gas velocity and pressure amplitude are related by the acoustic impedance. Velocity amplitude of a traveling in an acoustic wave guide (tube) is given by,

$$v_a = \frac{p_a}{\rho.c} \qquad (2)$$

In which p_a is the pressure amplitude, ρ the gas density and c the speed of sound.

Torque (To), pressure drop (Δp), flow coefficient (ϕ) and rotor efficiency (η_r) can be calculated using the expressions given in [3] which are summarized below.

$$To = C_T.0.5.\rho.(v_a^2 + U_R^2).b.l_t.z.r_R \qquad (3)$$

$$\Delta p = C_A.0.5.\rho.(v_a^2 + U_R^2).b.l_t.z.v_a \qquad (4)$$

In which ρ is the gas density, v_a the gas velocity in the blade section, U_r the circumferential velocity at mean radius of the rotor (r_R), b the blade height, l_t the blade chord and z the number of blades. These gas and geometric parameters can be used to dimension the turbine. The flow coefficient (ϕ) is defined as the mean axial flow velocity over the circumferential velocity $\phi = \frac{v_a}{U_R}$. Rotor efficiency is given by [ ] $\eta_r = \frac{C_T}{C_a.\phi}$

The torque coefficient (C_T), the input coefficient (C_A) represent the effect of blade shape, blade angle, aerodynamic losses, tip clearance etc. Both are a function of the Reynolds number and flow coefficient (ϕ).

Because of the nature of impulse turbines optimum performance is obtained when the circumferential speed equals the gas velocity ($\phi \Rightarrow 1$). In that case for an ideal turbine $C_T = C_A$. The performance of various impulse turbines therefore can be evaluated by measuring (or calculating) the C_T and C_A values as a function of ϕ.

Bi-directional turbines operating in acoustic flow conditions largely differ from those in OWC plants. In OWC plants the time between a change of flow direction is relatively long (10-30s) and is not constant in amplitude and interval time. This means that gas displacement through the turbine is large as compared to the blade chord leaving sufficient time for flow to develop during each half period even if the flow is irregular.

In acoustic wave motion the period time is short (e.g. 0.02s at 50Hz) but perfect regularly. As a consequence of the short period time the gas displacement in the turbine could be shorter than the blade chord. Consequently the short gas displacement prevents the flow to reach a steady state which will affect the C_T and C_A values in a positive way and from that the turbine performance.

On this turbines a series of measurements is performed of which the most remarkable results presented here is that bi-directional turbines operate well under high frequent acoustic flow conditions. From the measured data and the expressions given the rotor efficiency is measured and the result is plotted in Figure 2 for increasing acoustic input power at various frequencies.

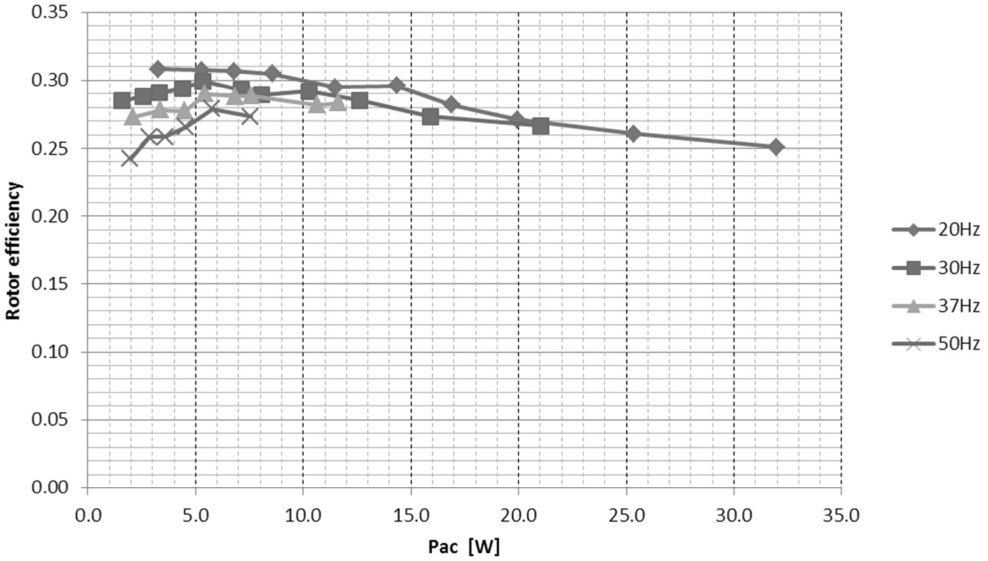

Figure 2 Measured rotor efficiency for the small bi-directional turbine

Initially, rotor efficiency for continuous flow is measured to be 23%. **Fout! Verwijzingsbron niet gevonden.** Figure 2 shows that rotor efficiency under AC flow conditions has clearly improves. It should be noted that the relatively strong fall-off with frequency at low power caused by the fact that displacement amplitude becomes in the range of the open space between rotor and guide vanes. For example, at low frequencies and 7W acoustic power the peak to peak gas displacement could be as large as 100mm. At 50 Hz and 2W the gas displacement is reduced down to only two times the gap width between rotor and guide vanes. Assuming that flow in the gap does not contribute to the torque this could explain the declining efficiency at low power.

3. Operation at elevated pressure

The measured efficiency for the small bi-directional turbine is in line with efficiencies reported in literature for OWC turbines operated with air at atmospheric pressure. Typical values are in the range of 30-40% and this efficiency is limited by the relative low density of the air.

Turbine operated with high density fluids like water could reach efficiencies up to 95%. Fortunately thermoacoustic engines are operated at high mean pressures proportionally increasing the density and with that the turbine efficiency. The relation between rotor efficiency and fluid density is given in Figure 3.

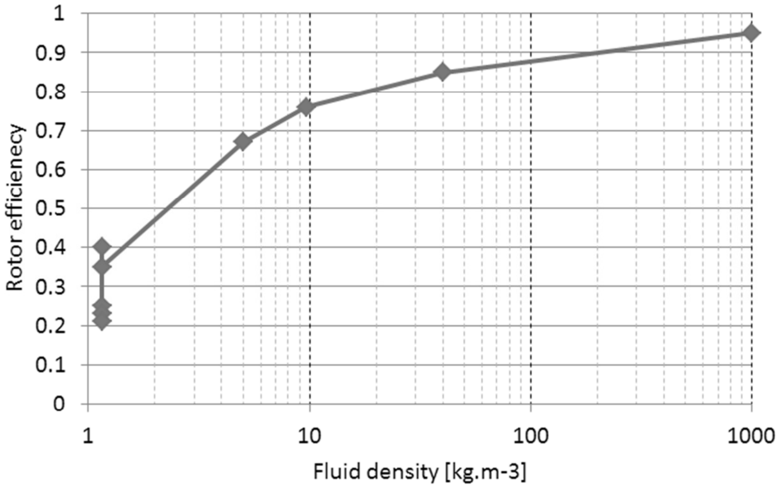

Figure 3 Turbine efficiency as a function of fluid density

Figure 3 shows that efficiency values found for bi-directional turbines operated at atmospheric pressure (≈ 1 kg.m^{-3}) are typical in the range of 20-40%. At increasing density, and finally for water (1000kg.m^{-3}), efficiency could be as high as 95%.

To confirm this trend an experiment (not describes here) is performed using a larger bi-directional turbine (300mm∅). This turbine is installed in a prototype of a multi-stage 100 kW$_T$ thermoacoustic power generator (TAP) build at a paper manufacturing plant in the Netherlands [5]. The test with the turbine is performed at with air at 1 MPa mean pressure. The measured efficiency defined as the mechanical shaft power over the acoustic power in that case is measured to be 76%. This result confirms that efficiency of bi-directional turbines improves with increasing mean pressure or fluid density.

High end thermoacoustic engines typically run at elevated mean pressures up to 4MPa. So in the end, for acoustic wave energy conversion, this type of turbines could reach an efficiency up to 85%. Combined with a commercial high power 3 phase asynchronous electromotor as generator ($\eta \approx 95\%$) an overall conversion efficiency from acoustic power to electricity of 80% seems feasible. This efficiency is comparable or even better than the performance reached for small scale linear alternators. Even more important, however is that bi-directional turbines for acoustic wave energy conversion eliminate the limitations in power and cost of linear alternators paving the way for up scaling thermoacoustic system to power levels in the MW range.

4. Conclusion

The feasibility of bi-directional turbines for the conversion of acoustic power into rotation and from there into electricity is experimentally investigated.

For a small axial bi-directional turbines a series of measurements is performed which confirms that bi-directional turbines operate well under high frequent acoustic flow conditions.

At elevated mean pressure as is common in thermoacoustic engines a rotor efficiency of 85% seems feasible

The bi- directional turbine as acoustic to electricity converter can be scaled up in power unlimited so eliminating the limitation in power and cost of linear alternators and paving the way for up scaling thermoacoustic system to power levels in the MW range.

5. References

[1] Bruno Pereias at all. “An improved radial impulse turbine for OWC”.
Renewable Energy 36 (2011) 1477-1484.

[2] A Thakker , J Jarvis, A Sahed. “Quasi-steady state analytical model benchmark of an impulse turbine for wave energy extraction” International journal of rotary machinery Volume 2008, Article ID 536079, 12 pages

[3] Toshiaki Setoguchi at all. “Current status of self- rectifying air turbines for wave energy conversion”
Energy Conversion and Management 47 (2006) 2382-2396.

[4] www.hacker-motor-shop.com

[5] Kees de Blok, “multi-stage traveling wave thermoacoustics in practice”, 19th International Congress on Sound and Vibration, Vilnius, Lithuania, July 8-12, 2012