ultrasonic industry association
UIA
powering sound ideas
19 - 21 March 2007
36th Annual Symposium
Teddington, Middlesex, England

CSIC

ADVANCES IN THE DEVELOPMENT OF POWER ULTRASONIC TECHNOLOGIES BASED ON THE STEPPED PLATE TRANSDUCERS

J. A. Gallego-Juárez, G. Rodríguez, E. Riera, V. M. Acosta, F. Montoya*, A. Blanco*

Instituto de Acústica, CSIC; Serrrano 144, 128006 Madrid
***Instituto de Física Aplicada, CSIC; Serrrano 144, 128006 Madrid**

Outline

- **High-power US transducers. Later Advances**
  - Mechanics
  - Electronics
- **Application of the US technology to different processes**
  - Ultrasonic Defoaming
  - Ultrasonic Drying of vegetables
  - Ultrasonic Washing of Textiles
  - Ultrasound-assisted Supercritical Fluid Extraction
- **Conclusions**

High-Power US Transducers
Later Advances

Problems

* Low specific acoustic impedance
* High absorption

Solutions

* Good impedance matching
* Large vibration amplitude
* Concentration of energy (directivity
  or focalization)

Needs for large-scale applications

* High-power capacity
* Extensive radiating area

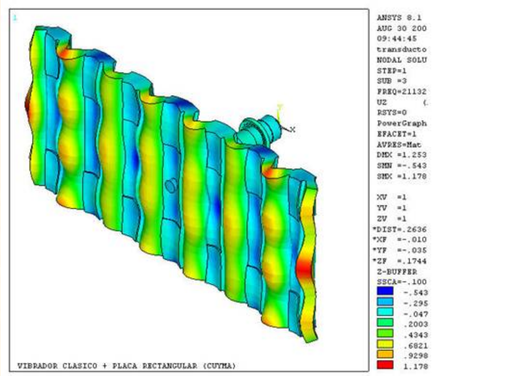
This generator is made of

*Piezoelectric transducer
*Stepped/Grooved/Flat plate radiator
*Electronic unit
    *Impedance adapter
    *Power amplifier
    *Resonance frequency
     control system

Advantages

*Powerful compact device
*Doesn't interfere in the process
*Easy to sterilize

High-Power Stepped Plate Transducers. Later Advances



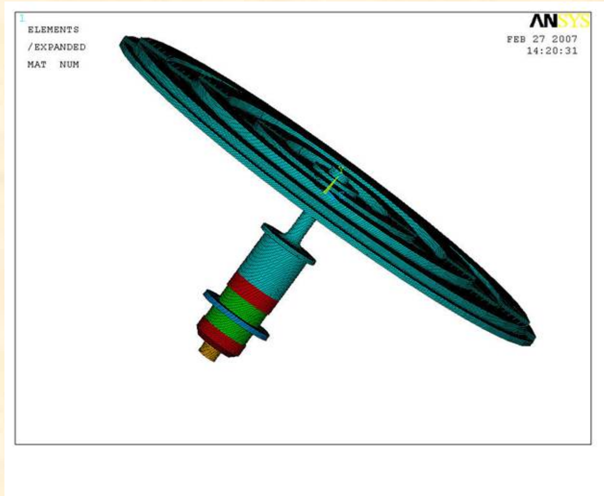
TRANSDUCERS WITH LARGE VIBRATING SURFACE

Geometry	**Circular, Square, Rectangular**
Profile	**Flat, Stepped, Grooved**
Frequency	**7 – 40 kHz**
Acoustic Field	**Coherent Focused**
Intensity	**Up to 172dB ($10 W/cm^2$)**

<u>**Problems at High-Power**</u>

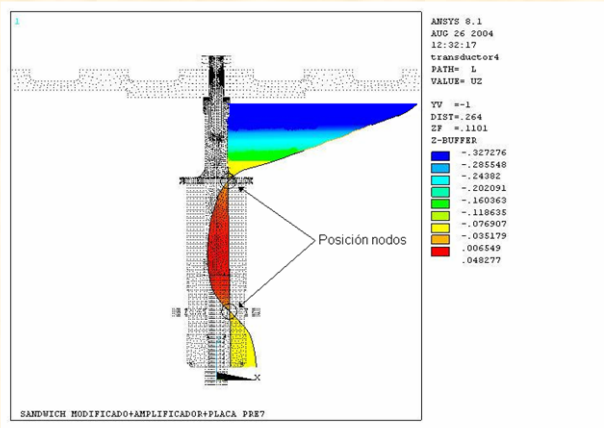
Fatigue Crack

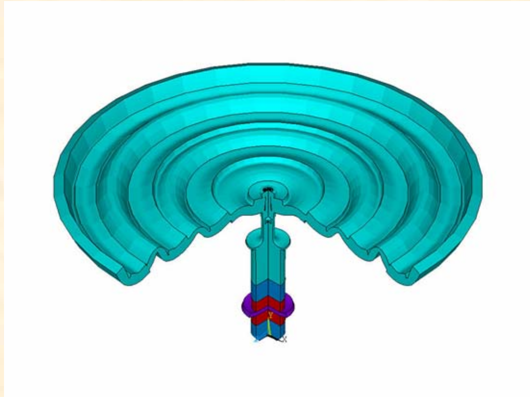
Mode Interaction

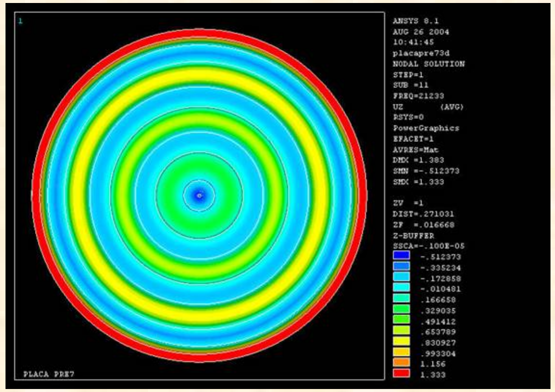


J.A. Gallego et al., (1994) US Patent 5,299,175

High-Power US Transducers
Later Advances by FEM

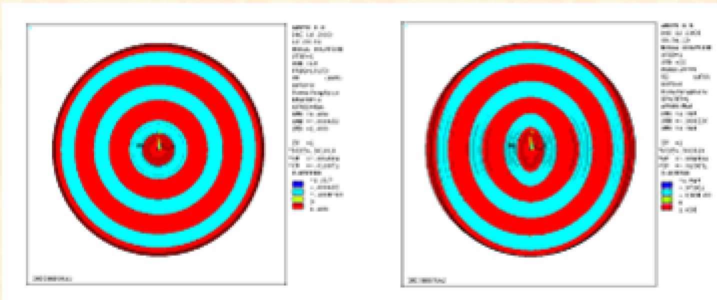


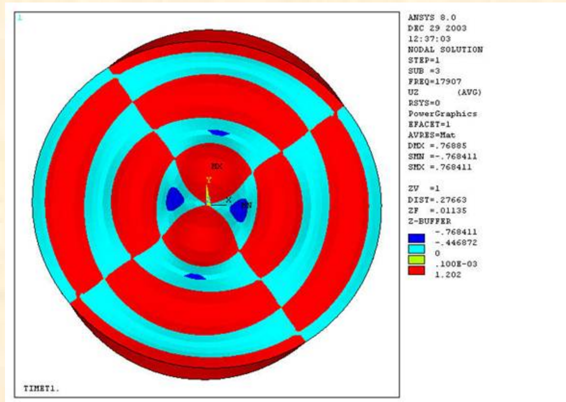




Mode Interaction
NC and Diametrical

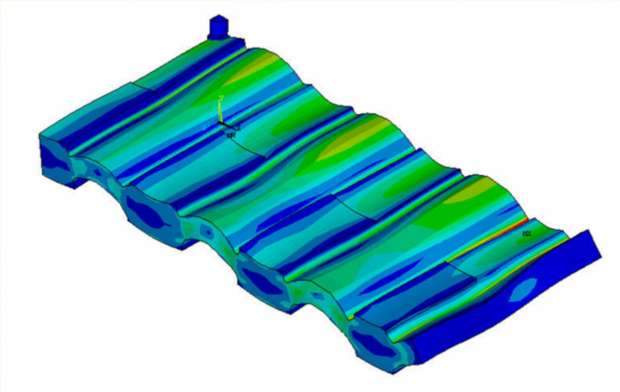
Material microstructure (1st -3rd NC deformed)



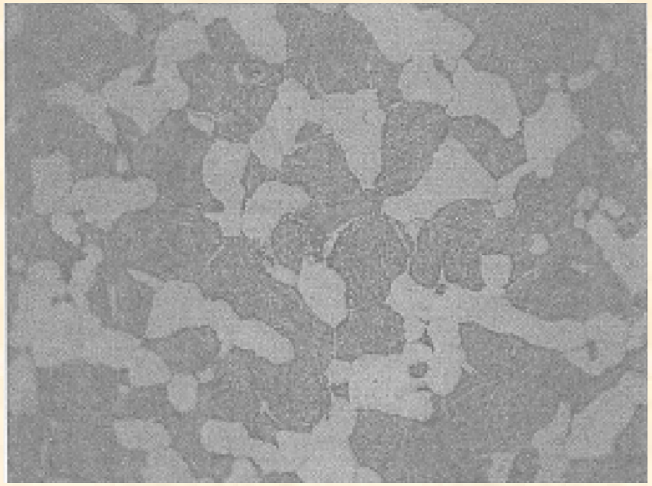


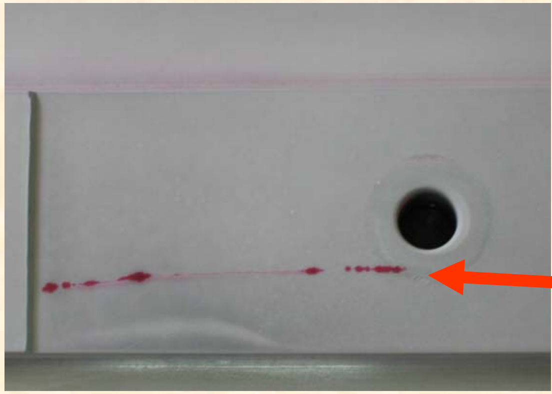
High-Power US Transducers
Later Advances

Vibration amplitud by FEM

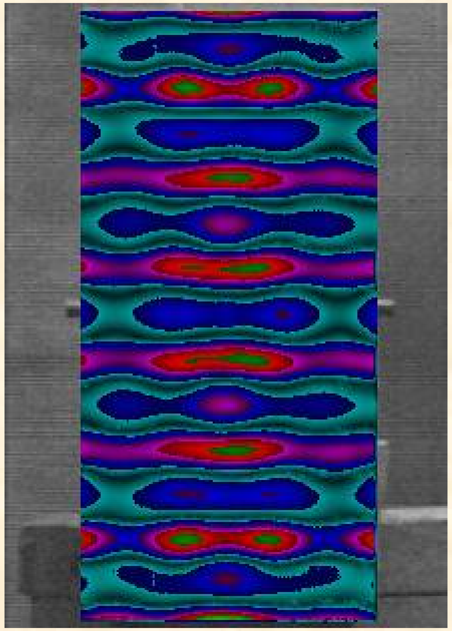


Material Microstructure





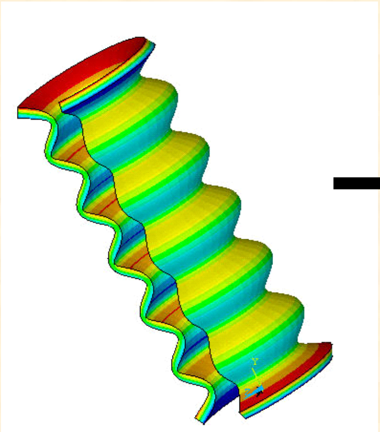
Vibration amplitude
by Laser Vibrometer



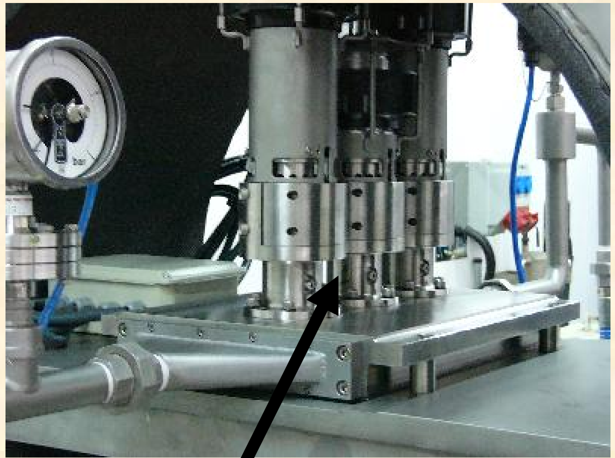
Fatigue Crack

High-Power US Transducers
Later Advances

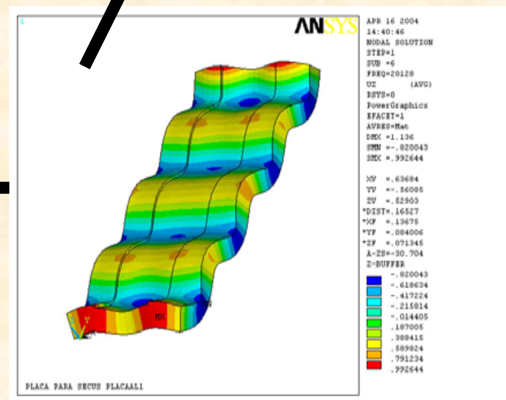
Mass transfer enhancement in food drying

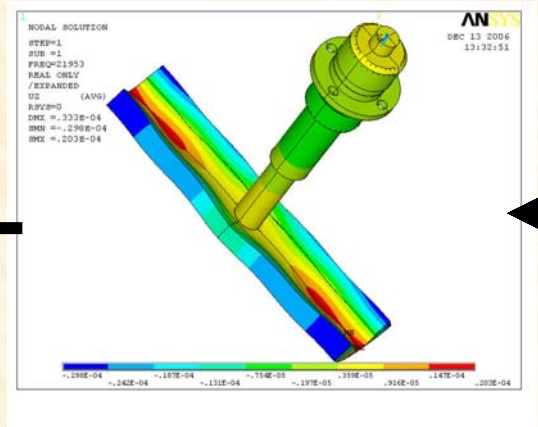


Enhancement of the dispersion of solid particles in liquids

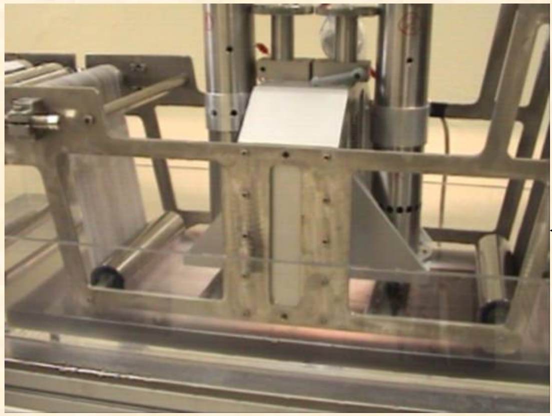


Grooved Plate





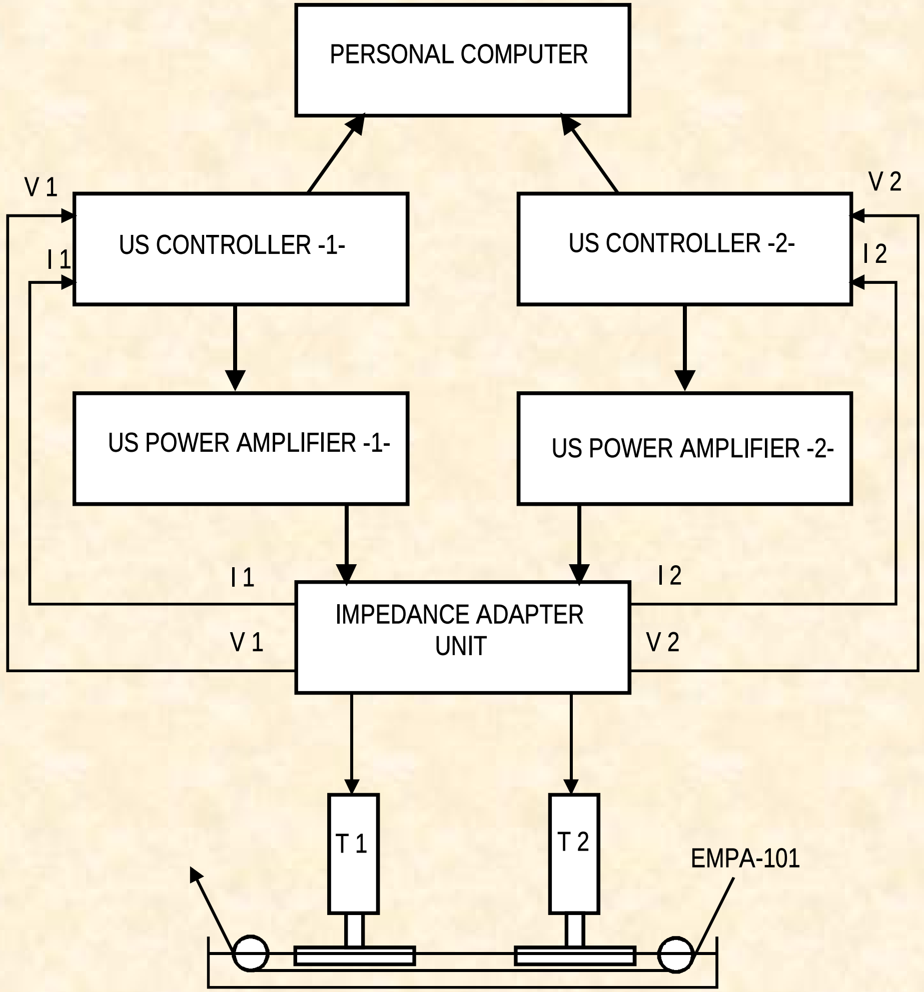
T1 T2



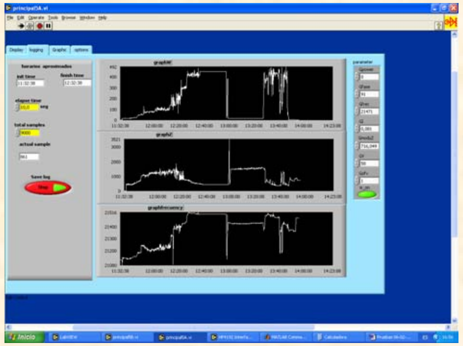
US system for textile washing

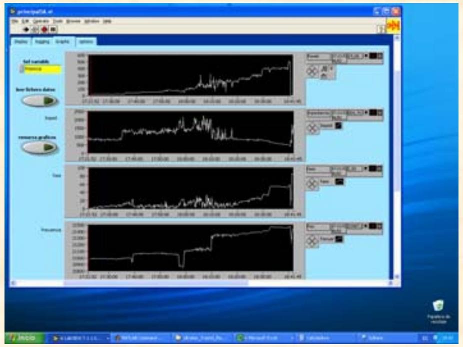
High-Power US Transducers
Later Advances in Electronics

Electronic Rack

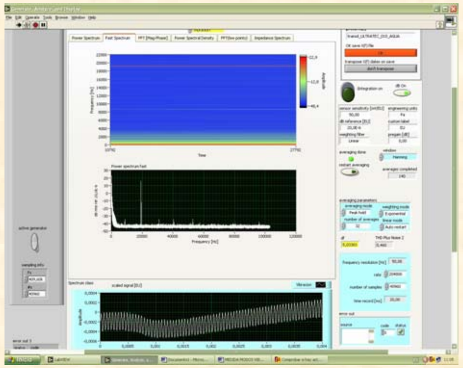


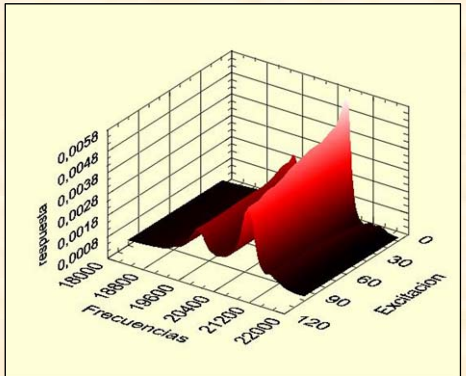
High-Power US Transducers
Later Advances in Electronics





Electronic unit
*Impedance adapt
*Power amplifier
*Resonance frequency control system

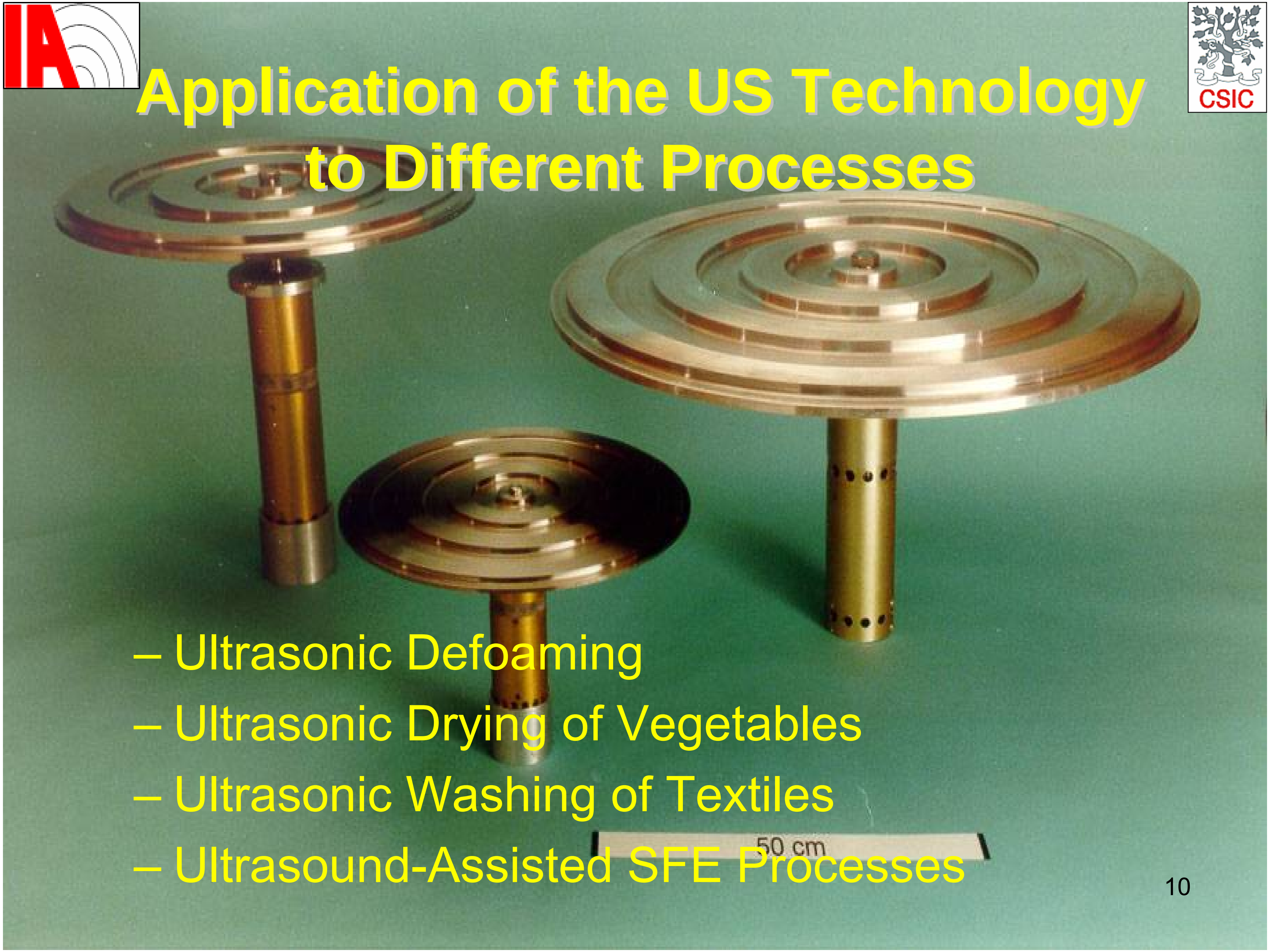




Computer
Hardware + LabView Software
Control and monitoring of the electrical parameters of the transducer under high-power operation

Electrical Characterization at High-power (Impedance analyzer)
Mechanical Characterization at High-power (Laser Vibrometer)
Acoustical Characterization at High-power (1/8" Microphone / Needle Hydrophone)
Temperature (IR)

Application of the US Technology to Different Processes



- Ultrasonic Defoaming
- Ultrasonic Drying of Vegetables
- Ultrasonic Washing of Textiles
- Ultrasound-Assisted SFE Processes

Ultrasonic Defoaming

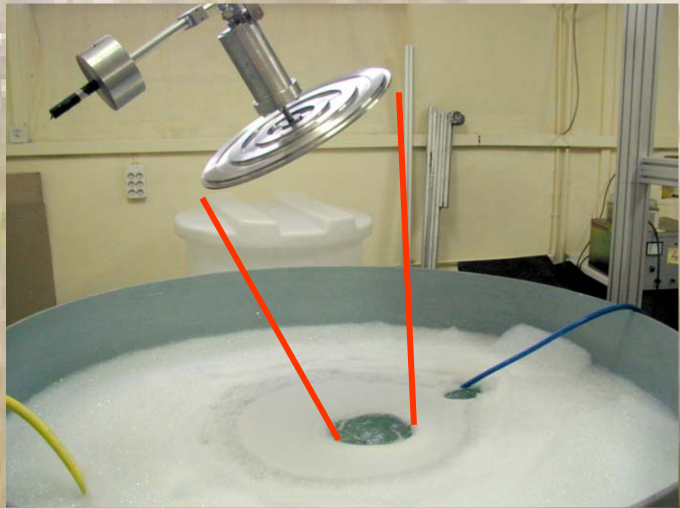
High-intensity air-borne US represents a <u>clean means</u> for breaking foams. This is a promising mechanical method.

The **mechanisms** of acoustic defoaming is a combination of:

- **High acoustic pressures**
- **Radiation Pressure**
- **Resonance of bubbles**
- **Cavitation**
- **Streaming**
- **Atomization from the film bubble surface**

Ultrasonic Defoaming

PATHS TESTED IN LABORATORY AT PILOT PLANT SCALE



FOAM BREAK IN THE CENTRAL AREA

FOAM BREAK IN THE CENTER OF THE REACTOR

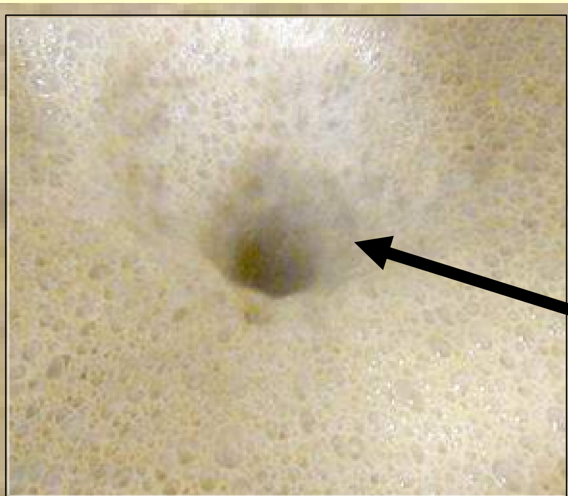
FOCUS PATH IN A SPIRAL IN THE CENTRAL AREA

EXTERNAL ANNULAR PATH. FOAM GROWTH IN THE CENTRAL AREA

Ultrasonic Defoaming

TESTS AT PILOT PLANT SCALE

Parameter	
Maximum power applied	350W
Frequency	20,95kHz
Acoustic intensity in the focus	10W/cm^2 <> 170dB
Focal distance	45cm
Focus diameter (-3dB)	3,5cm
Focus depth	12cm
Impedance	IZI = 500Ω
Inductance	L_0 = 9-10mH
Capacitance	C_0 = 6-8nF



FOAM COLLAPSE BY ULTRASOUND

Ultrasonic Defoaming

ULTRASONIC DEFOAMING FOR THE CONTROL OF THE EXCESS OF FOAM IN THE FILLING OPERATION OF CANS AND BOTTLES WITH A COMMERCIAL BEVERAGE

CANNING LINES

1-2 Focused Transd.

Fr = 20, 25, 40kHz

I = 165-172 dB

Plate Diameter = 24 - 48cm

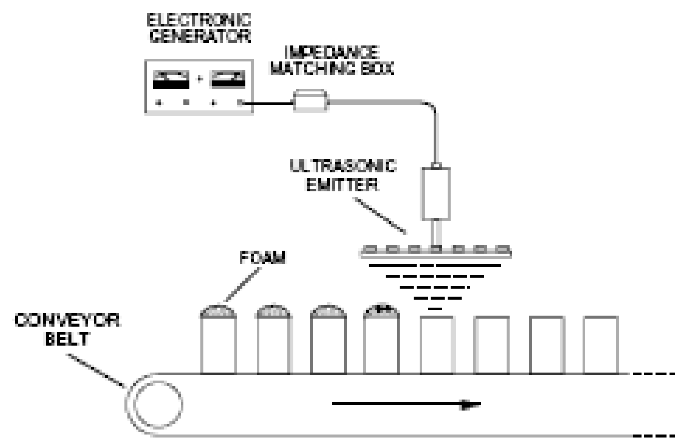
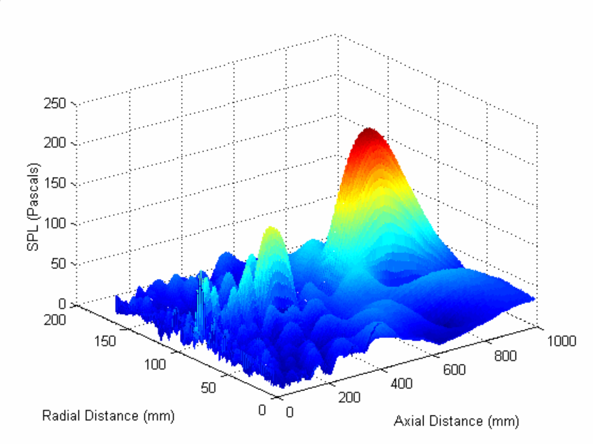


Fig. 7. Foam control at a canning line by means of high-intensity focused ultrasonic defoamer.

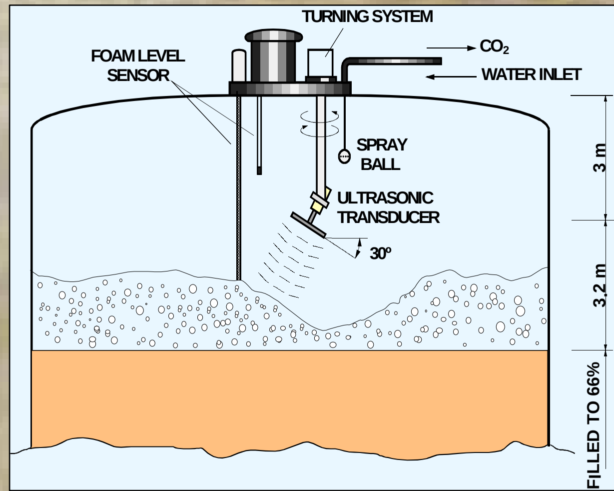


CANNING SPEED: 20 cans/s

Ultrasonic Defoaming

ULTRASONIC DEFOAMING IN A FERMENTER VESSEL OF 6 – 9 METERS IN DIAMETER

Focused Transducers



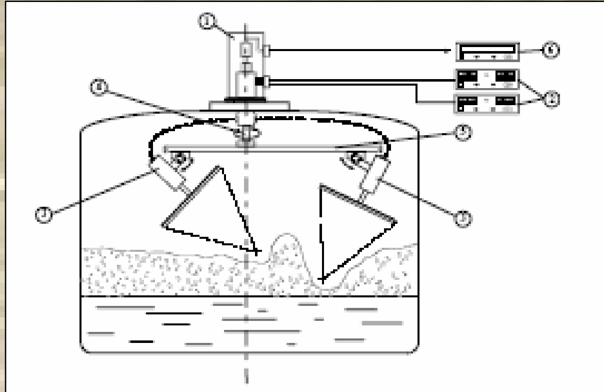


Fig. 9. Design of a twin set focused transducer system for the dissipation of foam in reactors.

J.A. Gallego et al., (2005) International Patent PCT/ES2005/070113
J.A. Gallego et al., (2003) International Patent PCT/ES2003/00465

Ultrasonic Defoaming

ULTRASONIC DEFOAMING SYTEM WITH TWO FOCUSED TRANSDUCERS, AND VARIABLE ROTATION

ULTRASONIC DEFOAMING TESTS IN A PILOT PLANT SCALE
DIAMETER = 2m
SCALE-UP WITH TWO FOCUSED TRANDUCERS (700W, 21kHz)
DIAMETER OF THE REACTOR UP TO 9m

Ultrasonic Drying

US does not lead to the product being heated to any significant degree
As a consequence, the use of US either to dry heat sensitive materials or to be applied in drying processes carried out at low temperatures **has a great potential**

Effects associated to acoustic energy

High intensity ultrasonic waves are able to increase the drying rate of materials

•***Ultrasonic vibrations*** may induce a kind of ***micro-sponge effect*** to extract the inside moisture. This alternating stress creates microscopic channels which may make the moisture removal easier.

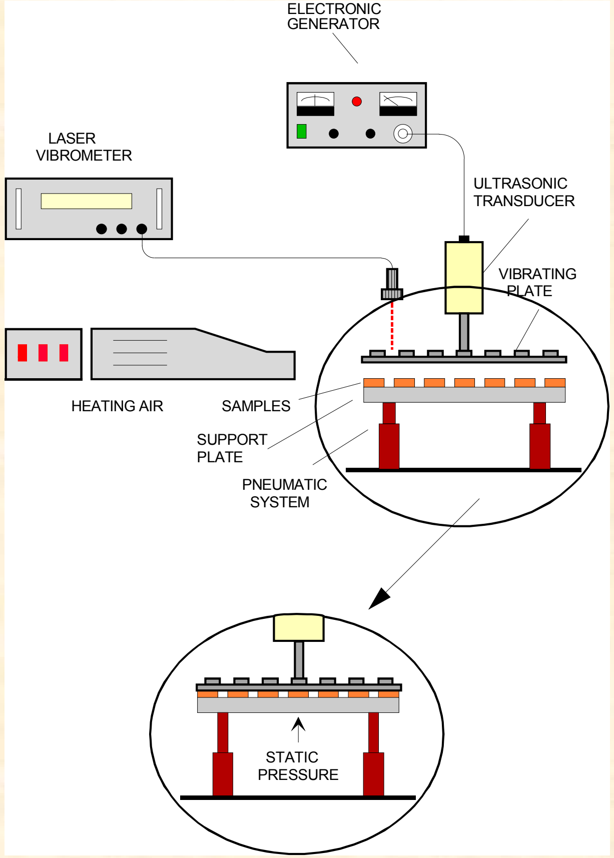
•***Pressure variations*** at the liquid/gas interface ***increases the surface moisture evaporation rate***.

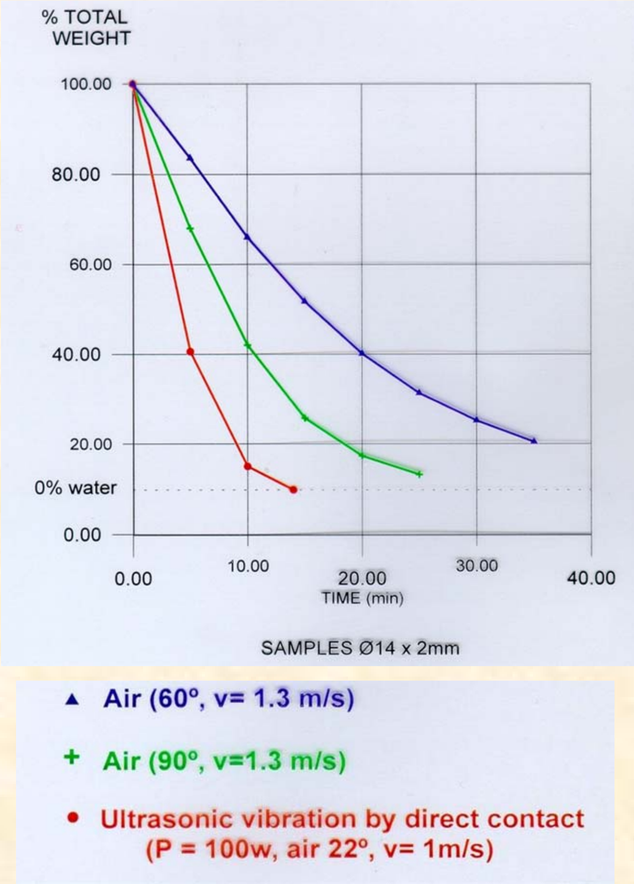
•Ultrasonic energy produces ***microstreaming at the interfaces*** increasing mass transfer and diffusion boundary layer.

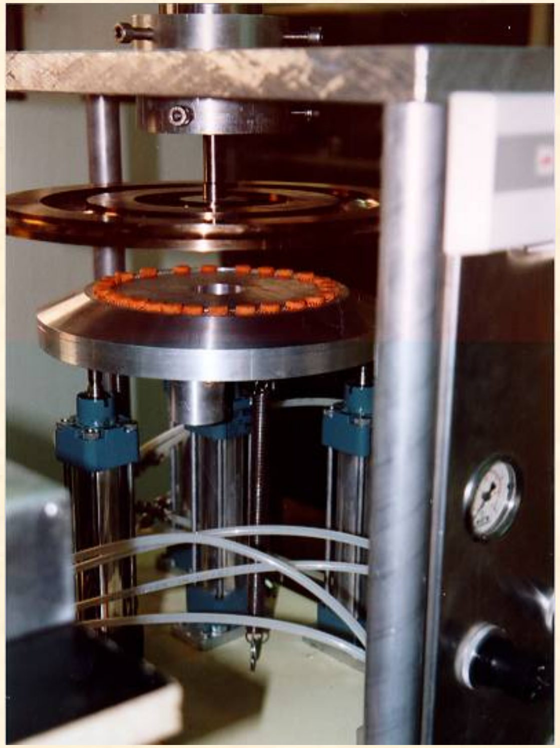
•Power US also may produce **cavitation** of water molecules inside the solid matrix which may be beneficial for the removal of strongly attached moisture.

Ultrasonic Drying

Comparison between contact US and hot-air drying



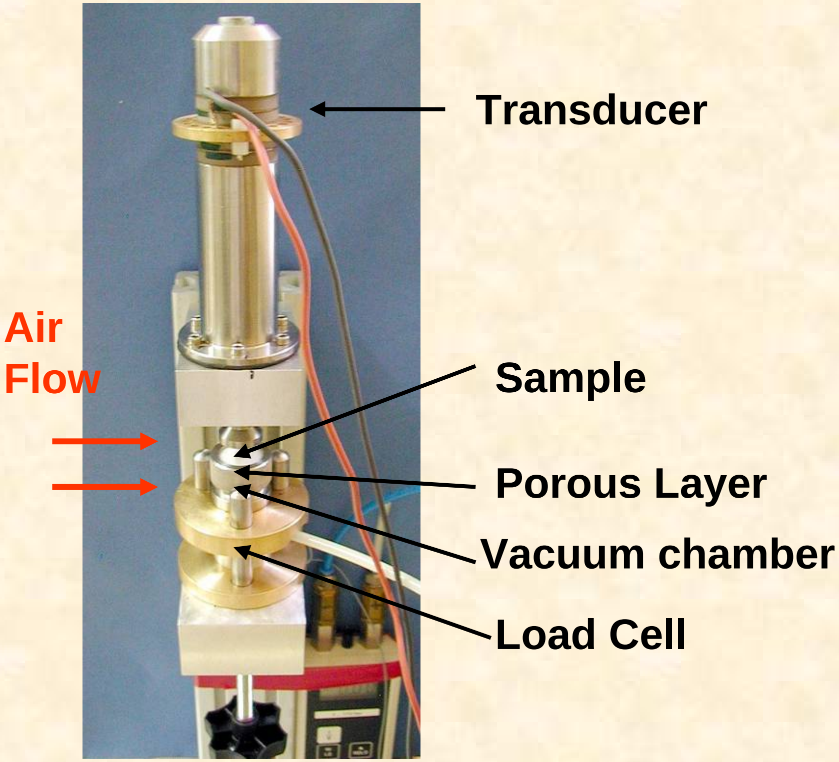




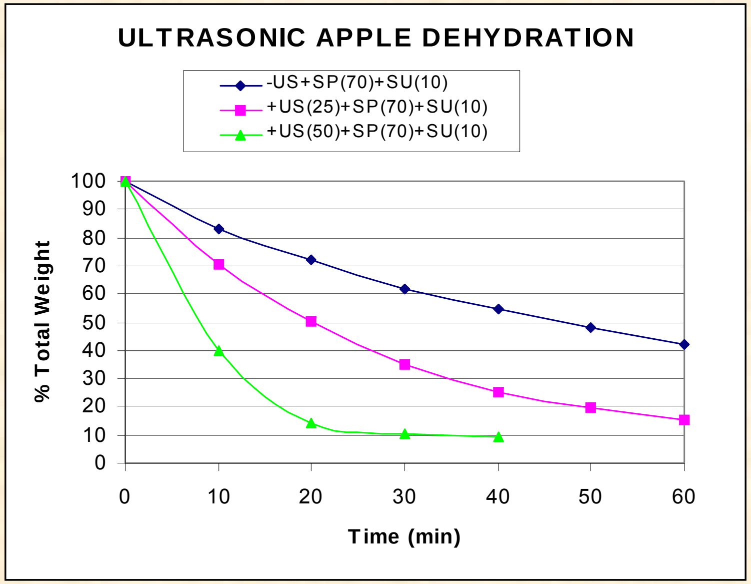
J.A. Gallego et al., (2001) US Patent 6,266,836 B1

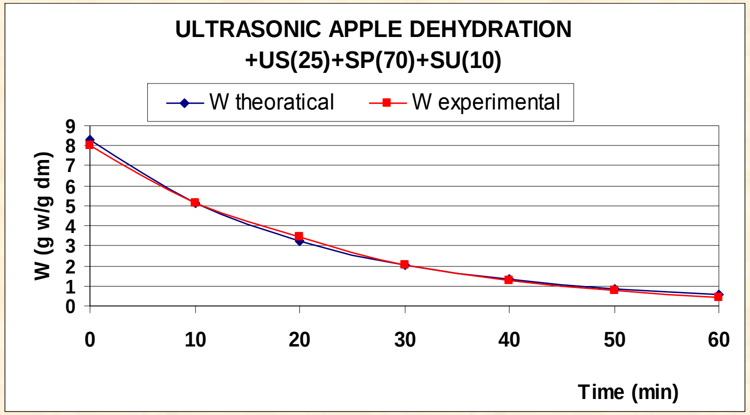
Ultrasonic Drying

Contact Ultrasound



Mono-sample ultrasonic drying unit

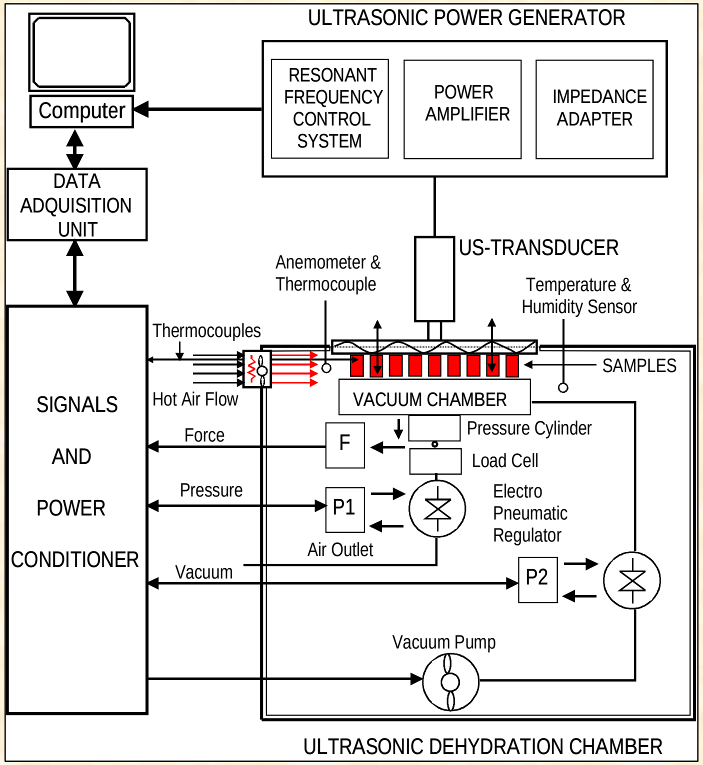


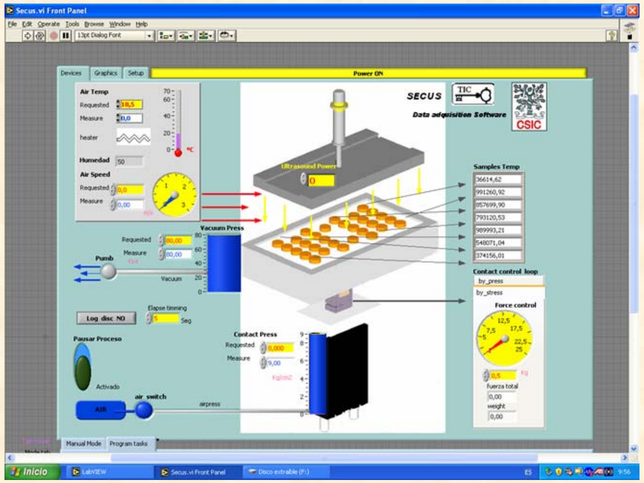


By means of the proposed diffusional model, effective water diffusivity coefficient was identified for the experiments carried out at the operational conditions

Ultrasonic Drying

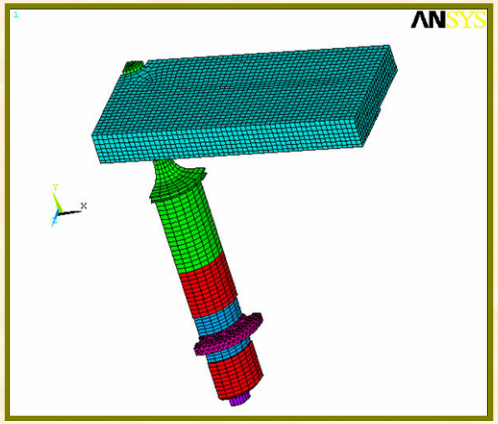
Multi-sample ultrasonic drying plant





SAMPLES

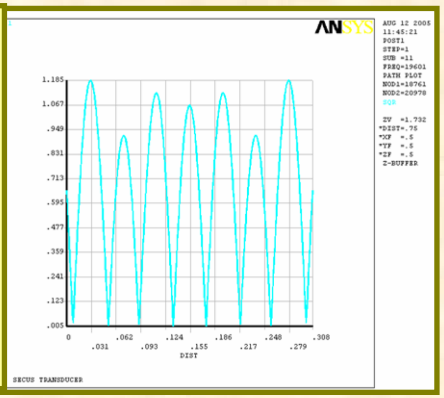
Ultrasonic Drying



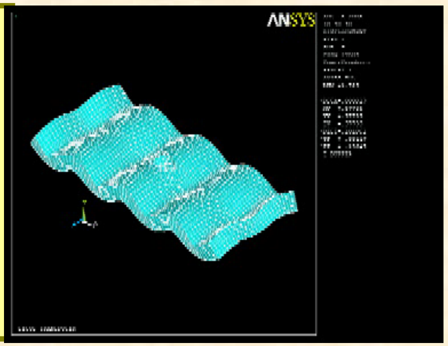
Trials were carried out to study the influence of US power in the kinetics of the drying process of carrot

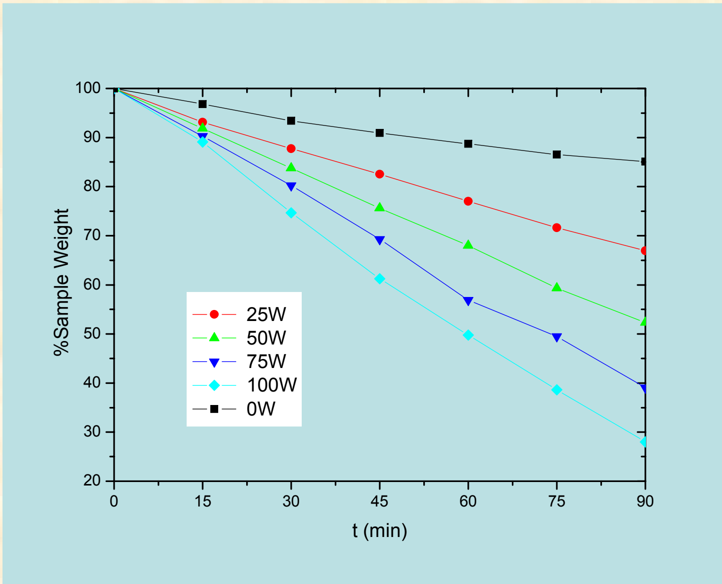
- Power ultrasound: 0, 25, 50, 75 and 100 W
- Vacuum pressure:60 mbar
- Static Pressure: 0,06 Kg/cm^2
- Air flow temperature: 30ºC
- Air flow temperature: 30ºC

VIBRATION AMPLITUDE



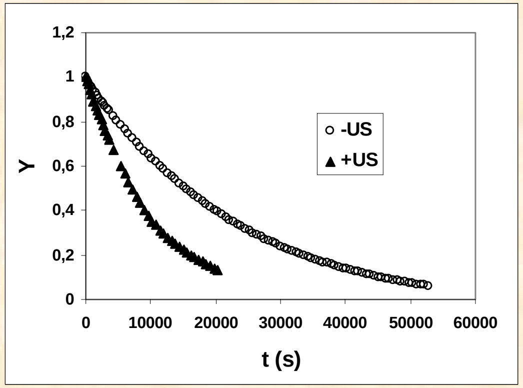
VIBRATION MODE





Ultrasonic drying of foodstuff in a fluidized bed

Carrot cubes 18 mm; 75W; 0.6 -10m/s



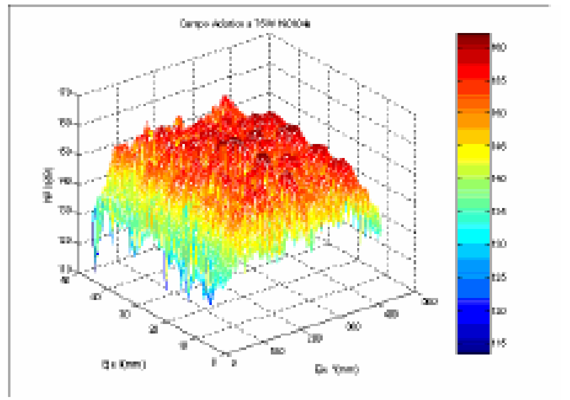
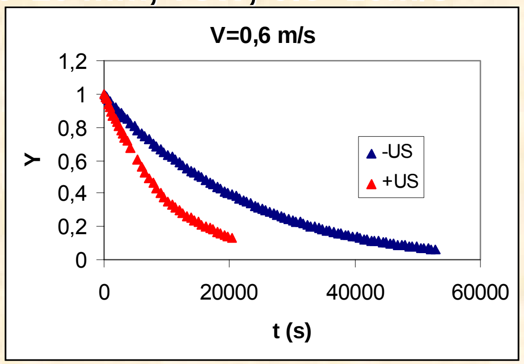
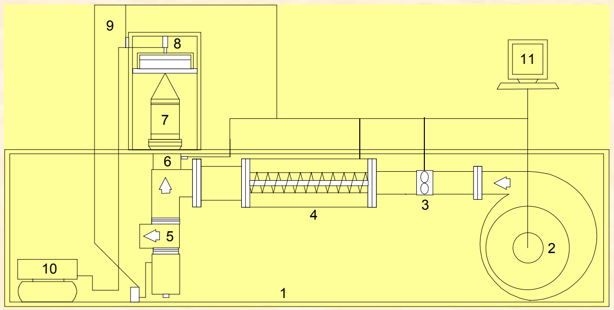


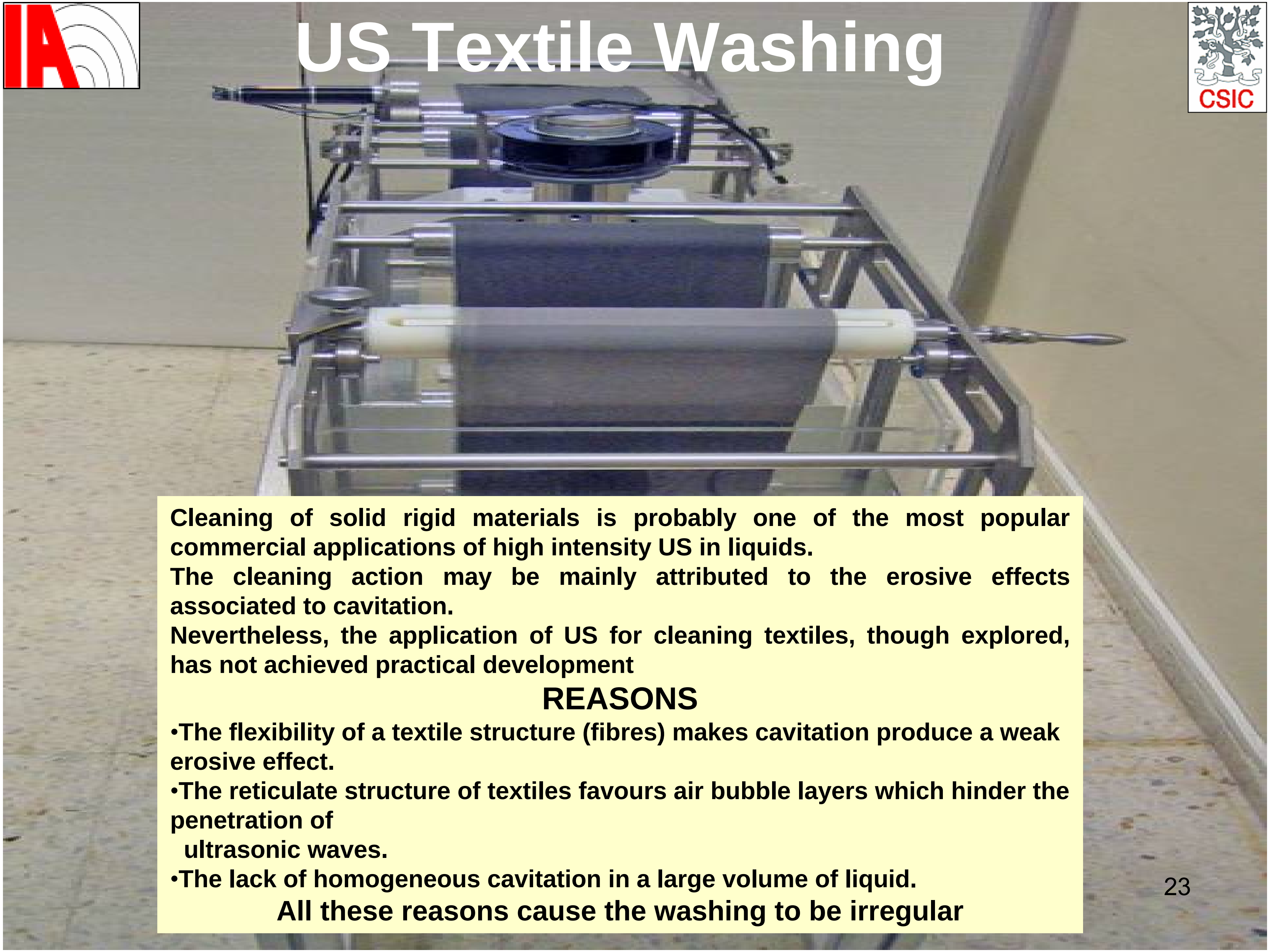
Fig. 4: Distribución 2D del campo acústico en el interior del radiador cilíndrico del transductor ultrasónico excitado con 75W

Lemon peel cylinders d=19 mm t=10 mm; 75W; 0.6 -10m/s





US Textile Washing



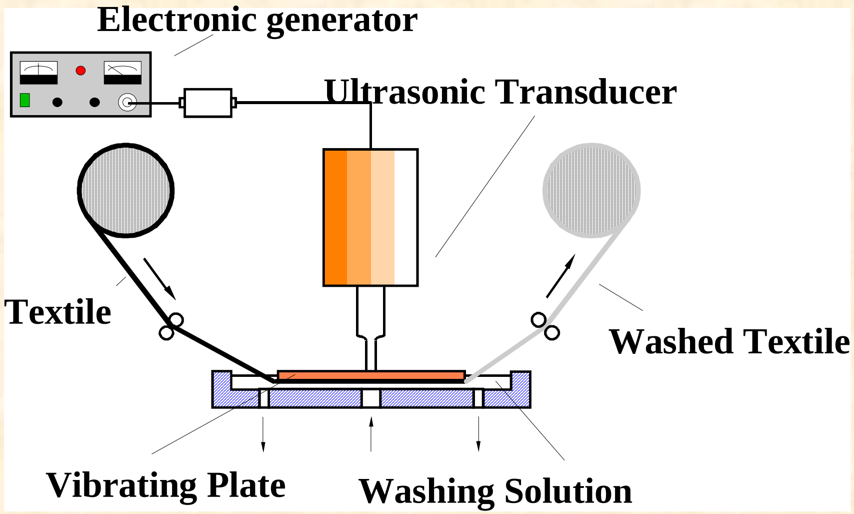
Cleaning of solid rigid materials is probably one of the most popular commercial applications of high intensity US in liquids.
The cleaning action may be mainly attributed to the erosive effects associated to cavitation.
Nevertheless, the application of US for cleaning textiles, though explored, has not achieved practical development

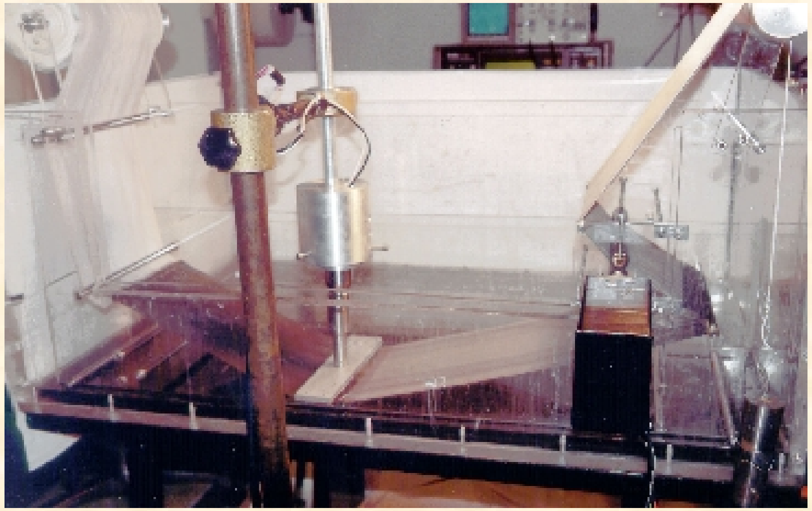
REASONS

- **The flexibility of a textile structure (fibres) makes cavitation produce a weak erosive effect.**
- **The reticulate structure of textiles favours air bubble layers which hinder the penetration of ultrasonic waves.**
- **The lack of homogeneous cavitation in a large volume of liquid.**

All these reasons cause the washing to be irregular

US-Textile Washing





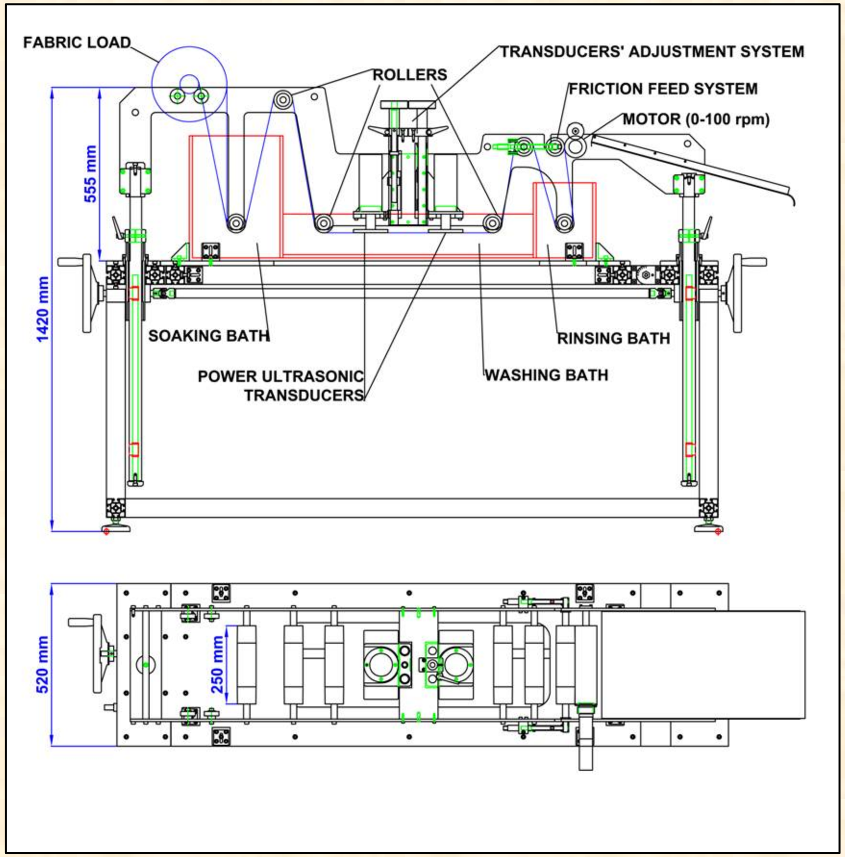
New Solutions

To overcome the above mentioned problems we have developed a new procedure based on the production of intense cavitation in liquid layers. Such procedure has been implemented for continuous washing of textiles on a flat format

Ultrasonic Transducers with a large vibrating surface generate an intense and homogeneous washing effect in a continuous process

J.A. Gallego et al., (2001) US Patent 6,266,836 B1

US-Assisted Textile Washing

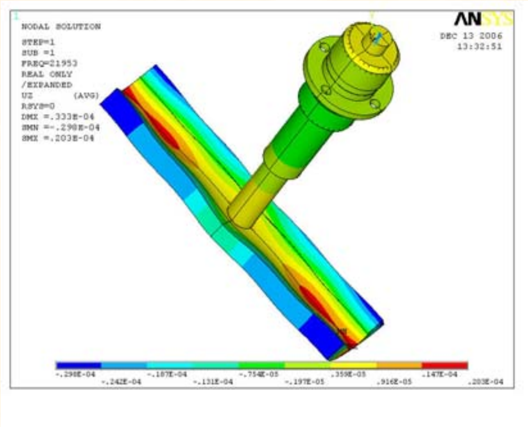


Development and characterization of an US system for textile washing in liquid layers in continuous operation

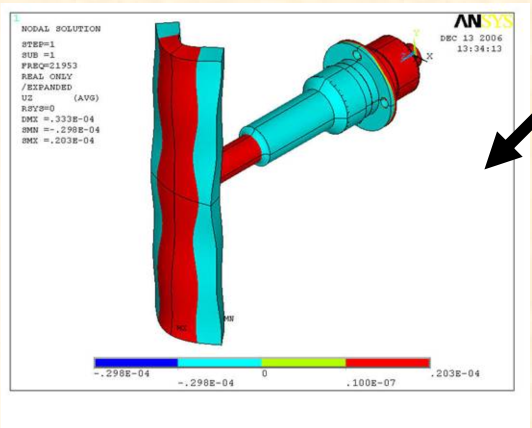
US-Assisted Textile Washing

Improvement of US Grooved-Plate Transducers Designed by FEM to Separate Vibration Modes

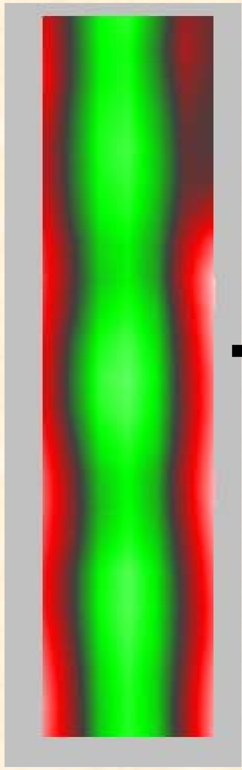
Vibration Amplitude Distrubution

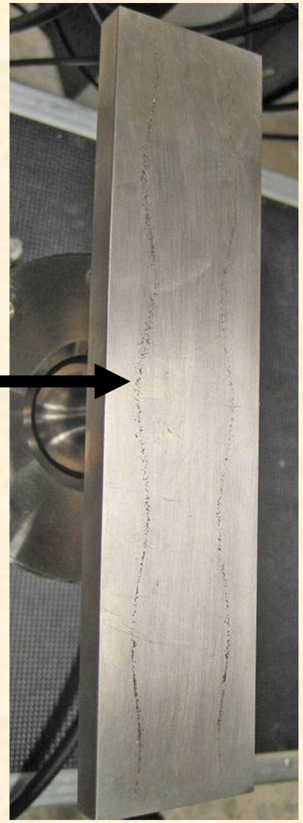


Vibration Phase Distrubution



Flexural Mode at 21 kHz:
2 NL parallel to the longer side



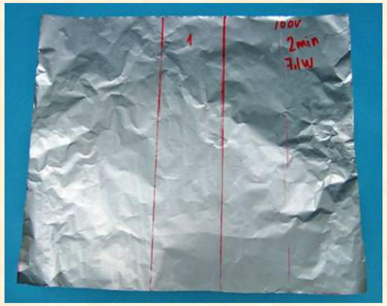


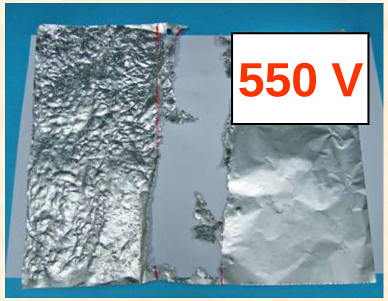
Validation by Laser Vibrometry

US-Assisted Textile Washing

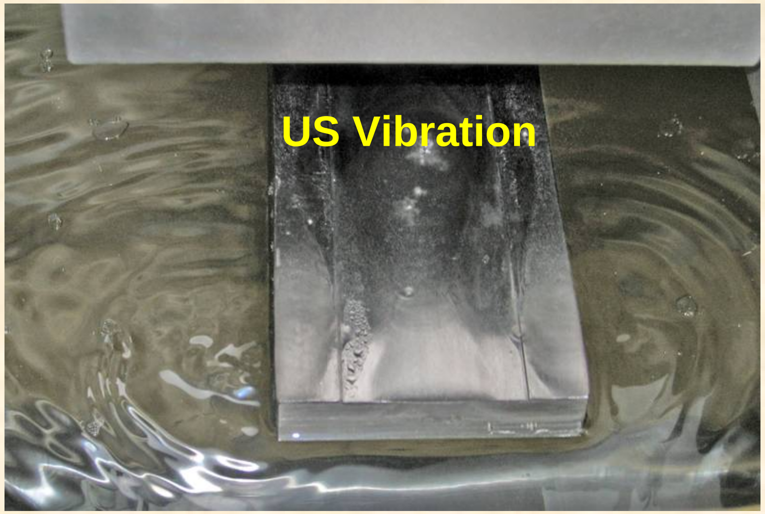
Cavitation Activity

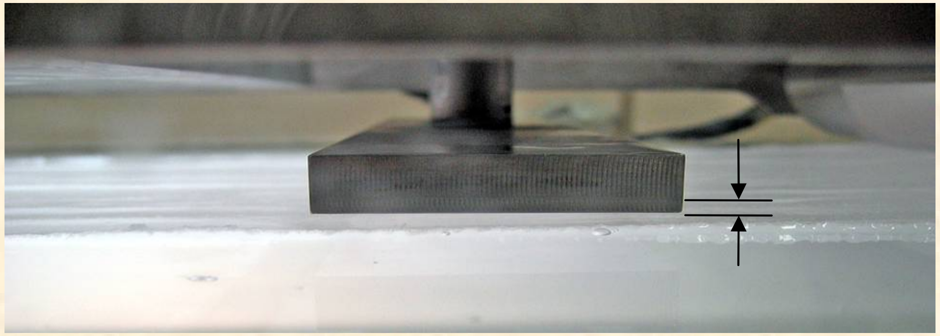
Bubble Tracks





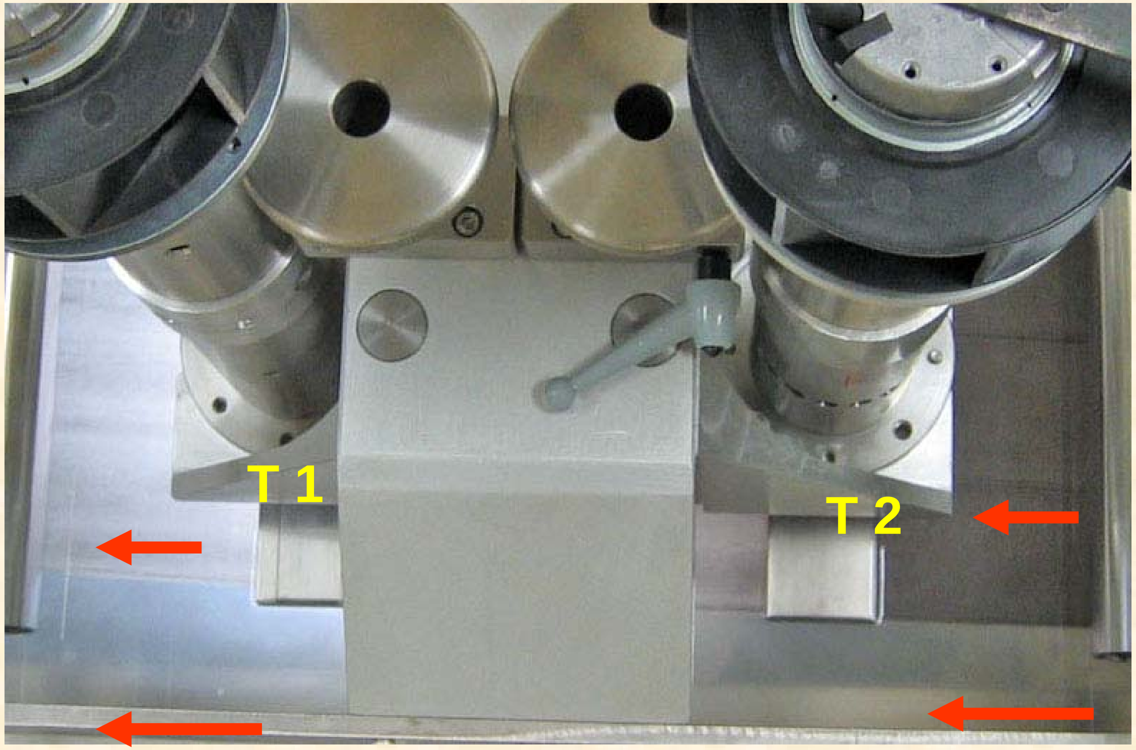
Aluminium Foil





Distance between transducer and fabric
D_{T-F} = 0,5 -1mm
All tests have been carried out without touching

US-Assisted Textile Washing



Under dynamic conditions, the textile will be conveyed perperdicularly to the 2 Nodal Lines (NL).

The fabric passes through the areas of maximum energy of the washing cavity

Control and Monitoring

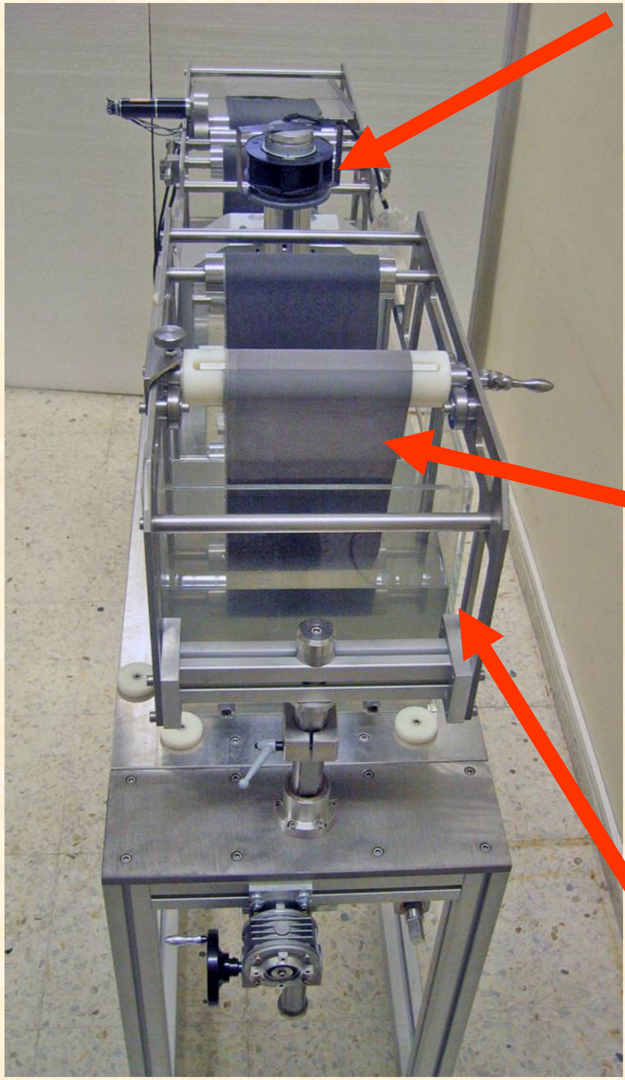
- **Fabric speed**
- **Water temperature**
- **Water level (volume)**
- **Gas content**
- **Transducer position**
- **Transducer- fabric distance**
- **Power**
- **Cavitation activity**

Characteristics

Continuous Washing System

*** 2 Transducers**
*** Fr = 19-21kHz**
*** P = 400-600W/unit**
*** S = 110 cm^2**
*** I = 3 – 5 W/cm^2**
*** V = 0 - 1 m/s**

US-Assisted Textile Washing

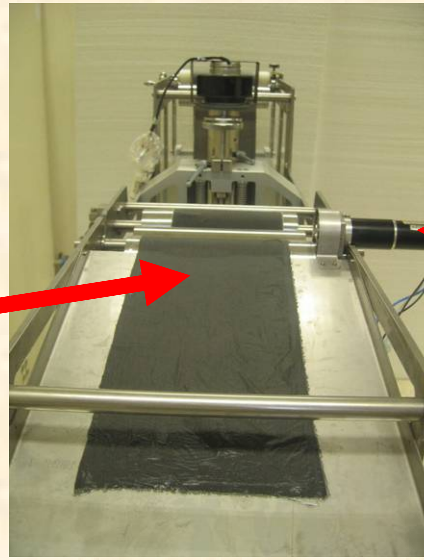


US Transducers

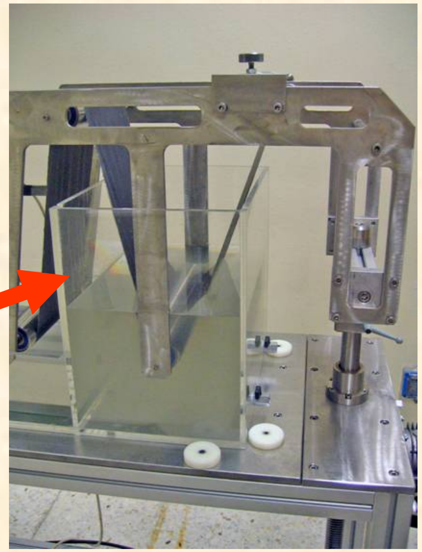
Fabric outlet

Empa-101

Soaking Bath

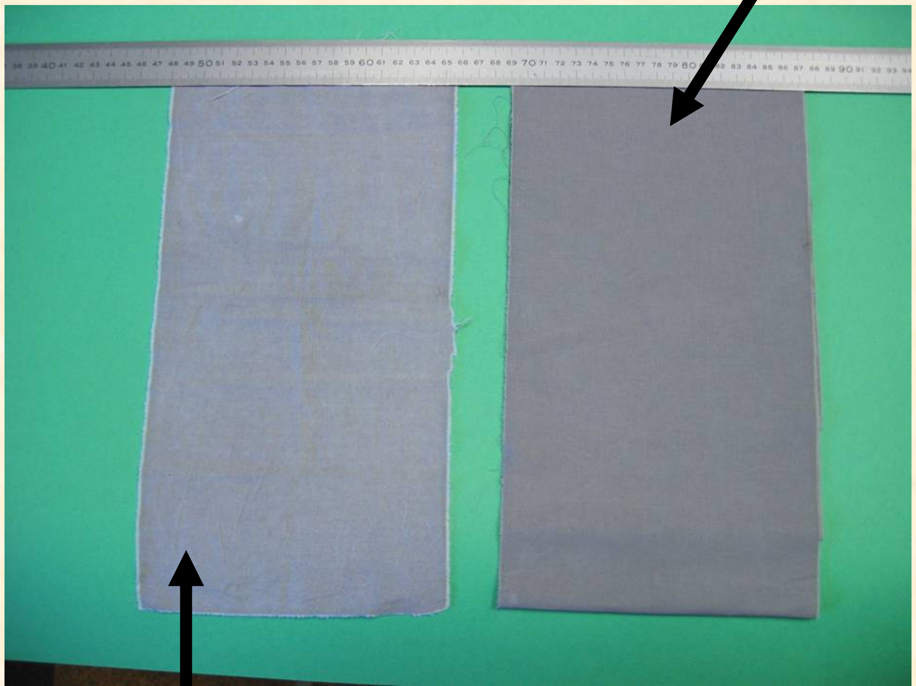


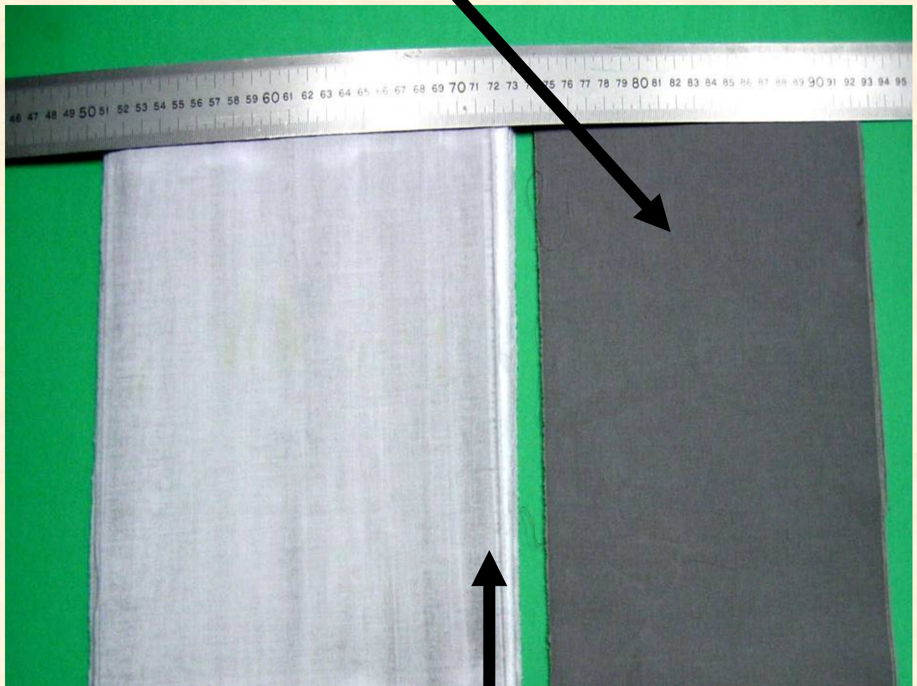
Motor



US-Assisted Textile Washing

EMPA-101
Original Sample





After 2 Conventional Washes at 20ºC and 50ºC

After 1 US Wash with 2Tx400W; 1cm/s

Ultrasound-Assisted SFE

- **SFE** is a separation process based on the contact of a substance containing the extractable compound with a solvent (CO_2) under supercritical conditions.
- **Motivations to use SFE:** Non-Toxic; Recyclable; Cheap; Relatively Inert, Non-Flammable; Improves Product Quality and Recovery
- **Disadvantages**: **Slow Dynamics**
- **Proposal**: US-assisted SFE **to enhance mass transfer** in almonds oil extraction because the use of mechanical stirrers is unable
- **Advantage**: **Ultrasonic energy acts without affecting the main characteristics and quality of the products**
- **Potential Applications**:

  Food, Pharmaceutical and Chemical Industries

Main Objective

Design of an US-System to evaluate the influence of US on the SFE-Kinetics of almond oil as a new technique

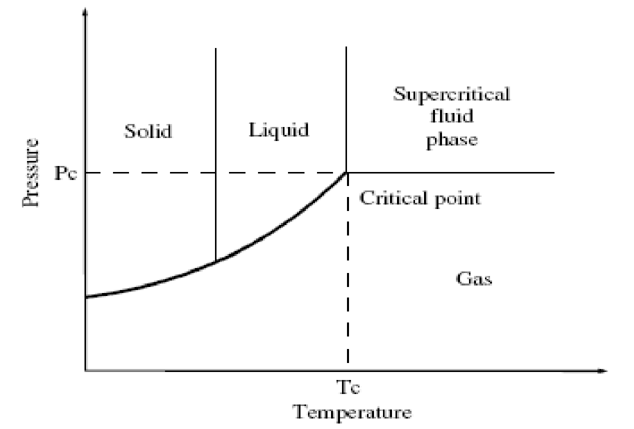


Fig. 1. Pressure–temperature phase diagram of a pure substance.

T_C = Temperature above which it cannot be liquefied by increase of Pressure

P_C = Critical Pressure

$(CO_2)^{SC}$ T_C= 304,2K = 31,2ºC

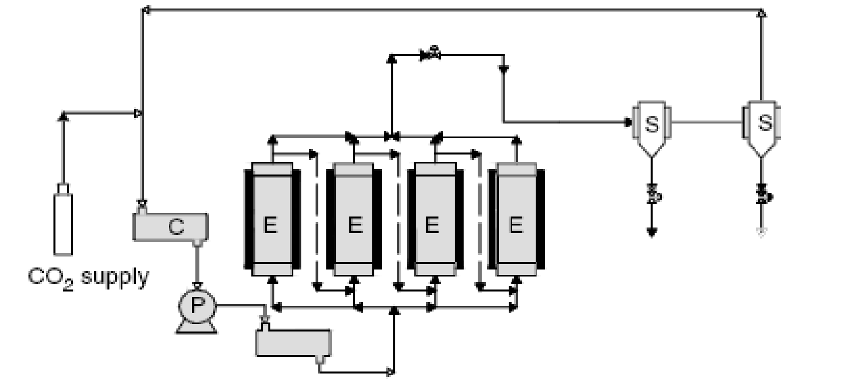
P_C = 72,8atm

SF: Have lower viscosity and higher diffusivity than liquid solvents. Can penetrate into porous materials more effectively than liquid solvents

Ultrasound-Assisted SFE

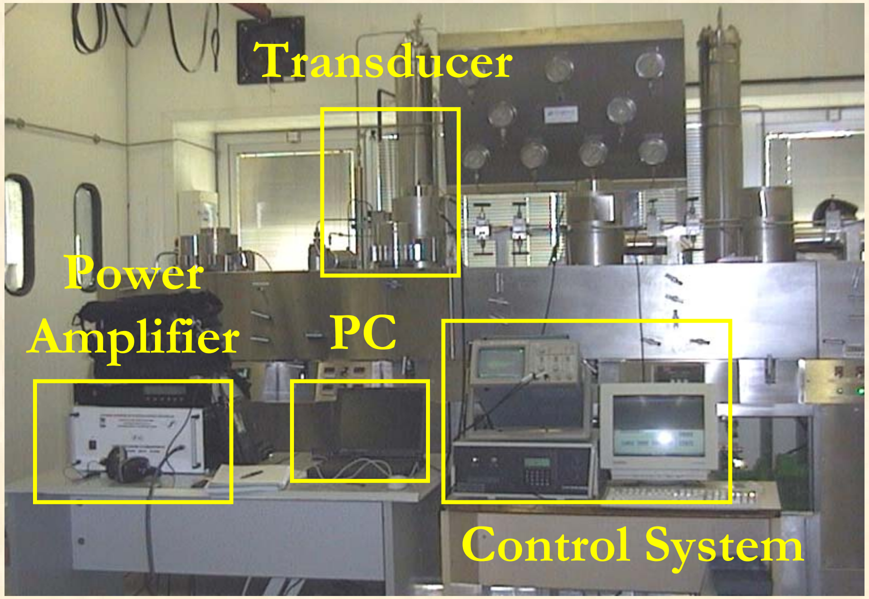
SFE Facility Pilot Plant

- **4 High-pressure vessel extractors**
- **Extractor capacity: 5 Liters**
- **2 Separation units (Cyclone and Decanter).**
- **1 Diaphragm pump**
- **Sensors for monitoring and control T, P, Flow rate of CO_2^{SC}**



(E) Extractors; (S) Separators; (C) Cooler and (P) High Pressure Pump.

Fig. 2. Scheme of the basic experimental set-up used for SFE assisted by power ultrasound.



Ultrasound-Assisted SFE

US-Transducer
F = 20kHz
P = 100W
Z_T = 300-500Ω
Material: Titanium Alloy
Efficiency: 92%

Electronics
Impedance Adapter
Power Amplifier
Control System: Keep constant the power applied at the resonance frequency

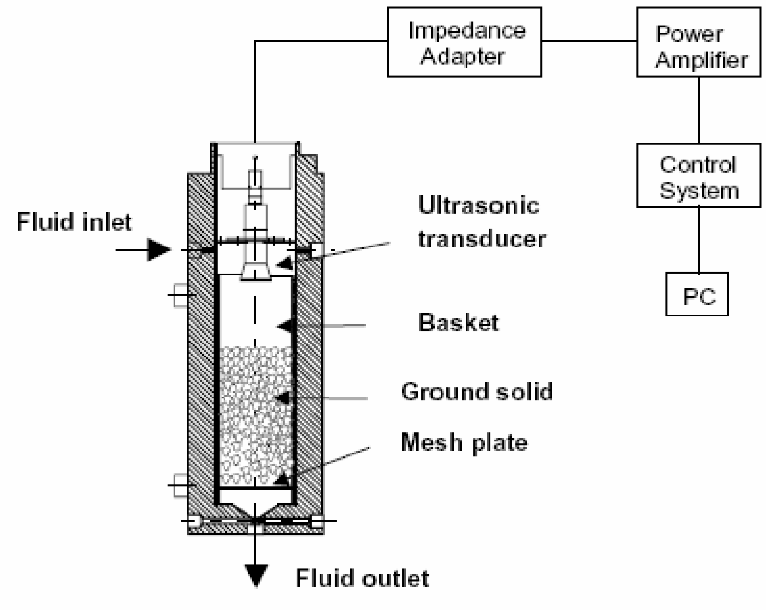
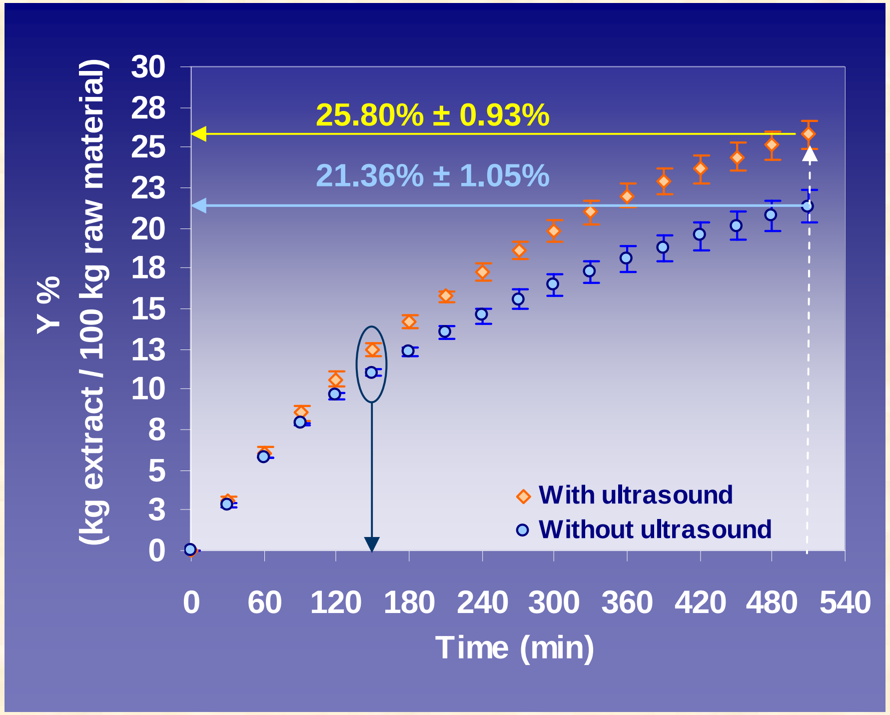


Fig. 3. Scheme of the extractor used for SFE.

Computer
LabView Software & Hardware **to control and monitoring** in real time the parameters of the transducer **(f_T, V, I, ϕ, P, Z_T)** and the extractor **(P, T, ρ, Q)**

E. Riera et al., (2002) Spanish Patent 2199683
E. Riera et al., (2005) European Patent EP 1547679 A1

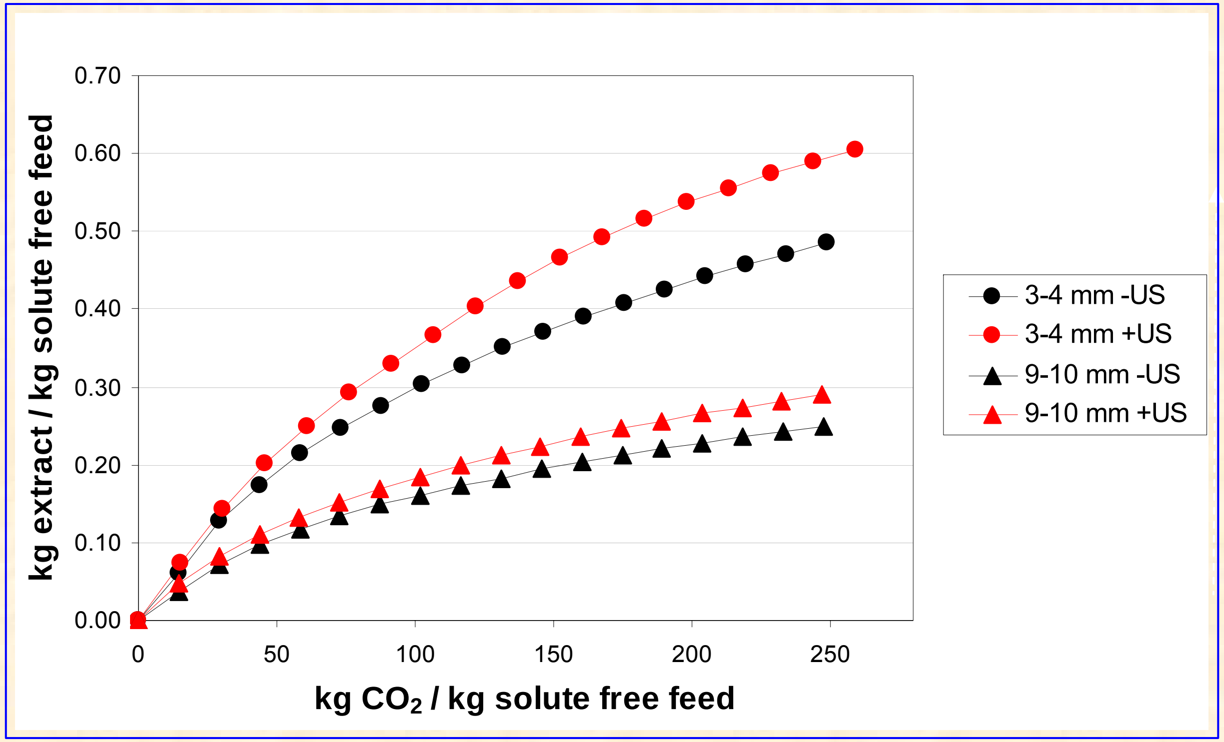
Ultrasound-Assisted SFE

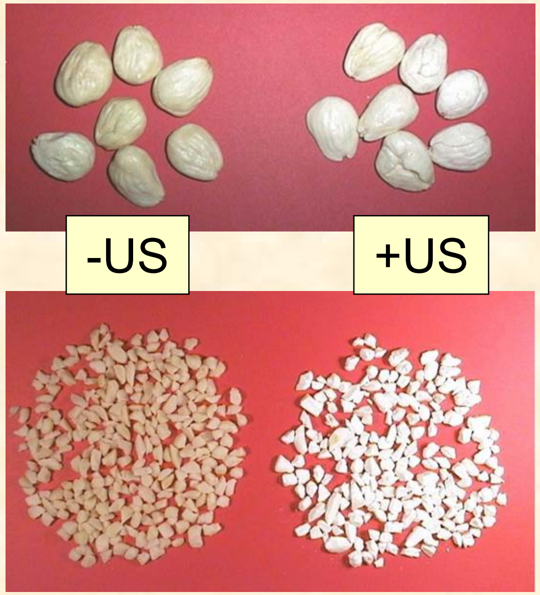


Improvement of the extraction yield: 20.8%

At the end of the extraction time (after 8.5 hours) the amount of extract <u>was significantly higher with US</u>. As a result, the acoustic waves enhanced the final extraction yield in <u>20.8%</u> <u>with 50W</u> at 20kHz

Ultrasound-Assisted SFE
Almond Oil





At the end of the extraction time (after 8.5 hours) <u>the loss of oil from the almonds was about 30% higher with US (50W at 20kHz).</u>

Small almond particulated size favors the US action.

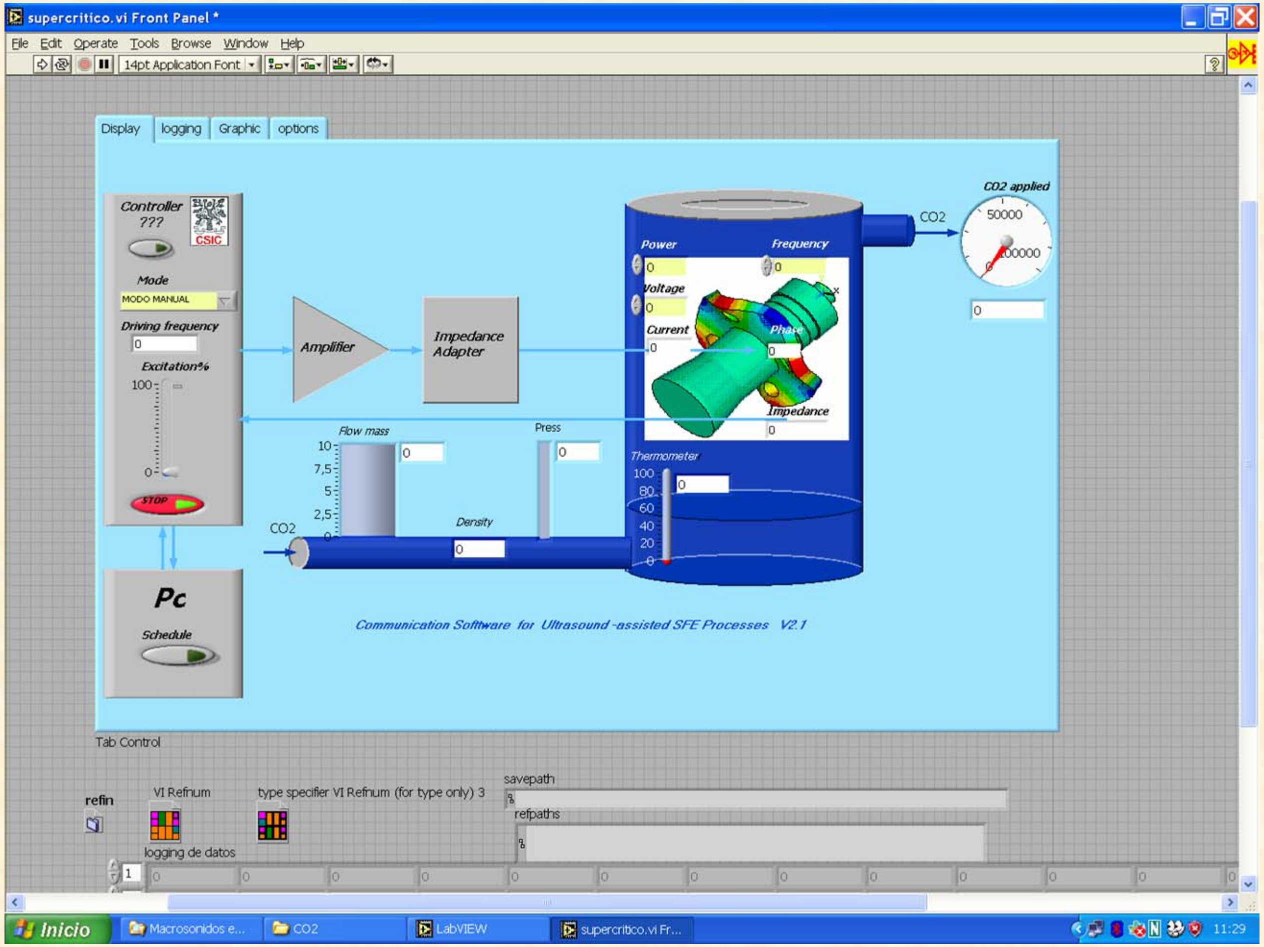
The results have shown that <u>US significantly accelerates</u> the kinetics of the process and improves the final extraction yield.

Ultrasound-Assisted SFE Processes Control and Monitoring

Transducers
Langevin
Stepped-Plate

Parameters
Frequency (18-50kHz)
Voltage (V)
Current (mA)
Phase (º)
Power (0-150W)
Impedance (Ω)
Time (s)

Extractor (CO_2)
Temperature (0-80 ºC)
Pressure (1-1000 bar)
Density (0,2 – 0,9 g/cm^3)
Mass Flow (1-25 kg/h)



Conclusions

- **New specific macrosonic transducers** for different capacities and frequencies has been developed, tested and applied in different industrial processes.
- **A new concept** of high-intensity US defoamer based on **stepped plate transducers** for airborne has been successfully applied to the **control of foam** excess in canning and bottle lines before capping.
- **A Focused transducer system** has been developed with an electronically controlled rotation system for the dissipation of foams in reactors.
- A **multi-sample ultrasonic drying system** for the application of the process at pre-industrial stage has been designed, constructed and tested. The system has the automatic control and monitoring of all the variables of the process.
- **A semi-industrial US system for textile washing** in liquid layers has been designed, constructed and tested. **New grooved-plate transducers** have been developed and used in the continuous washing system with promising results.
- **A pilot-plant scale** has been developed and tested for power ultrasound-assisted SFE processes with CO_2. US significantly **accelerates** the kinetics of the process and **improves** the final extracted yield.