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Abstract

A model of a musical event venue is devised to convert the sound energy produced by a source in a dome-shaped air cavity surrounded by water into thermal energy to vaporise it and run a steam turbine. By consideration of acoustic impedance's and attenuation within relevant mediums, the time-scale after which steam is produced is found to be extremely large ($t \sim 2 \times 10^7$ years). The potential of this model is thus limited unless optimised by design and choice of materials.

Introduction

Acoustic damping in a medium causes the gradual attenuation of sound energy by molecular absorption and scattering [1], leading to a temperature rise.

A sound source centred in a spherical, dome-shaped shell with air cavity of radius r is constructed by a material of thickness d, where musical events can occur; illustrated by Figure 1. Surrounding this dome structure is a comparatively, large volume of water, contained by arbitrary physical dimensions. It is assumed that such a structure is structurally stable and the water is highly insulated. By utilising this model the feasibility of the attenuation process to run a steam turbine is investigated.

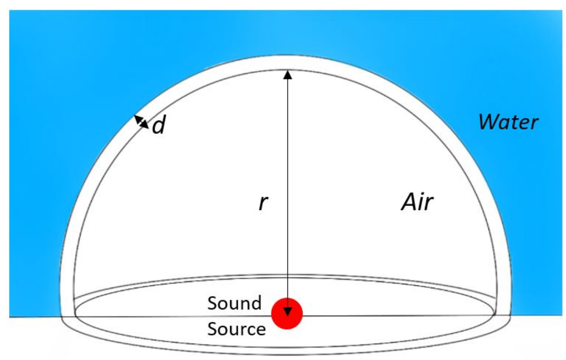

Figure 1: Spherical dome shell of arbitrary material and thickness, d, is surrounded by water and contains an air cavity with centred sound source.

Theory

Due to reflection, only a fraction of the propagating sound encountering the air-dome and dome-water interface is transmitted, T_{ad} and T_{dw}, respectively. The subscripts ad and dw, refer to the air-dome and dome-water interface, respectively. Eq (1) quantifies the transmission ratio, T, which is related to the acoustic impedance of the first and second medium, Z_1 and Z_2, respectively, within which the wave propagates.

$$T = 1 - \left(\frac{Z_1 - Z_2}{Z_2 + Z_1}\right)^2 \qquad (1)$$

Attenuation due to acoustic damping occurs within the air and along the dome shell of thickness, d, until the dome-water interface is encountered. Attenuation of the sound power, P, is an exponential relation governed by Eq (2), where P_i is the initial power, α is the acoustic damping coefficient associated with the medium, and Δx is the distance traversed by the sound wave.

$$P = P_0 e^{-\alpha \Delta x} \tag{2}$$

Thus combining these effects, the fraction of the initial power emitted by the sound source, P_0, which is transmitted into the water, P_w, is given by Eq (3), where the subscripts a and d refer to the air and dome, respectively.

$$\frac{P_w}{P_0} = T_{ad} T_{dw} e^{-(\alpha_a r + \alpha_d d)} \tag{3}$$

P_w is assumed to be entirely absorbed by the water before collision of attenuating sound waves with the boundaries containing the water.

Discussion

To evaluate $\frac{P_w}{P_0}$ and assuming music with average frequency of ($\sim 4000 Hz$), $\alpha_a = 3\ dBm^{-1}$ [2] for air and $\alpha_d = 0.12\ dBm^{-1}$ for a glass dome. The latter is a linear combination of the scattering and absorption coefficients from [3] and [4], respectively. Utilising $Z_a = 400 kgm^{-2}s^{-1}$ [1], $Z_d = 13.1 \times 10^6 kgm^{-2}s^{-1}$ [5] and $Z_w = 1.5 \times 10^6 kgm^{-2}s^{-1}$ [1], for air, glass and water, respectively, alongside Eq (1), T_{ad} and T_{dw} are evaluated to be 1.22×10^{-4} and 0.369, respectively. Thus, to 3 significant figures:

$$\frac{P_w}{P_0} = 6.94 \times 10^{-5} (e^{-(3r + 0.12d)}) \tag{4}$$

Eq (4) indicates an exponential decay relation between the proportion of the initial power emitted by the sound source that is transmitted into the water. For a given dome thickness, d, increasing the dome radius, r, results in $\frac{P_w}{P_0}$ diminishing rapidly. Thus, one could maximise P_0 to a safe level to maximise P_w. For a practical event venue size ($r = 2.4m$, $d = 30cm$ and $M = 1000kg$) $\frac{P_w}{P_0} \sim 5 \times 10^{-8}$, which indicates a highly inefficient model. Assuming water temperature of $300K$ and $P_0 = 75 Js^{-1}$, steam production would occur after an extremely large time-scale ($t \sim 2 \times 10^7$ years). This t value would only increase for higher M needing to be vaporised because the energy required is directly proportional to M, which further limits the potential of this model. In reality t would be larger yet because it was assumed the water is heated uniformly and highly insulated, which is unlikely for large volumes of water and over large time scales, respectively. The scattering due to interface roughness is also not considered, which would increase the attenuation coefficient and hence t.

Therefore, further investigation is required on the acoustic impedance's and attenuation coefficients of materials, physical dimensions and properties of boundaries within the model such that P_w is optimised for efficiency and t is minimised.

Conclusion

A model was devised where a sound source could vaporise water to run a steam turbine. Attenuation consideration within the various mediums and reflections at boundaries reveals the time-scale after which steam is produced is much too large ($t \sim 2 \times 10^7$ years) for this to be a practical and efficient method of recycling energy.

References

[1] P. Regtien and E. Dertien, *Sensors for Mechatronics* (Elsevier, Amsterdam, 2018), 2nd ed., p. 270.

[2] H Shankar and P. S. Pagel, *Potential Adverse Ultrasound-related Biological Effects*, Anesthesiology 115(5): 1109-24.

[3] Z. Sü and M. Çalıskan, *Acoustical Design and Noise Control in Metro Stations: Case Studies of the Ankara Metro System*, Building Acoustics 14(3): 231-249.

[4] X. Zeng, C. L. Christensen and J. H. Rindel, *New Methods of Scattering Coefficients Computation for the Prediction of Room Acoustic Parameters*, (2005).

[5] `https://www.signal-processing.com/table.php` [Accessed 1 November 2021]