Thermal Analysis of a piezo-disk ultrasound probe

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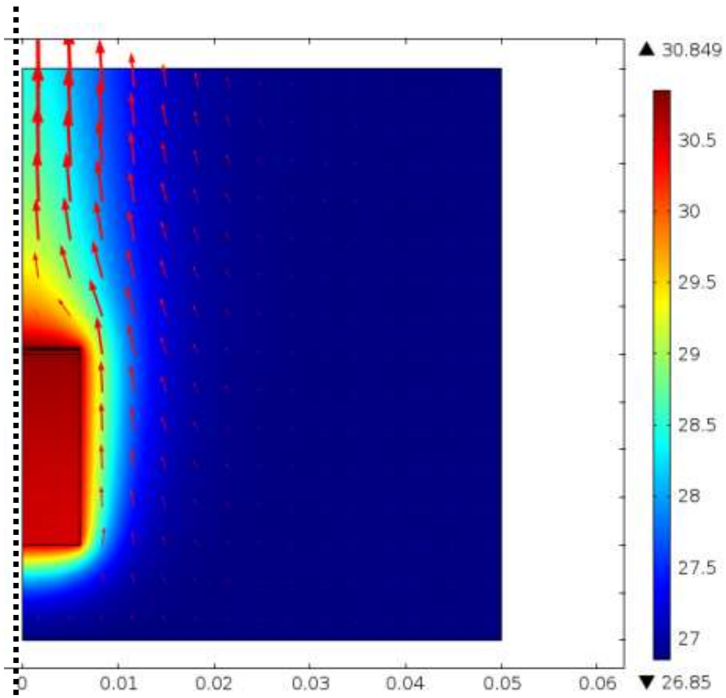
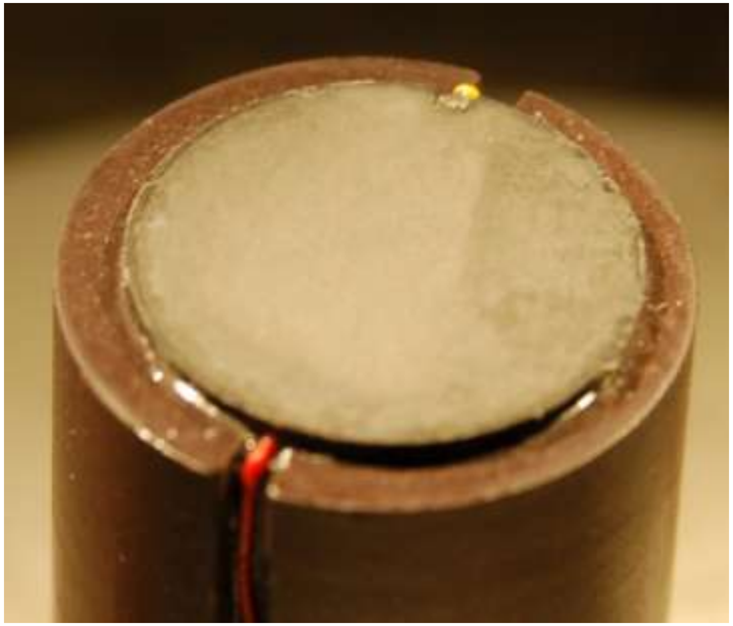
A Finite Element Model (FEM) for an ultrasound piezoelectric disk transducer has been developed.

The FEM design followed a *"step approach"* (development of the model along with the transducer manufacturing stages)

The purpose of the present study is the analysis of the thermal behaviour of a disk type ultrasound probe under the most demanding operating condition



Axial-symmetric 2D FEM

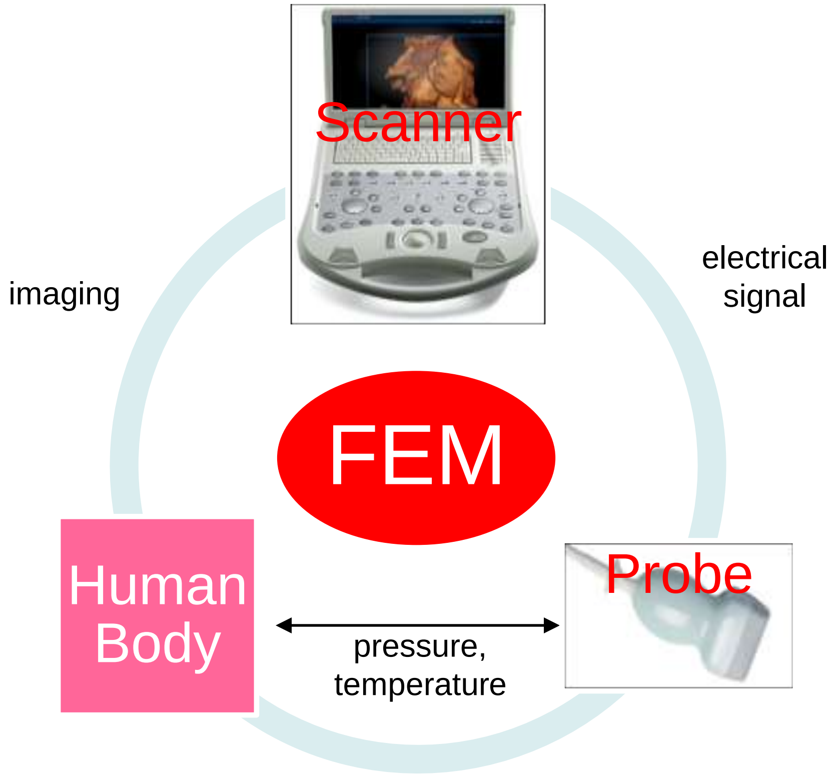


Piezoelectric disk transducer

Ultrasound Imaging Transducer and FEM

The ultrasound image quality is strictly related to the technology level of the design and materials involved in the transducer manufacturing

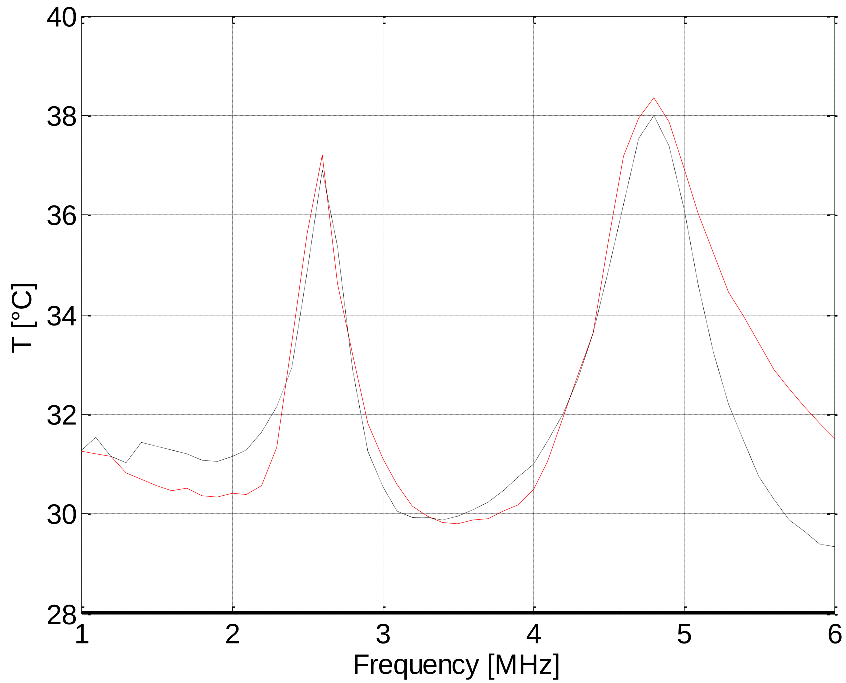
Finite Elements Model (FEM) can greatly help in the study and optimization of its efficiency



FEM can predict the temperature rise of the probe front surface under a given operating condition, in order to fulfill the International standard (IEC 60601-2-37) limit of 43°C, in contact with patient skin (50°C in air)

Important Simulation Result anticipation

Good agreement between measurement and simulation results for the probe front face temperature :



Transducer front face equilibrium temperature, dependency on frequency.
Comparison between simulations (solid) and measurements (dashed).
Environment temperature: 28°C.

→ even at the maximum value, the temperature limit of 50°C (in air) is not exceeded

Piezoelectricity equations in COMSOL

Constitutive equations for a piezoelectric material (*stress-charge* form) :

$$\begin{cases} \mathbf{T} = \left[\mathbf{c}^{\mathbf{E}}\right] \mathbf{S} - \left[\mathbf{e}^{t}\right] \mathbf{E} \\ \mathbf{D} = \left[\mathbf{e}\right] \mathbf{S} + \left[\boldsymbol{\varepsilon}^{\mathrm{S}}\right] \mathbf{E} \end{cases}$$

where :

T is the stress vector

c is the elasticity matrix

S is the strain vector

e is the piezoelectric matrix

E is the electric field vector

D is the electric displacement vector

ε is the dielectric permittivity matrix

(superscripts indicates a zero or constant corresponding field)

→ elasticity, piezoelectric and dielectric permittivity matrices must be specified to build the model in Comsol

manufacturer data are often incomplete or should be optimized for the particular operating condition

Electric equations in COMSOL

Electrical impedance of the piezoelectric disk (general ohm law) :

$$Z = \frac{V}{I}$$

where V is the potential difference voltage across the two disk faces and I is the current flowing inside.

Electric current flowing in the disk (axial symmetry):

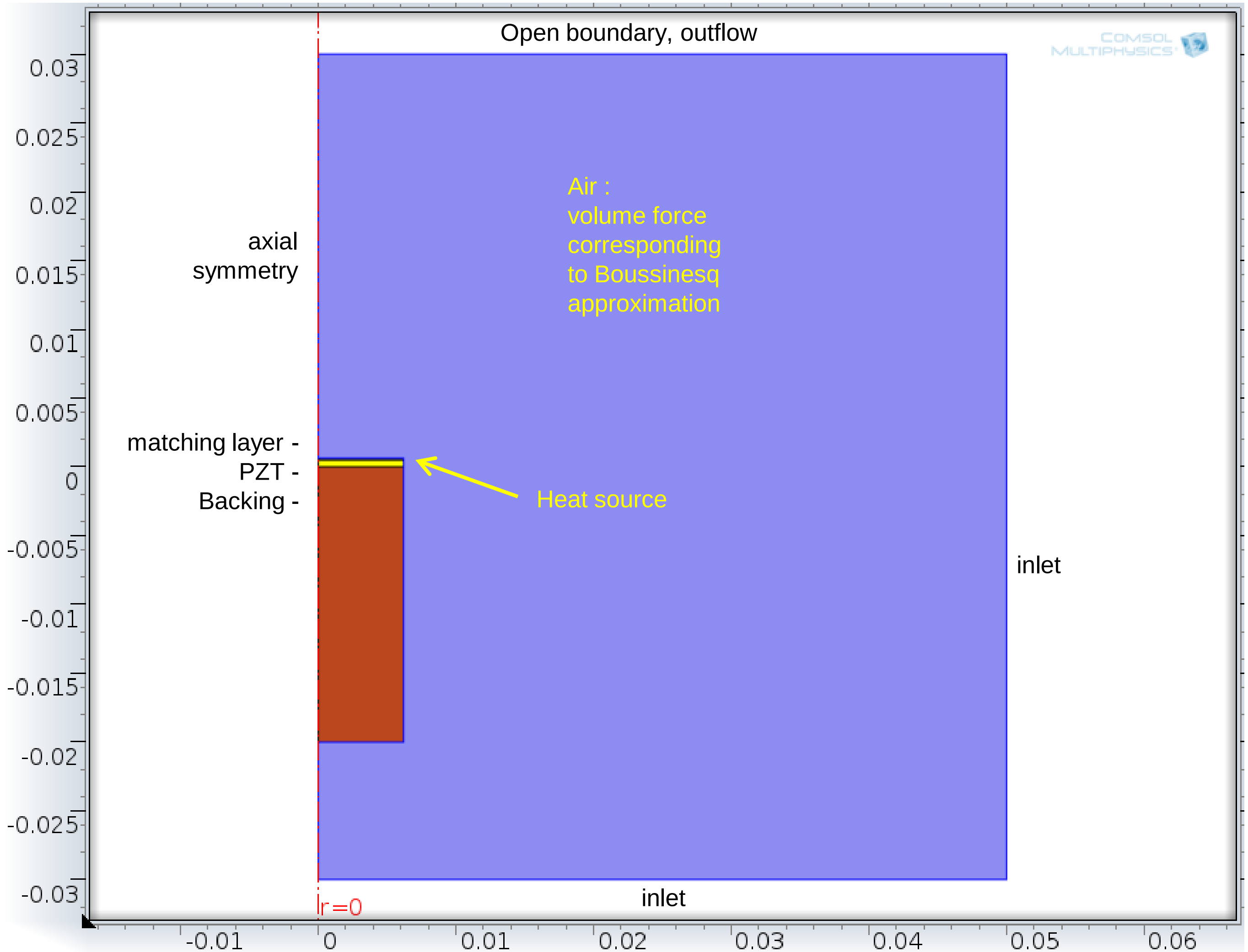
$$I = \int_0^r j_z(r) 2\pi r dr$$

where $\boldsymbol{j_z}$ is the current density component along z axis.

This integral has been used in COMSOL as integration variable across the disk surface, in order to use the optimization module with objective function given by the difference of measured and simulated electrical impedance.

Fluid flow and heat transfer in COMSOL

FEM design :



Building the model with a 'Step approach'

Due to the large number of parameters to be determined, we decided to follow a *step approach* procedure, summarized in the following:

- Simulation and measurements for the piezoceramic disk alone

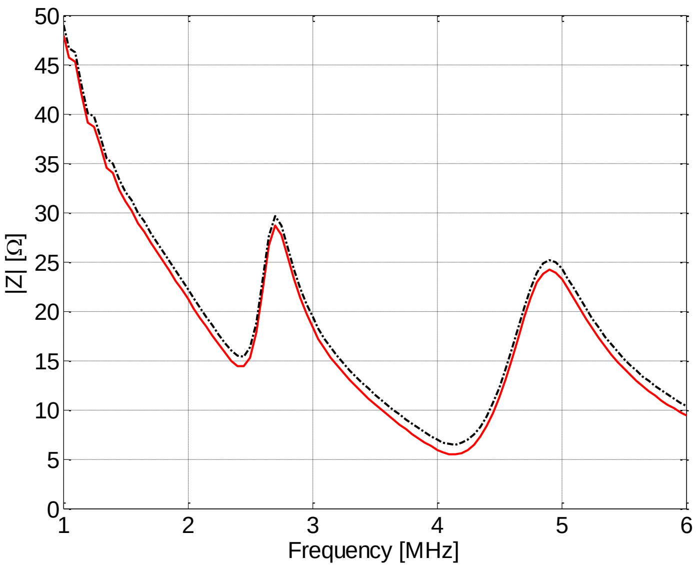
- Simulation and measurements for the complete transducer : piezoceramic disk, backing substrate and front matching layer

Optimization :

RMS minimization of an objective function given by the difference between the measured and simulated electrical impedance of the disk

Complete transducer electrical impedance results

A frequency response analysis was performed, between 1 and 6 MHz . The measurement and simulation results are the following :



Piezo-disk transducer electrical impedance magnitude. Comparison between simulations (solid) and measurements (dashed).

Good fit to measurements, with resonance and antiresonance frequency error below 5%.

Multiple resonances :

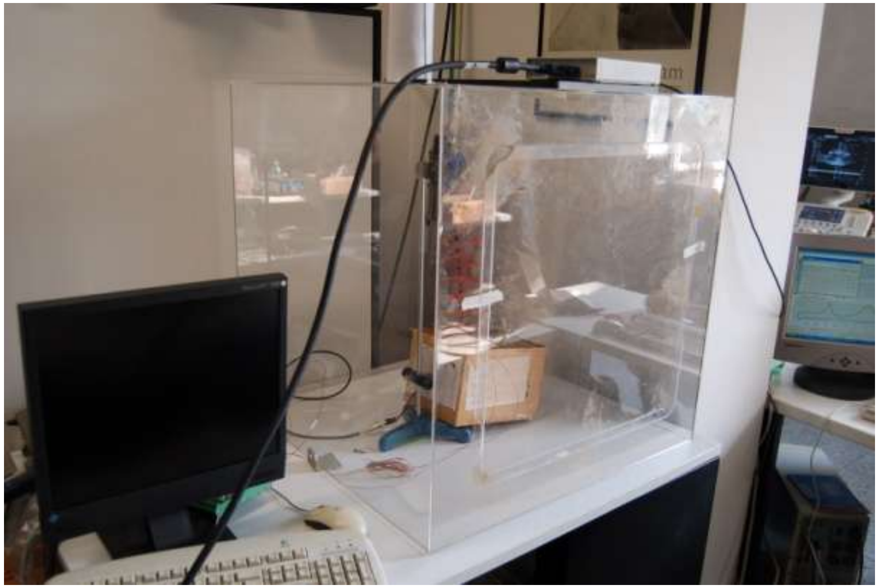
- piezoceramic (~4MHz)

- matching layer (~2.4MHz)

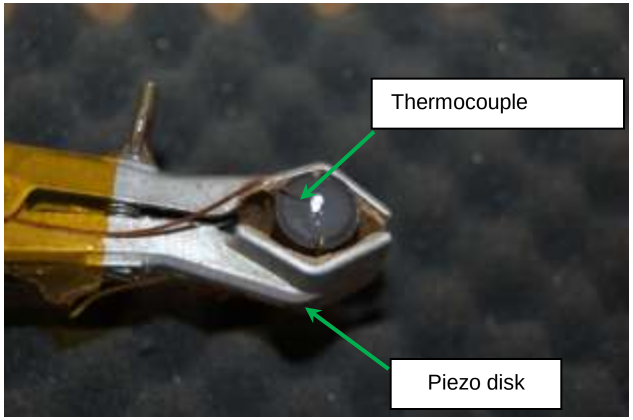
Optimization :

Both the piezoelctric , backing and matching layer parameters greatly influence the electrical impedance response

Experimental set-up



Specialized plexiglass box.

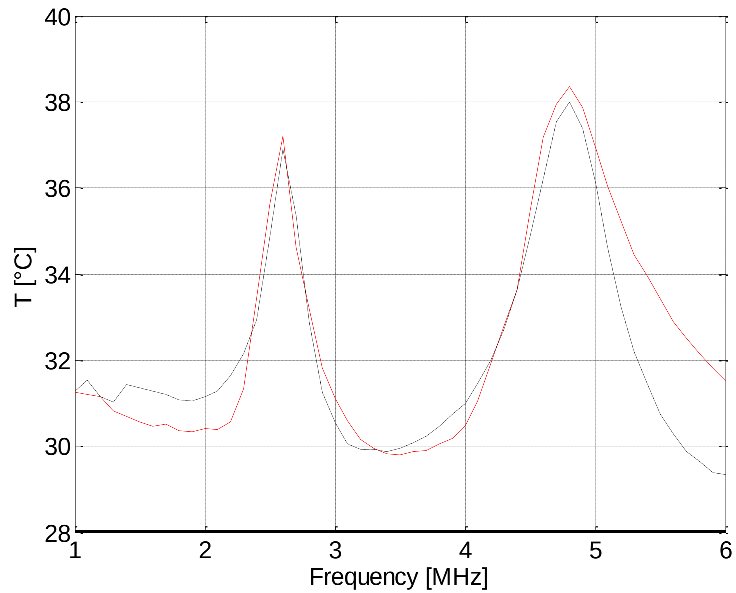


k type thermocouple measurement

Thermal analysis results (1)

Frequency sweep (between 2 MHz and 6 MHz operative range) for the heating of the transducer front face

- driving sinusoidal voltage amplitude of 10 V (corresponding to the "worst heating case" configuration)
- environment temperature of 28 °C



Transducer front face equilibrium temperature, dependency on frequency. Comparison between simulations (solid) and measurements (dashed). Environment temperature: 28°C.

Good agreement between measurement and simulation results (error of about 1°C for final equilibrium temperature)

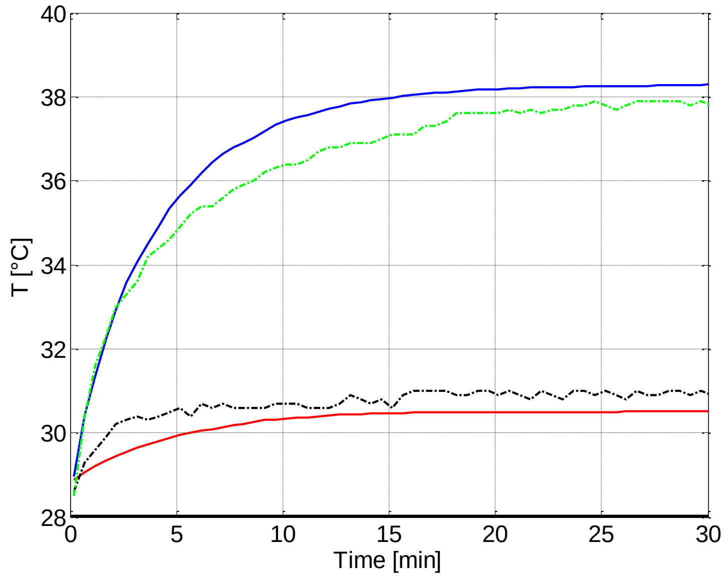
Large temperature difference between resonance and antiresonance operating frequencies :
Maximum heating at antiresonance, minimum at resonance.

Safety :

even at 4.8 MHz, where the temperature value is maximum, the limit of 50°C is not reached

Thermal analysis results (2)

Heating transfer behaviour at resonance and antiresonance frequencies:



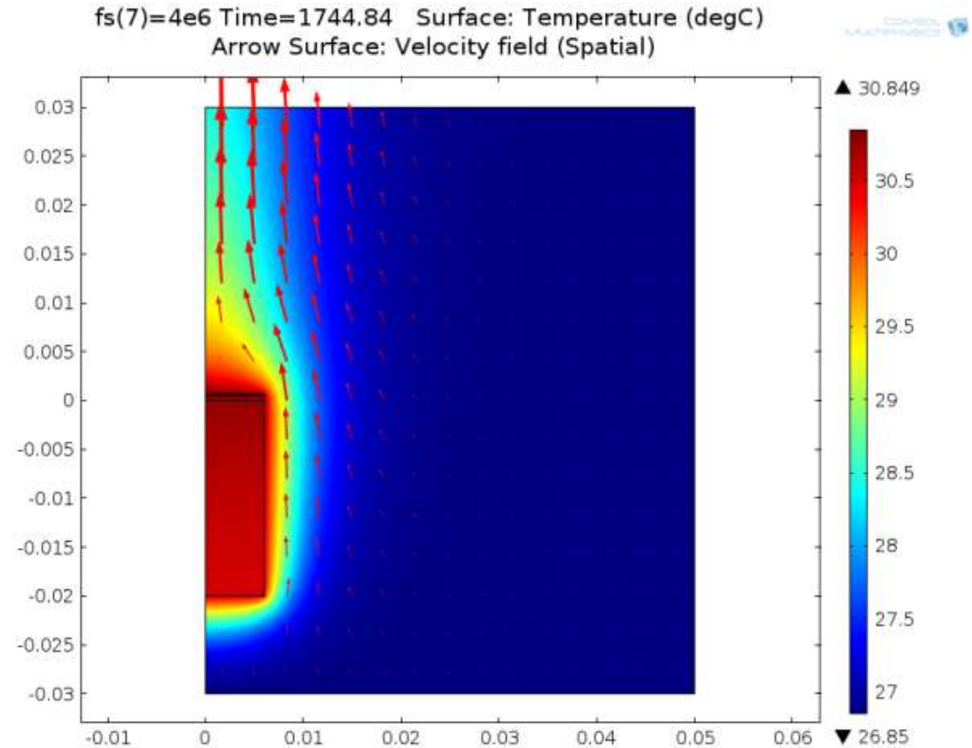
Transducer front face temperature rise at 4 MHz (resonance) and 4.8 MHz (antiresonance). Comparison between simulations (solid) and measurements (dashed).

Good agreement between measurement and transient simulation results (error less than 1°C at stationary temperature)

The FEM can be used to determine the temperature of probe head after a given time of CW operation

Thermal analysis results (3)

Temperature and field velocity map for the fluid, for 4 MHz CW excitation:

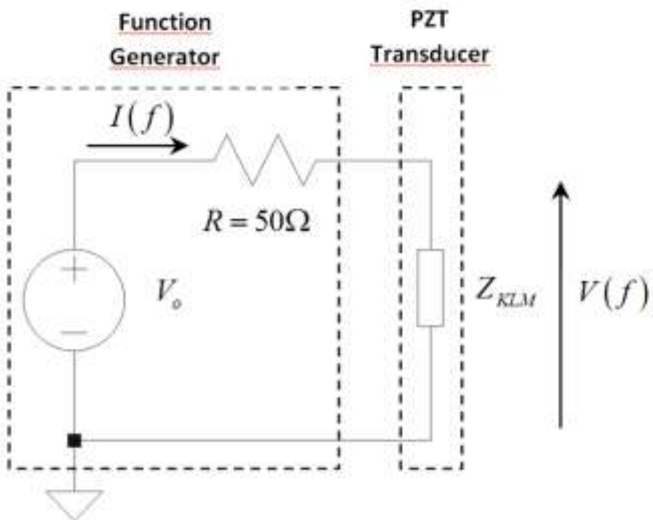


Fluid (air) temperature and velocity map at 4 MHz excitation frequency (resonance)

the transversal section of the fluid subjected to some heating effect is limited to some millimeters around the lateral surface of the piezo-disk transducer

Equivalent circuit model for the dissipated power

KLM equivalent circuit model allows to calculate the electrical impedance of the transducer and the dissipated power (from measured values for electrical impedance and driving voltage) :

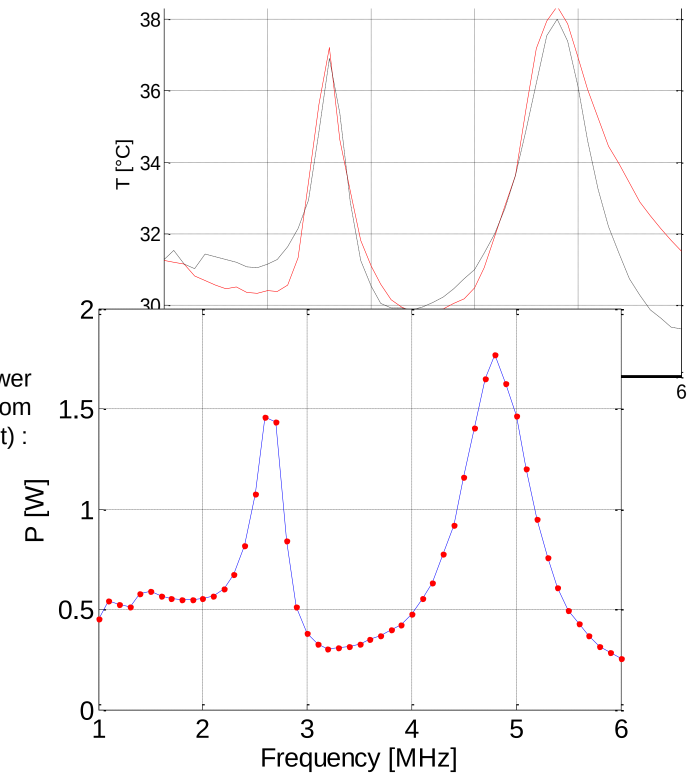


$$P(f) = \mathrm{Re}\{Z(f)\}\left|I(f)\right|^2$$

$$I(f) = \frac{V(f)}{Z(f)}$$

$$P(f) = \mathrm{Re}\{Z(f)\}\left|\frac{V(f)}{Z(f)}\right|^2$$

Dissipated power (calculated from equivalent circuit) :



Clear correspondence between dissipated power and measured/simulated temperature of probe front face

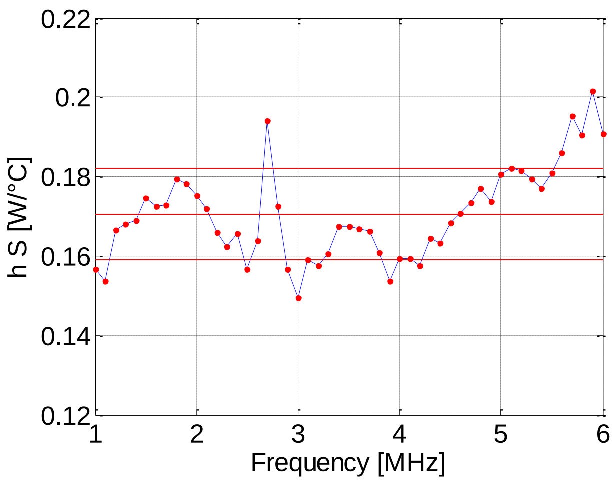
Heat transfer coefficient and specific thermal conductance

Heat transfer coefficient "h" for the piezo-transducer :

$$h = \frac{P}{S \cdot \Delta T}$$

Where:

P is the dissipated power,
S is the heat transfer surface area
ΔT is the difference in temperature between the solid surface and the fluid in contact



Piezo-disk transducer specific thermal conductance hS versus frequency.

Specific thermal conductance hS : approximately constant over the overall frequency range, with mean value of 0.17 W/°C and with a standard deviation of 6.8% .

Conclusion

- A FEM model has been developed and validated to study the heating of an ultrasound piezo-disk transducer, operating in CW mode and coupled in still air

- The upper limit for the surface temperature imposed by International Safety Standard IEC 61000-2-37 is fulfilled. Such limit correspond to 50°C in still air and 43°C in contact with human body

- Frequency analysis and transient simulations showed a good agreement between measured and simulated performances both in term of stationary final temperature (error less than 1°C) and in term of heating transient time constant

- The temperature rise is found to be larger at anti-resonance with respect to resonance frequencies, suggesting that the absorbed input power is larger

- The theoretical model presented showed that it is possible to use a simplified equivalent circuit in order to estimate both the superficial temperature rise, both the specific thermal conductance of the transducer, with an error of less than 10%.