

THALES



# Thermoacoustic sound generation model in porous nanomaterials

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# Table of contents

## ➤ I. Introduction

- Context
- Thermoacoustic Principle
  - Sound Generation process
  - Thermophones examples

## ➤ II. Theory

- One Temperature Model (1T)
  - Conservation Equations
  - Solutions and Boundary Conditions
  - Performances & Limitations
- Two Temperature Model (2T)
  - Motivation
  - Conservation Equations
  - Solutions
  - Boundary conditions
- Acoustic Diffraction

## ➤ III. Analysis

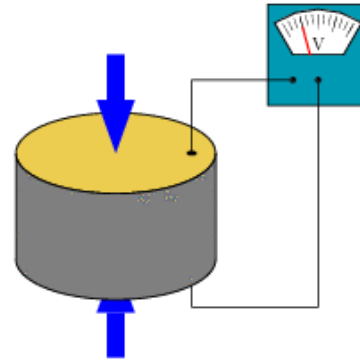
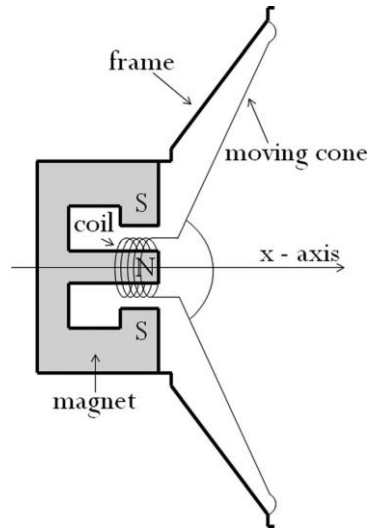
- Near Field Sound Generation
- Frequency and Power Spectrum
  - Thin Thermophone
  - Thick Thermophone

# I. Introduction: Context

## Conventional Sound Generating devices

➤ Electroacoustic transducer

➤ Piezoelectric devices



➤ Pros

- Low power driven devices
- Sound quality optimized for more than one century

➤ Cons

- Shape dependent devices
- Mechanically resonant devices

[https://www.researchgate.net/publication/277928278\\_A\\_Model\\_Updating\\_Technique\\_Based\\_on\\_the\\_Constitutive\\_Relation\\_Error\\_for\\_In\\_Situ\\_Identification\\_of\\_Admittance\\_Coefficient\\_of\\_Sound\\_Absorbing\\_Materials](https://www.researchgate.net/publication/277928278_A_Model_Updating_Technique_Based_on_the_Constitutive_Relation_Error_for_In_Situ_Identification_of_Admittance_Coefficient_of_Sound_Absorbing_Materials)

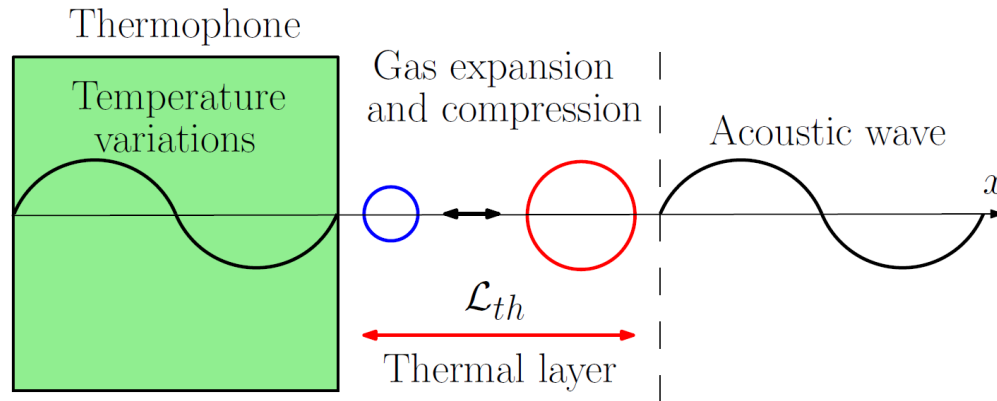
<https://fr.wikipedia.org/wiki/Piezoelectricite>

# I. Introduction: Thermoacoustic Principle

## Sound Generation process

An alternative current is applied to a material with a **high thermal conductivity** and a **low thermal capacity**.

The heat profile of the material follows the current profile and the compression dilatation of the air on the surface of the material due to **the fluctuating temperature generates an acoustic wave** whose frequency is proportional to the input frequency of the current.



### > Pros

- Generation process independent of the shape
- Wideband sound generation
- Flexible design

### > Cons

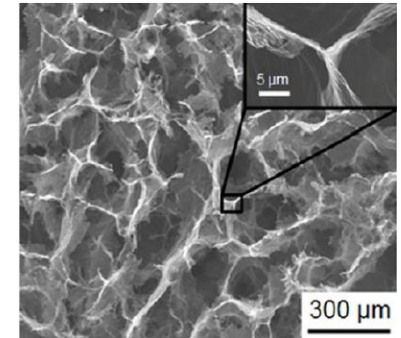
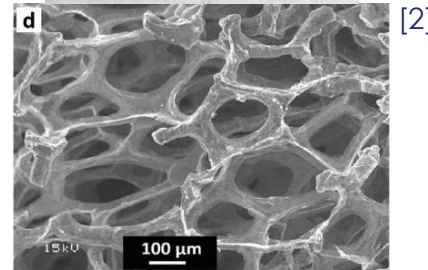
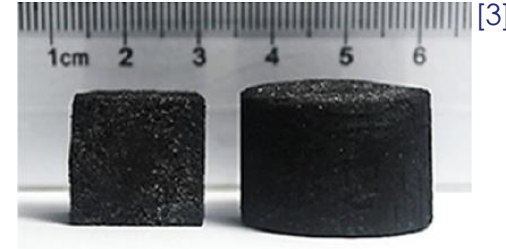
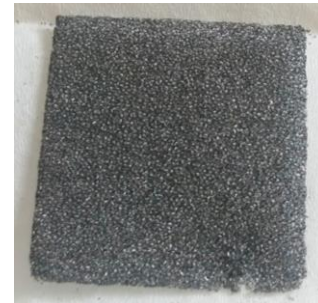
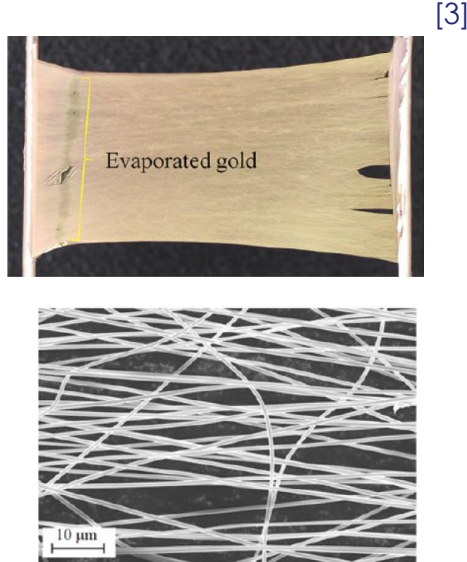
- Not efficient generation compared to conventional speakers
- New, not yet optimized, not well understood technology

# I. Introduction: Thermoacoustic Principle

## Thermophones Examples

➤ Thinfilm Thermophones (suspended nanowires, paper based, laser scribing...etc

➤ Thick Thermophones (foam, sponge... etc)



[1] Xiao et al., *Flexible, stretchable, Transparent Carbon Nanotube Thin Film Loudspeakers*, Nano Letters, 2008

[2] Loeblein et al., *Configurable 3D Boron Nitride-Carbon Architecture...*, Small, 2014

[3] Aliev et al., *Alternative Nanostructures for Thermophones*, ACS Nano 9, 2015

Réf: Thèse CIFRE Défense - le 19 août 2019

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## II. Theory: One Temperature Model (1T)

### Conservation Equations

► In a liquid

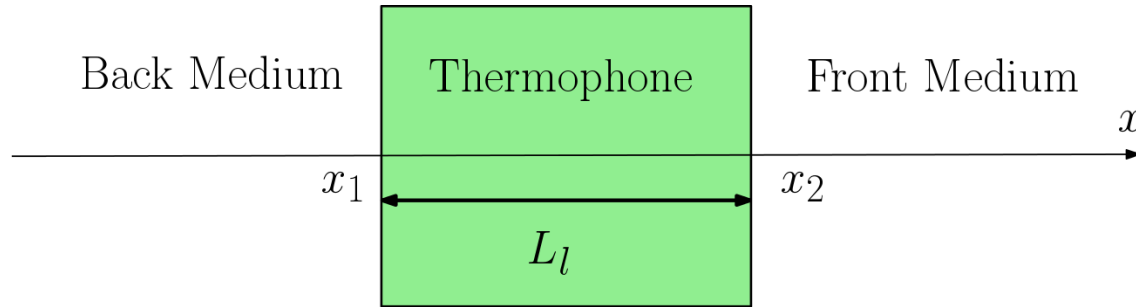
$$- \frac{\rho}{B} \frac{\partial p}{\partial t} - \rho \alpha_T \frac{\partial T}{\partial t} + \rho \vec{\nabla} \cdot \vec{v} = 0$$

$$- \rho \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} p + \mu \nabla^2 \vec{v} + (\lambda + \mu) \vec{\nabla} (\vec{\nabla} \cdot \vec{v})$$

$$- \rho C_p \frac{\partial T}{\partial t} = \kappa \nabla^2 T + \alpha_T T_0 \frac{\partial p}{\partial t}$$

► In a solid

$$- \rho_s \frac{\partial^2 \vec{u}}{\partial t^2} = (\lambda_{0,s} + \mu_{0,s}) \vec{\nabla} (\vec{\nabla} \cdot \vec{u}) + \mu_{0,s} \nabla^2 \vec{u} + (\lambda_s$$



[4] Guiraud et al., *Multilayer modeling of thermoacoustic sound generation for thermophone analysis and design*, Journal of Sound and Vibration 2019

## II. Theory: One Temperature Model (1T)

### Solutions

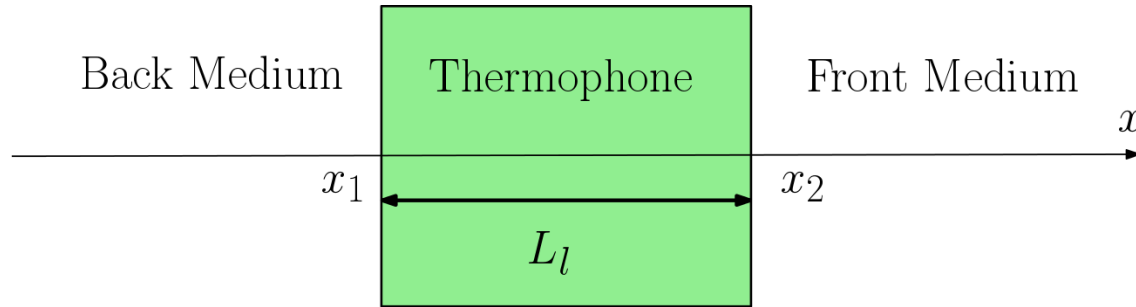
➤  $T = Ae^{-ik_{ac}x} + Be^{+ik_{ac}x} + Ce^{-\theta_{th}x} + De^{+\theta_{th}x}$

➤  $\tilde{p}(T), v(T), q(T)$

### Boundary Conditions

➤ Continuity of :  $T, \tilde{p}(T), v(T), q(T)$

➤ Semi infinite back and front mediums

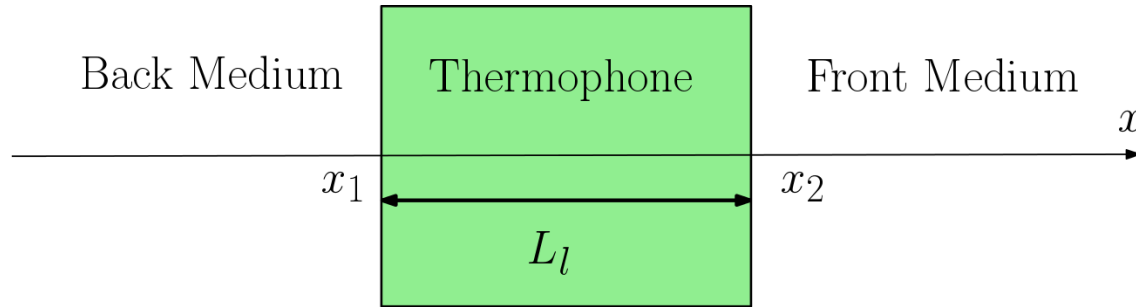


[4] Guiraud et al., *Multilayer modeling of thermoacoustic sound generation for thermophone analysis and design*, Journal of Sound and Vibration 2019

## II. Theory: One Temperature Model (1T)

### Performances & Limitations

- **Uniform distribution** of the power, **not realistic** in a complex foam like geometry
- The thickness of the thermophone only influence the **HCPUA** but the sound generation process remains solely at the surface

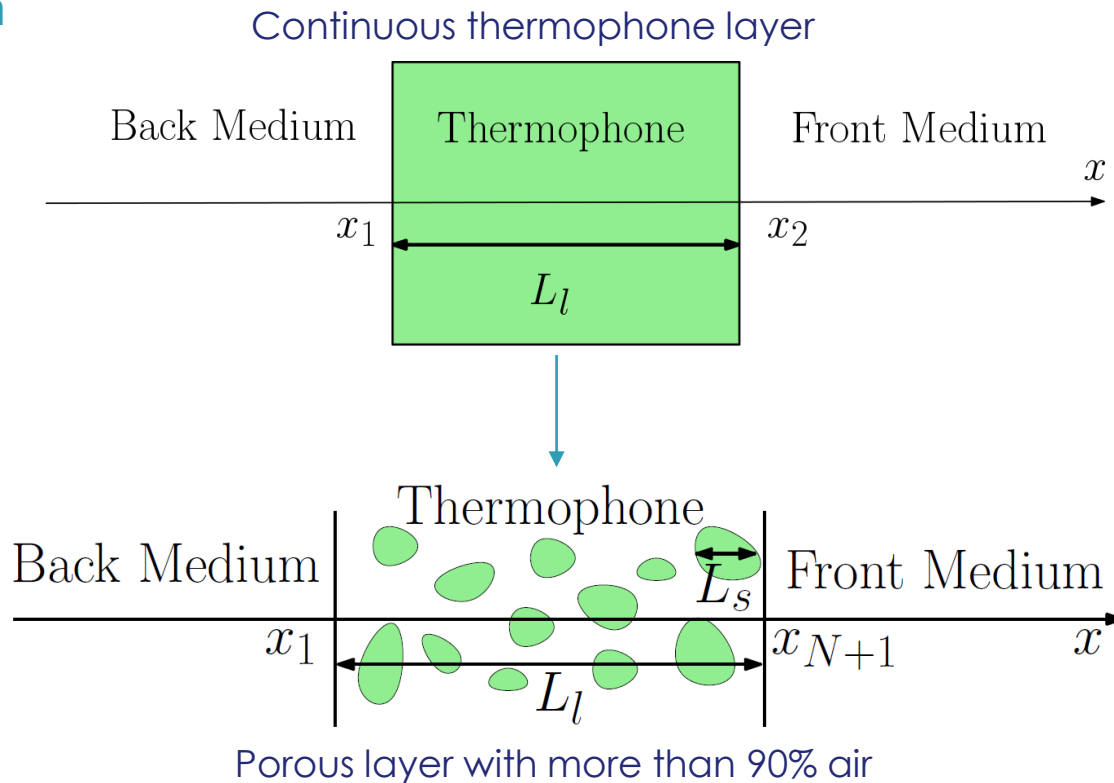


[4] Guiraud et al., *Multilayer modeling of thermoacoustic sound generation for thermophone analysis and design*, Journal of Sound and Vibration 2019



## II. Theory: Two Temperature Model (2T)

### Motivation



## II. Theory: Two Temperature Model (2T)

### Conservation Equations

➤ In a fluid

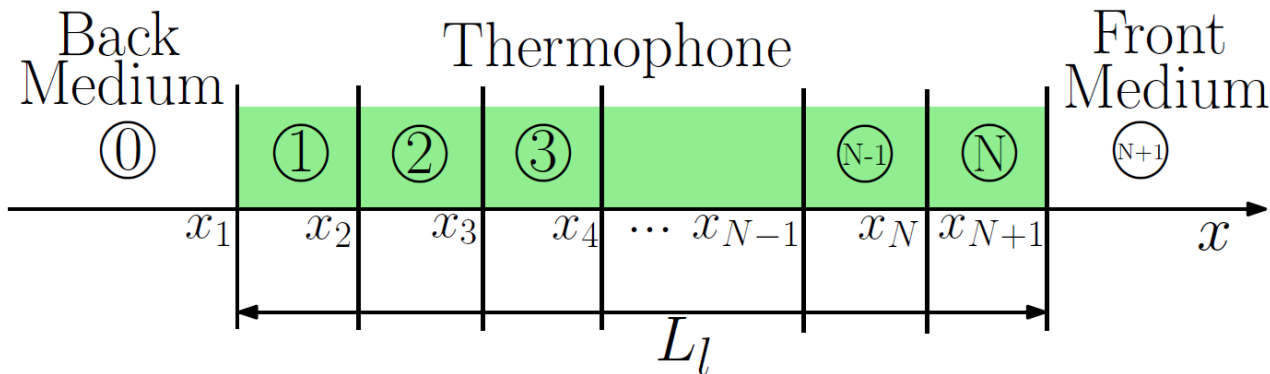
$$- \frac{\rho}{B} \frac{\partial p}{\partial t} - \rho \alpha_T \frac{\partial T}{\partial t} + \rho \vec{\nabla} \cdot \vec{v} = 0$$

$$- \rho \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} p + \mu \nabla^2 \vec{v} + (\lambda + \mu) \vec{\nabla} (\vec{\nabla} \cdot \vec{v})$$

$$- \rho C_p \frac{\partial T}{\partial t} = \kappa \nabla^2 T + \alpha_T T_0 \frac{\partial p}{\partial t}$$

➤ In a solid

$$- \rho_s C_{V,s} \frac{\partial T_s}{\partial t} = \kappa_s \nabla^2 T_s + S_0$$



6 Parameters in each layers:

- $p$
- $v$
- $q$
- $T$
- $q_s$
- $T_s$

## II. Theory: Two Temperature Model (2T)

### Solutions

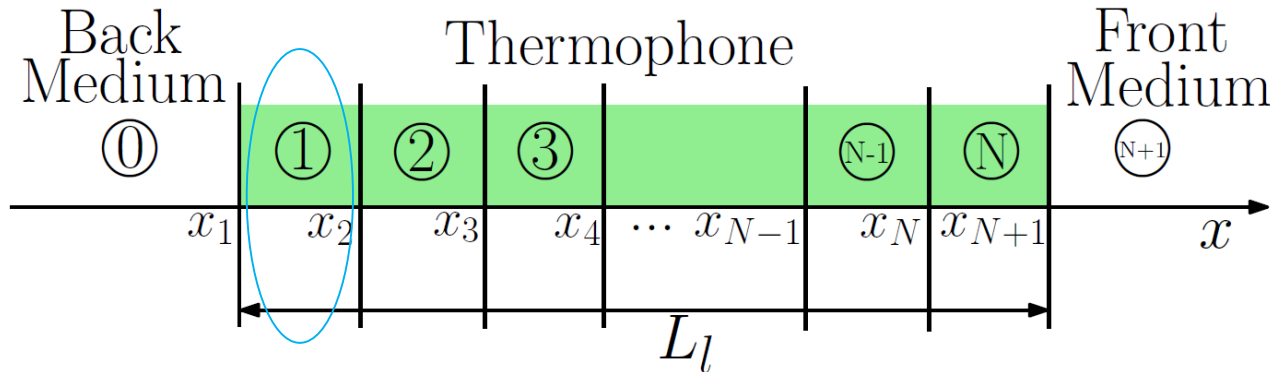
$$\triangleright T = Ae^{-ik_{ac}x} + Be^{+ik_{ac}x} + Ce^{-\theta_{th}x} + De^{+\theta_{th}x}$$

$$\triangleright \tilde{p}(T), v(T), q(T)$$

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

$$\triangleright q_s(T_s)$$

6 constants (A,B,C,D,E,F) are necessary in each layers to fully define all the parameters



## II. Theory: Two Temperature Model (2T)

### Boundary conditions

➤ In the fluid (0 to N+1)

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

↙ coupling term

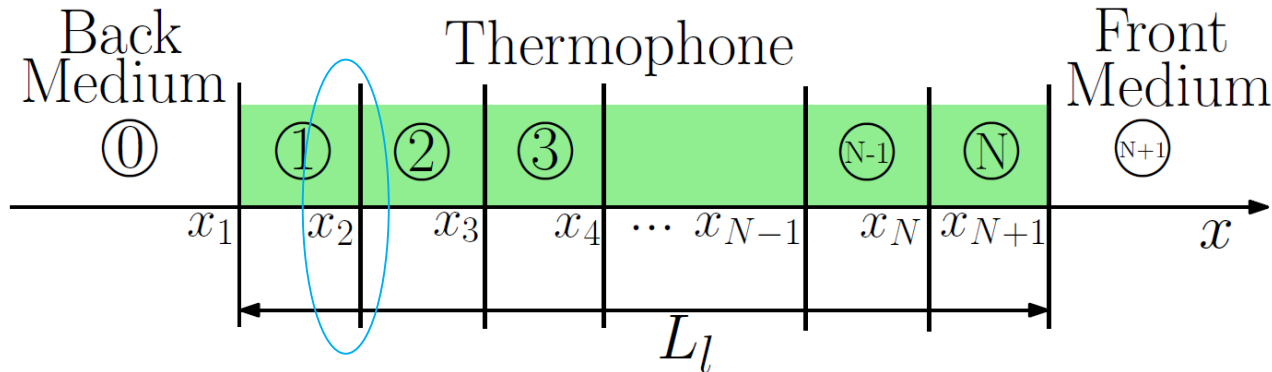
➤ In the solid (1 to N)

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

↖ coupling term

➤ At the Edges (0 and N+1)

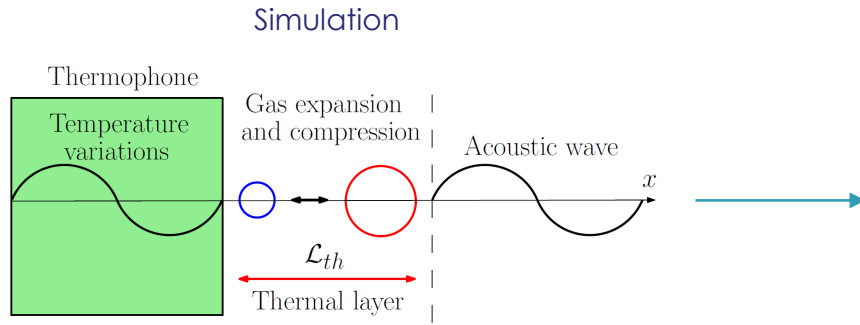
- Semi Infinite Back Medium
- Semi Infinite Front Medium



6N + 4 Unknowns  
6N + 4 Equations

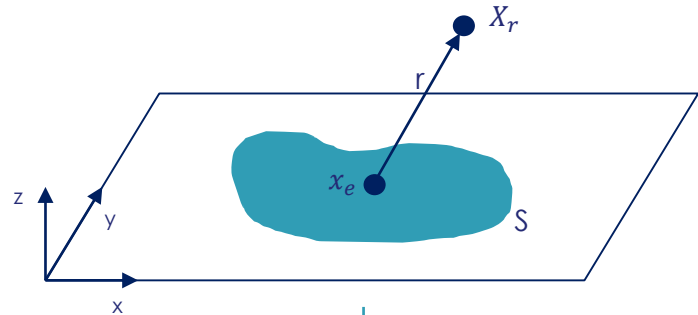
## II. Theory: Acoustic Diffraction

### Use of Rayleigh's integral to Compare Simulations and Experiments



Add the Diffraction using the calculated generated velocity

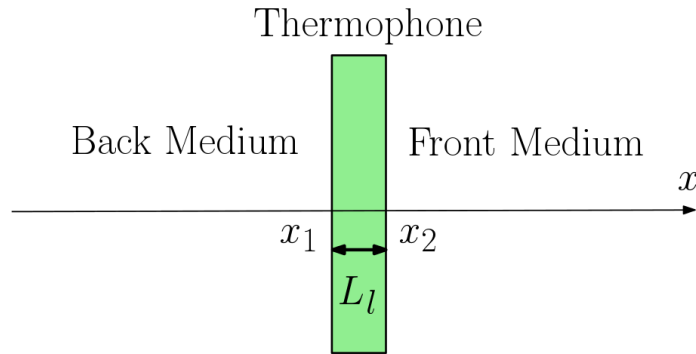
$$\triangleright p_{FF}(X_r) = \frac{i\omega\rho_g}{4\pi} \int_S v(x_e) \frac{e^{-ikr}}{r} dS$$



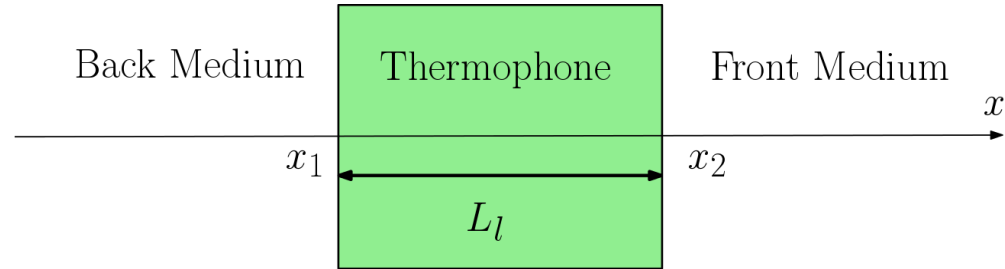
Generate the Frequency and Power Spectrum of the Thermophone

# III. Analysis: Near Field Sound Generation

## Comparison of the 1T and 2T model



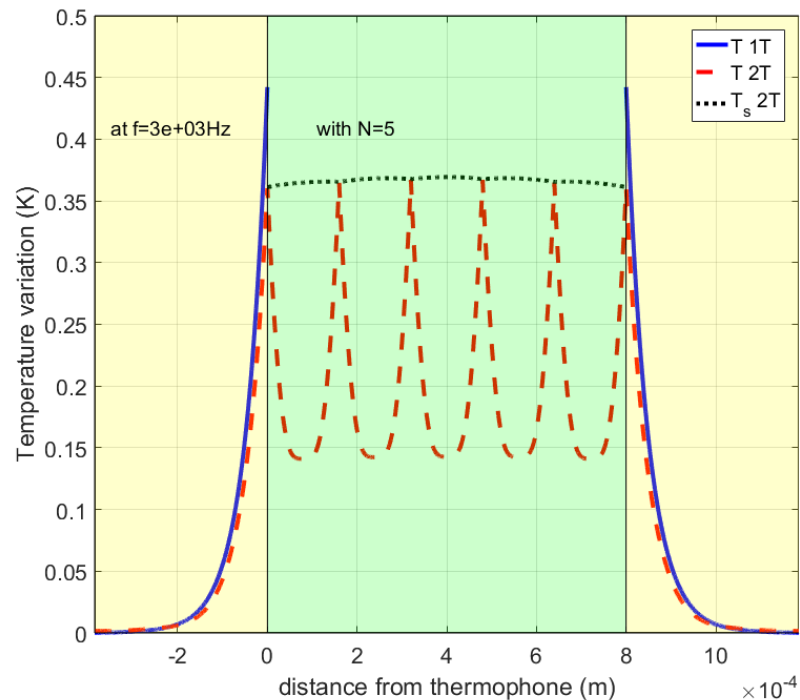
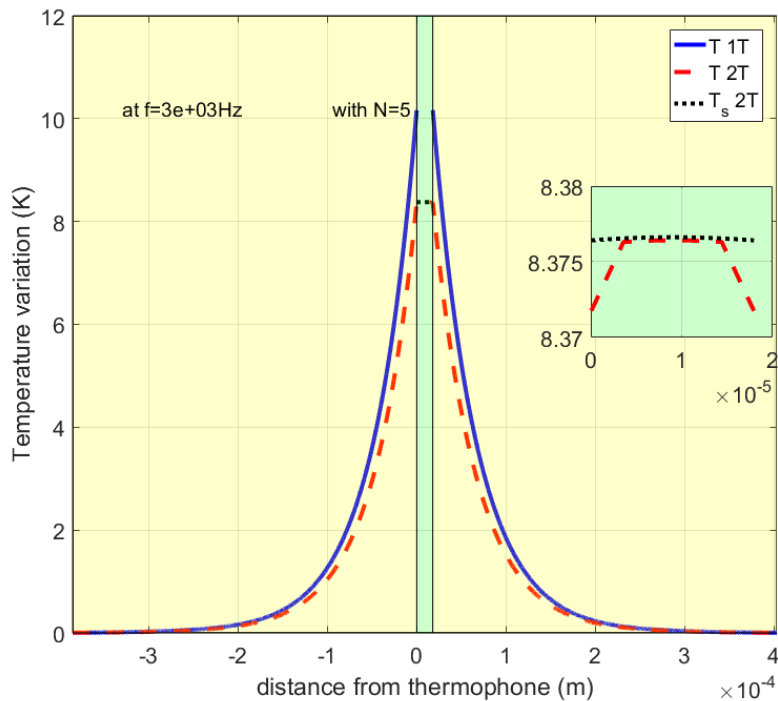
Thin Thermophone  
(20  $\mu\text{m}$ )



Thick Thermophone  
(800  $\mu\text{m}$ )

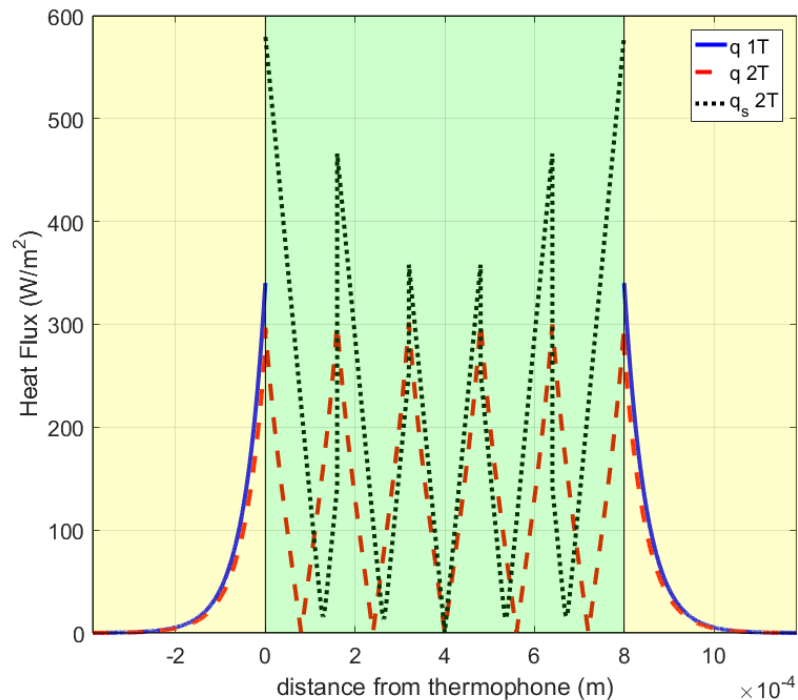
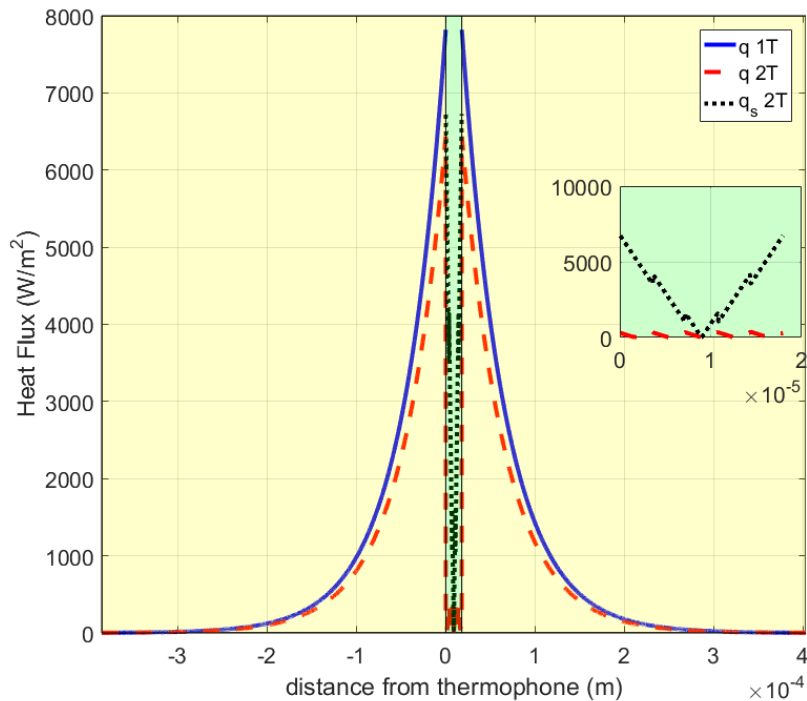
# III. Analysis: Near Field Sound Generation

## Thick and Thin Thermophone at 3kHz: Temperature



# III. Analysis: Near Field Sound Generation

## Thick and Thin Thermophone at 3kHz: Heat flux

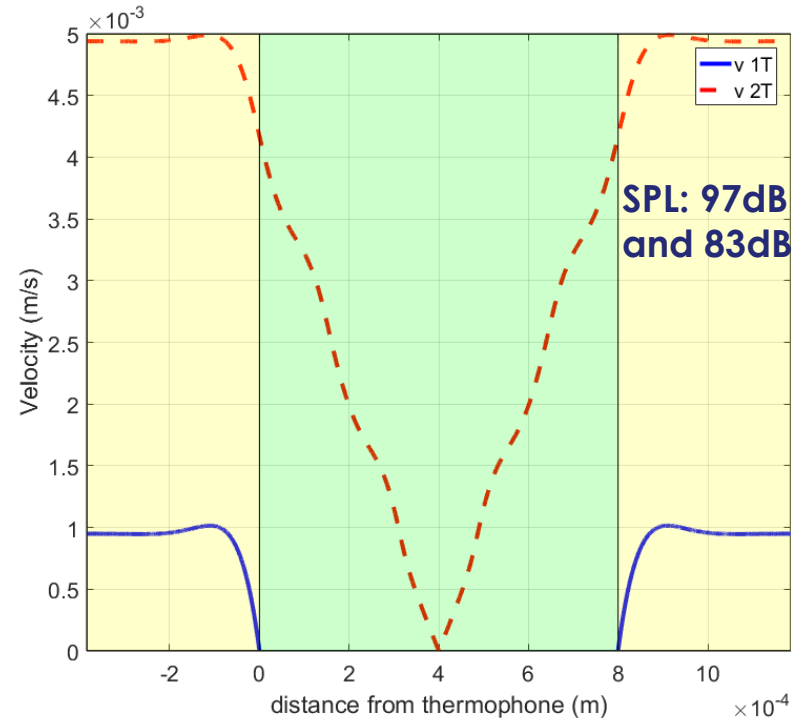
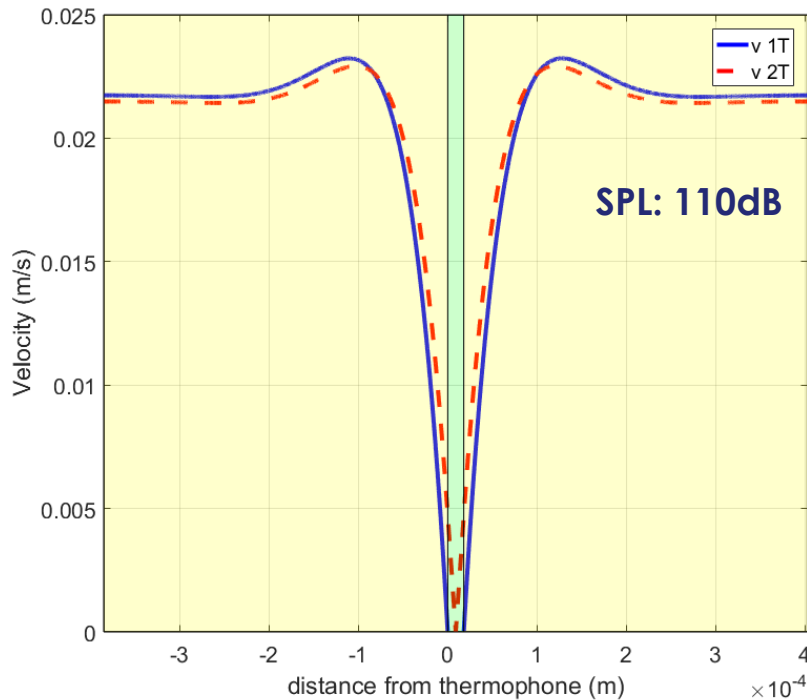


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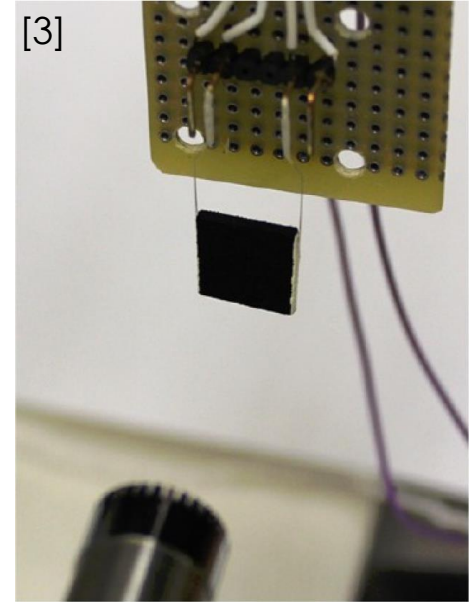
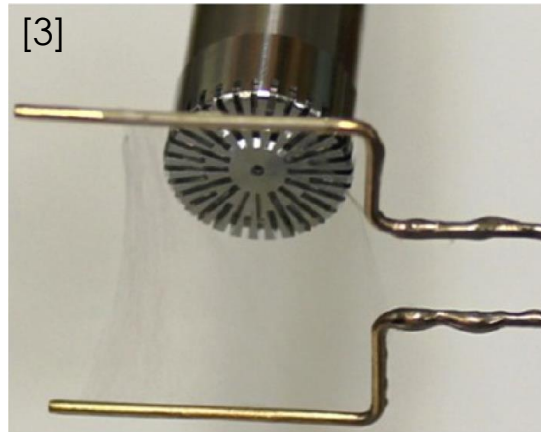
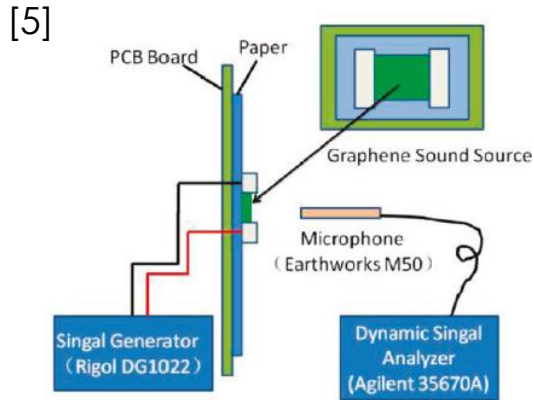
# III. Analysis: Near Field Sound Generation

## Thick and Thin Thermophone at 3kHz: Particle Velocity



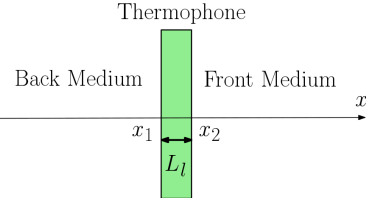
# III. Analysis: Frequency and Power Spectrum

## Comparison with experimental results from Aliev and al<sup>[3]</sup>

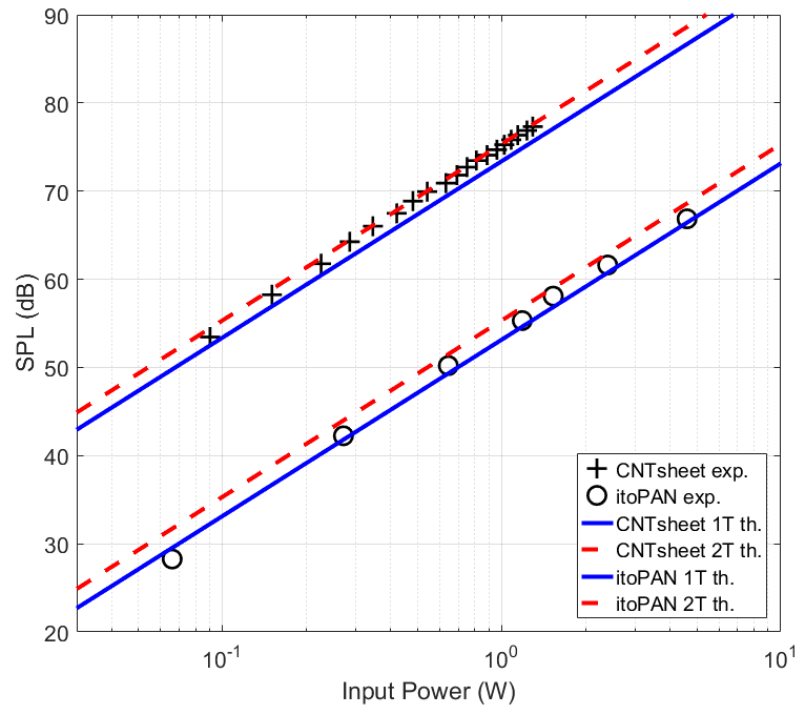
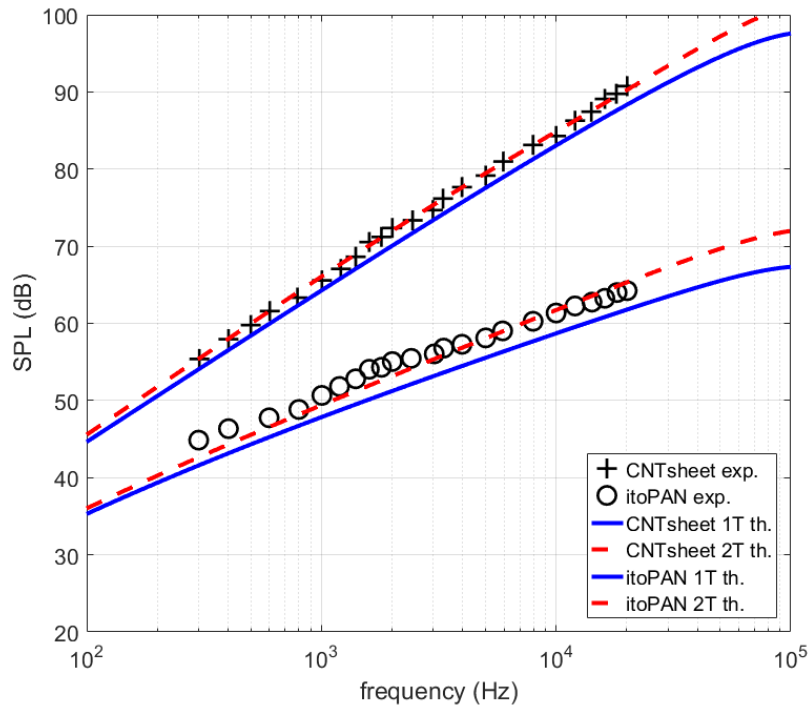


- [3] Aliev et al., *Alternative nanostructures for thermophones*, ACS Nano 9, 2015  
[5] Tian et al., *Graphene-on-Paper Sound Source Devices*, ACS Nano 2011

# III. Analysis: Frequency and Power Spectrum



## Thinfil Thermophone Spectrum



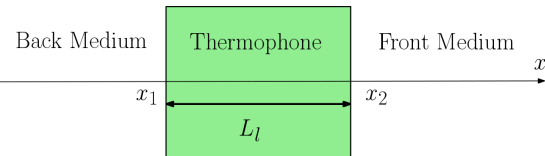
[3] Aliev et al., *Alternative nanostructures for thermophones*, ACS Nano 9, 2015

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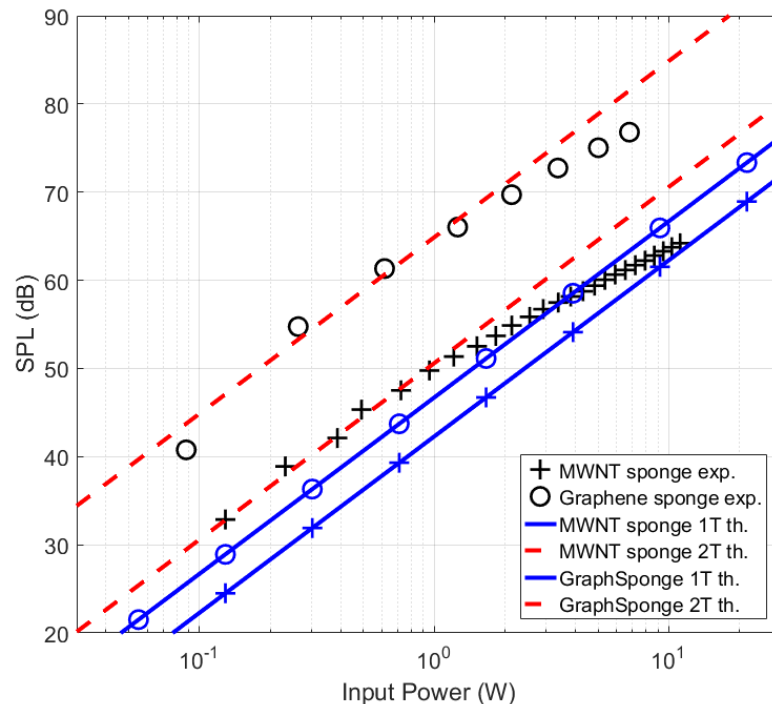
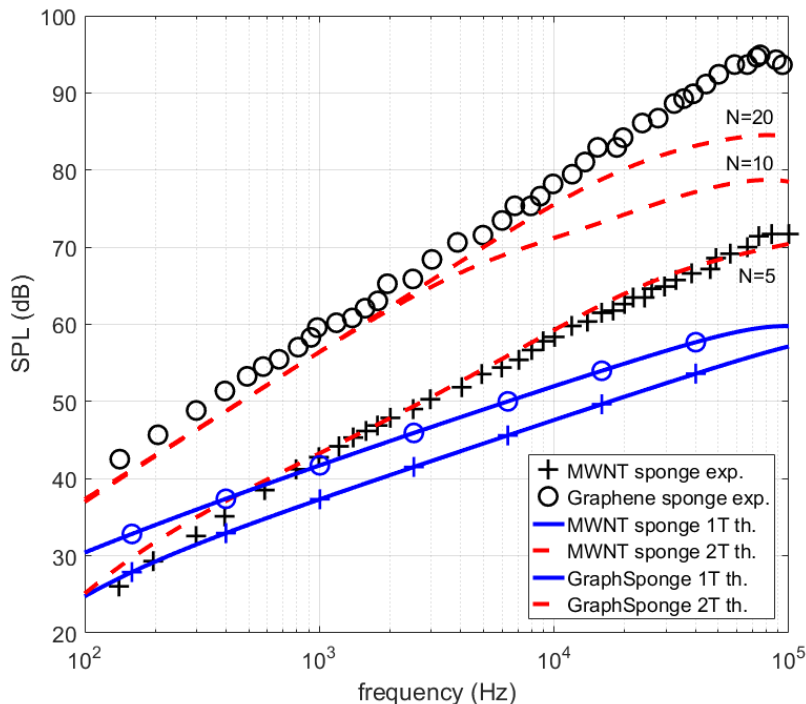
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# III. Analysis: Frequency and Power Spectrum



## Thick Thermophone Spectrum



[3] Aliev et al., *Alternative nanostructures for thermophones*, ACS Nano 9, 2015

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OPEN



# I. Theoretical models: Conclusions

## One Temperature model

### ➤ Strengths

- Consider the propagation of the wave in the solid
- Flexible design of thermophone with any number of different layers
- Working for planar, cylindrical and spherical waves

### ➤ Weaknesses

- Not adapted for thick, complex thermophone geometry

## Two Temperatures model

### ➤ Strengths

- Novel thermophone theoretical model
- More adapted for complex, thick, foam like thermophone geometry
- Simpler model performing almost as well as the one temperature one for thin thermophones

### ➤ Weaknesses

- For now only for free field configuration with planar waves
- Only the energy conservation equation is considered in the solid

- None of them take the static raise of temperature in the pores into account for high input power

# THALES



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## Thank you for your attention

### Guiraud Pierre

Bou-Matar Olivier (IEMN)

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Pernod Philippe (IEMN)

Hourlier Djamila (IEMN)

Coquet Philippe (CINTRA)

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Bazzali Emmanuelle

Teo Edwin

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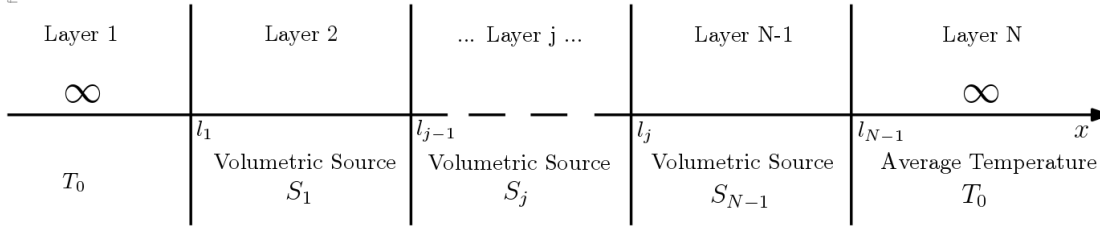
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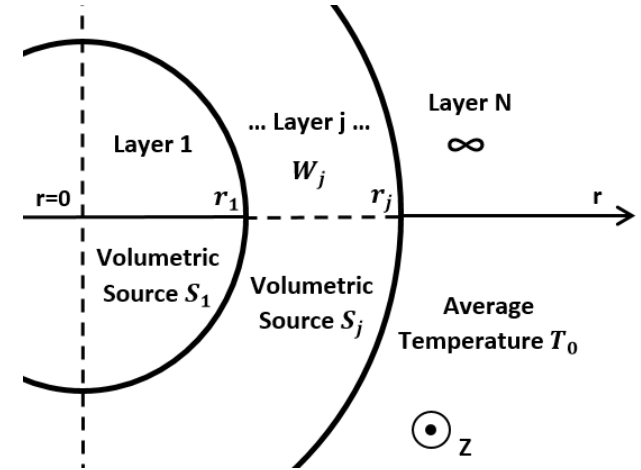
# Bonus: One Temperature Model (1T)

## Model extension

façon, en tout ou partie, ni divulgué à  
2018 - Tous Droits réservés.



Multilayer for planar waves

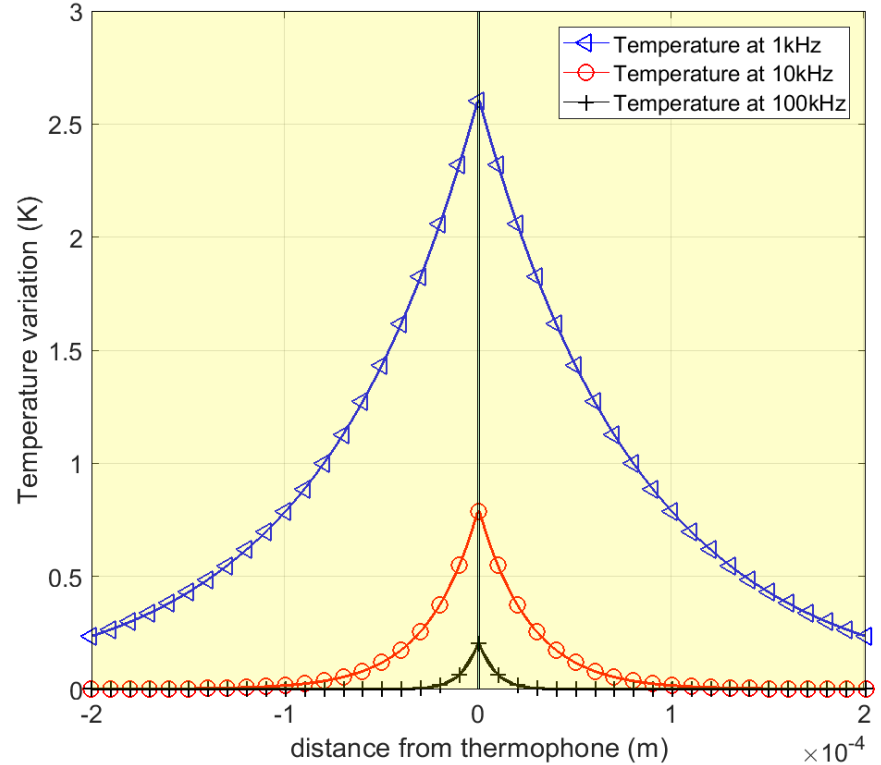
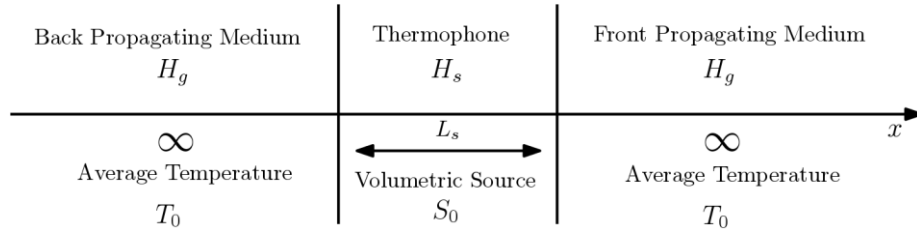


Multilayer for cylindrical or spherical waves

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# Bonus: Thermal Layer (1T)

## Free Field radiation





# Bonus: Added Losses at the Boundaries

## Equations

### > In a liquid

$$- \frac{\rho}{B} \frac{\partial p}{\partial t} - \rho \alpha_T \frac{\partial T}{\partial t} + \rho \vec{\nabla} \cdot \vec{v} = 0$$

$$- \rho \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} p + \mu \nabla^2 \vec{v} + (\lambda + \mu) \vec{\nabla} (\vec{\nabla} \cdot \vec{v})$$

$$- \rho C_p \frac{\partial T}{\partial t} = \kappa \nabla^2 T + \alpha_T T_0 \frac{\partial p}{\partial t}$$

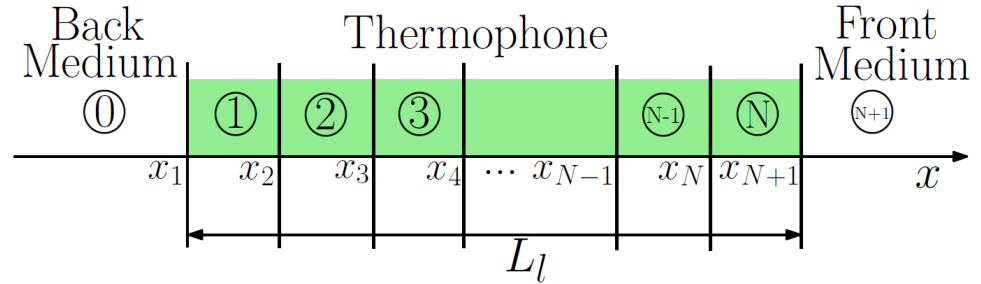
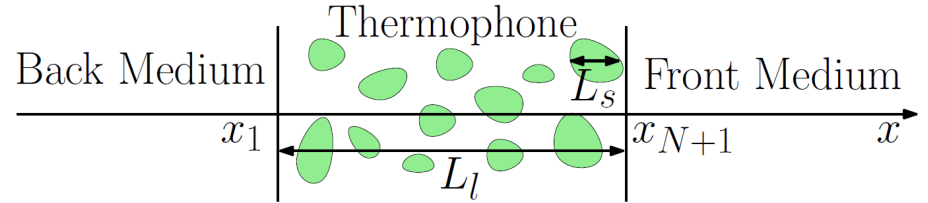
### > In a solid

$$- \rho_s C_{V,s} \frac{\partial T_s}{\partial t} = \kappa_s \nabla^2 T_s + S_0$$

### > Heat flux continuity

$$- q^+ = q^- + g(T_s - T) - \beta_s T$$

Added coefficient for conduction, convection and radiation losses



# Bonus: Coupling Coefficient Determination

## Equations

- Real total contact area between solid and air:

$$NSg = a\rho_s Vh$$

$$\text{Then } g = \frac{a\rho_s Vh}{NS} \cong 10^5 \text{ W/m}^2\text{K}$$

## New Parameters

- $a$ : Specific area of the foam (about  $2000 \text{ m}^2/\text{g}$ ) [6,7,8]
- $h$ : Real heat film transfer coefficient (about  $200 \text{ W/m}^2\text{K}$ ) [9]

[6] Peigney et al., *Specific Surface Area of Carbon Nanotubes and bundles of Carbon Nanotubes*, Carbon 39, 2001

[7] Drieschner et al., *High surface area graphene foams by chemical vapor deposition*, 2D Materials, 2016

[8] Zhang et al., *Porous 3D graphene-based bulk materials with exceptional high surface area and excellent conductivity for supercapacitors*, Scientific Reports, 2013

[9] Silvestri et al., *Thermal characterization of carbon nanotube foam using MEMS microhotplates and thermographic analysis*, Nanoscale, 2016

# Bonus: Theoretical Parameters used

	$\rho$ [kg·m <sup>-3</sup> ]	$C_p$ [J·kg <sup>-1</sup> ·K <sup>-1</sup> ]	$C_V$ [J·kg <sup>-1</sup> ·K <sup>-1</sup> ]	$B$ [Pa]	$\alpha_T$ [K <sup>-1</sup> ]	$\kappa$ [W·K <sup>-1</sup> ·m <sup>-1</sup> ]	$\lambda$ [N·s·m <sup>-2</sup> ]	$\mu$ [N·s·m <sup>-2</sup> ]
Gas, air	1.20	$9.96 \times 10^2$	$7.17 \times 10^2$	$1.01 \times 10^5$	$3.33 \times 10^{-3}$	$26.2 \times 10^{-3}$	$16.82 \times 10^{-6}$	$5.61 \times 10^{-6}$

TABLE I. Parameters of the propagating medium (air).

	$\rho_s$ [kg·m <sup>-3</sup> ]	$C_{V,s}$ [J·kg <sup>-1</sup> ·K <sup>-1</sup> ]	$B_s$ [Pa]	$\kappa_s$ [W·K <sup>-1</sup> ·m <sup>-1</sup> ]	$L_l$ [m]	$L_s$ [m]	$A$ [cm×cm]
CNT Sheet	1	716	$1.11 \times 10^{11}$	50	$18 \times 10^{-6}$	$10 \times 10^{-9}$	Square $1.5 \times 1.5$
ITO PAN	220	606	$1.65 \times 10^{11}$	310	$5 \times 10^{-6}$	$450 \times 10^{-9}$	Square $1.2 \times 1.5$
MWNT Sponge	30	716	$1.11 \times 10^{11}$	100	$100 \times 10^{-6}$	$10 \times 10^{-9}$	Square $1 \times 1$
Graphene Sponge	2.75	660	$1.44 \times 10^8$	6.3	$800 \times 10^{-6}$	$5 \times 10^{-9}$	Circle $d = 1.8$

TABLE II. Parameters of the thermophone materials used in the experiments and theoretical models. <sup>3</sup>

[3] Aliev et al., *Alternative nanostructures for thermophones*, ACS Nano 9, 2015

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