COMPLETE DESIGN OF A HIGH POWER ULTRASONIC FLOW-CELL REACTOR WITH SPECIAL AIR COOLING SYSTEM

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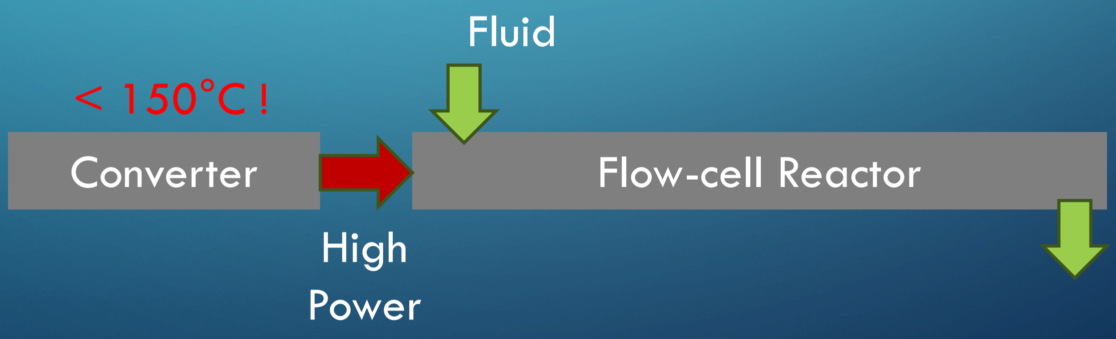
INTRODUCTION

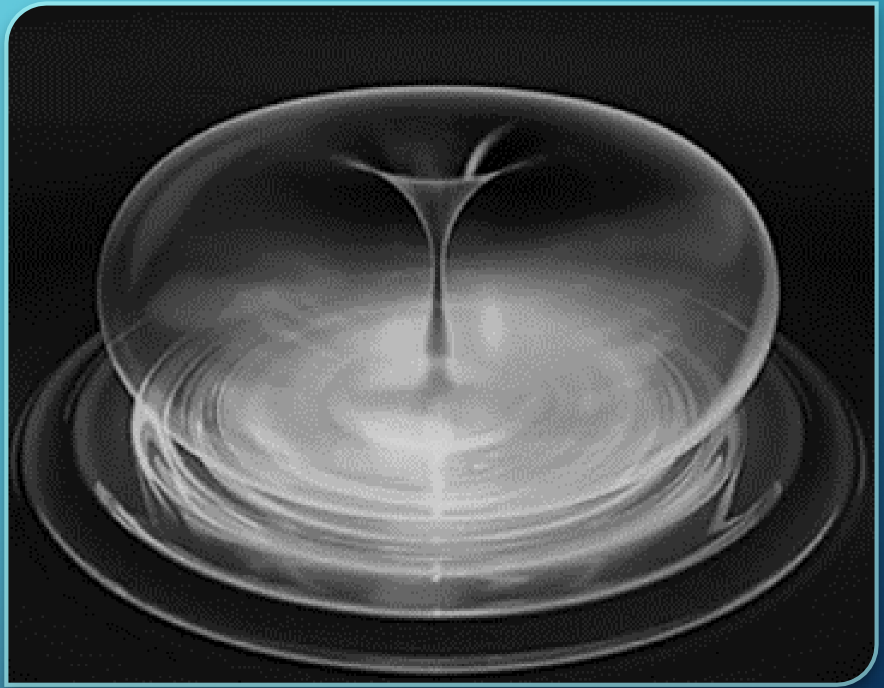
Ultrasonic flow-cell reactors are used for many industrial applications, where fluid substrate is sonicated in a small region, with a very high ultrasonic power.
The electromechanical transducer (‘converter’) that drive the sonotrode inside the flow-cell can operate with efficiency up to 98%, so thermal loss are quite low. Nevertheless, since the reactor may be in service 24 / 7 and the converter cannot operate above 150°C, thermal management solutions are very important.
Among these , best would be to employ a liquid cooling system inside the converter, where heat is generated, but the device is not generally compatible with standard liquids and the solution could be quite complicated.
A novel low pressure / high flow system was conceived for the application, making use of Comsol Fluid-flow and Heat-transfer modules, in order to get an efficient thermal drain and temperature control



HIGH POWER ULTRASONIC AND CAVITATION

Sonochemistry and ultrasonic processing of fluid products are based on the phenomenon of cavitation.

Cavitation in a liquid occurs due to the stresses induced in the liquid by the passage of a sound wave : at high power, the liquid can be torn to pieces to leave small bubbles, that are the heart of the sonochemistry systems. These bubbles grow and eventually implode : they can be seen as a micro-reactors, with actual temperatures reaching an estimated 5000°K and pressures of several hundred atmospheres

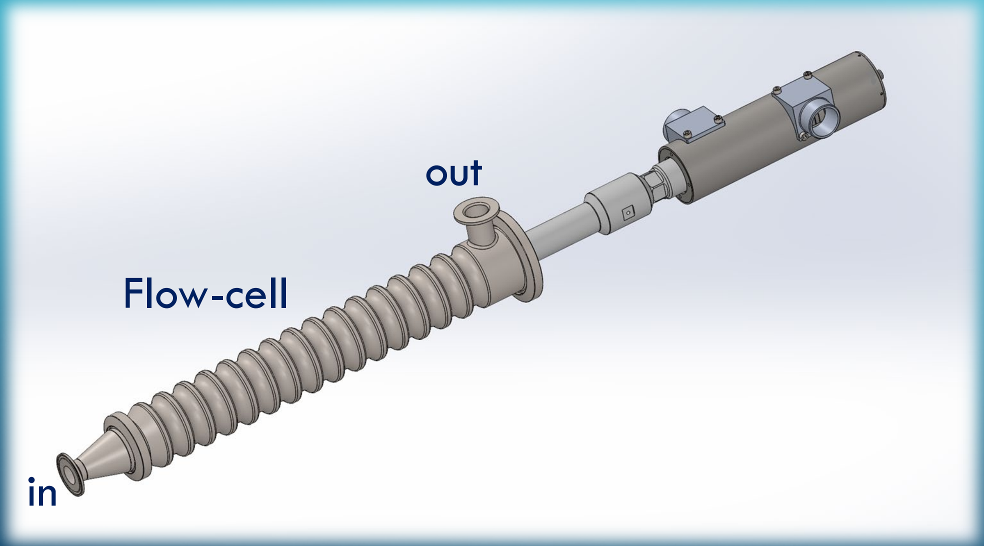


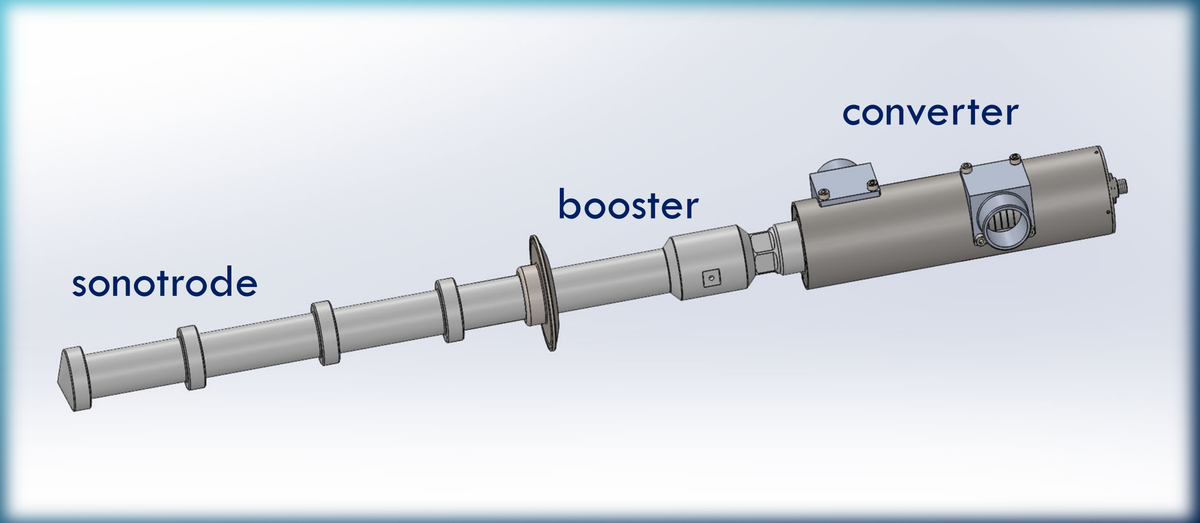
ULTRASONIC HIGH-POWER, FLOW-CELL REACTOR

A 3D design of the complete device was completed with SolidWorks CAD and live-linked to Comsol.

The system consists of three parts:

- 20kHz piezoelectric transducer or ‘converter’
- ‘Booster’ connection unit
- Sonotrode with ‘tuned rings’, named ‘steprod’
- Cylindrical reactor , or ‘flow-cell’





SPECIAL CONVERTER

The electromechanical transducer or ‘converter’ is based on a novel conception of the standard ‘Langevin structure’, with many design details and innovations to get the maximum efficiency. Just to name one, the present converter is not based on a single stack of Hard-PZT piezoelectric rings (as usual), but on two stacks to increase its maximum power

BOOSTER

The booster is a device that ‘boosts’ the amplitude of vibration on the thinner side with respect to the thicker one (with nodal region in the middle). Such device is important to limit the required electrical current to drive the sonotrode vibration and reduce the piezo-rings fatigue, thus resulting in a higher possible operating power

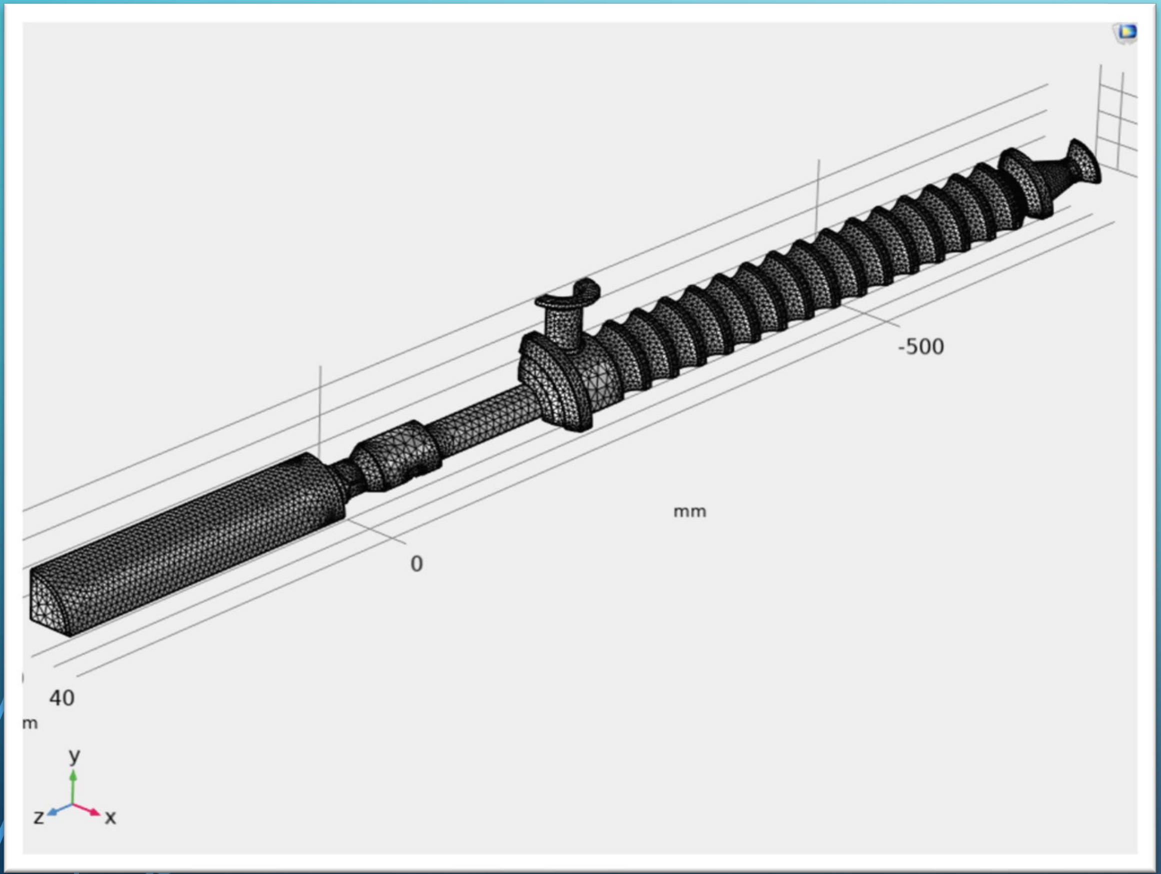
SONOTRODE & FLOW-CELL

As regard the special sonotrode with ‘stepped tuned’ rings named ‘steprod’, it is a very complicated part to design because the geometry of the rings on the rod must be studied carefully to guarantee a high level of pressure field in the surrounding fluid and, on the other hand, to limit spurious resonances close to the main one, which may be generated by the complex geometry. Finally, also the geometry of the reactor was deeply analyzed through FEM and special features were developed to reduce the transmission of undesired vibration along the flow-cell walls

STRUCTURAL-ACOUSTIC FEM MODEL

The complete ultrasonic reactor system was designed in Solidworks and live link to Comsol 6.1 was used to get directly the 3D Model.

For the first set of simulation Solid Mechanics, Piezoelectric, and Acoustics modules were employed. Then Fluid flow and Heat transfer modules were used for thermal simulations.



The converter was designed to operate with a resonance frequency of 20kHz and power up to 3kW. The FEM Optimization process was focused on eliminating spurious resonances in all the components of the device , thus allowing high efficiency and power. The process led to important modifications of mechanical parts with respect to standard technology. It’s not possible to analyze all of them, since they’re confidential details of the project.

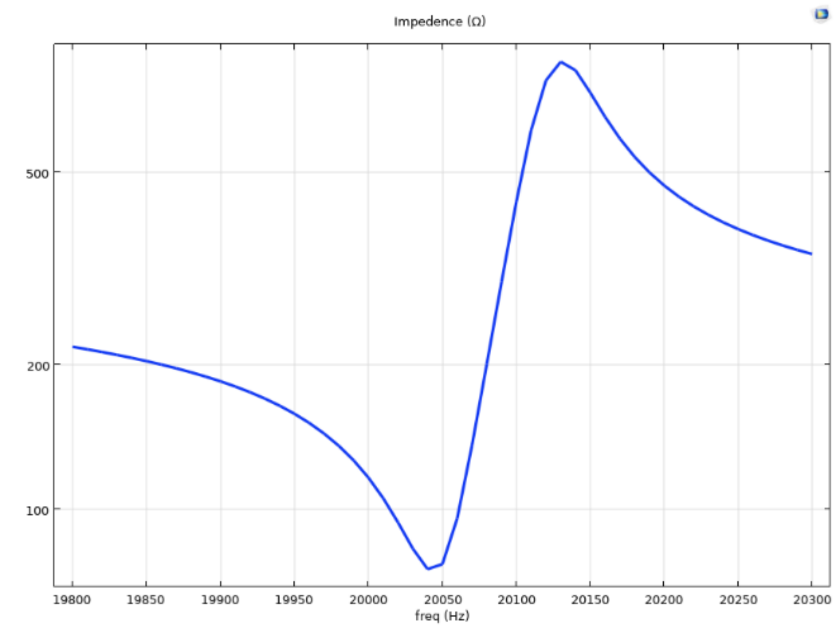
Here is a mesh of the 3D model , where section and symmetries are evident

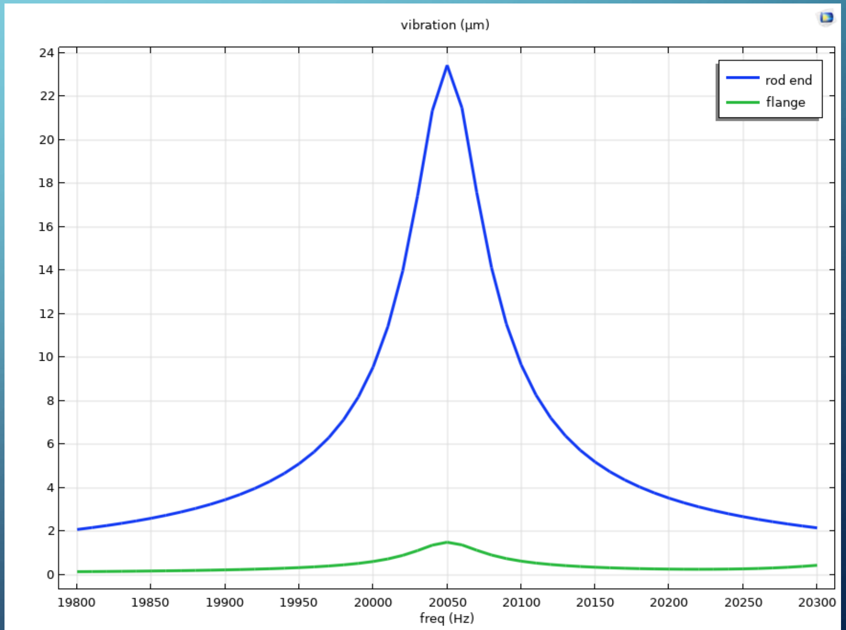
STRUCTURAL-ACOUSTIC RESULTS

The following data are the result of the complete design and optimization process, which is not described for the sake of briefness.

As it's clear from the electrical impedance plot below, a strong resonance is present at 20.05 kHz, as required, and the electrical impedance at resonance is approx. 80Ω.

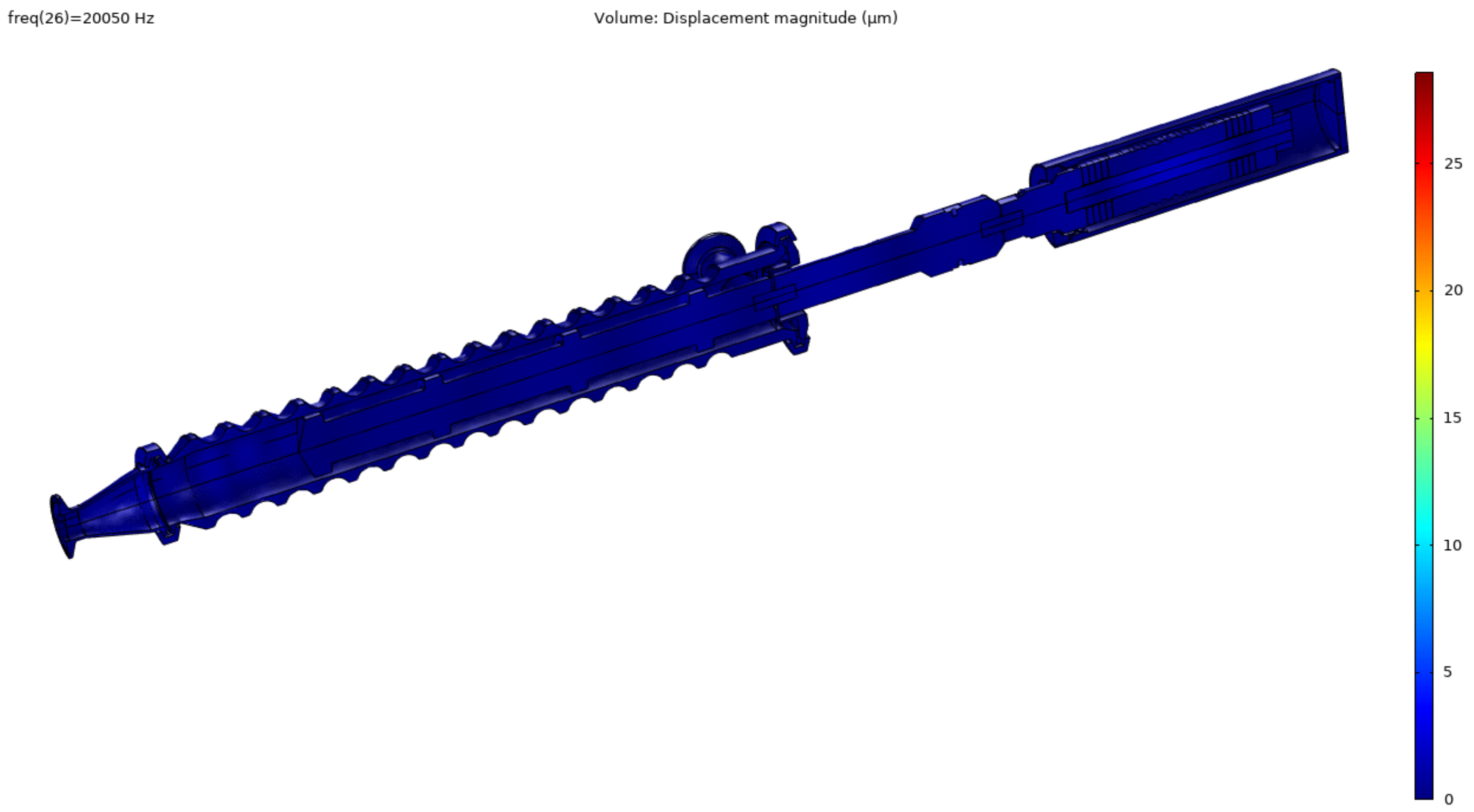
Next, on the vibration vs. frequency plot two points are reported: the end of sonotrode and the side of connection flange to flow cell. The first vibrates with amplitude up to 24μm while the latter vibrates only with 1.5μm amplitude : that is a good result, as it's important that vibration is not wasted on transverse undesired directions.





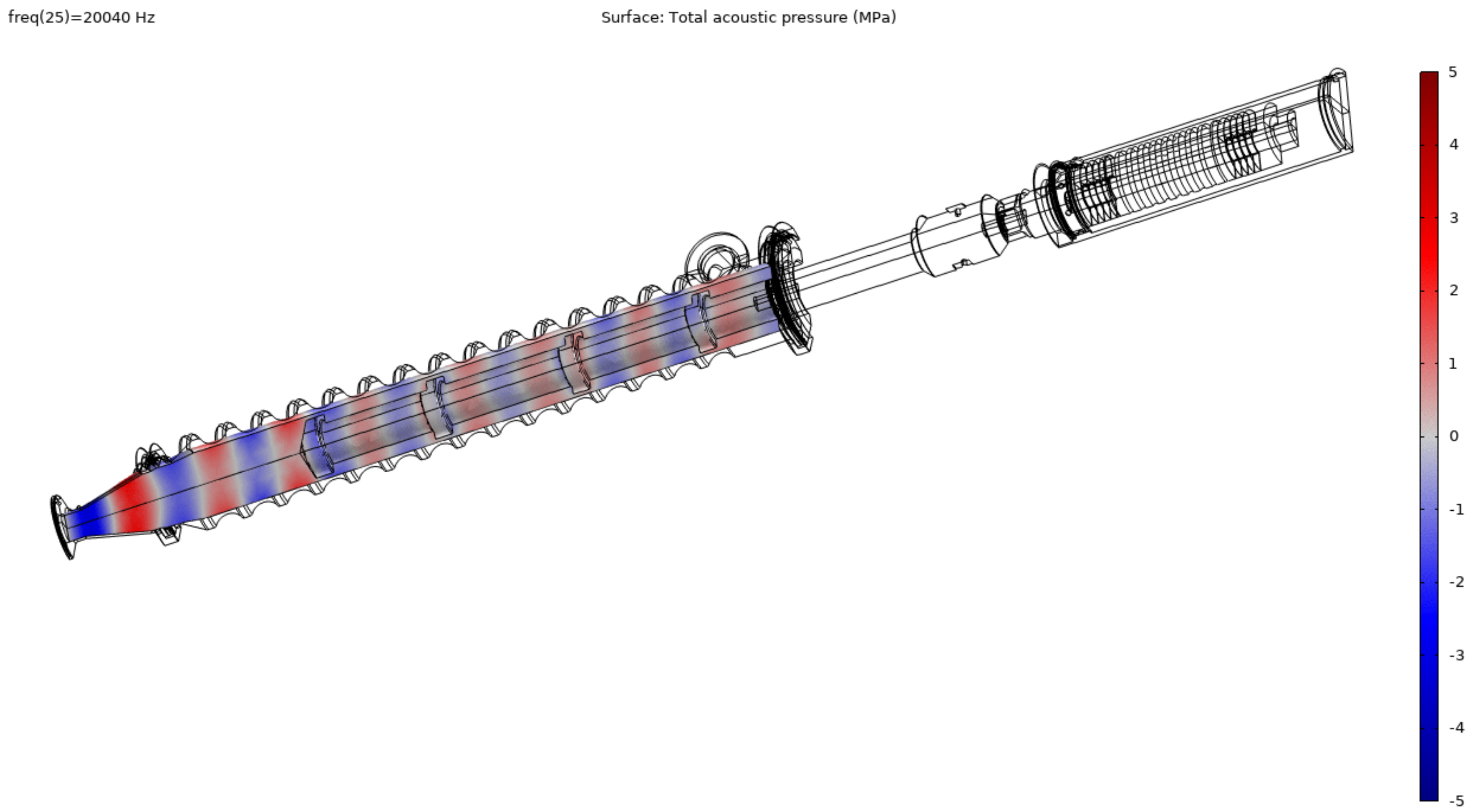
STRUCTURAL-ACOUSTIC RESULTS

Moreover, a vibration map of the entire structural domain is reported, at resonance frequency: it's clear that the sonotrode vibrates with amplitude much higher than the flow-cell, as desired



STRUCTURAL-ACOUSTIC RESULTS

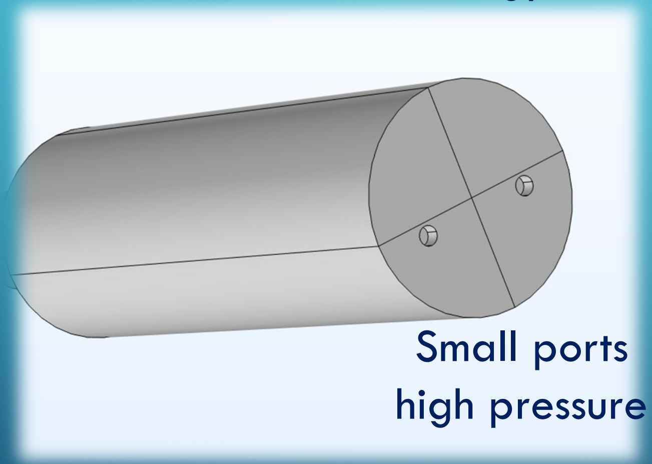
In the acoustic domain it's possible to check the ultrasonic field pressure amplitude : 5Mpa are available at 20kHz (with max values close to the rings), which is enough to get very strong cavitation phenomena in the fluid, as required for industrial applications



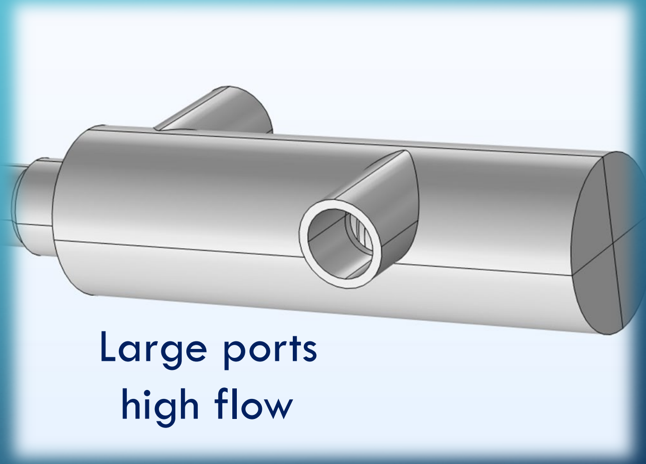
THERMAL ANALYSIS

Finally, Fluid-flow and Heat-transfer physics were added to the ultrasonic converter model, in order to analyze cooling air flow and efficiency of a novel impeller-based solution.
The cooling system geometry below is the result of an optimization process which is not described for the sake of briefness.
The novel high flow / low pressure solution (from an impeller) is compared to the typical high pressure / low flow standard system (compressed air flowing through small connectors on the cover back) in order to assess the cooling improvement

Standard technology



New solution



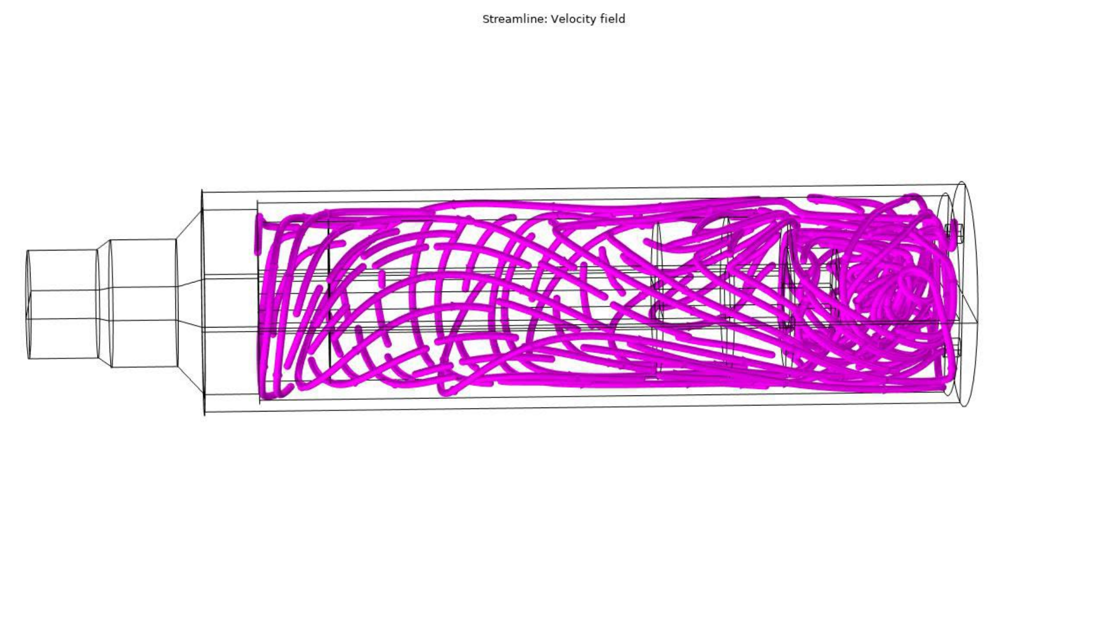
Typical values for air speed and pressure were used, accordingly to the type of system.

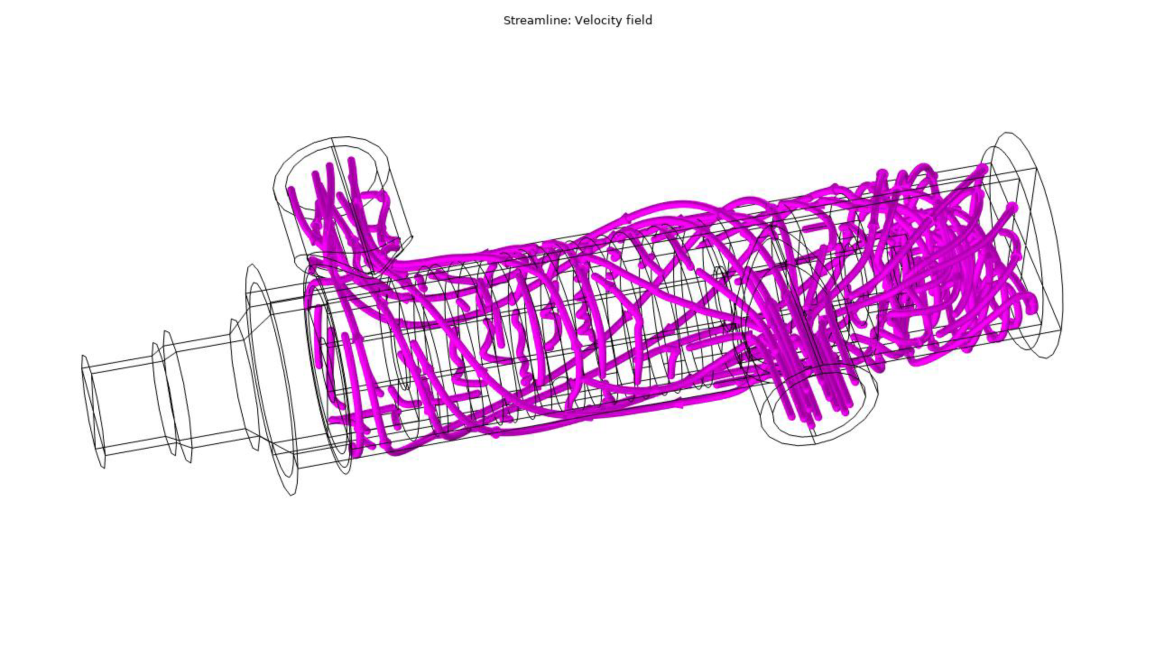
THERMAL ANALYSIS RESULTS

Some simplification were considered in the model, neglecting many parts that are not significant for the thermal analysis. Only the converter was considered , and a dissipation heat source was considered in the piezo-ring volume, corresponding to 30W (2% losses at 1.5kW operating power).

The following are reported for both standard and new solution :

- 3D air flow maps
- 3D air velocity maps
- Temperature maps





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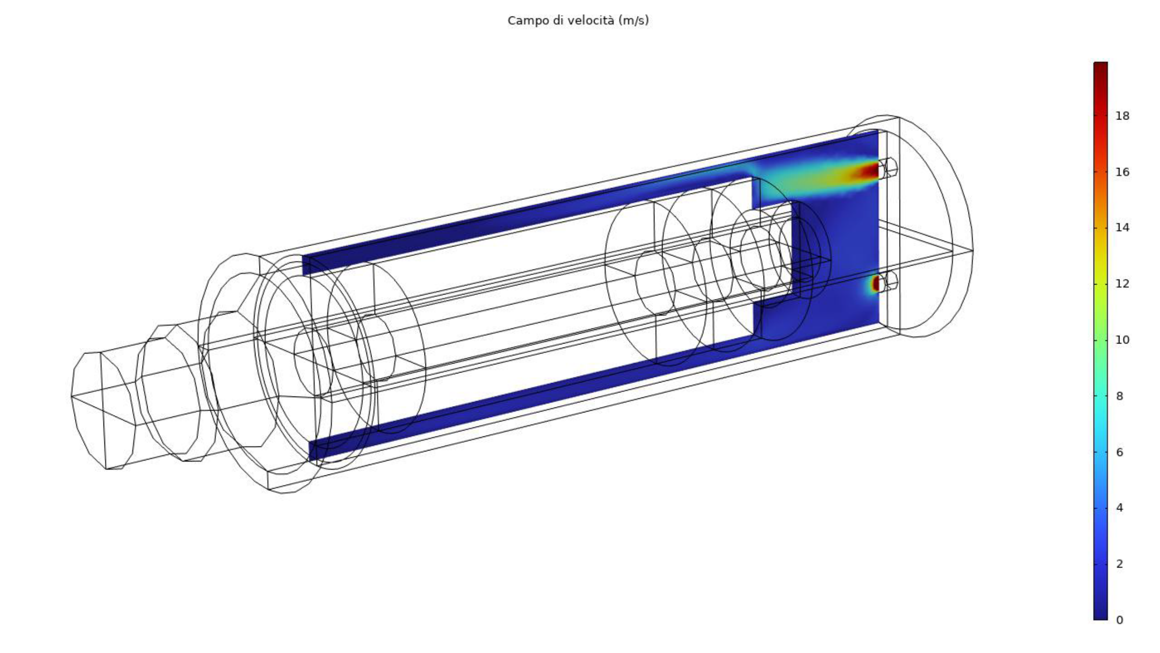

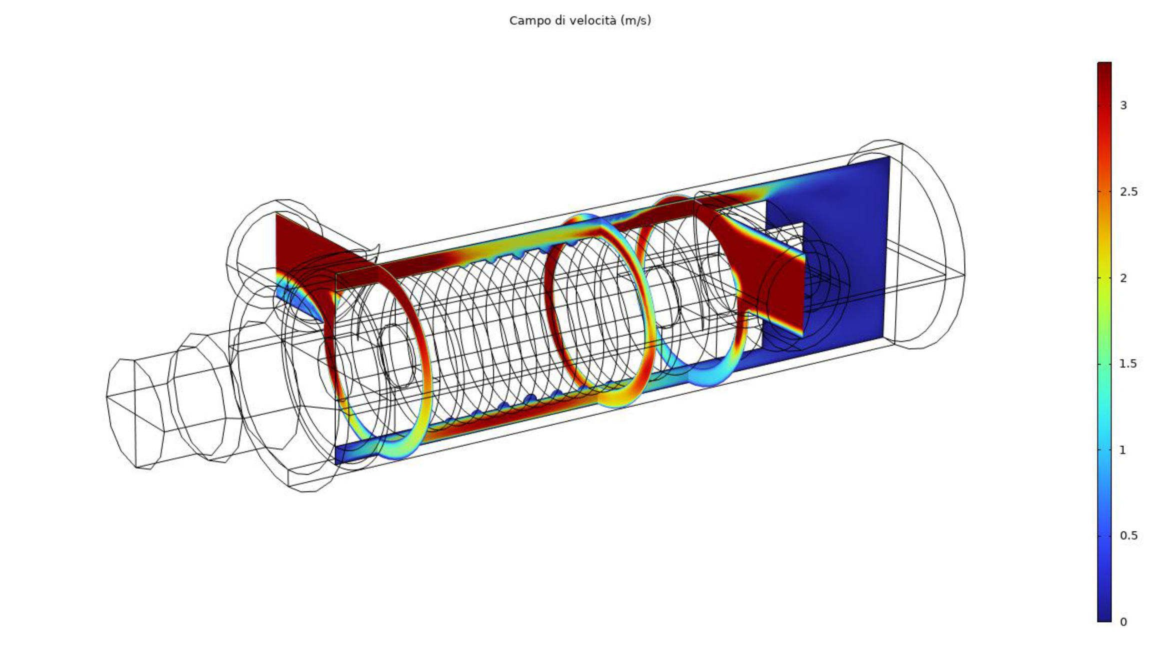

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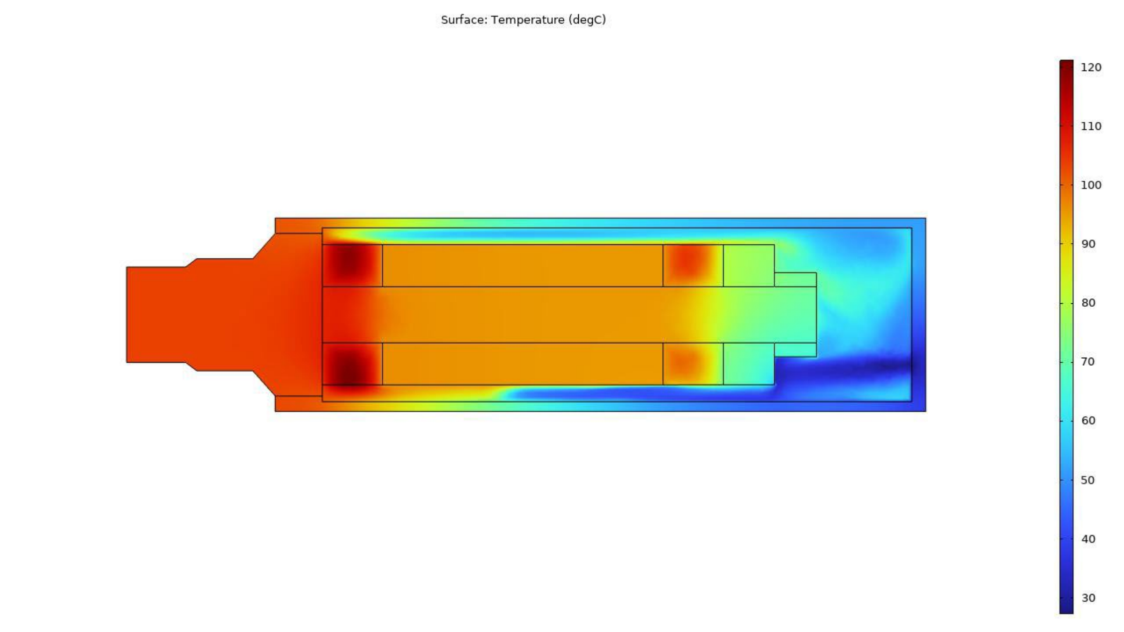

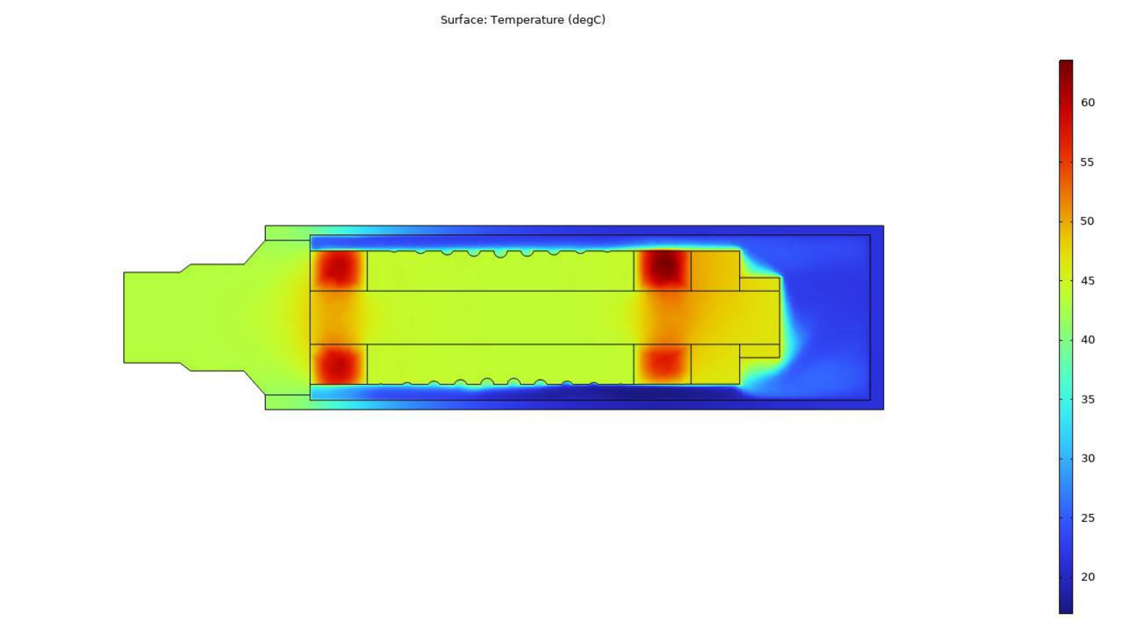

THERMAL ANALYSIS RESULTS

Previous results clearly show a large improvement with the novel impeller based system, that leads to a omogeneous air flow, entering from the input port, spinning around the central mass of the converter and exiting from the out port. With the old configuration there's no effective air movement inside the converter, leading to a much higher operating temperature.

From the temperature maps, at 1.5kW operating power the novel cooling system leads to 60°C maximum temperature for the piezo-rings, to compare with 120°C obtainable from the old system

CONCLUSIONS

COMSOL Multiphysics® was used to design a multi-purpose ultrasonic reactor, consisting in a high-power piezoelectric converter, a cylindrical flow cell and a special sonotrode.
The design involves a special converter structure, that employs two stacks of piezo-rings, and a novel cooling system, based on an external impeller that forces high flow of air into a large input port on the converter cover, so that the air flow wraps around the central mass of the converter end exits tangentially from the exit port, resulting in efficient heat drain.
The system was designed with a parametrized structural / acoustic / heat transfer & fluid flow multiphysics model and a complete optimization process was performed.
The simulation results were up to the required level of efficiency and very high levels of cavitation could be obtained in the reactor, in order to fulfill new industrial demands.
Moreover, the novel cooling system reduces the piezo-rings operating temperature value to about half compared to the old one, allowing for a higher level of continuous operating power.