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INTERACTION OF ULTRASONIC AND HEAT FLOW IN ESSENTIAL OIL EXTRACTION – A CONSTRUCTAL GLIMPSE

YELDA VELI[a,*], FLORIN SĂFTOIU[b], ALEXANDRU M. MOREGA[a,c]

[a] National University of Science and Technology POLITEHNICA Bucharest, Faculty of Electrical Engineering, yelda.veli@upb.ro [a]

[b] National University of Science and Technology POLITEHNICA Bucharest, Doctoral School of Electrical Engineering, florinsaftoiu@gmail.com

[c] 'Gheorghe Mihoc-Caius Iacob' Institute of Statistical Mathematics and Applied Mathematics, Romanian Academy, amm@iem.pub.ro

*Correspondence: yelda.veli@upb.ro; Tel. +40728049500.

Micro-cavitation processes through ultrasonic transducers are an unconventional way to extract essential oil rapidly. This paper numerically studies the interaction between the fluid and the heat flow from a constructal perspective. The ultrasound source is the pressure the piezoelectric transducer gives, which sources the flow–heat transfer interaction in the working pot. The three flows (the US, the working fluid flow, and the heat produced) interact and morph in response to the mechanical stress created by its source, a sonotrode.

Keywords: Constructal; Ultrasonic; Transducer; Piezoelectric; Micro-cavitation; Heat flow.

1. INTRODUCTION

Ultrasonic (US) machines are used in a variety of applications, ranging from industrial [1] (cleaning, welding, detecting, *etc*.) to medical [2] and biological [3] (medical diagnosis, cell disruption, *etc*.). For membrane disruption and essential oil extraction, the piezoelectric (PZE) US transducer is used in the frequency range of 20 kHz – 40 kHz, with higher values providing qualitative in-depth processing since the cavitation effect is more pronounced, but at the cost of increasing the extraction time, lower values causing a coarse extraction in a much shorter time, but with unwanted thermal effects [3].

This paper analyses the effects of a PZE US transducer on the essential oil extraction process of lavender leaves and the subsequential heat flow generation inside the work vessel (liquid medium – water with solvent and solid medium). The most straightforward setup used in extraction is the PZE source, US transducer, and vessel. An amplifying case and a sonotrode enhance and focus on the US wave. The Constructal law states that a given finite volume changes its structure over time to facilitate the flow of different currents and fluxes. The model is solved using acoustic-piezoelectric, pressure-acoustics, laminar flow, and heat transfer. Two fluxes – mass flux and heat flux – are interacting and changing their configuration continuously.

2. PHYSICS

For the acoustic-piezoelectric problem, the transducer is considered without a vessel; for the pressure-acoustic and heat transfer problem, only the vessel is considered, and the laminar flow considers the fluid as a homogenized medium.

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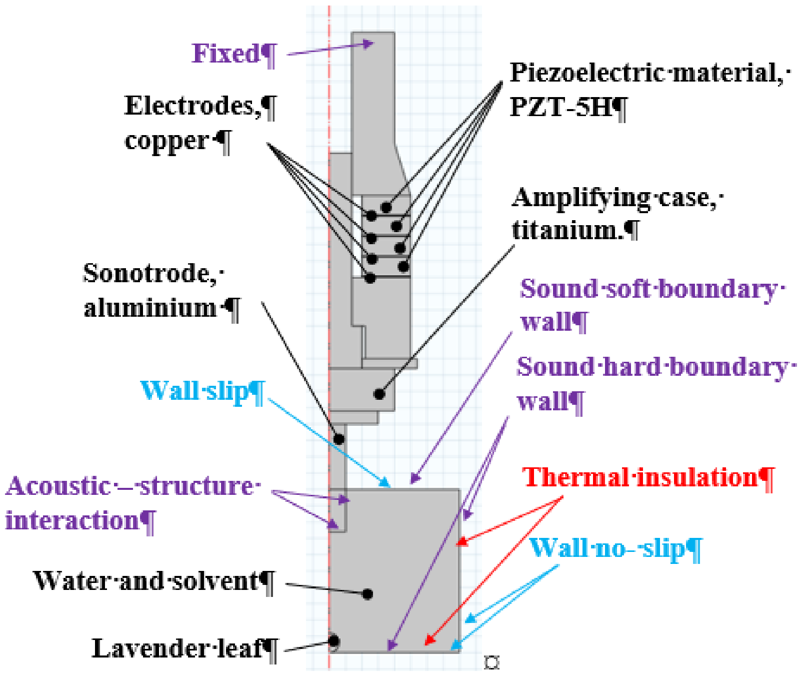


Fig. 1 – The model and the BCs for the acoustic-piezoelectric interaction problem (violet), the laminar flow (blue), and the heat transfer problem (red) – the sonotrode and the work vessel.

3. MATHEMATICAL MODEL

The equation of the sound wave represents the mathematical model for the acoustic problem:

$$\nabla \cdot \left(-\frac{1}{\rho_0} (\nabla p) \right) - \frac{\omega^2 p}{\rho_0 c_s^2} = 0, \tag{1}$$

where p [Pa] is the sound pressure, c_s [m/s] is the US velocity, ρ_0 [kg/m^3] is the mass density. The laminar flow of the water and the solvent inside the vessel is modeled by:

$$\rho_0 (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho_0 \mathbf{f}, \tag{2}$$

$$\nabla \cdot \mathbf{u} = 0, \tag{3}$$

where **u** [m/s] is the velocity, and μ [1/s] is the dynamic viscosity. The volumetric force **f** [N/m^3] of the liquid is given by:

$$\mathbf{f} = \frac{2\alpha}{c_s} \mathbf{I}, \tag{4}$$

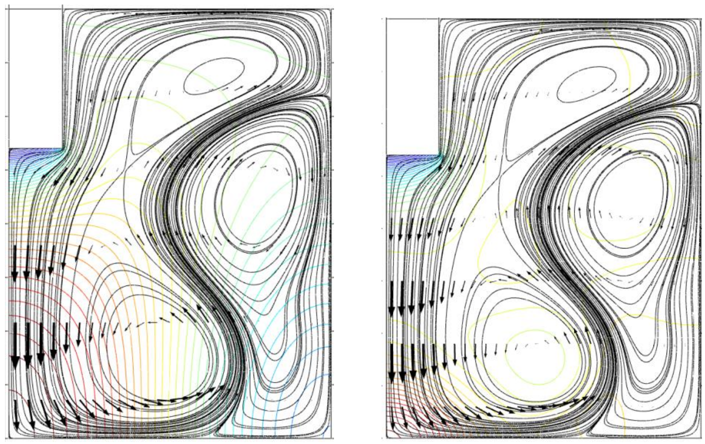
where α [Np/m] is the attenuation coefficient and **I** [W/m^2] is the sound intensity.

The equation for the time-dependent heat transfer problem is given by:

$$\rho_0 C_p \frac{\partial T}{\partial t} = k \nabla^2 \mathrm{T} - \rho_0 C_p (\mathbf{u} \cdot \nabla) T + \dot{Q}, \tag{5}$$

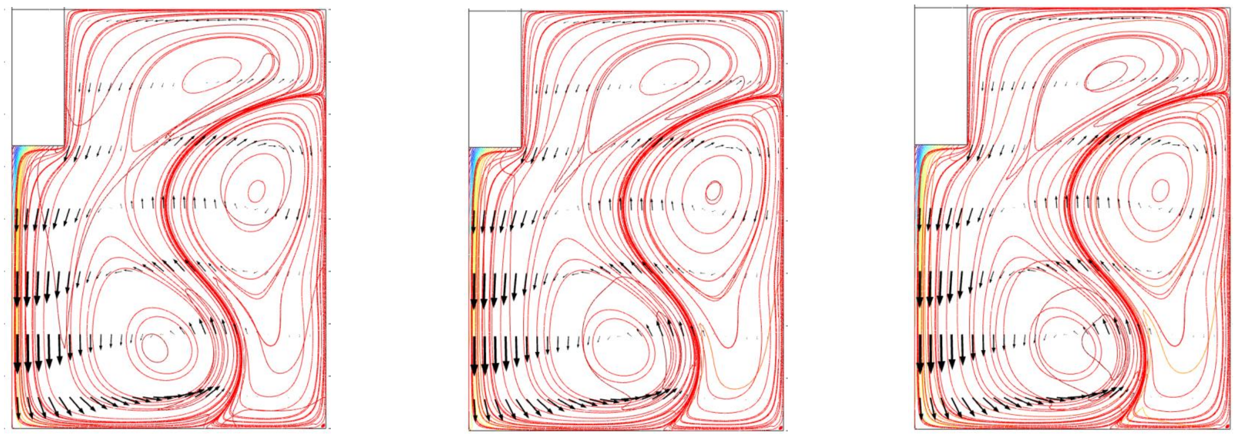
where C_p [J/kg·K] is the specific heat, k [W/m·K] is the thermal conductivity, and $\dot{Q}$ [W/m^3] is the heat source, which is obtained by computing the acoustic-piezoelectric interaction and the pressure-acoustic physics.

4. NUMERICAL SIMULATION RESULTS



(a) Isobars and flow. (b) Isobars and flow.

Fig. 2 – The lines of the input pressure (applied as BC), and the pressure established in the work vessel, along with the velocity streamline and arrows (black).



(a) Isotherms, heat flux (red) and flow, *t* = 10 s. (b) Isotherms, heat flux (red) and flow, *t* = 100 s. (c) Isotherms, heat flux (red) and flow, *t* = 900 s.

Fig. 3 – The temperature contour lines and the streamlines of the heat flux (red) and fluid flow (black) for three different moments, at *t* = 10 s, *t* = 100 s, and *t* = 900 s.

5. CONCLUSIONS

The temperature distributes from the tip of the sonotrode along the fluid flow, reaching an isothermal uniform distribution. The heat flux is in the same direction as the fluid flux, with which it interacts, and the temperature uniformly distributes along the lines.

The extraction process in this paper is not accounted for, as the fluid is considered a homogenized medium with lavender leaf suspension. Here, a 20% lavender leaf suspension is considered. The pressure-acoustic and thermal material property values are a mean value considering the percentage of each constitutive part of the mix inside the working vessel.

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