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# Study of low frequencies on cooled water: development and analysis

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**Abstract.** The development of new and sustainable technologies to avoid hazards created by the freezing of substances has been a priority of safety more and more in the past decades. With this study, we want to give a first glance and start a series of experiments and researches which would lead us to results useful for future technologies. By starting from a numerical model, we studied the effects of constant frequencies applied to a cylindrical vessel filled with water. The enhancement of certain heat transfer processes was verified with particularly strange reactions for certain values of gain.

## 1. Introduction

In the past decades, many studies have been brought on how to keep certain emulsions in a liquid state under critical conditions. Nowadays, we can find a lot of researches especially about the usage of different mechanisms to obtain these results: from the use of chemicals to ultrasonic vibrations. With this research we want to give a general idea on this subject. The results of such research will allow us to pursue future studies: from considering the most affordable liquid (tap water) to more challenging substances (like crude oil and fuels). The idea behind the usage of such vibrations is that it is possible to find them in our everyday life (think about the vibrations developed by a car engine or by construction equipment). Moreover, they are still a source of energy that has not yet been understood completely and has not yet been used at its full potential. By following the studies done in the field of acoustic theory and the field of vibrations affecting liquids, we want to develop a new environmental-friendly mechanism of demulsification of water-in-oil emulsions and to find a general model for keeping fuels in a liquid state under critical temperature conditions. Once the literature has been completely analysed, we should start with first experiments on how low-frequency vibrations affect the simplest of all the liquids: tap water. This contains minerals and elements which already affect the behaviour of this liquid. By understanding the behaviour of a sample of water affected by external vibrations at room temperature, we will analyse the setup under critical conditions at first with a simulation and subsequently with a physical probe.

In many scientific studies conducted until today [1-5], it has been demonstrated that, among the existing ways of enhancing heat transfer processes, the application of vibrations is one of many known sensible methods which does not imply changes in the original system and is still not fully comprehended.

Modern technologies cause or implement pulsating regimes in the working volume of systems by applying vibrations to the basic flow field of a medium. This is usually considered as a disadvantage. According to many studies, this mechanical process needs more attention, because it may be used as a method for intensification of heat- and mass-transfer processes and be a quite promising technique [1].



For the same reason, to optimize and increase the performance of combined industrial equipment, Zaitsev D. E. [2] conducted a research regarding heat transfer processes in closed vessels filled with liquid under vibration. At first, a comparison between a sample in a steady state and a vessel under vibration was pursued. There was detected an increase of 50 % in the convective heat transfer process of the vibrated liquid compared with the same system but in a stationary state. It was also brought to the attention that the heat transfer coefficient grew with the increase in the acceleration. The material employed in the experiment and the diameter and height of the liquid column were studied to influence the heat-exchange rate phenomenon. Briefly, the development of new combined equipment using this new obtained knowledge produced the desired results in productivity enhancement.

Many studies focused on the relationship between heat transfer and the intensification of boiling processes phenomena [3-4]. The will of increasing the heat transfer phenomena led to many improvements: concentrating on studies regarding the point of phase change from liquid to vapour became the basis for novelties in the heat transfer processes studies. Another point of interest was the enhancing of the boiling status and heat transfer. Active techniques were applied with external vibration among them. Alangar [3] described this process with exactitude. It was noted that boiling processes began at much lower superheat values for the same heat flux when external sollecitations were applied to the surface. Other phenomenon discovered was that vibrations encouraged the quick departure of bubbles from the vibrated surface. As a followed effect, the bubbles diameter decreased.

Chekanov and Kul'gina [4] demonstrated that increasing both  $\alpha$  (the oscillation amplitude, between 0,0 and  $0,4 \times 10^{-4}$  m) and  $f$  (frequency, in the range of 20-100 Hz) played a fundamental role in the process of heat liberation, establishing that vibrating effects led to a decrease in the bubbles detachment frequency and the phenomenon of dispersion of these.

Other researchers, e.g., Chen et al. [5], performed heat transfer under ultrasonic conditions (with frequencies in the range of 40 kHz). A considerable heat transfer enhancement was discovered depending on the distance from the transducer. It should be stressed that the enhancement ratios were higher, with a decreasing trend while increasing the heat flux.

In this paper, we provide a description of the setup and the results of the vibrational simulation done on a column of water subjected to a vibration through an exciting body and placed in an air environment at the controlled temperature of 263.15 K for a time period of 12 hours. In this research, we focus on the study of the frequencies between 30 Hz and 4900 Hz due to technological limits of our laboratory.

Mathematical models allowed us to design a system with the best conditions that we are supposed to reach with physical experiments in the future. The system was first modelled and tested both numerically and experimentally to establish the natural frequencies and the eventual resonance frequencies in the range studied. Defined the model and the environment, the system was tested.

The environment we want to recreate embodies the critical conditions at which a substance at its liquid state should solidify [6]. By starting with simple water, with this research we want to give practical examples of the theory studied up to now and to describe a first general model for future studies. By subjecting the fluid to the right frequency, keeping the range between 30 Hz and 4900 Hz, it should be possible to induce and control the phenomenon of cavitation, studied to play an important role in the freezing of liquids. In fact, with the development of cavitation bubbles in the fluid and the subsequent increase in the pressure around these, we would be able to have water under pressure and in a liquid state also several degrees below the natural freezing point [7-12].

## 2. Methods

The modelling approach consisted in designing a 3D model of the apparatus that will be used in the future for the experimental analysis. The system considered is a cylindrical structure with two circular bases presenting six mounting holes each. Through these ones, during the experiment, the system will be connected to a vibration exciter (at the bottom base) and, during further experiments, to a motor-driven metering pump, eventually, for simulations in presence of fluid flow. This has been already designed to be attached to the upper base of the system. After the designing phase, we were ready to simulate the system. The material used to recreate the designed layout is PMMA (Polymethyl

methacrylate). First, inside the hollow central cylinder, the presence of air has been simulated, to define the natural frequencies of the structure alone. After having found these values, the simulation proceeded filling the setup with water as a fluid. The natural frequencies of the “PMMA structure + water” configuration have been evaluated in order to have an idea of the change in the natural frequencies and of the resonance frequencies in presence of different fluids. Figure 1 shows the 3D model (left) and the real one placed in our laboratory (right). In Table 1, the parameters of the studied setup are presented. The environment in which the setup is placed is described by the parameters listed in Table 2.



**Figure 1.** (Left) 3D model of the setup; (right) real setup in our laboratory.

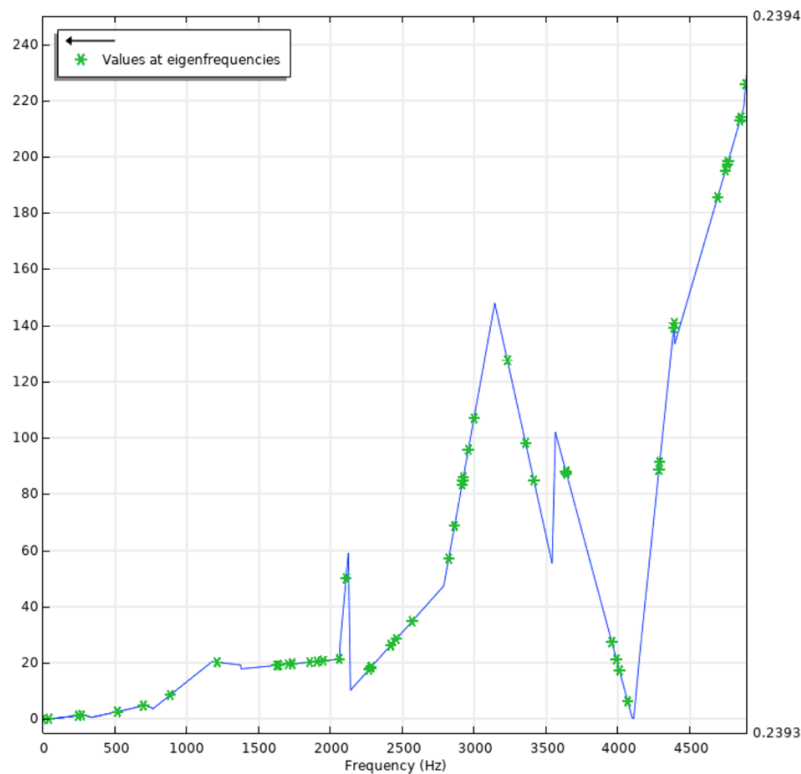
**Table 1.** Parameters describing the PMMA setup.

Parameter	Value	Description
r_base_ext	0.0025 m	External radius of the circular bases
r_base_int	0.0030 m	Internal radius of the circular bases for the insertion of the cylindrical main structure
h_base	0.0025 m	Thickness of bases
h_tube	0.052m	Height of the PMMA cylindrical main structure
r_tube_ext	0.0030 m	External radius of the main cylindrical structure
r_tube_int	0.0025 m	Internal radius of the main cylindrical structure. Within this internal cylinder the fluid is placed
r_screw	0.00025 m	Radius of the mounting holes
T_water	293.15 K	Initial temperature of the water positioned in the hollow cylinder

**Table 2.** Parameters describing the controlled environment.

Parameter	Value	Description
T_amb	267.15 K	Temperature of the air
p_amb	1 atm	Pressure of the environment
$\phi$ _amb	0.1	Relative humidity
V_amb	0 m/s <sup>2</sup>	Wind speed
h_air	500 W/(m <sup>2</sup> ·K)	Heat transfer coefficient considered

The eventual limits of the model have been tested with the available tools at the laboratory. For the results of this study, we approached the problem by evaluating the natural frequencies of the system. The supposedly verified results can be seen in Figure 2.



**Figure 2.** Supposed values of the natural frequencies of our system with acceleration related.

Thanks to the simulation developed, we were able to analyse the effects of the heat exchange processes on our setup. In a range of 12 hours, with step of 3 hours each, we evaluated the effects of the environment on the system. After this study, we introduced a load, defined by the function  $F$ , on the system described by the following formula:

$$F(t) = F_0 \cdot \sin(2\pi f_0 t) \quad (1)$$

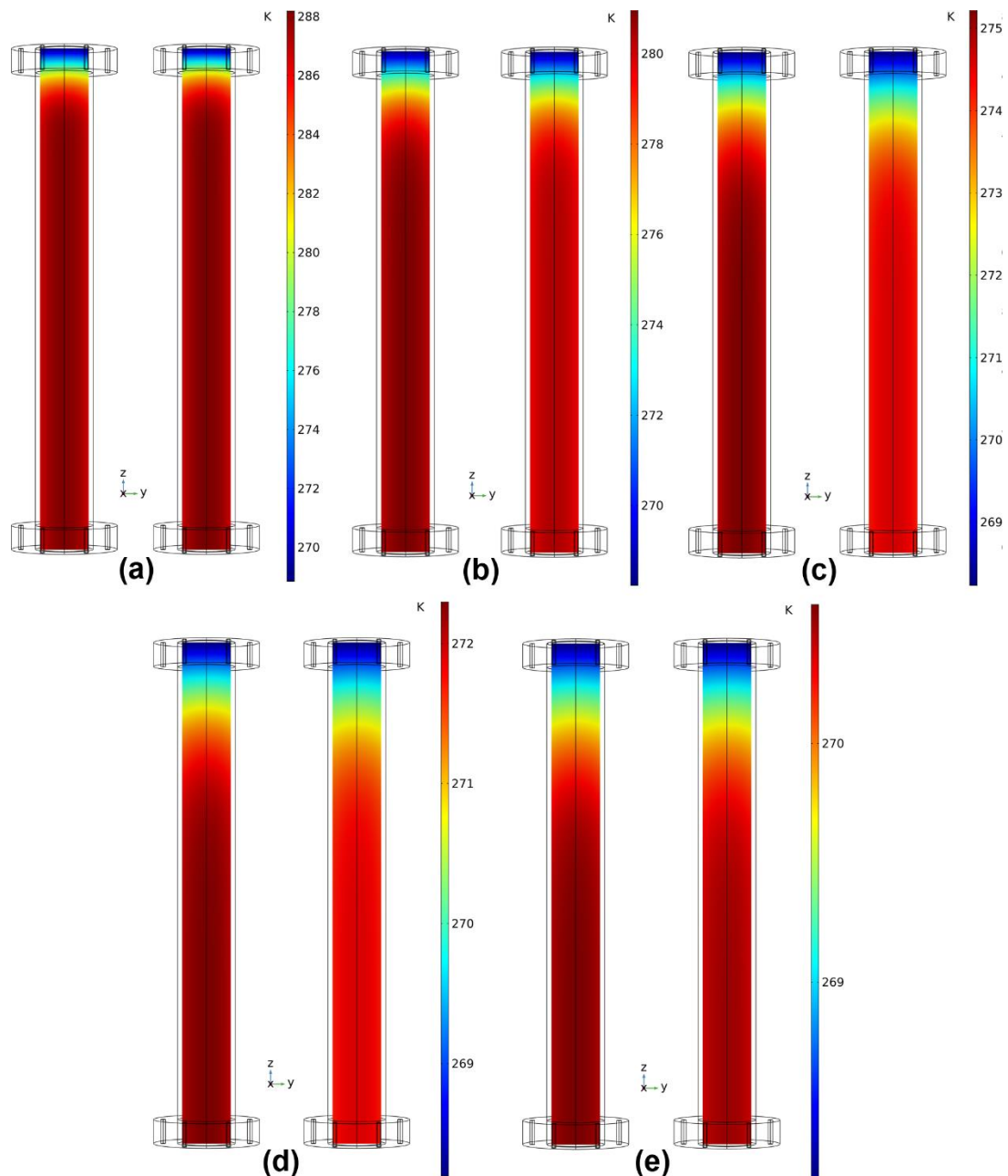
where:  $F_0$  is the load which is applied by the shaker and which is controlled;  $f_0$  is the resonance frequency.

We decide to consider the frequency of vibration as the resonance frequency of the system because in this way we would have been sure of putting the system under maximum stress. By comparing the stress results obtained and the data sheets online, it was then possible to confirm that the value of stress at the resonance frequency was not enough to keep the system in a condition of elastic response.

### 3. Results

After the collection of the data, we could compare the results of the system with the applied force and the one stated above in normal conditions. The evaluation of the acquisitions was done considering the plane YZ at coordinate  $X = 0$  mm. In Figure 3, it is possible to evaluate the results acquired.

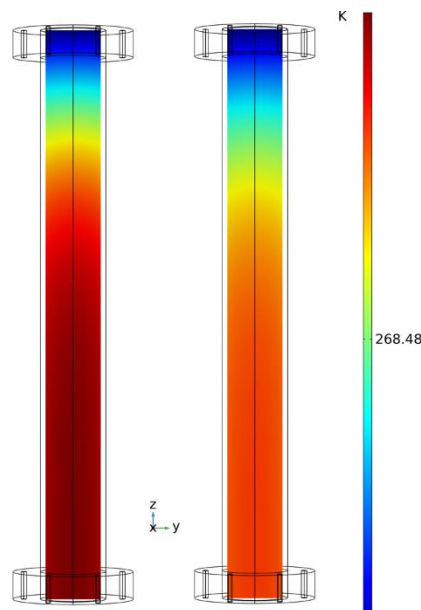
From the numerical analysis we obtained the following results. By considering the system under the conditions previously mentioned, during all the period of analysis, the force  $F(t)$  results to enhance the heat transfer phenomena, increasing the process of the cooling down of the water placed inside the hollow cylinder.



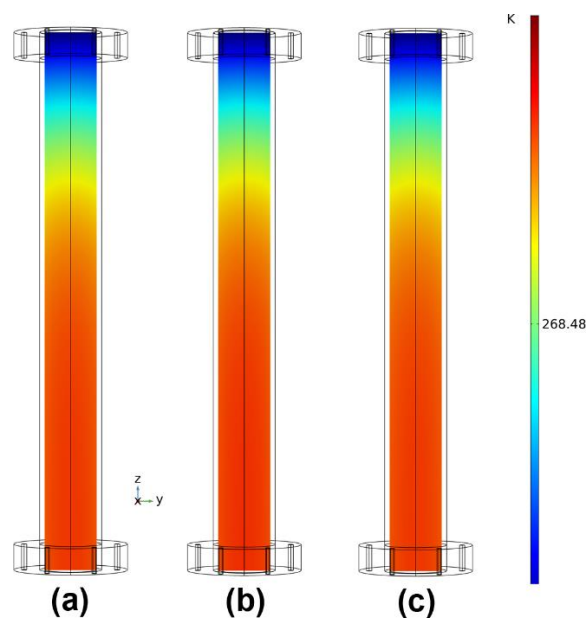
**Figure 3.** Development of the heat transfer processes, left – stationary state; right – system under vibration: (a) after 1 hour; (b) after 3 hours; (c) after 6 hours; (d) after 9 hours; (e) after 12 hours.

We continued analysing the data working up to the changes after 24 hours and we saw how, with the parameters set, the enhancement of the heating exchange process is clear (Fig. 4)

Subsequent step involved the variation of the parameters  $F_0$  and  $f_0$ . We first fixed the value of  $F_0$  to 1 N. In Figure 5, we highlighted the comparison in a time span of 24 hours between  $f_1 = 3142.9$  Hz (Fig. 5a) (the studied resonance frequency),  $f_2 = 3563.4$  Hz (Fig. 5b), and  $f_3 = 2124.2$  Hz (Fig. 5c). These values were evaluated as natural frequencies during the simulation phase. We proved that by increasing the range of frequencies studied, always keeping the study in the audible range of frequencies, and by keeping the gain constant, the process of heat transfer was prone to change the process of freezing without the application of any stress. By fixing the frequency and comparing the effects with gain 1 N and 100 N, we did not obtain better results than those in previous researches.



**Figure 4.** Comparison of the heat exchange processes after 24 hours, left – stationary state; right – system under vibration.



**Figure 5.** Comparison of heat transfer processes after 24 hours at fixed gain of 1 N for different frequencies: (a) 3142.9 Hz (the studied resonance frequency), (b) 3563.4 Hz, and (c) 2124.2 Hz.

#### 4. Conclusion

In this article, we studied the effects of low-frequency vibrations on cooled water in a controlled temperature environment. We were able to obtain data by numerical modelling and to give a comment by comparing them with previous studies. By simulating the apparatus, that we would in future continue using in the acoustic laboratory of Bauman Moscow State Technical University, we developed a simulation of a PMMA structure filled with water and placed in a vibrating-controlled environment. By applying a load, described by a sine function, we tested the system at its resonance frequency. By

changing the gain, in a range between 1 N to 100 N, the data collected allowed us to see in this range there is an enhancement of the cooling process. This seems to reduce when the value of  $F_0$  is 20 N. The already observed phenomena remain constant until values of the gain of 100 N.

Knowing that the vibration exciter B&K Type 4808 that we acquired and placed in the laboratory has a limited gain given to the probe, we could not go over this limit. For future analysis and studies, we will provide our laboratory with more powerful vibration exciters in order to study different configurations.

Due to the impossibility of sealing the probe, the idea of development of cavitation bubbles and using their energy to discourage the freezing process was not achieved in this experiment. Thanks to many studies, it is a valid experiment that needs to be developed and proved in the coming years.

The following study has been pursued not following the ideas studied by previous scientists. We tried changing the gain function to find a first glance of solution on how to change the status of static fluids placed under vibration. By continuing the simulations after retrieving the results described, we decided not to add the results of how the phenomenon under study behaves in presence of a fluid flow. We noticed that water, in a controlled environment as described in Table 2, behaved in two different ways if the flow had an ascending or descending direction. In both ways, we saw how the freezing processes were discouraged. This concept will be studied further in near future.

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