Thermophone or the future of ultrasound transducers: Modelling of thermoacoustics generation in porous materials

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Electroacoustic transducers along with piezoelectric devices are the most widely used methods for acoustic sound generation in gas and liquids. A mechanical movement of a membrane induces fluid vibration thus creating an acoustic wave. The thermoacoustic process on the other hand uses fast paces temperature variations in a sample to excite the fluid (generally air). The rapidly changing temperature generate a compression expansion of the air and thus creates an acoustical wave. Such materials are called thermophones. They were discovered in the same time period as traditional electroacoustic transducers but their limited efficiency coupled with the technological limits of fabrication prevented scientific craze at the time. In 1999 a new thermophone was presented with a significant improvement compared to the samples used a century prior. This article coupled with the newly found ease of access to complex fabrication process of nanomaterials rekindle the interest in thermoacoustic for audio purposes. In this work a thorough literature review is presented and a novel multilayer model for thermoacoustic sound generation is derived. This model was solved for plane wave, cylindrical wave and spherical wave generation. Another model based on a two temperatures hypothesis for plane wave generation is also solved to represent more accurately the generation of thick porous thermophones. An extensive analysis of those models allowed for a detailed understanding of the thermoacoustic sound generation: its strengths, weaknesses and differences with traditional speakers. Lastly, experimental investigations of porous carbon foams in partnership with CINTRA Singapore are presented. Validation of the models and insights about the handling of such flexible and lightweighted but fragile samples are presented as well at their potential applications for scientific or commercial purposes as broad band sensors.

AIMAN-FILMS

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Modelling of thermoacoustics generation in porous materials

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Thermoacoustis and Thermophones

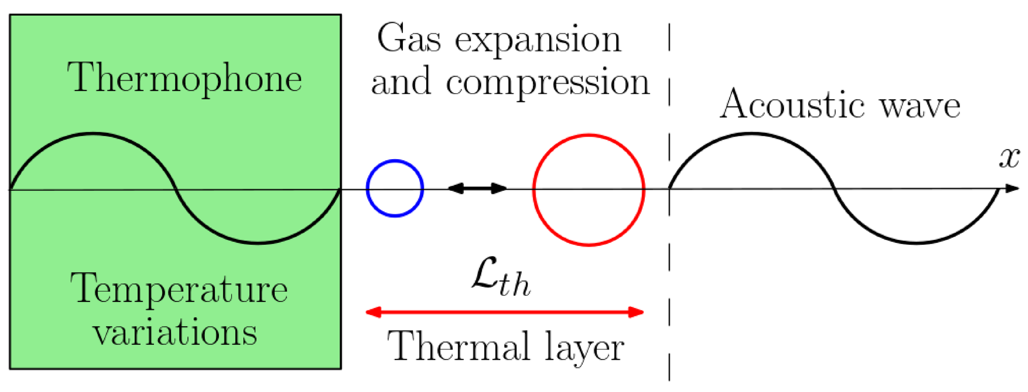
Thermoacoustic principle

- **Thermoacoustics**

The **thermoacoustic** process uses **fast paces temperature variations** in a sample to excite the fluid (generally air). The rapidly changing temperature generate a **compression expansion of the air** and thus creates an **acoustical wave**. An **electrical current** or a **laser** can be used to generate such temperature variations.

- **Thermophones**

Materials displaying thermoacoustics capabilities posses a **low thermal capacity** and a **high thermal conductivity** and are called **thermophones**. Since no resonating part are involved in the process the generation is **wideband**



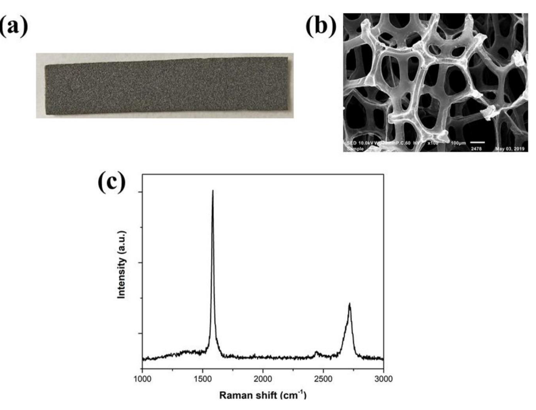
Schematic representation of the thermophone sound generation

3D-C Fabrication and Acoustic Experiments

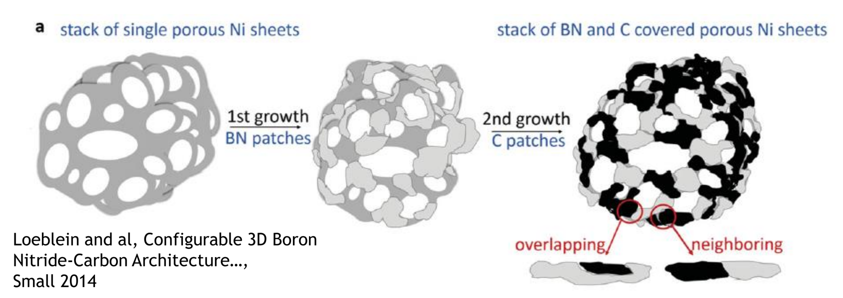
- **In Partnership with CINTRA Singapore and Thales**

Sample Fabrication in CINTRA

- **Carbon based foam (3D-C)**
  - Fabricated using **TCVD**
  - **Pristine** Carbon quality
  - **High Specific Surface Area**
  - **Lightweight**
  - **Flexible** Geometry
  - **Low Production Costs**



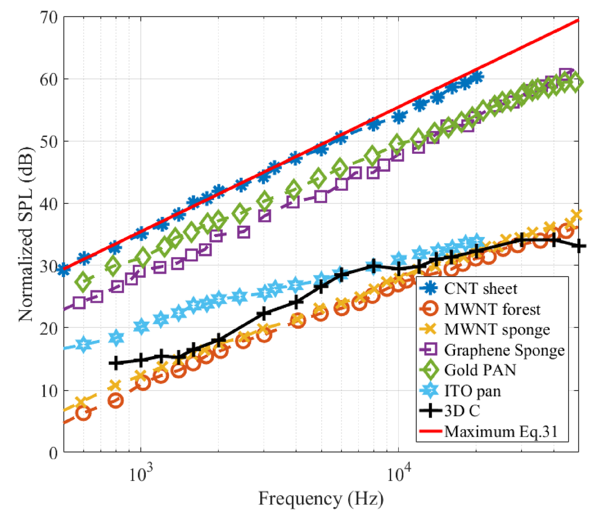
Chemical characterization of 3D-C. (a) Visual image of 3D-C; (b) SEM micrograph of 3D-C; (c) Raman spectrum of 3D-C.



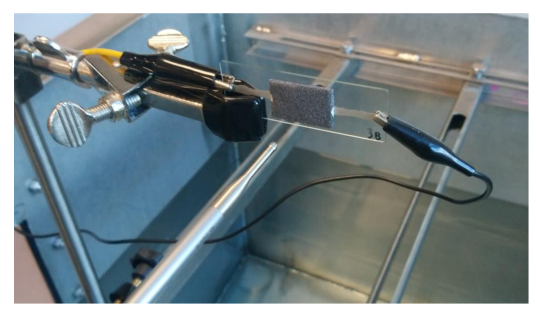
Thermal Chemical Vapor Deposition (TCVD) method used for nanomaterial fabrication

Acoustic Experiments

- **Experimental set up and early conclusions**
  - **Airborne** and **Underwater** Acoustic Measurements
  - **Power driven** sound generation
  - **Non Linear** sound generation process
  - Measured spectrum from **100Hz to 1MHz** (using laser interferometry)
  - **Low** and **constant Impedance** up to MHz
  - Rapid **Thermal Cooling** due to the porous structure
  - **Comparable** results with the **literature** (spectrums **normalised** for 1W at 1m)



Comparison of 3D-C with other thermophones from the literature.



Visual image of 3D-C mounted in set-up.

THEORETICAL MODELS AND ANALYSIS

Equations and Models based on the Conservation Equations

- **One temperature model for continuous media (1T)**
- **Two temperatures model for porous media (2T)**

Temperature Variation, Particle Velocity, Pressure and Heat Flux.

In 1T the parameters are continuous in every media

- $T = Ae^{-ik_{ac}x} + Be^{+ik_{ac}x} + Ce^{-\theta_{th}x} + De^{+\theta_{th}x}$
- $\tilde{p}(T), v(T), q(T)$

In 2T the solid has its own parameters added to the ones from 1T

- $T_s = Ee^{-\theta_{solid}x} + Fe^{+\theta_{solid}x} + T_{s,0}$
- $q_s(T_s)$

Boundary Conditions

Parameter continuity between layers/media

- No reflection conditions:
  - Semi Infinite Back Medium
  - Semi Infinite Front Medium

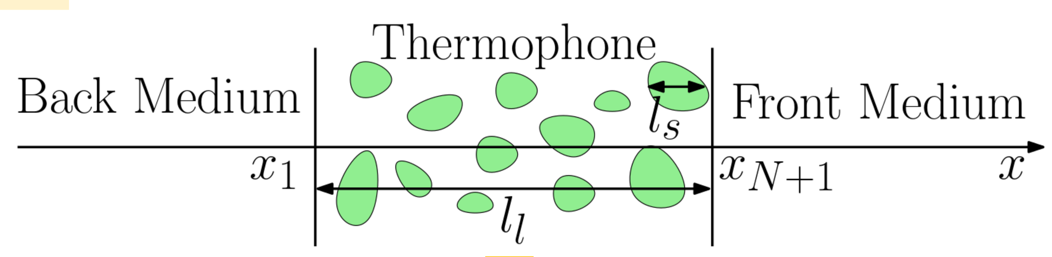
In 2T the g parameter describes the fluid/solid coupling at the interface

- $T^+ = T^-$
- $\tilde{p}^+ = \tilde{p}^-$
- $v^+ = v^-$
- $q^+ = q^- + g(T_s - T)$

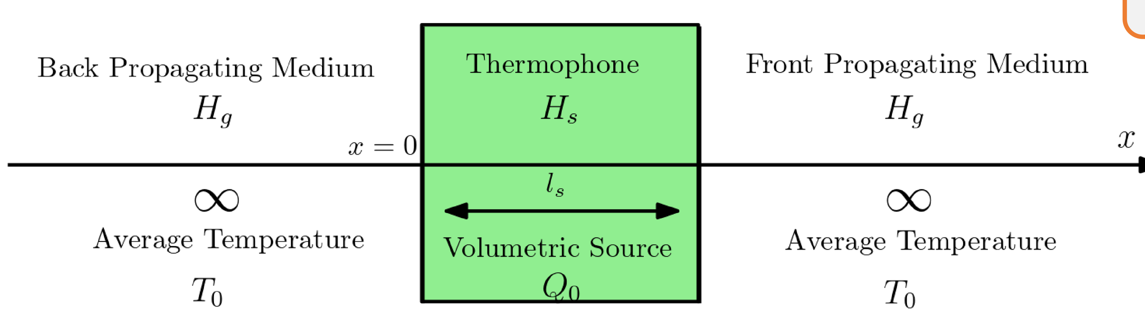
T_s does not exist and $g = 0$ in 1T

- $T_s^+ = T_s^-$
- $q_s^+ = q_s^- - g(T_s - T)$

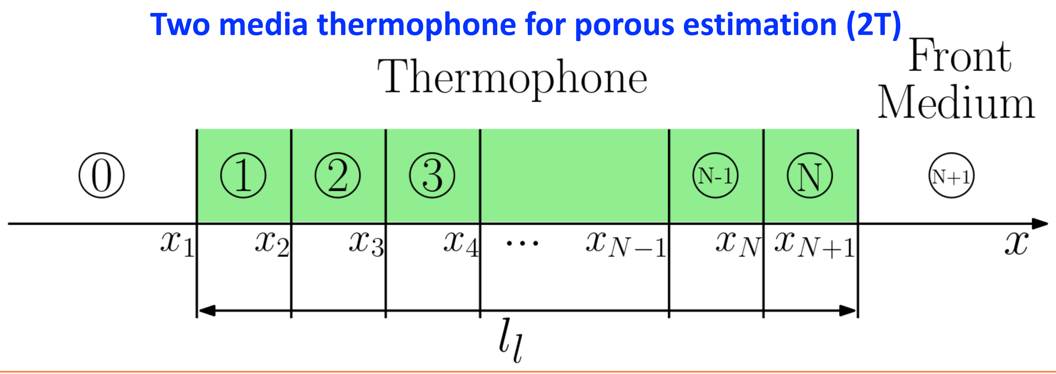
Real porous thermophone



Continuous thermophone estimation (1T)

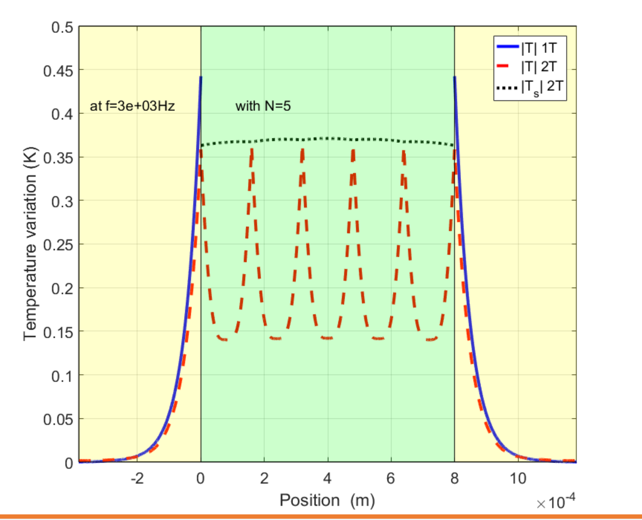


Two media thermophone for porous estimation (2T)

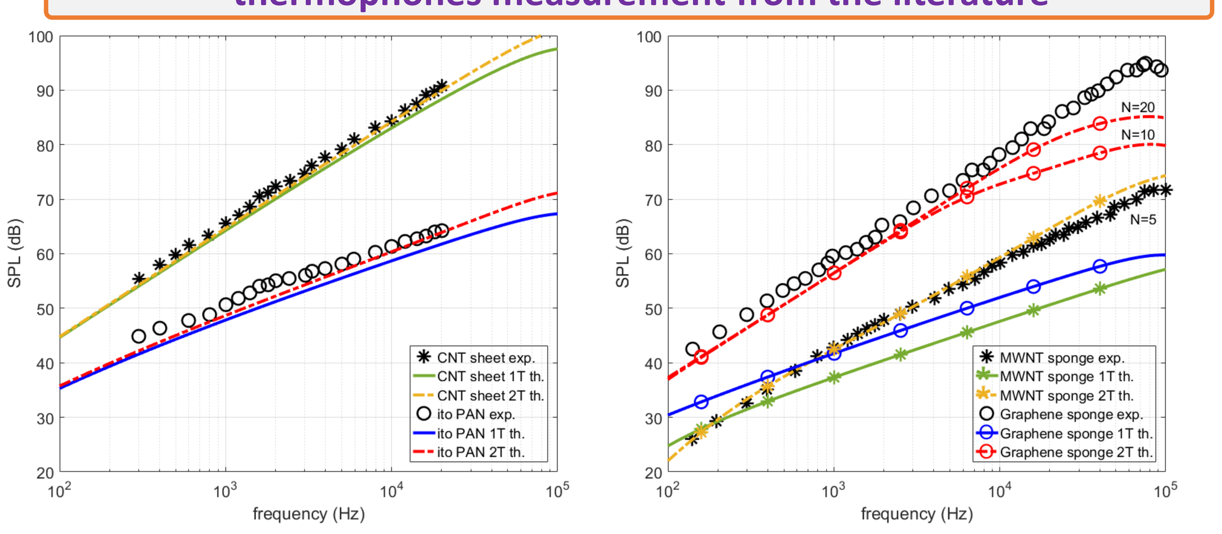


Spatial and Frequency analysis

- **Spatial representation of the temperature variation and the thermal generating layer using 1T and 2T models**

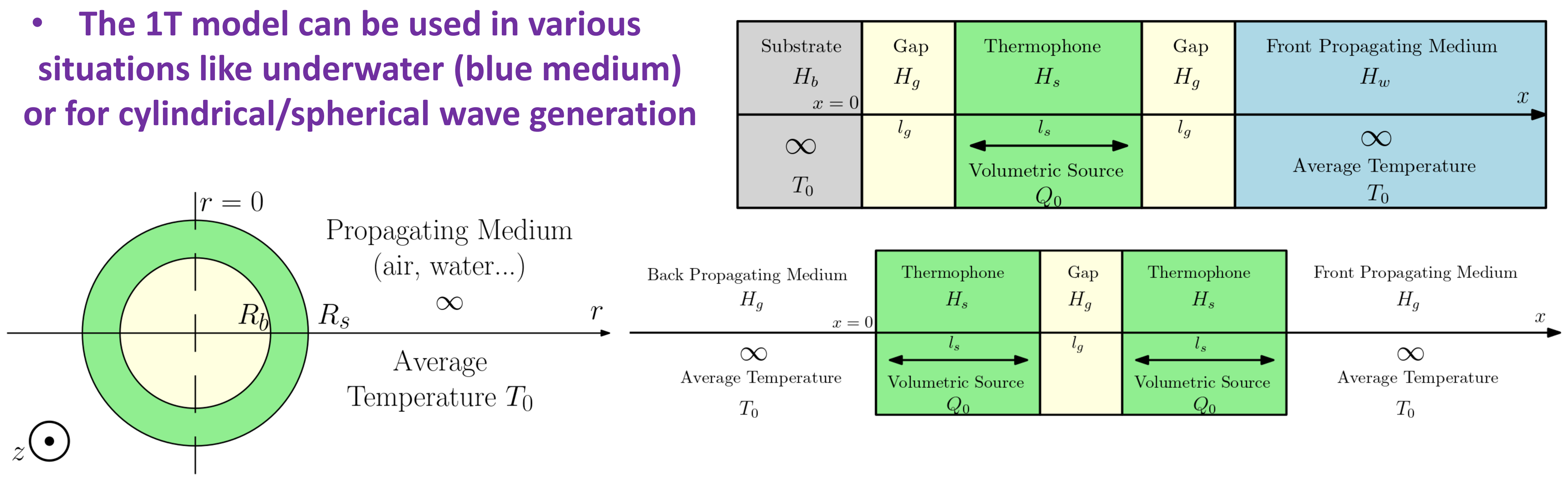


- **Comparison of 1T and 2T models for thin (left) and thick (right) thermophones measurement from the literature**



Complex Design Analysis Example

- **The 1T model can be used in various situations like underwater (blue medium) or for cylindrical/spherical wave generation**



Conclusion and Perspectives

Exchange in CINTRA Singapore in January 2020. From left to Right, Ms.Tan Dunlin, Ms.Ngoh Zhi Lin, Mr.Guiraud Pierre and Mr.Coquet Philippe.

1T

- **Flexible** design
- Solved for **plane, cylindrical** and **spherical waves** generation

2T

- **Novel** use of **2T** for thermoacoustics
- **More accurate** representation of **thick, porous materials**

- Consider **wave propagation** in **solid** media
- Consider **viscosity** of **all media**

Thermophones are promising high frequency transducers. Their flexible geometry could help create novel acoustical patterns. Otherwise thermoacoustics is also of use in non-destructive testing as medical sensors requiring broadband sensing for instance.

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- P. Guiraud, S. Giordano, O. Bou-Matar, P. Pernod and R. Lardat, **J. Appl. Phys.** 126, 165111 (**2019**), DOI: 10.1063/1.5121395
- Z.L. Ngoh, P. Guiraud, D. Tan, S. Giordano, O. Bou-Matar, E. Teo, P. Pernod, P. Coquet, R. Lardat, **Carbon** 169, 382-394 (**2020**), DOI: 10.1016/j.carbon.2020.06.045