PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Acoustic design principles for energy efficient excitation of a high intensity cavitation zone

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ABSTRACT

Energy-efficient process intensification is a key aspect for a sustainable industrial production. To improve energy conversion efficiency high intensity cavitation is a promising method, especially in cases where the material to be treated is valuable and on the micro meter scale. Transient collapsing cavitation bubbles gives powerful effects on objects immersed in fluids, like cellulose fibers, mineral particles, enzymes, etc. The cavitation process needs optimization and control, since optimal conditions is a multivariate challenge. This study focuses on different design principles to achieve high intensity cavitation in a specific volume in a continuous flow. The investigation explores some potential design principles to obtain energy efficient process intensification. The objective is to tune several different resonance phenomena to create a powerful excitation of a flowing suspension (two-phase flow and cavitation bubbles). The reactor is excited by sonotrodes, connected to two coupled resonant tube structures, at the critical frequency. Finally cavitation bubbles are initiated by a flow through a venturi nozzle. The acoustically optimised reactor geometry is modelled in Comsol Multiphysics®, and excited by dedicated ultrasound signals at three different frequencies. The effect of the high intensity cavitation is experimentally evaluated by calorimetric method, foil tests and degree of fibrillation on cellulose fibers.

Keywords: Structural acoustics, Ultrasound, Hydrodynamics, Cavitation

1. INTRODUCTION

Process industries are cornerstones in today’s industrialized society for the manufacturing of various goods and products used in our day to day life. Process intensification is a strategy developed to satisfy these demands and at the same time improve production capabilities. One promising example is the implementation of devices using the principle of hydrodynamic and acoustic cavitation. High-intensity cavitation in the ultrasonic range can change the physical and chemical properties of a wide range of substances and hence, improve the production rate and quality.

Pulp and paper production and extraction of metals from minerals are two industrial sectors that need to meet new demands regarding energy efficiency. Special focus is on fibrillation which is the most energy demanding processes within pulp and paper industry, with an energy efficiency of 1%. Leaching of minerals characterized by high activation energy is another energy demanding process. Minerals that fall into this category are tetrahedrite, nickel laterites, scheelite, wolframite, etc., these types of minerals are typically leached in autoclaves at elevated pressures and temperatures making them highly energy intensive.

There are two main reasons for the limited use of dedicated devices for hydrodynamic and acoustic cavitation in process industry: (i) The method requires extensive optimization that depends on multiple process parameters and (ii) Problems in the implementation on a larger scale with respect to, stability and robustness, energy efficiency and high flow rates.

This study focuses on the methodology for the design and optimization of a scalable flow through reactor. In the applications mentioned above, with respect to high-power ultrasound, various reactor concepts exist (1 - 5). Focusing on energy efficiency and a scalable flow through concept has governed

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the design ideas towards a double tube type of reactor, combining both hydrodynamic and acoustic cavitation. The outer tube is made of stainless steel. The two-phase flow that needs to be processed flows through the inner tube of plastic material containing the venturi. Before entering the reactor, bubbles are initiated when the flow passes through the optimized nozzle (venturi). The water volume between these tubes is filled with degassed water. The goal of optimization is to create high vibration amplitude in the tube wall, coupled to a resonant mode in the enclosed water volume causing a high-pressure zone in the center of the tube. Zones with high sound pressure variation are directly related to high cavitation intensity.

2. Acoustic and hydrodynamic design methodology

2.1 Acoustic design principles

The objective is to design and match different resonance phenomena to achieve a flow through reactor resilient for high intensity acoustic cavitation. The idea is to fully couple a number of resonant structures, to generate an efficient power transmission between electrical input and high intensity cavitation output. In order to achieve the same, different wave types need to be analyzed and controlled. One fundamental assumption is the pressure that builds up inside the tube, is maximized, if the standing waves in the water column are excited by a combination of bending wave and breathing mode resonances in the tube walls.

The design strategy starts from classic linear structural acoustic theory, followed by a stepwise and multivariate approach using multiphysic simulation software. Start values for optimization are linked to: a) Wave speeds in fluids and solid materials, b) Fluid eigenmodes in a cylindrical volume, c) Longitudinal resonances in a shell structure, d) Bending wave resonances in a free cylindrical shell and e) Critical frequency of a bending wave in a cylindrical shell structure.

The design parameters are:

I. Temperature (T),
II. The diameter of fluid volume (D_i) or tube mean diameter (D_m),
III. Length of fluid volume (L_f),
IV. Wall thickness of the surrounding tube (h),
V. Length of the tube (L_s) and
VI. Fluid and physical properties of the inner tube. *

** The goal is to design the reactor, so that it is as robust as possible with respect to losses in the central volume.*

Varying the design parameters I to VI in three levels, 729 combinations need to be considered. However, initially three of the design variables were kept fixed. Temperature was set to 20 °C, diameter D_i and water volume length L_f, are set to values that give appropriate mode shapes of the contained volume at the target frequency and temperature. However, in the practical application these variables are dependent on the effective wave speed of the contained fluid and the cavitation effects.

a) Wave speeds in fluids and solid materials

The speed of sound in water is dependent on temperature and the amount of gas and particles in the water. However, since the design of the reactor allows the water jacket volume to be degassed by the ultrasound only the temperature dependence is considered. The inner volume where solvents and mixtures flow through is controlled by variable boundary conditions and loss factors. Compression speed of sound in solids and fluids is defined by the Bulk of modulus of elasticity (K) and the fluid density (ρ), which both are temperature dependent. Stainless steel (*K =163E9 Pa)* is approximately 80 times harder to compress than water, *K= 2.20E9 Pa* at 20°C. The speed of sound in water varies to a greater extent with temperature than stainless steel. In water at 20°C, speed of sound c = 1480 m/s, but the temperature dependence is useful for tuning the final response. In the tube structure, the longitudinal speed of sound needs to be corrected since the wall thickness is much smaller than the wavelength. In plate and shell structures, the quasi-longitudinal wave speed is defined by Equation 1.

$$c_L = \sqrt{\frac{E}{\rho(1-v^2)}} \tag{1}$$

b) Fluid eigenmodes in a cylindrical volume

For the reactor type aimed for, the geometry of the fluid volume is defined so that two independent mode shapes can co-exist at the same eigenfrequency. Like a pure mode in the radial direction axial and a pure mode in axial direction. Positive interference between these two modes will get maximum amplification. But also benefit from the excitation of the related complex mode at a higher secondary frequency.

The inner diameter (D_i) of the tube is the first parameter to be defined. If $D_i = 90\ mm$ then the pure radial cross-sectional eigenmode ($l = 0,\ m = 0,\ n = 1,\ \beta_{0,1} = 3.83$) occurs at around $20\ kHz$ as in Equation 2.

$$f_{l,m,n} = \frac{c}{2}\sqrt{\left(\frac{2\beta_{m,n}}{\pi D_i}\right)^2 + \left(\frac{l_f}{L_f}\right)^2} \tag{2}$$

The mode shape generates maximum pressure at the center and along the walls as shown in Figure 1. The two wavelength radial eigenmode will be at around $37\ kHz$. The pure radial and axial modes are the least sensitive to the losses that occur in the central region where an inner tube in soft plastic material will be located. However, real boundary conditions will alter the eigenfrequency e.g. caused by resonances in the tube structure and due to changes in the effective fluid wave speed due to cavitation.

At $20°C$ and $20\ kHz$ the wavelength in water is $74\ mm$. The length of the water column (L_f) is defined to create a pure axial standing wave $(m = 0, n = 0)$ at the target frequency see, Equation 4. Two options exist: (i) l_f defined as an even number, i.e. *full* wavelengths and (ii) l_f defined by an odd number, i.e. half wavelength, The benefit of an even mode number is the symmetric field and stronger pressure build up at high cavitation intensity. However, there are multiple competing modes in the frequency range of interest. Some frequencies may not contribute to the objective and need to be avoided.

The best result is can be achieved by superposition of a pure axial mode and the first radial mode, due to expected losses along the reactor centerline, both by the presence of the plastic tube and the changed wave impedance due to high cavitation activity in the two-phase flow inside the tube.

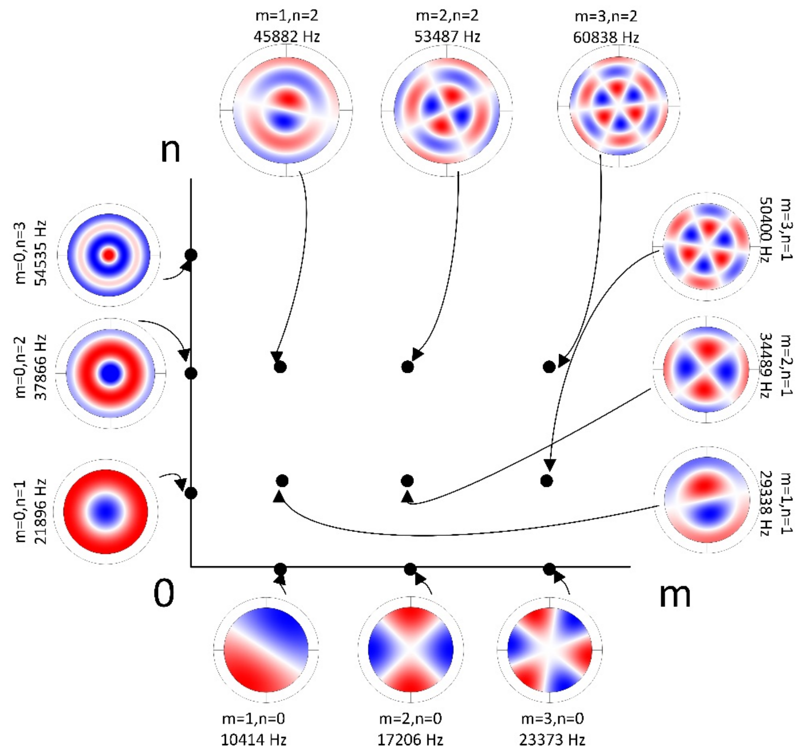

Figure 1: Different types of eigenmodes in a circular cross-section of a water filled tube in stainless steel.

c) Longitudinal eigenmodes in a cylindrical shell structure

The tubes structural modes are coupled to the contained fluid of the tube. A key frequency (f_O) is related to the breathing mode of the tube, a longitudinal eigenmode in the circumference of the cylinder (m_x=*1*, l_z=*0*), as described in Equation 3. The breathing mode is strongly coupled to the water column inside the tube. The idea is to enhance the breathing mode and suppress the axial longitudinal eigenmodes, by mistuning of the tube length ($L_S \neq l_z \lambda_S/2$). $f_O = 16.6\ kHz$ for a cylinder in stainless steel with $D_M = 100mm$. $f_O < f_{US}$ to maximize the acoustic coupling between structure and fluid (6).

$$f_{n,l} = \sqrt{\frac{E}{\rho(1-v^2)}\left[\left(\frac{m_x}{\pi D_M}\right)^2 + \left(\frac{l_z}{2L_S}\right)^2\right]} \tag{3}$$

d) Bending wave eigenmodes in a cylindrical shell with free boundaries

Bending waves exist in plate or shell-like structures and is the wave type that radiates sound most efficiently. The bending wave phase speed (c_B) is frequency dependent. Equation 4, defines c_B for specific eigenmodes of a thin walled cylinder ($h \ll D_M$) with finite length (L_S) and free boundaries.

$$c_B = \frac{2\pi f}{\sqrt{\left(\frac{\pi l_z}{L_s}\right)^2 + \left(\frac{2m_x}{D_M}\right)^2}} \tag{4}$$

The idea is to excite bending waves in the tube wall in three points, normal to the wall surface, forming an equal-sided triangle seen in cross-section. The circumference of the neutral layer is divided by three ($m_x=3$) defines a tangential wavelength (λ_x). An even integer of l_z will give a symmetrical mode along the tube.

e) Critical frequency of a bending wave in a cylindrical shell structure

The design strategy was to set the target resonance frequency of the tube structure (f_{US}= 20.0 kHz) close to the critical frequency (f_c). At f_c, c_B equals the fluid wave speed. The critical bending wavelength λ_B then needs to be equal or greater than 74 mm. The bending wave in a tube travels normally in spiral form, and by unfolding the cylinder λ_B can be decomposed in axial (λ_z) and tangential components (λ_x), see Equation 5. However, due to the difference in acoustic impedances and the bending wave radiation, the boundary was assumed to be defined by the mean diameter of the tube (DM). Another aspect of importance is that the bending wave speed (c_B) also depends on material properties (ρ, E, v) and the wall thickness (h), see Equation 6, valid if $h \ll \lambda_B$ and $f > f_O$.

$$\lambda_B = \frac{\lambda_x \lambda_z}{\sqrt{\lambda_x^2 + \lambda_z^2}} \tag{5}$$

$$c_B^2 = 2\pi f \sqrt{\frac{Eh^2}{12\rho(1-v^2)}} \tag{6}$$

A bending wave speed (c_B) of 1480 m/s at $f_{US}=20.0\ kHz$ requires a wall thickness of 11.5 mm (stainless steel). By that, the assumption of a thin structure is not valid, and c_B need to be corrected due to the inertia of rotating segments and Poisson effects (6).

To summarize aspects of start values regarding tube structure dimensions. If the circumferential bending mode number (m_x) is set to 3, $h = 11.5\ mm$ and $D_M = 101.5\ mm$, $\lambda_x = 106.3\ mm$. With respect to $\lambda_B = 74\ mm$ then $\lambda_z = 103.0\ mm$. If $l_z=8$ the tube length L_S will be 412 mm, and Equation 4 give $f_{3,8}$ = 20028 Hz. However, these start values are limited to the eigenmodes of an uncoupled tube structure. Simulating the forced pressure response of the complete reactor with respect to fluid loading and different loss factors, require a multi-physical FE-modelling approach.

2.2 Hydrodynamic design principles

Several principles for hydrodynamic cavitation have been investigated (6 – 8, 15). Shankar (7) has shown the potential of CFD-optimization with the purpose of significantly lowering the energy consumption in case of fiber refining. The idea comes from the fact that cavitation has been noted to contribute to the fibrillation and processing of fibers already in the disc refiners in place today.

The design should induce hydrodynamic cavitation when the pulp stream flows through a venturi nozzle. By this, an increase in flow speed and hence the dynamic pressure is achieved and at the same time the static pressure is reduced, as both mass and energy must be conserved in the passage through the nozzle. The cavitation bubbles, thus induced, will then collapse, in the greater area of the venturi and the static pressure increases. The idea is to focus the bubble collapse on the surface of the fibers to achieve fibrillation and intensified processing (15). Therefore, the venturi nozzle needs to be carefully designed, so that the cavitation can be controlled and used in order to concentrate the processing energy on to the fibers and provide effective refinement of the fibers in the flow (13). To improve process efficiency further the hydrodynamic cavitation is combined with acoustic control of the bubbles collapse. So instead of having to pressurize or heat the entire stream, the same similar effects can be achieved by inducing cavitation in the flow, where the only energy consumption correlates to the pressure drop over the cavitation zone. The disadvantage is that it is hard to control and therefore has been considered too complicated to be used on an industrial scale, but with the rapid development of CFD technology and engineering design in the past decades, the potential of hydrodynamic has received ever more interest, in particular from chemical and process industries (9).

3. Numerical Simulation

Optimization of the geometrical design requires a combination of numerical modeling and experimental verification. The software Comsol Multiphysics®, used during the numerical analysis, has inbuilt defined modules to connect and optimize the vibration response of solid materials, dynamic behavior of piezoelectric materials, structure vibrations and coupling to the surrounding fluid, both outside and inside of the closed volumes of the reactor. It is also possible to modify the numerical model with respect to the nonlinear response caused by cavitation (11).

In short, the system's linear response is tweaked with the assumption of a global loss factor continuously determined by means of experiments. To speed up the numerical calculation procedure two important simplifications applied corresponds to: 1) Modeling the loss factors and impedance characteristics of the inner-tube by a complex valued Young modulus and 2) Handling the harmonic response caused by cavitation by analyzing pressure responses mode shape at specific harmonics.

High cavitation intensity requires a matching between the mechanical components, like transducers – tube reactor – and the acoustic wave propagation in the water volume inside the reactor tube. Customizing the tube thickness, inner diameter, length, and boundary conditions, created a coupled resonance inside the reactor tube. This forms a standing wave, linking structural vibrations to the wave propagation in water volume as shown in Figure 4. During the process of numerical optimization, eigenmode analysis is first used to balance the contribution from different eigenmodes. When matching of modes are satisfactory, the force response is then calculated and analyzed with respect to vibration displacement and pressure distribution. Since resonance frequencies of the sonotrodes shifts down in frequency when fed with high power, the same is compensated by adjusting the sonotrode geometrical properties in the numerical simulation model.

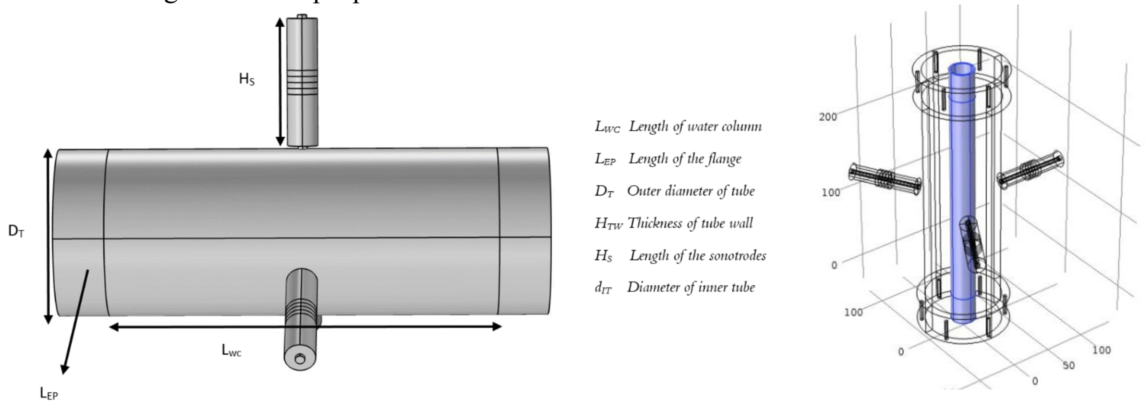

Figure 2: The reactor model with three attached sonotrodes and the inner tube along the center line.

4. Experimental Setup

High energy efficiency of a hydrodynamic and acoustic cavitation reactor concept require extensive experimental tuning in order to: (i) Obtain impedance matching between components, (ii) Equalize sonotrodes resonant frequencies, (iii) Minimize coupling losses and (iv) Determine the required electrical power to reach optimum cavitation intensity. The loss factor is determined as the sum of all losses in the system. Losses occur due to geometrical deviations, the mismatch between the sonotrodes and tube reactor, and friction between the sonotrode masses and the piezoelectric discs.

Verification of the reactor design has been executed by measuring frequency response and mode shapes in the center of the tube. Signal conditioning and analysis was conducted using a PC-based software and hardware (CLIO) for frequency response measurements in time and frequency domain at 192 kHz sampling rate. Pressure responses were measured at 4 - 400VA electric input power. A pressure sensor (Dytran model 2200V1) and a miniature shock type accelerometer (PCB 353M15) were connected to the analysis system by a signal conditioning amplifier (B&K NEXUS 2692). The pressure transducer has an upper-frequency limitation of 300 kHz. Pressure response was also measured using an oscilloscope with a bandwidth of 1 MHz.

Measuring the impedance during chirp-excitation at various levels enabled tuning and matching of the sonotrodes to the specific target frequency, slightly above the eigenfrequency of the tube structure. The sonotrode resonance frequency response varies with the electrical input power. Both as free and when attached to the tube structure. The optimum input power was to some extent balanced by the changes in electrical impedance. Finally the effect of the high intensity cavitation was experimentally evaluated by calorimetric method, foil tests and degree of fibrillation on cellulose fibers.

5. Results and Discussions

The most critical step in the acoustic modeling was to model the boundary conditions in a physically realistic way. Critical aspects are the attachment of the end caps to the tube reactor, and the connection of the sonotrodes to the tube wall. The length of the tube structure in relation to the water column inside the tube had a major impact on the pressure response, and therefore variable in the prototype. Sonotrode responses (defined by the piezoelectric material, the length, stiffness and mass) required extensive tuning to get best possible results. Each sonotrode was tuned separately to the same frequency (impedance minimum) and then tested together to ensure an equal input power distribution. The numerically optimized reactor design deviated from the start values defined by structural acoustic theory. The largest deviations were related to wall thickness and the tube structure length.

The final design was validated by pressure measurements, foil tests, and calorimetric tests. Single frequency power conversion efficiency was 35% in stationary mode. Double frequency excitation in flow through mode was, however, superior especially when the flow conditions were optimized. Figure 3 shows a comparison between the simulated and measured frequency response in the center of the prototype reactor. The smoothed and compressed spectrum in case of swept sine is due to losses and a disturbed field. The calculated mode shapes were verified by testing the erosion rate of aluminum foil in pure water. Erosion patterns correspond to a superposition of the simulated modeshapes of sound pressure variation in the water volume.

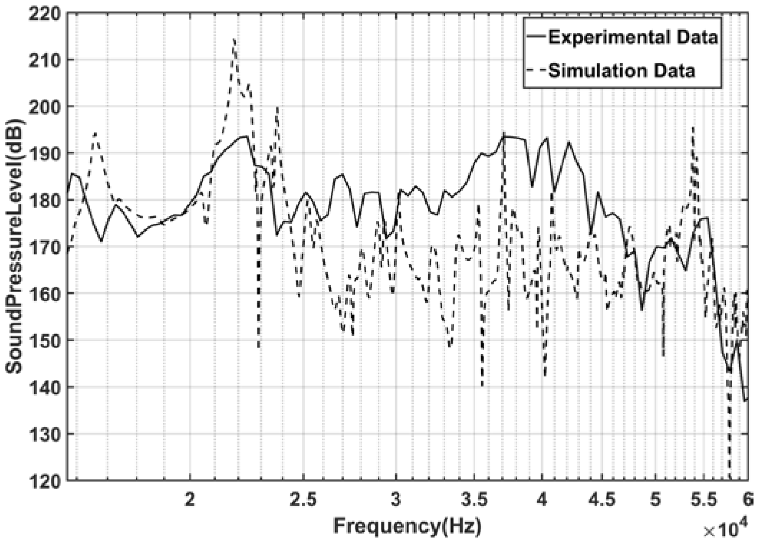

Figure 3: Modeled pressure response compared to measured response at high power excitation (200 W).

A good reactor design provides high gain while it is relatively robust to geometric deviations due to manufacturing and assembly. The results of the sensitivity analysis showed that the lengths of the water column and impedance properties of the inner tube are the most critical parameters. In reality the response became more robust due to higher losses. The most important aspect related to optimal input power level and excitation frequencies with respect to the properties of the flow through solvent.

Figure 4, presents the simulated vibration and pressure modeshapes at three resonance frequencies. However, excitation of the sonotrodes with a high power pure sine at the resonance frequency creates a broad band harmonic pressure response (14), affected by the reactor volume resonances. Cavitation intensity is also temperature dependent. Pressure measurements in the center of the reactor showed that the sound intensity increases by 10 dB when the water temperature increased from 21 to 55°C. Foil tests verified that the erosion rate increased in a similar way (12).

Foil-tests carried out in a fiber suspension (1% conc of wet fibers) showed that the erosion rate decreases significantly compared to tests in pure water. One reason is the attenuation of the resonant gain, which increases electrical impedance and reduces input electric power, and thus the sound pressure and cavitation intensity. The main reason for reducing erosion rate is that the fiber wall absorbs the cavitation energy in the form of mechanical processing of the fiber wall and friction losses.

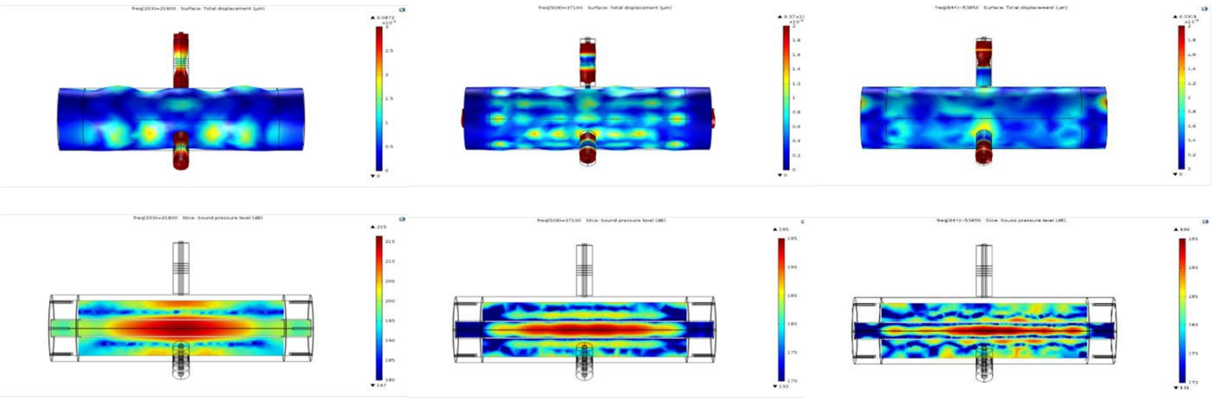

Figure 4. Vibration and pressure modeshapes at target frequencies: 22 kHz; 37 kHz; and 53 kHz.

The excitation signal and duty cycle has a profound impact on cavitation intensity. The pure sine, with onset and off set makes a difference. A duty cycle of around 30/70 gives maximum energy efficiency (10). With respect to energy efficiency and robustness, a narrow chirp signal has shown to be promising. A chirp signal is of special interest when resonance peaks shift in frequency. The chirp signal characteristics produce an onset/offset response since electrical impedance varies.

In the case of two-phase and non-Newtonian flow, the nozzles designed for hydrodynamic cavitation also gave a much better mix of the pulp, and sedimentation was avoided. In case of fiber treatment, the duty cycle of acoustic cavitation was 10/90 (circulating system). The duty-cycle was not optimized but produced better results than in case of a stationary system with acoustic cavitation only. Figure 5(a) shows the effect on the fiber walls mechanical properties in case of two frequency excitation and a top-down flow through a venturi type of nozzle (12, 13). With respect to modifying the absorption properties of the fiber wall an optimum was identified at an input power level of 186 kWh/bdt. At 568 kWh/bdt fibers were damaged, which was observed by SEM analysis.

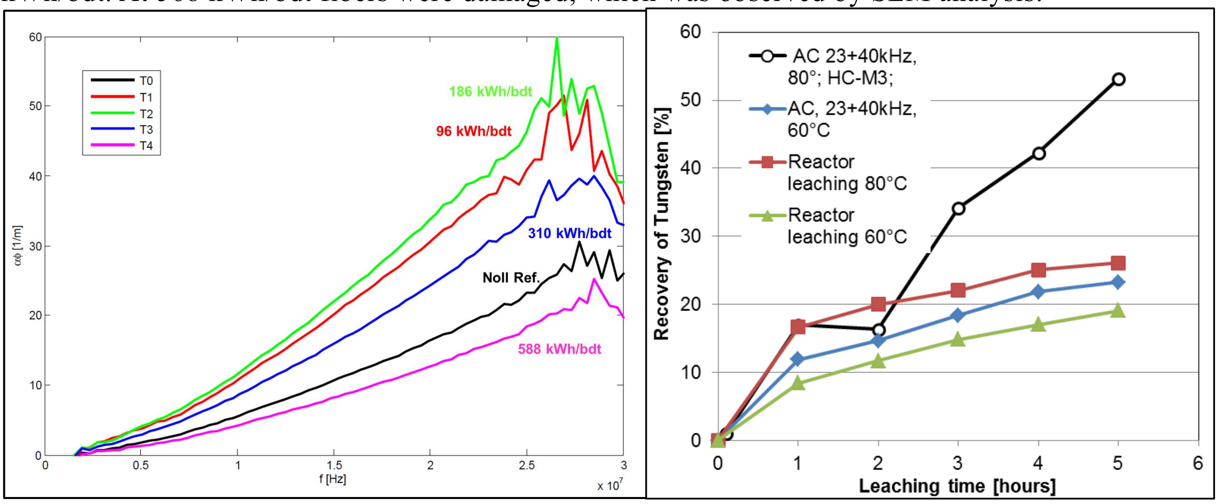

Figure 5 (a) and (b): Effects of hydrodynamic and acoustic cavitation. a) Treatment of cellulose fibers - Black curve represents no cavitation, only flow through, and b) Recovery rate of tungsten - Best result was achieved at 80°C with bottom up flow, a new nozzle design (M. 3) and acoustic excitation by 23 and 40 kHz at 350 VA.

When recovering tungsten from scheelite ore concentrates, leached by sodium hydroxide solution at 80°C, the duty cycle was 20/80. In the experimental validation, both flow direction and the nozzle design had a significant impact on the results. Figure 5b shows the recovery rate of tungsten by hydrodynamic and acoustic cavitation (HAC) compared to traditional chemical leaching. At 60°C, acoustic cavitation only, increased recovery rate from 18% to 23%. Best result was obtained using bottom up flow, a new nozzle design, and acoustic excitation at 23 kHz and 40 kHz. The HAC combination increased the recovery rate, in comparison to traditional chemical leaching, from 26% to 54 % during 5h exposure. The new nozzle design has probably an even greater potential, since the effect of the secondary excitation signal became weak, due to impedance mismatch. A shift in resonance frequency at 40 kHz, caused by a more turbulent flow, decreased the power input.

6. Conclusions

The developed reactor concept is based on the principles of hydrodynamic and acoustic cavitation. The final design is the result of an iterative optimization process using multi-physics simulations and experiments. The fundamental design principles were inspired by previous research (1 - 6 and 8 - 11). The aim of this investigation has been, to define criteria for a robust, energy efficient and scalable design to be applicable in the process industry. High cavitation intensity is generated in the center of the reactor where the solvents to be processed flow through. The degassed water volume between the tube wall in stainless steel (excited by piezo electric driven sonotrodes) and plastic inner tube, acts as effective wave carrier of high intensity ultrasound. Optimized vibration patterns allows pressure maximum to appear in the center of the inner tube, which impedance characteristics can vary within a rather big range without losing its basic performance. Also, cavitation efficiency is to a great extent dependent on the flow characteristics and properties of the flow through medium.

ACKNOWLEDGEMENTS

The project was funded by Swedish Energy Agency and VINNOVA, and has been supported by ÅF, SCA, Stora Enso, Holmen, Innventia AB, TU Dresden and Mid Sweden University.

REFERENCES

1. T. J. Mason. Large scale sonochemical processing: aspiration and actuality, V. 7, pp. 145–149, 2000.

2. Timothy J. Mason, Dietmar Peters. Practical Sonochemistry: Power Ultrasound Uses and Applications, 2nd Ed., 2003.

3. P.R. Gogate, A.B. Pandit, Engineering design method for cavitational reactors: I.Sonochemical reactors, AIChE Journal 46 (2000) 372–379.

4. Keil F. J. (ed.), 2007. Modeling of Process Intensification – Ch 8 Ultrasound reactors.pp 192-279.

5.. Moholkar, Vijayanand S., and Marijn MCG Warmoeskerken. "Integrated approach to optimization of an ultrasonic processor." AIChE journal 49.11(2003):2918-2932.

6. F. Fahy. Sound and Structural Vibration,Radiation, Transmission and Response, Ac. Press, (1987).

7. V. Shankar. Fluid induced cavitation to improve energy efficient in disc refiner for paper and pulp production - application of advanced research techniques. Technical report, ÅF Consulting, 2014.

8. P. R. Gogate and A. B. Pandit. A review and assessment of hydrodynamic cavitation as a technology for the future. *Ultrasonics sonochemistry*, 12(1):21–27, 2005.

9. P. R. Gogate and A. B. Pandit. Hydrodynamic cavitation reactors: a state of the art review. *Reviews in Chemical Engineering*, 17(1):1–85, 2001.

10. P. R. Gogate. Hydrodynamic cavitation for food and water processing. *Food and Bio- process Technology*, 4(6):996–1011, 2011

11. Rashid Jamshidi,*, Birte Pohl, Urs A. Peuker, Gunther Brenner. Numerical investigation of sonochemical reactors considering the effect of inhomogeneous bubble clouds on ultrasonic wave propagation. Chemical Engineering Journal 189– 190 (2012) 364– 375.

12. Ö. Johansson, T. Pamidi, T. Löfqvist. Design of a high-intensity ultrasound reactor. 2017 IEEE International Ultrasonics Symposium (IUS) 6-9 Sept. 2017 Washington, DC, USA.

13. V. Shankar, A. Lundberg, K. Frenander; L. Landström, T. Pamidi, Ö. Johansson. Flow Induced Venturi Cavitation to Improve Energy Efficiency in Pulp Production. Journal of Fluid Flow, Heat and Mass Transfer Volume, 2018.

14 V.I. Ilyichev, V.L. Koretz and N.P. Melnikov. Spectral Characteristics of Acoustic Cavitation, Ultrasonics 1989;27 357-36

15 S. Goto, T. Noda, C Yuzawa, T Iimori, Cellulose-based fibrous materials. Patent No.: US 8,012,312. Sep. 6 2011.