AIRBORNE POWER ULTRASONIC TECHNOLOGIES FOR INTENSIFICATION OF FOOD AND ENVIRONMENTAL PROCESSES

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OUTLINE

- *1. Introduction*
- *2. Dense Gas Extraction (DGE) assisted by gas-borne power ultrasound*
- *3. Convective Drying (CD) assisted by airborne power ultrasound*
- *4. Agglomeration of aerosol particles by power ultrasound*
- *5. Conclusions*
- *6. Acknowledgements and introduction of our Collaborator, PUSONICS SL*

INTRODUCTION (1)

*The use of ultrasonic energy in air or in a gas for the **production of permanent effects** has been hampered by the difficulties involved in the **generation and propagation** of ultrasound in very low density media.*

Conventional airborne sound sources

Aerodynamic devices - Sirens and whistles

Acoustic energy is provided by a gas jet

Practical constraints

Low efficiency (10-20 %)

Difficulties to reach ultrasonic frequencies

Poor directivity

INTRODUCTION (2)

CHALLENGES

New airborne sonic and ultrasonic devices

Power ultrasonic transducer with extensive plate radiator

Practical Advantages

- *These transducers have adequate performances for use in air/gas: High efficiency: 70-80 %*
- *Energy concentration (very high directivity and/or focalization)*
- *Power capacity up to 0.5 kW (increasable)*
- *Frequency: 10 - 40 kHz*

Commercialization of ultrasonic technology at lab, semi-industrial and industrial scales: PUSONICS SL

DENSE GAS EXTRACTION (DGE) ASSISTED BY GAS-BORNE POWER ULTRASOUND

Dense gas extraction (DGE) is carried out with gases (CO_2) under supercritical conditions (SFE)

DGE ASSISTED BY PU

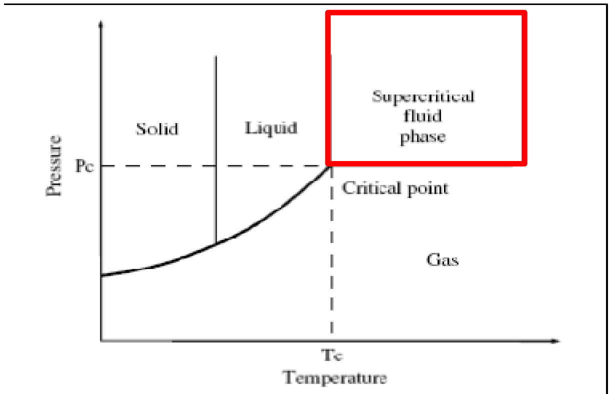


Fig. 1. Pressure–temperature phase diagram of a pure substance.

- ***DGE*** *is a separation process based on the contact of a substance containing the extractable compound with a solvent* ***(CO_2)*** *under supercritical conditions*
- ***Disadvantages**: **Slow Kinetics***
- ***Proposal**: US-assisted DGE **to enhance mass transfer** in extracted product*
- ***Advantage**: **Ultrasonic energy acts without affecting the main characteristics and quality of the products***

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

P_C = *Critical Pressure*

$(CO_2)^{SC}$ T_C= 304,2 K = 31,2 ºC

P_C = 72,8 atm

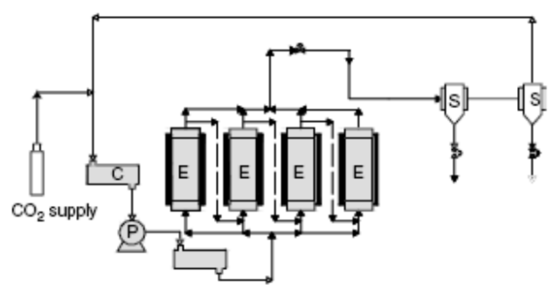
SC: *Have **lower viscosity and higher diffusivity than liquid solvents**. Can penetrate into porous materials more effectively than liquid solvents*

PU ENHANCES MASS TRANSFER PROCESSES
due to
Compressions and decompressions; Radiation pressure; Streaming; Agitation; Turbulence; Cell structure damage; Intra-particle diffusivity,…

Potential Applications
Food, Pharmaceutical, Cosmetic and Chemical Industries

MAIN OBJECTIVE

Design and construct a Robust and Autonomous PU-System to evaluate the influence of US on the DGE-Kinetics and final quality of the extracted product as a new ultrasonic technology



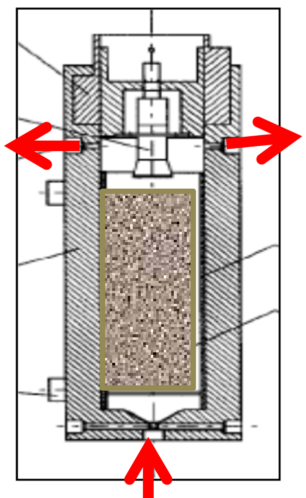
(E) Extractors; (S) Separators; (C) Cooler and (P) High Pressure Pump.

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

*E. Riera et al. Ultrasonics Sonochemistry **11** (2004) 241-244.*
E. Riera et al., European Patent EP 1 547 679 A1 (2005)
E. Riera, et al., Ultrasonics 50 (2010) 306-309

TESTS (1)

Evaluation of the new technology in the extraction ***of almond oil*** *and as a* ***new ultrasonic technology***



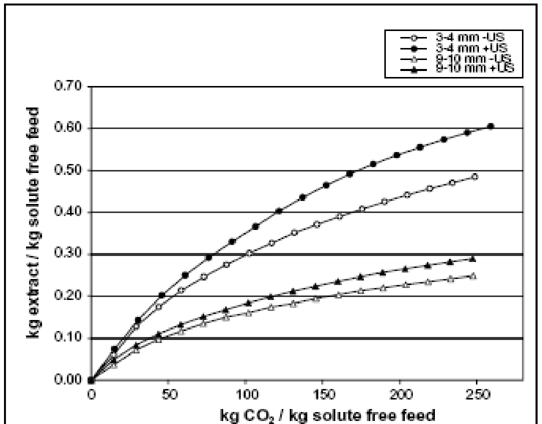


Fig. 6. Particulate almond oil extraction kinetics using supercritical CO_2 with and without ultrasound. Influence of particle size.

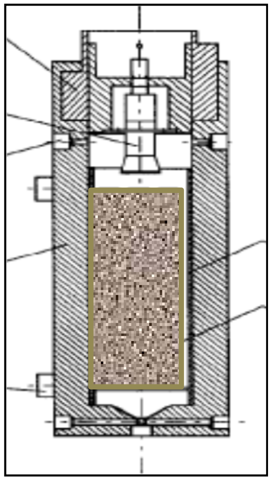
Pilot Plant - Extractors 5 Liters

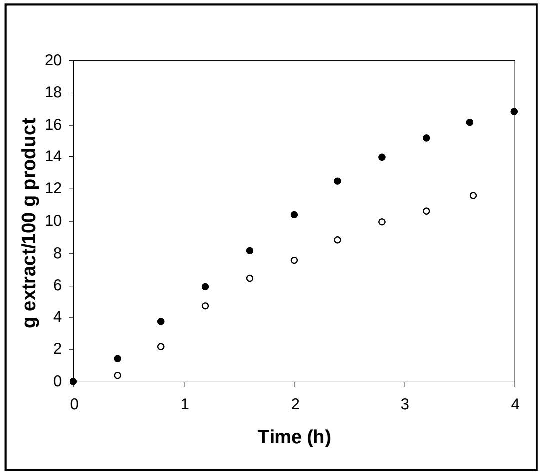
Operational Conditions inside the Extractor (5L)
P ≤ 350bar
D ≤ 900 kg/m3
T ≤ 80ºC
F ≤ 24 kg/h
Product mass in the basket =1.5 kg (grounded almond)

Almond oil extraction using supercritical CO_2
PE=280bar, TE=55ºC, FE=20kg/h,
f=20 kHz, P=50W
Extraction rate enhanced by 30%
Yield extracted increased up to 28%
Grounded almond: 3-4 mm to 9-10mm

TESTS (2)

To enhance the extraction rate and to increase the yield extracted





Pilot Plant - Extractors 5 Liters

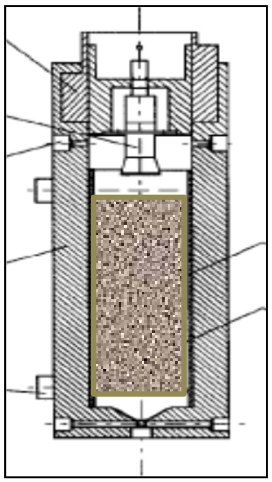
Optimal Conditions inside the Extractor (5L)

PE ≤ 280bar
D ≤ 900 kg/m3
TE ≤ 45ºC
FE ≤ 12 kg/h
Product mass in the basket =1.5 kg (grounded almond)
Initial oil content 56%
f=20 kHz, P=75W

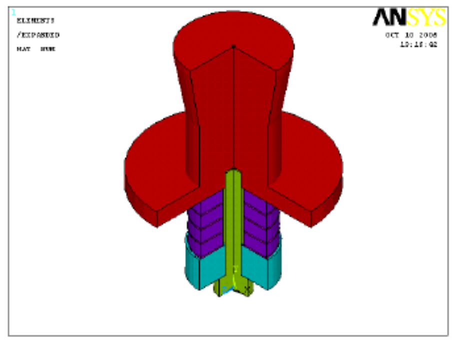
Extraction rate enhanced by 90%
Yield extracted increased up to 89%
Grounded almond: 3-4 mm

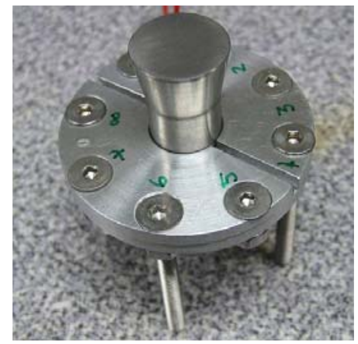
TRANSDUCERS AND DEVICES (3)

***Power Sandwich Ultrasonic Transducers** for 5 Liters Extractor*



*f = 20 kHz P =**125W***

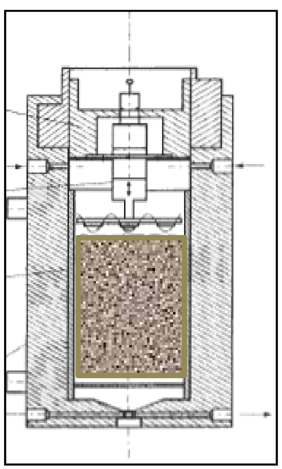


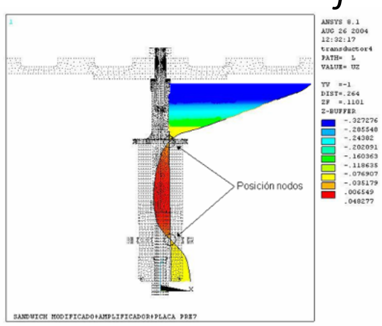


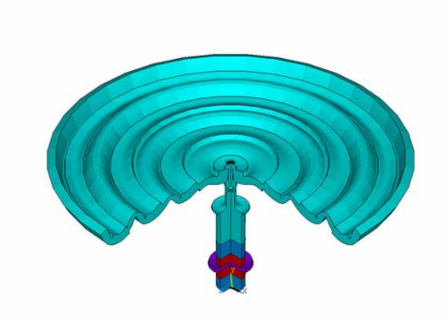
*f = 46 kHz P =**50W***

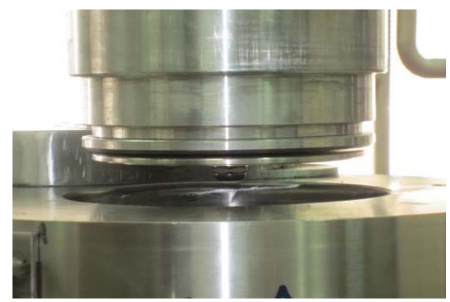
***Power Plate Transducers** for 20 Liters Extractor*

*f = 21 - 56 kHz , **P= 75W - 300W/500W***



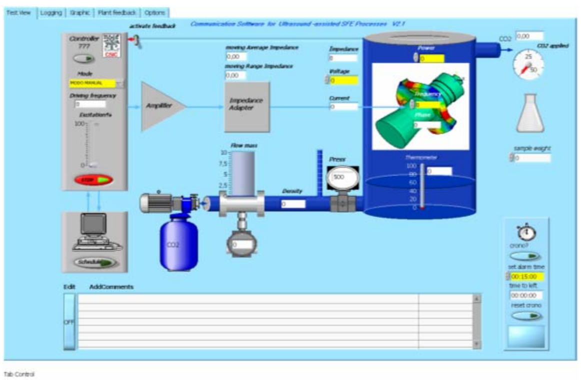




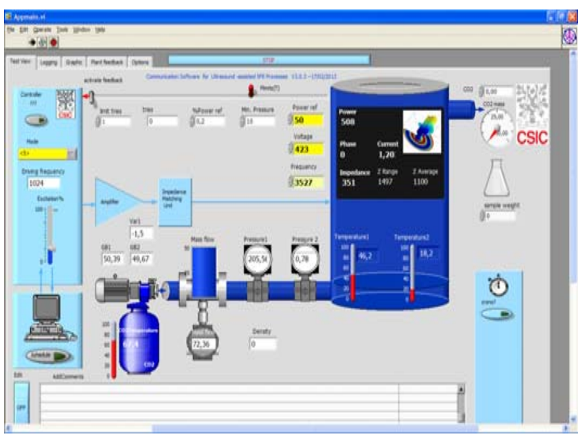


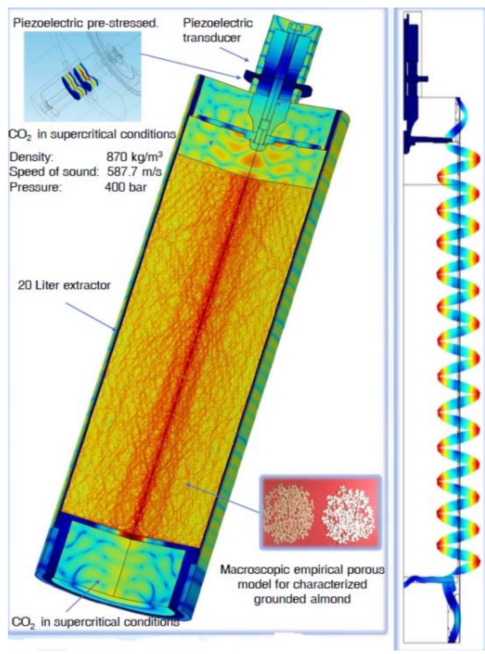
Control and Monitoring Tools, and Modelling *(4)*

5 L



20 L

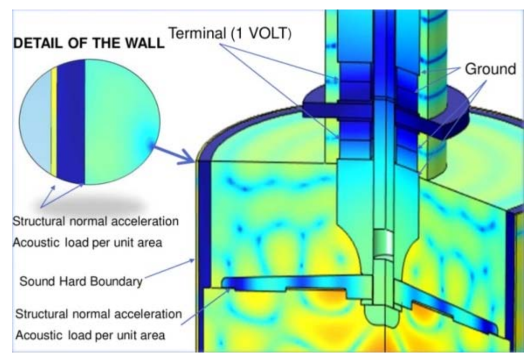




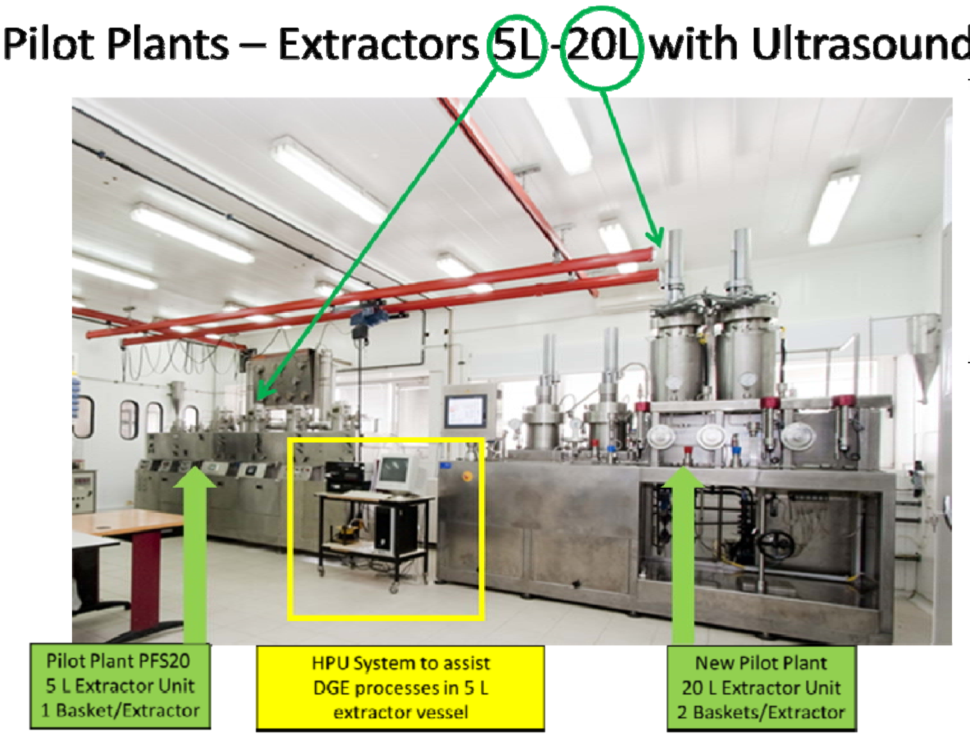
CHARACTERISTIC IMPEDANCE IN THE EXTRACTOR UNIT

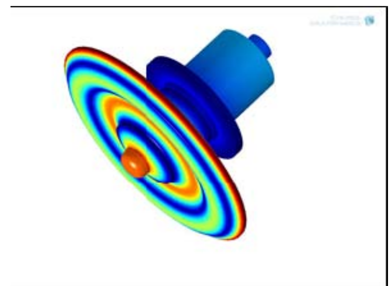
20ºC 1bar Z=5x10^2 Rayls

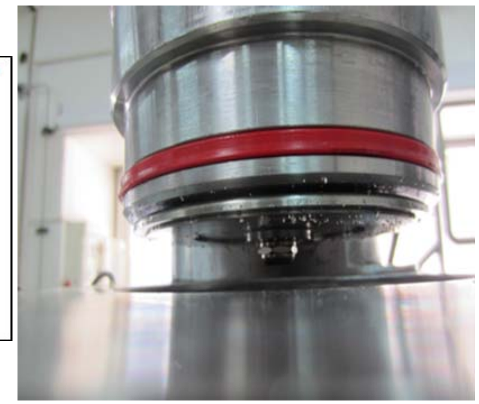
55ºC 280bar Z=5x10^5 Rayls



Extraction Plants Assisted by Power Ultrasound







Lateral view of the plate transducer placed on the upper lid of the vessel

Top view of the extractor with 1,5 kg of grounded almond in the basket

CONVECTIVE DRYING ASSISTED BY AIRBORNE POWER ULTRASOUND

ALTERNATIVES FOR DRYING INTENSIFICATION

Thermal energy (Traditional alternative):

Direct increase of drying air temperature

Degradation of heat sensitive compounds

Mechanical energy:

Power ultrasound (US)

Not degradation of heat sensitive compounds

COMPARISON:

Kinetic and energy efficiency

Product quality

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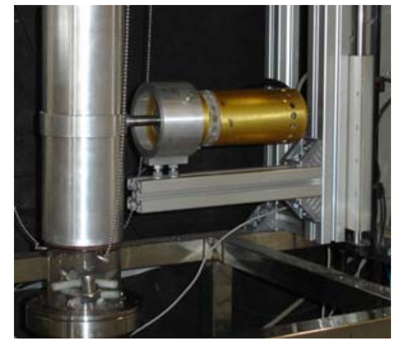
MATERIALS AND METHODS

RAW MATERIAL:

Materials with **very different internal structure** have been used

Structure has been characterized by **macroscopic and microscopic analysis**

- Density and porosity measurements
- SEM and Cryo-SEM observations
- Instrumental texture tests have been performed



CR

DRYING TESTS:

DEVICES: Stepped-plate (SPR) and cylindrical (CR) ultrasonic radiators driven by piezoelectric transducers

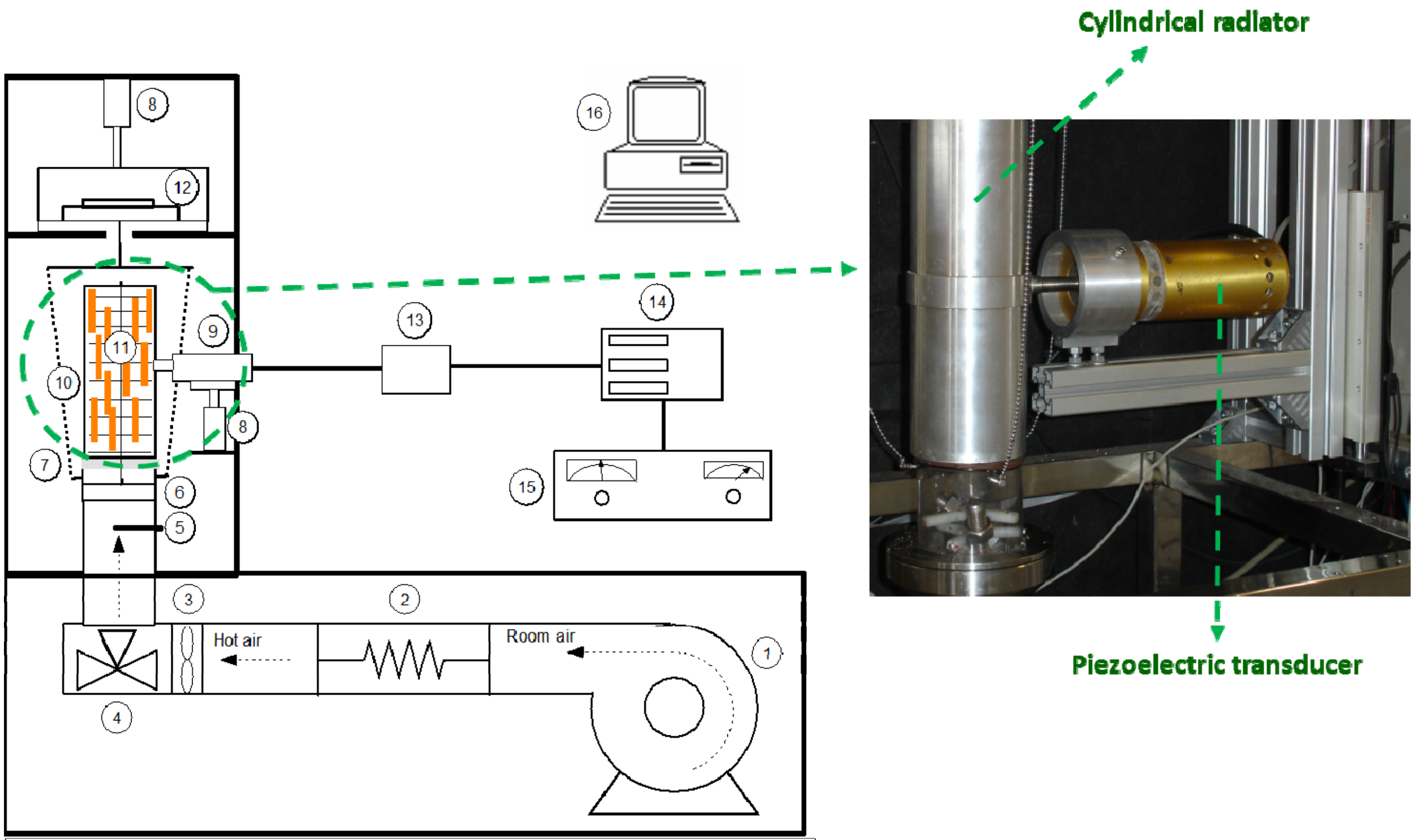
PROCESS VARIABLES: Air velocity (0.5 to 10 m/s); Air Temperature (-15 to 70ºC); Mass load up to 108 kg/m3; US power applied up to 37 kW/m3

DIFFUSION MODELS were used to describe the water transport mechanisms during drying, as well as to quantify the influence of PU on kinetic parameters (**De** and **k**)

SPR

SYSTEMS

CHALLENGE: ***Development of the convective drier with the cylindrical ultrasonic radiator***



1. Fan, 2. Heating unit, 3. Anemometer, 4. 3-Way valve, 5. Thermocouple, 6. Sample loading chamber, 7. Coupling material, 8. Pneumatic moving arms, 9. Ultrasonic transducer, 10. Vibrating cylinder, 11. Sample loading tree, 12. Balance, 13. Impedance matching unit, 14. Power meter, 15. High power ultrasonic generator, 16. PC

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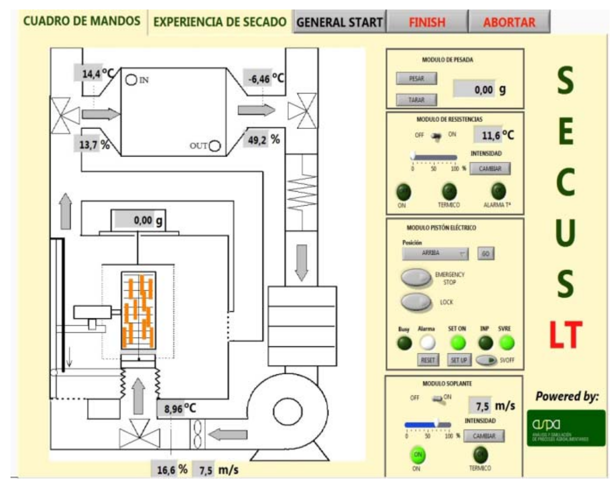
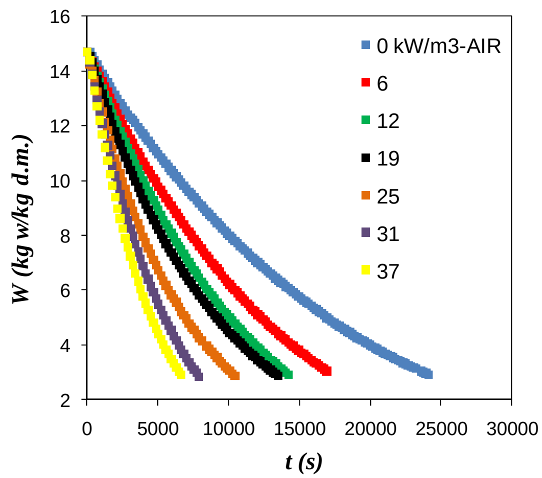
SYSTEMS

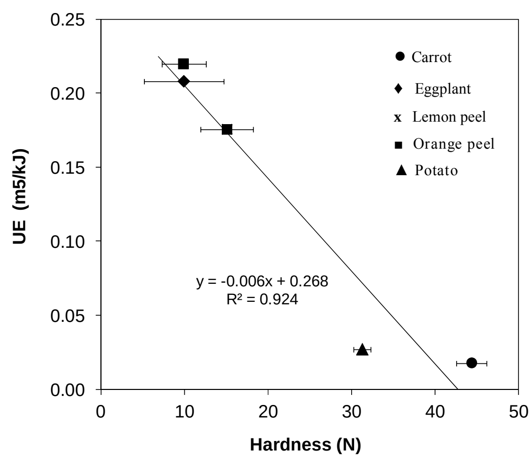
Development of two low temperature driers with the cylindrical ultrasonic radiator



RESULTS AT ROOM TEMPERATURE



Influence of US on drying kinetics



Influence of product hardness on US effectiveness

Reductions of drying time up to

70% for eggplant; 53% in lemon peel; 45% in orange peel; 40% in potato; 32% in carrots

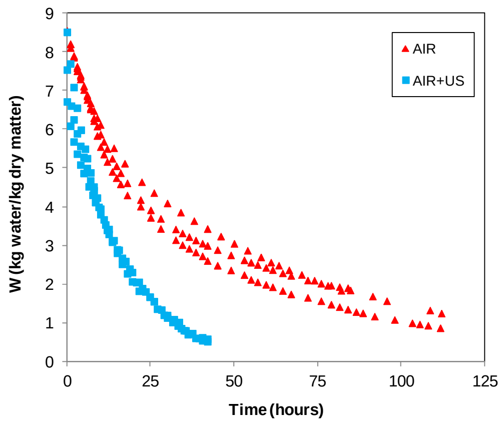
Ultrasound reduced both internal (diffusion, De) and external (convection, k) resistance to mass transfer

Linear relationships *were established between the effective moisture diffusivity and the external mass transfer coefficient with the ultrasonic power applied.*

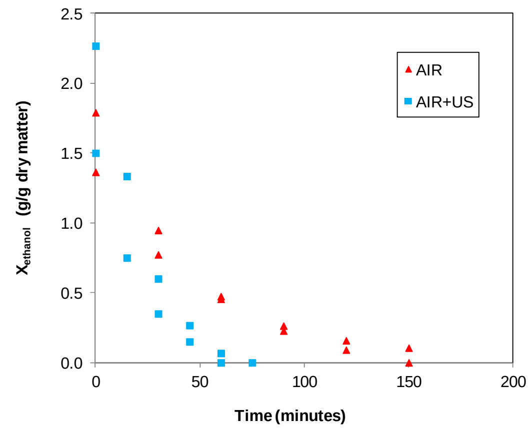
The effect was more intense ***in porous and soft products*** *than in dense and hard materials*

The influence of the hardness *of the material being dried on the US effectiveness was observed and quantified.*

RESULTS AT LOW TEMPERATURE



Influence of air temperature of carrot cubes at -14 ºC and 2 m/s with (AIR+US) and without (AIR)



Ethanol removal kinetics from apple cubes at -14 ºC and 2 m/s with (AIR+US) and without (AIR)

Applications at low temperature have been explored, event at temperatures below the freezing point and not only to remove water but also organic solvents (like ethanol)

The feasibility of power ultrasound to improve convective drying of foodstuffs has been confirmed

Ultrasound was able to speed-up both internal and external water transport in a wide range of food commodities and experimental conditions

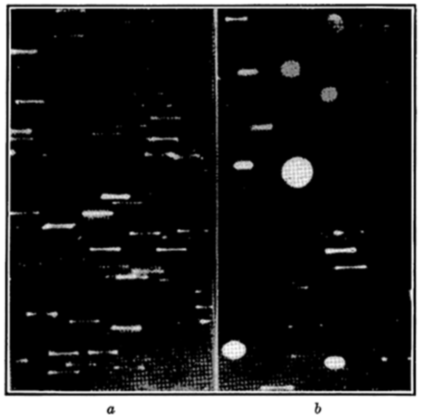
AGGLOMERATION OF AEROSOL PARTICLES BY POWER ULTRASOUND

ACOUSTIC AGGLOMERATION OF AEROSOL PARTICLES

Air Cleaning – Environment - Fine removal from industrial fumes

ACOUSTIC EFFECTS THAT DETERMINE THE AGGLOMERATION PROCESS

- ***Orthokinetic particle interaction (linear)***



OE

- ***Second order effects*** *(non-linear)*
  Mutual radiation pressures effect (MRPE)
  Acoustic wake effect (AWE)

AWE

Gallego-Juárez, J.A., et al., (1994) USA Patent No. 5299175.
Gallego-Juárez, J.A., et al., (1996) 'High Temperature Gas Cleaning, Karlsruhe, Inst. Mech. Verfahrenstechnik und Mechanok, 60-68.
González, I., et al., (2001) Acta Acustica united with Acustica, 87, 544-460.
González, I., et al., (2001) Acta Acustica united with Acustica, 87, 454-450

PILOT PLANT FOR ACOUSTIC AGGLOMERATION OF AEROSOL PARTICLES

Air Cleaning – Environment - Fine particle removal from industrial fumes

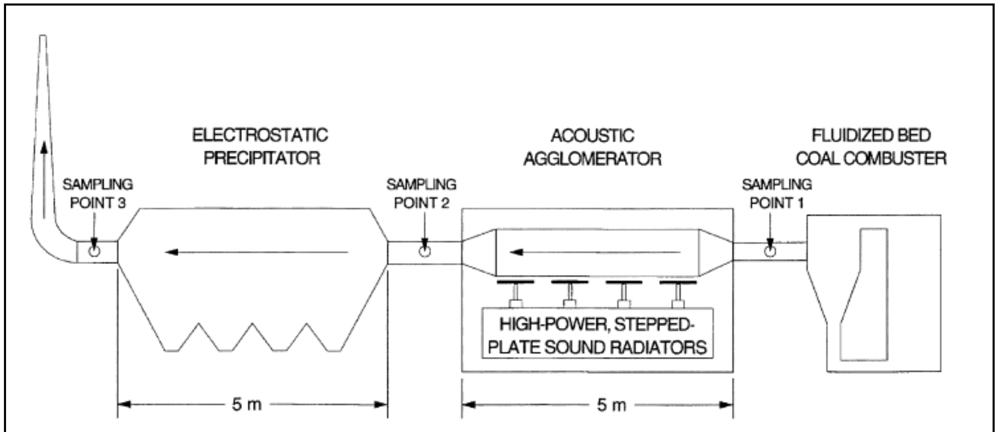
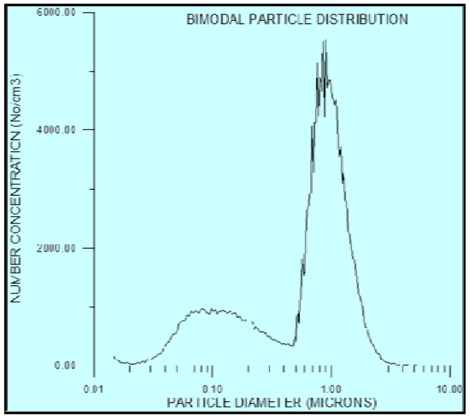


Fig. 3. Scheme of the pilot installation for particle removal from coal combustion fumes.

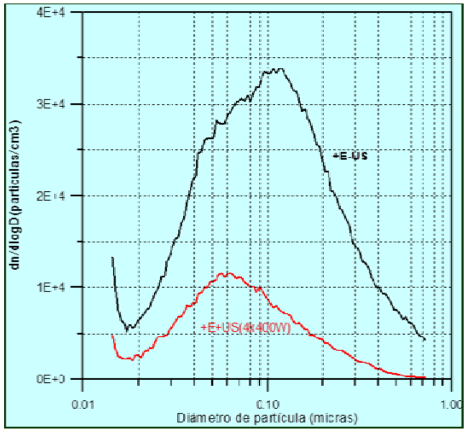
Gallego-Juárez, J.A.et al., (1999) *Environ. Sci. Technol.*, 33, 3843-3849
Gallego-Juárez, J.A.et al. (2000) *Ultrasonics,* 38, 331-336
Riera, E. et al. (2006) *Ultrasonics Sonochemistry*, 13, 107-116

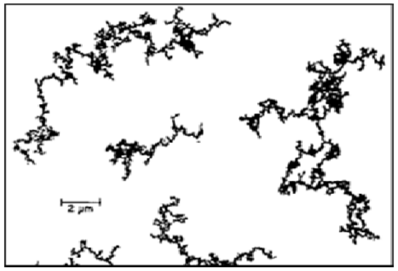
FINE REMOVAL FROM INDUSTRIAL FUMES RESULTS

REDUCTION OF PARTICLE EMISSIONS

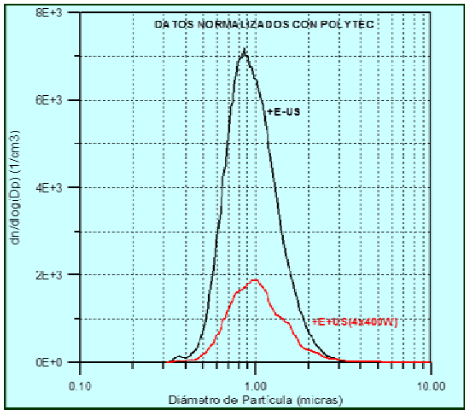


Submicron particles (DMA)
η= 70% → **87%**





Micron particles (APS)
η= 90% → **97%**



Riera, E., et al., (2000) Ultrasonics, 38 (1-8), 642-646.
Riera, E., et al., (2000) J Aerosol Sci, 31 Suppl.1, S827-S828.

PASSIVE AND ACTIVE SYSTEMS ON SEVERE ACCIDENT SOURCE TERM MITIGATION (FP7-FISSION-2012)

WP4: INNOVATIVE FILTRATION SYSTEMS
WP4.1 (ACOU): Acoustic Agglomeration Systems (CSIC – CIEMAT)

OBJECTIVE

To investigate the performance of an acoustic agglomerator system at lab-scale under conditions as close as possible to those prevailing under containment venting

- *To design and develop an acoustic agglomeration system (MSAA, Mitigative System Acoustic Agglomerator)*
- *To measure the aerosol growth and/or precipitation in the MSAA.*
- *To find out the best operational conditions of the acoustic agglomeration system to work with aerosols taken as a model of those present in accident scenarios.*

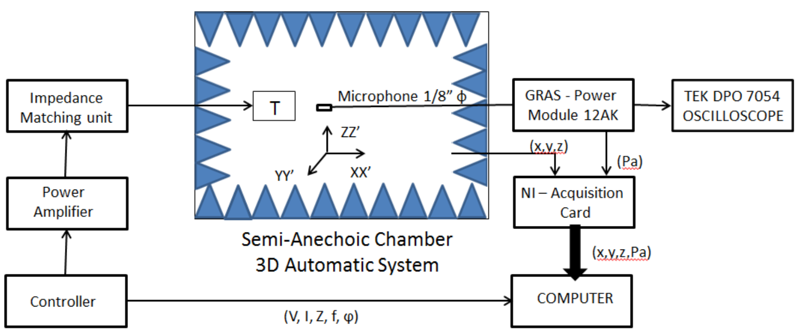
Riera, E., et al., (2000) Ultrasonics, 38 (1-8), 642-646.
Riera, E., et al., (2000) J Aerosol Sci, 31 Suppl.1, S827-S828.
González, I., et al., (2001) Acta Acustica united with Acustica, 87, 544-460.
González, I., et al., (2001) Acta Acustica united with Acustica, 87, 454-450

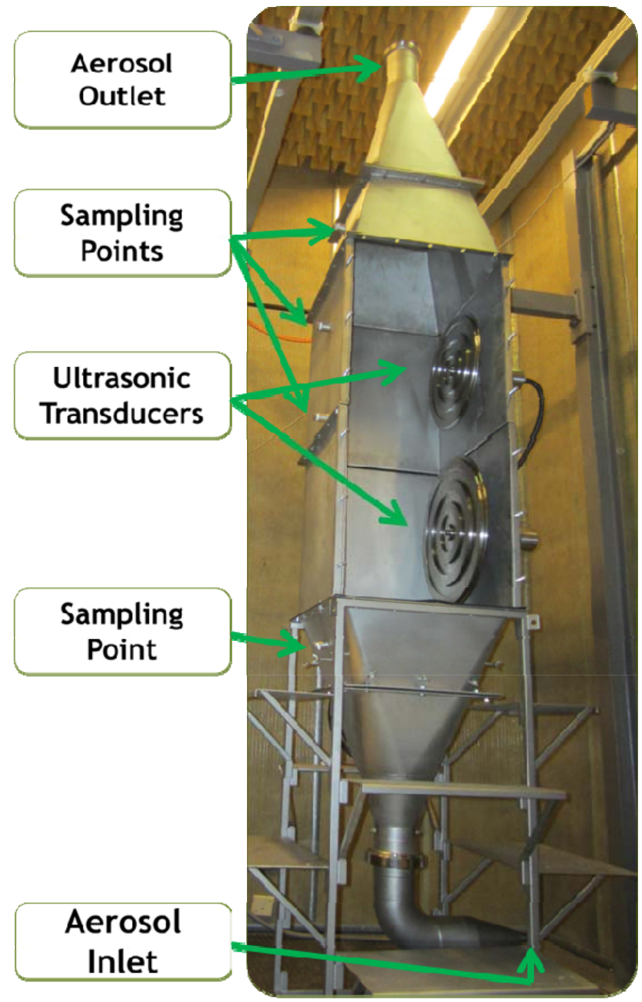
MSAA - Mitigative System - Acoustic Agglomerator (CSIC)

MSAA is a system to induce particle agglomeration through the application of high intensity ultrasonic waves through the aerosol.

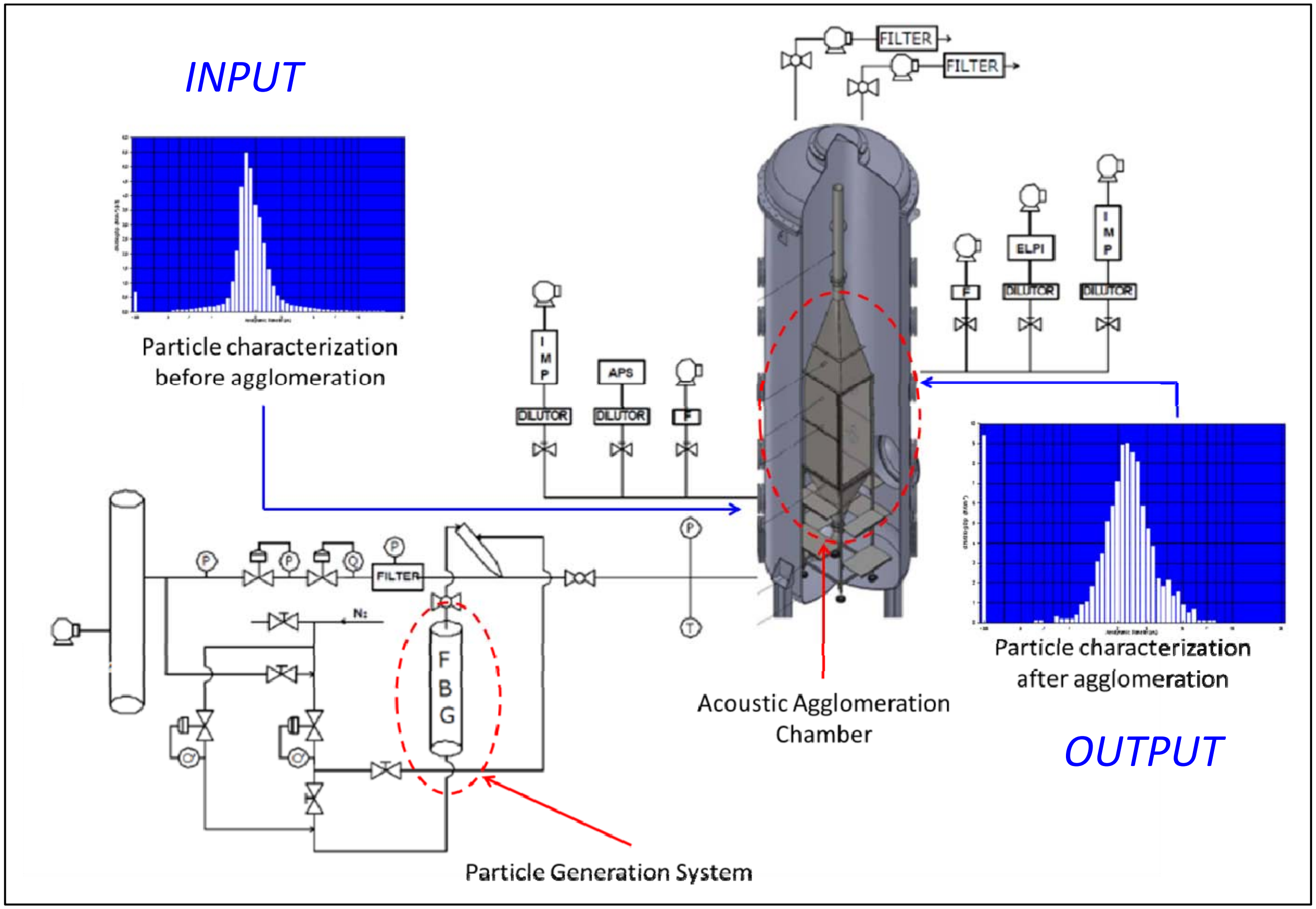
The system basically consists of:
i) A modular acoustic agglomeration chamber
ii) 2 stepped-plate power ultrasonic transducers
iii) A power electronic generators

Main characteristic of the system
Acoustic frequency = 21 kHz
Sound threshold for AA > 140 dB
<SPL> inside MSAA = 155dB (measured)





MSAA - Mitigative System - Acoustic Agglomerator (CSIC)

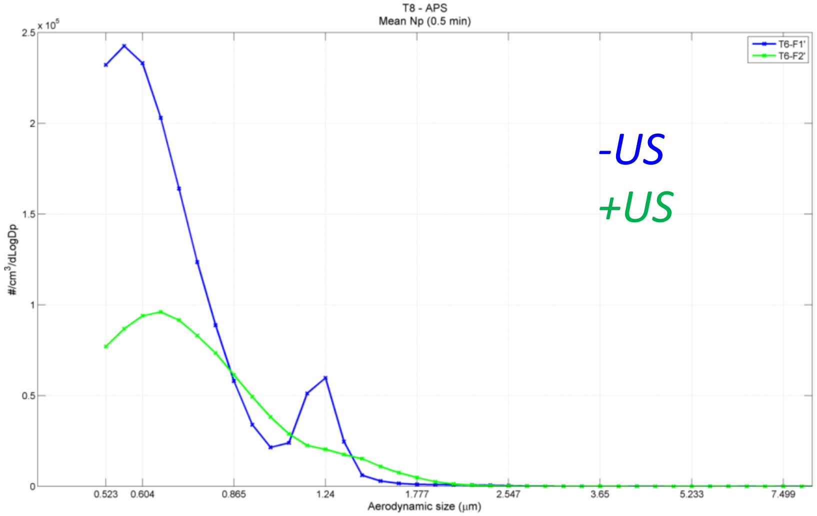


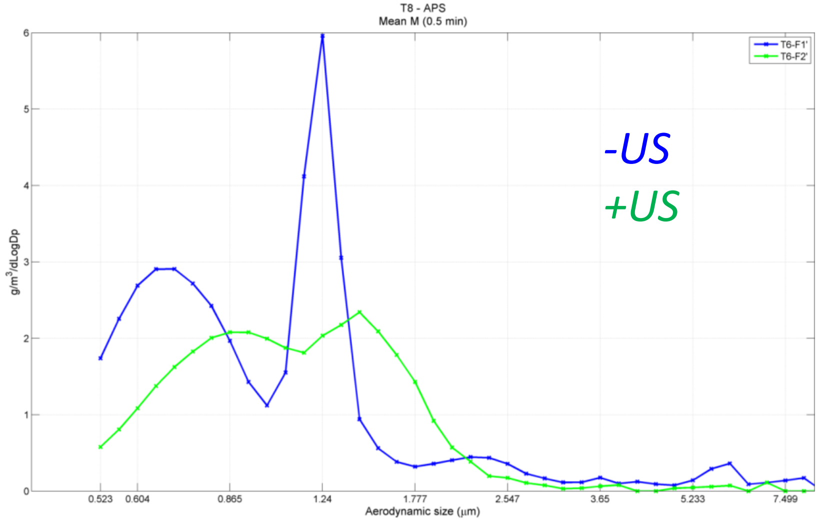
Riera, E. et al., Chapter 34 Ultrasonic agglomeration and preconditioning of aerosol particles for environmental and other applications, in J.A. Gallego-Juárez and K. F. Graff, Power ultrasonics: applications of high-intensity ultrasound, Woodhead Publishing, Cambridge, UK (in press)

PRELIMINARY RESULTS PECA-MSAA-PASSAM

OUTPUT

Normalized number distribution from the APS measurements





__Boundary Conditions__

Bimodal distribution

Particles: Silica ($SiO2$)

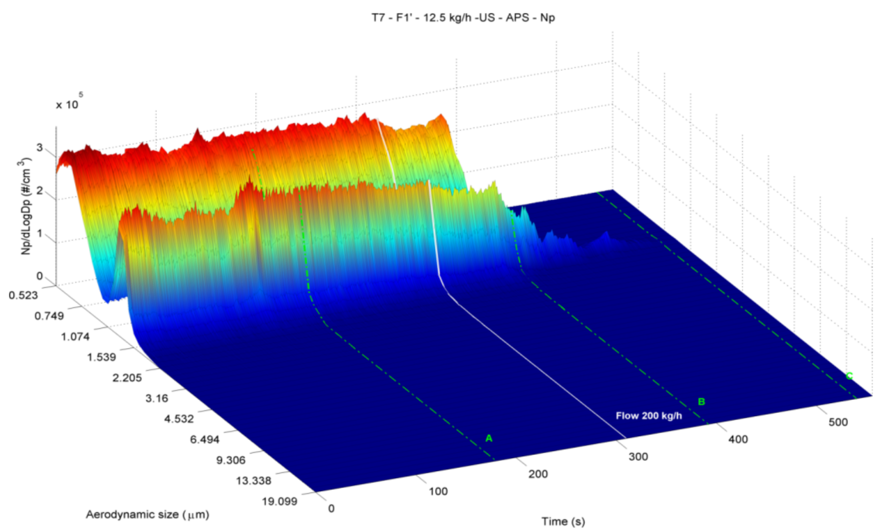
Small particle mass (0.3 µm) 90%

Big particle mass (1.0 µm) 10%

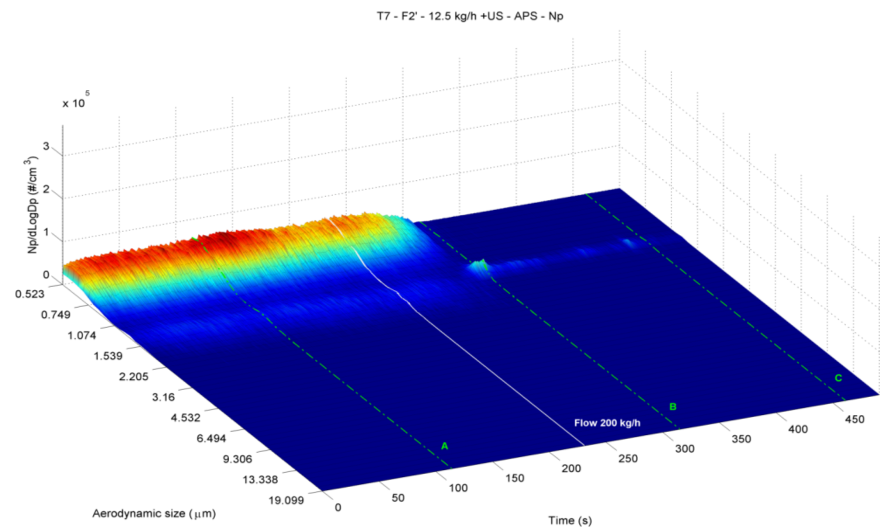
PRELIMINARY RESULTS PECA-MSAA-PASSAM

OUTPUT (APS)

Number distribution from the APS measurements



-US



+US

Boundary Conditions

Bimodal distribution

Particles: Silica (SiO_2)

Small particle mass (0.3 µm) 75%

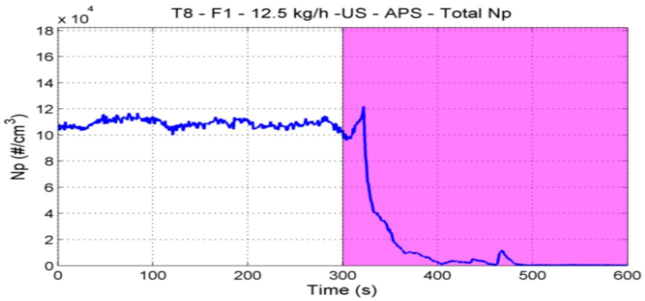
Big particle mass (1.0 µm) 25%

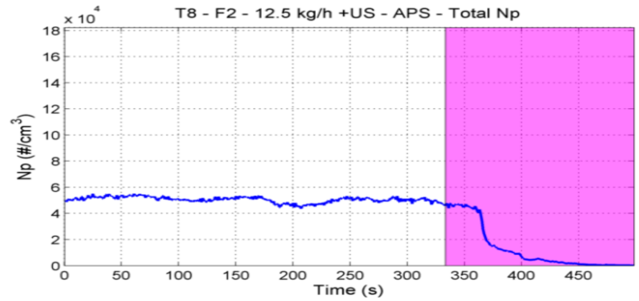
PRELIMINARY RESULTS PECA-MSAA-PASSAM

OUTPUT (APS)

Number distribution from the APS measurements

-US





+US

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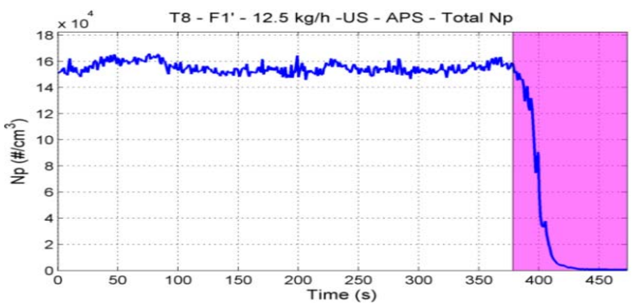

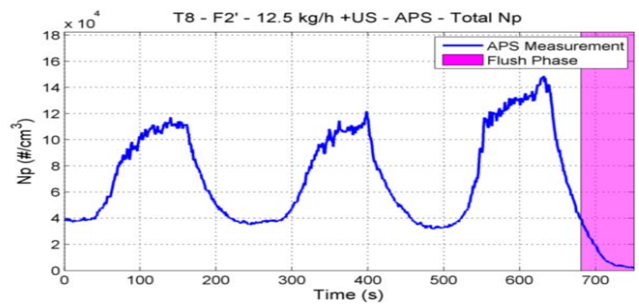

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__Boundary Conditions__

Bimodal distribution

Particles: Silica (SiO2)

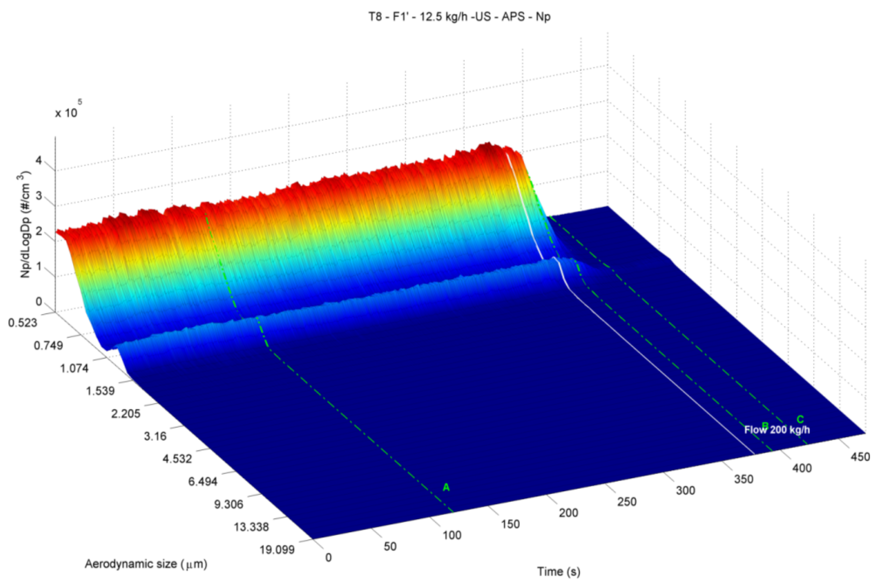
Small particle mass (0.3 µm) 90%

Big particle mass (1.0 µm) 10%

PRELIMINARY RESULTS PECA-MSAA-PASSAM

OUTPUT (APS)

Number distribution from the APS measurements



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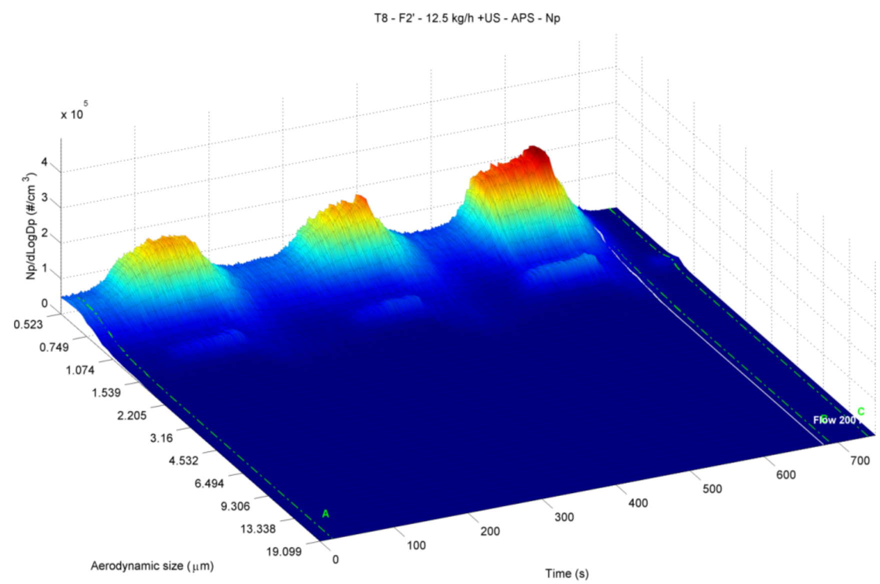

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Boundary Conditions

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CONCLUSIONS

- *Two innovative systems for PU application in SFE processes at two pilot plant scales (5L, 20L) were implemented and validated experimentally. Both systems have shown to be an efficient solution applicable at industrial scale in food industry*

- *The feasibility of PU to improve convective drying of foodstuffs has been confirmed. PU was able to speed-up both internal and external water transport in a wide range of food commodities and experimental conditions at medium and low temperature*

- *Finally, an acoustic agglomeration developing system at pilot plant scale as an innovative system for source term mitigation for severe accidents of nuclear plants has been presented*

Acknowledgements

- *We would like to acknowledge our spin- off **PUSONICS** SL for their remarkable scientific and technical assistance throughout the years (since 2008) in the fabrication of the power ultrasonic systems applied to our investigations.*
- ***PUSONICS** SL collaborates with **CSIC** along with other **R**esearch **I**nstitutions and **I**ndustries around the **W**orld towards the design of novel devices for efficient application of ultrasound energy in gas, liquid, solid, and multi-phasic media.*
- *Through continuous efforts into the development of application-specific ultrasonic systems for laboratory and practical operations **PUSONICS** SL is in the unique position to aid on bringing power ultrasound advances into the Society.*
- *Applications investigated by PUSONICS involving airborne power ultrasound have been highlighted in this presentation. This company also develops devices for liquid processing such as mixing, degassing, atomization, etc., and for ultrasound interactions with solids.*

Description of PUSONICS

***MAIN ACTIVITIES*:**

- *Development and manufacture of competitive high-tech products adaptable to market needs.*
- *Development of custom-based ultrasonic system solutions according to client requirements via conceptual design, finite element modelling, and system prototyping.*
- *Design and manufacture ultrasonic devices and components for the OEM market.*
- *Exclusive supplier of the airborne ultrasonic systems.*

Company clients are industries and research laboratories interested in producing the multiple beneficial effects of ultrasonic energy at lab, pilot plant, and full scale levels.

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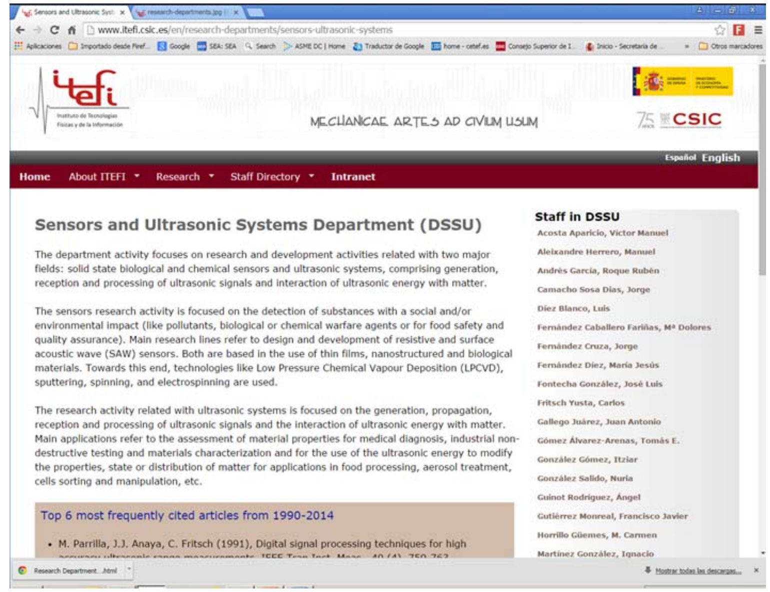

http://www.itefi.csic.es

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THANK YOU VERY MUCH

FOR YOUR ATTENTION