FOSSEE, IIT Bombay
OpenFOAM Case Study Project
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Heat Transfer Enhancement In Fluids Using UltraSonic Waves

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Abstract

Ultrasonic waves are pressure waves with frequencies greater than 20 kHz. When introduced in a liquid, these waves generate high-pressure amplitude variations, leading to phase change, cavitation, turbulence and intense mixing. These phis phenomena are desirable in enhancing heat transfer rates in fluids. This case study aims to study the variation of the heat transfer due to ultrasonic waves relative to a stationary fluid where heat transfer occurs mainly due to natural convection.

1 Introduction

Many various scientific and medical sectors, including cleaning, homogenization, humidification, sonochemistry, medical imaging, drying, speeding up the reaction rate, welding, and others, use ultrasonic waves because of their chemical and mechanical effects on fluids. The purpose of this case study is to investigate how these waves affect heat transport. An experimental setup described in (Dehbani et al., 2014) is attempted to be recreated in order to compare and study the heat transfer rates properly. To make the geometry simpler, the setup was changed from a cylindrical flask to a cuboidal one, and the wire's diameter was increased. For two situations of the transducer in the off and on states, the heat transfer from wire to fluid is compared. By analysing heat transfer coefficients and wire core temperatures, heat transmission is qualitatively determined.

2 Problem Statement

The case study aims to determine the heat transfer rate from a wire placed in a cuboidal water flask filled with water. The water volume comprises a cuboid of $14cm \times 14cm \times 8cm$ with a wire of $0.5cm$ diameter and $2cm$ length placed at the centre and $2cm$ above the bottom of the flask. An ultrasonic transducer of $2cm \times 2cm$ is placed at the centre of bottom of the flask. The wire is being heated by passing current. The Joules heating is approximated by constant volumetric heat generation of 7×10^6 W/m3. The walls of the flask are maintained at 280K.

Heat transfer rates are to be determined for the two cases-

- **Transducer is off** - Heat transfer from the wire happens through natural convection.

- **Transducer is on** - Ultrasonic waves with 24kHz frequency are generated from the transducer.

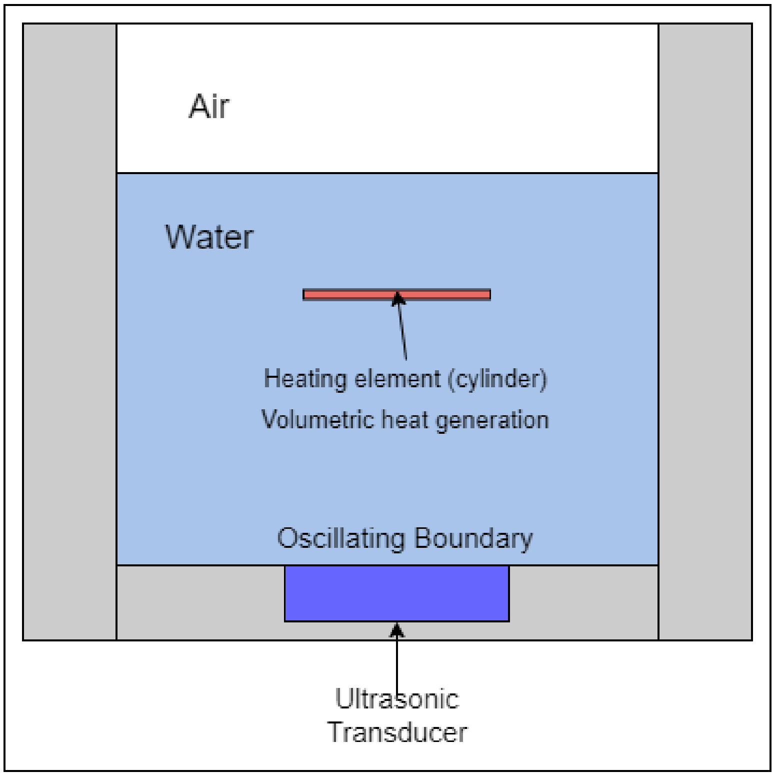


Figure 1: Problem Shematic

3 Governing Equations and Models

Mass conservation is formulated by the continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \tag{1}$$

The equation of motion are written for a moving frame of reference

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_{rj} u_i) + \rho \epsilon_{ijk} \omega_i u_j = -\frac{\partial p_{rgh}}{\partial x_i} - \frac{\partial \rho g_j x_j}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij} + \tau_{t_{ij}}\right) \tag{2}$$

u represent the velocity, u_r the relative veloicty, g_i the gravitational acceleration, $p_{rgh} = p - \rho g_j x_j$ the pressure minus the hydrostatic pressure and τ_{ij} and $\tau_{t_{ij}}$ are the viscose and turbulent stresses. The energy equation describes the transfer of thermal energy within the fluid

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j h) + \frac{\partial (\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j k) = -\frac{\partial (q_i + q_{ti})}{\partial x_i} + \rho r + \frac{\partial p}{\partial t} - \rho g_j u_j + \frac{\partial}{\partial x_j}(\tau_{ij} u_i) \tag{3}$$

where h is the enthalpy of the fluid, $k = 0.5 u_i u_i$ the kinetic energy, $q_i + q_{ti}$ are diffusion and turbulence terms, and the heat source term r.

The equations governing heat transfer in the solid region is

$$\frac{\partial(\rho h)}{\partial t} = \frac{\partial}{\partial x_j}\left(\alpha\frac{\partial h}{\partial x_j}\right) \tag{4}$$

The constraints at the fluid-solid interface are

$$T_f = T_s \tag{5}$$

$$Q_f = -Q_s \tag{6}$$

$$\kappa_f\frac{dT_f}{dn} = -\kappa_s\frac{dT_s}{dn} \tag{7}$$

4 Simulation Procedure

4.1 Geometry and Mesh

The water-filled volume of the flask is modelled as a cuboid with a cylindrical wire placed inside. The meshing of the geometry was done using blockMesh and topoSet utilities in the openFoam. Blockmesh was used to divide the whole domain into various blocks. Hexahedral cells were used. Multigradind was used to achieve fine meshing at regions of interest and expected high gradient regions. The topoSet utility was used to divide the domain into fluid (water) and solid (wire) and the ultrasonic transducer patch.

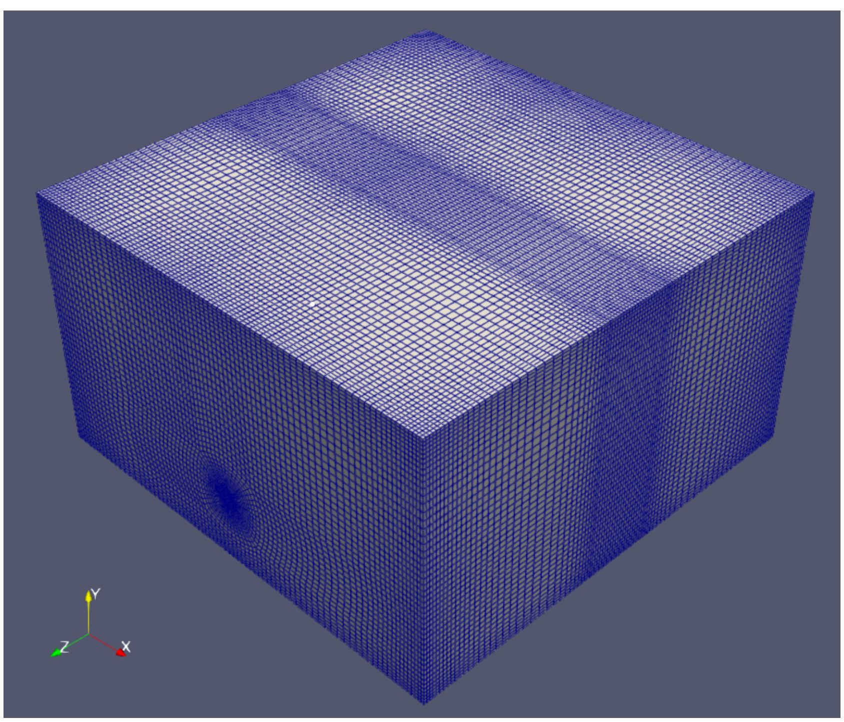


Figure 2: Isometric view

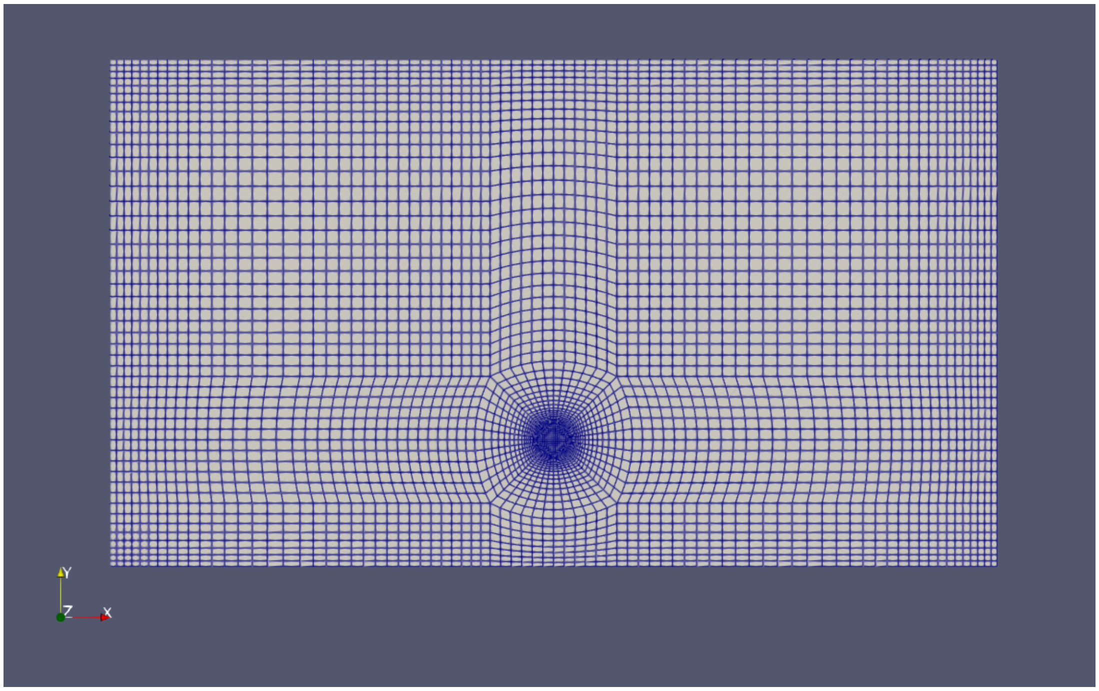
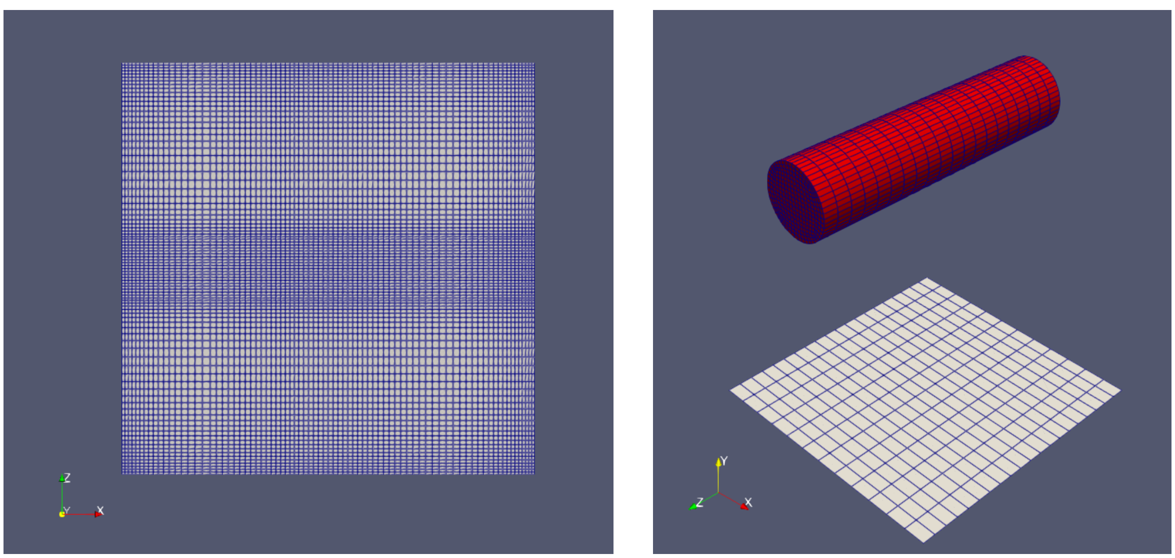


Figure 3: Front View



(a) Top view (b) Wire and Transducer Patch

Figure 4

4.2 Initial and Boundary Conditions

Fluid flow was modelled as laminar. Radiation is neglected in heat transfer. The wire is considered stationary in the fluid. Flask walls act as constant temperature walls. The free surface is open to atmospheric conditions. Boundary conditions for U, p, p_rgh, T are tabulated below.

	U	p_rgh	p	T
Walls	noSlip	fixedFluxPressure	calculated	280K
Interface	noSlip	fixedFluxPressure	calculated	turbulentTemperature-CoupledBaffleMixed
Top	zeroGradient (UST) inletOutlet (NC)	P_atm = 1e5 Pa	calculated	zeroGradient
Transducer	Coded (UST) noSlip (NC)	fixedFluxPressure	calculated	280K

In the case of transducer on case, the waves are generated using sinusoidal time varying velocity at the transducer patch. The velocity amplitude is approximated by

$$V_0 = A_0 \times \omega$$

$A_0 = 0.2\mu m, \omega = 2\pi \times 24 \times 10^3 rad/s$ so, $V_0 \approx 3cm/s$

```
transducer
{
    type            codedMixed;

    refValue        uniform (0 0 0);
    refGradient     uniform (0 0 0);
    valueFraction   uniform 1;

    name        rampedMixed;

    code
    #{
        const scalar t = this->db().time().value();
        const scalar pi = constant::mathematical::pi;

        this->valueFraction() = 1.0;
        this->refValue() = vector(0, 1, 0)*(0.03*sin(2*24000*pi*t));
        this->refGrad() = Zero;

    #};
}
```

Figure 5: Coded velocity boundary condition at the transducer patch

4.3 Constant files

Thermophysical properties of water are defined as a function of temperature using equationOfState as icoPolynomial. The property functions are polynomial fits for physical data.

$rho = -0.00365471 \times T^2 + 1.93017 \times T + 746.025$ kg/m^3
$\mu = -2.80572e - 9 \times T^3 + 2.90283e - 6 \times T^2 - 0.00100532 \times T + 0.116947$ kg/m/s
$C_p = -0.000127063 \times T^3 + 0.13736 \times T^2 + -48.6714 \times T + 9850.69$ J/kg/K
$\kappa = -9.29827e - 6 \times T^2 + 0.0071857 \times T - 0.710696$ W/m/K

Wire material was modelled as iron. Thermal properties were taken as following constants
$rho = 7800$ kg/m/s
$C_p = 450$ J/kg/K
$\kappa = 80$ W/m/K
Volumetric heat generation was defined in the fvOptions as scalarSemiImplicitSource.
$h = 710^6$ W/m^3

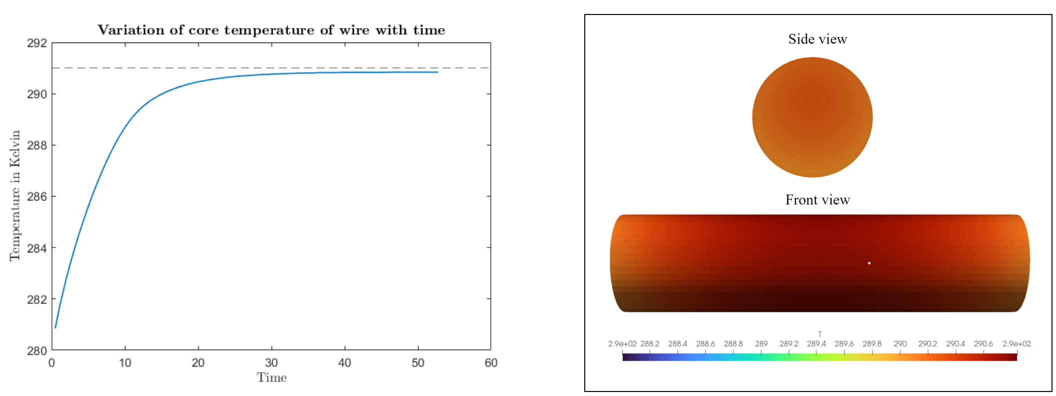
4.4 Solver

ChtMultiRegionFoam is used as a solver in this case study. It is a transient compressible, flow based solver of steady or transient fluid flow and solid heat conduction, with conjugate heat transfer between regions, buoyancy effects, turbulence, reactions and radiation modelling. The solver follows a segregated solution strategy. This means that the equations for each variable characterizing the system are solved sequentially, and the solution of the preceding equations is inserted in the subsequent equation. The coupling between fluid and solid also follows the same strategy: First, the equations for the fluid are solved using the temperature of the solid of the preceding iteration to define the boundary conditions for the temperature in the fluid. After that, the equation for the solid is solved using the temperature of the fluid of the preceding iteration to define the boundary condition for the solid temperature. This iteration procedure is executed until convergence. A script to calculate the average surface temperature at the interface is included in the systems.

5 Results and Discussions

5.1 Transducer Off Case

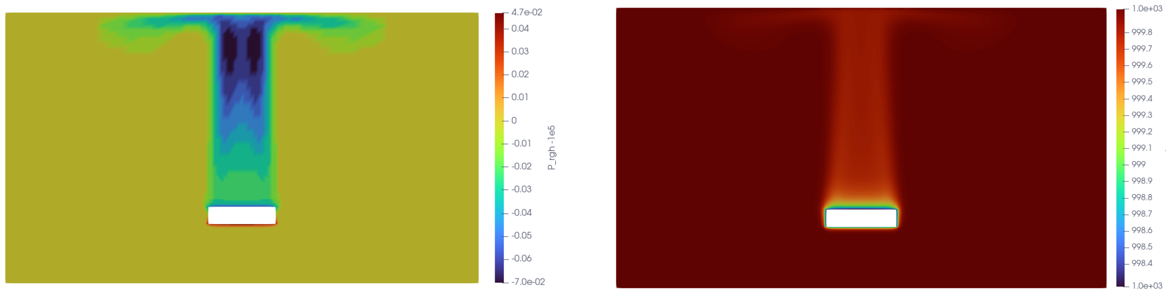
Transducer off case, i.e. natural convection case was simulated till 55 sec. The temperature at core of the wire when plotted reaches saturation at around 291 K indicating the wire has reached steady state.



(a) Wire core temperature (b) Wire surface temperature

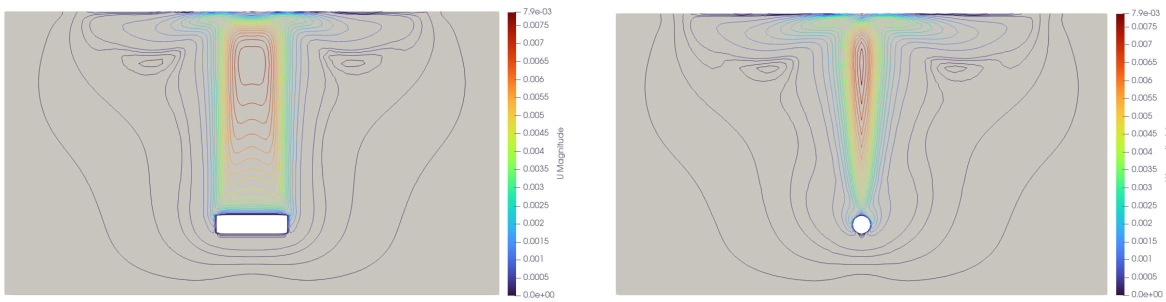
Figure 6: Wire temperatures

The wire temperature is lower towards the ends as the h/d ratio of wire is significant, and the area towards the end increases, increasing effective heat transfer.



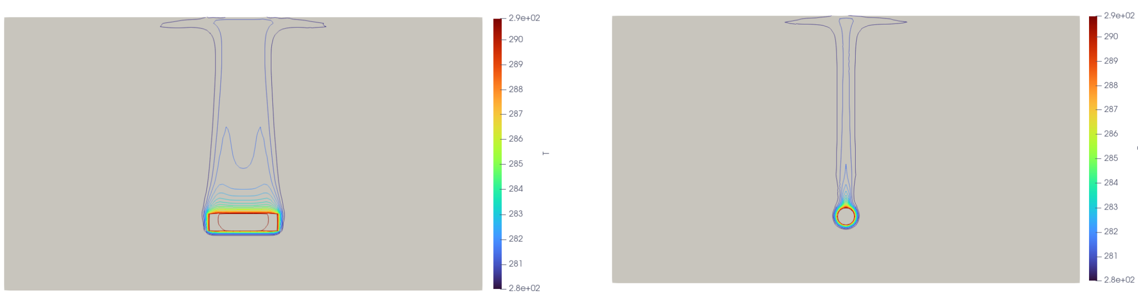
(a) p_rgh - p_atm (b) Water density

Figure 7: Fluid plots



(a) Front view (b) Side view

Figure 8: Fluid velocity (magnitude) contours



(a) Front view (b) Side view

Figure 9: Fluid temperature contours

As the wire temperature increases leading to surrounding fluid temperature increase and thus decrease in density leading to the upward velocity of water due to buoyancy. At the end of the simulation, the convection current has reached the top. The temperature profile of the wire was stabilized. The value of average heat transfer coefficient h_{avg} from the wire can be calculated as-

$$h = \frac{Q}{A(T_{avg} - T_{amb})} = \frac{3 \times 10^7 \times \pi \times (0.0025)^2 \times 0.02}{2\pi \times 0.0025 \times (0.0025 + 0.02) \times (291 - 280)} = 707$$

Using the empirical relation to find the h_{avg}

$$Gr = \frac{g\beta(T_{avg} - T_{amb})D^3}{\nu^2} = 1304.2$$

$$Ra_D = Gr.Pr = 10797$$

$$Nu_D = \left\{0.6 + \frac{0.387Ra^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\} = 4.31$$

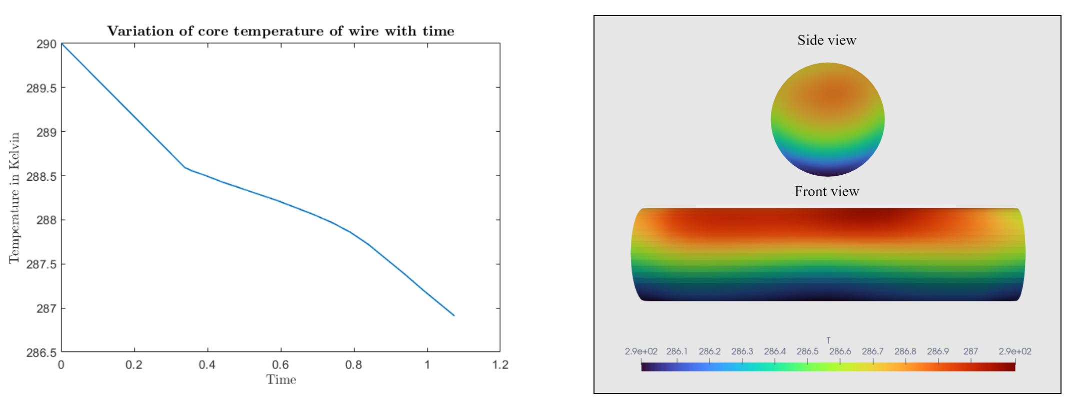
$$h_{avg} = \frac{Nu_D\kappa}{D} = 500$$

$$Error = \frac{\mid (h_{avg})_{emp} - (h_{avg})_{CFD} \mid}{(h_{avg})_{emp}} \times 100 = 41.4\%$$

This error is because the empirical relations are for long cylinders, i.e. h/d »1. But for the wire modelled h/d ratio is 4 and hence the large error in h_avg. The higher value can be justified by the fact that the Nusselt number would be almost twice if the wire had been considered as a disc. As the wire is an intermediate geometry between a long cylinder and a flat disc, the value should lie in between.

5.2 Transducer On Case

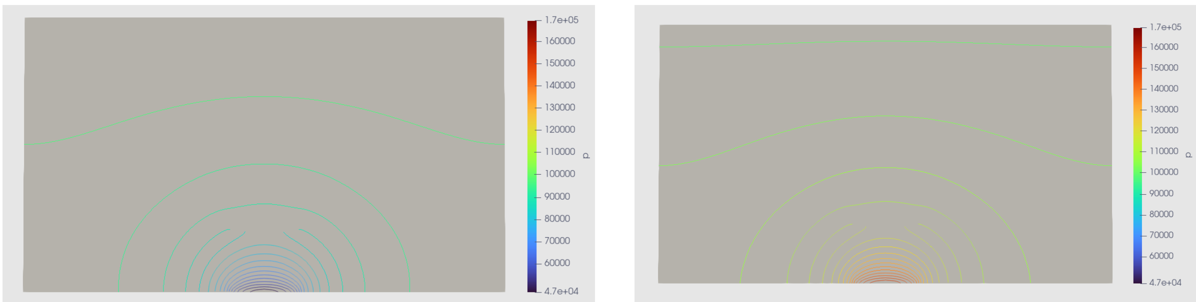
This simulation was run for just 1.08 sec as this simulation is computationally expensive owing to the very small time step required to capture wave nature at boundary conditions. The simulation took 50 hrs on a 16 GB RAM 8-core processor. To tackle the time limit and wait to increase temperature from 280K to a stable value due to heat generation, the initial temperature of the wire was changed to 290K. As the results were expected to be of lower temperature (<291K) at the core than the transducer off case, this was done in the hope of achieving steady state quickly. Even though the results obtained were qualitatively comparable, the phenomenon of ultrasonic waves is fast enough to give a good mixing of water in the container flask.



(a) Wire core temperature (b) Wire surface temperature

Figure 10: Wire temperatures

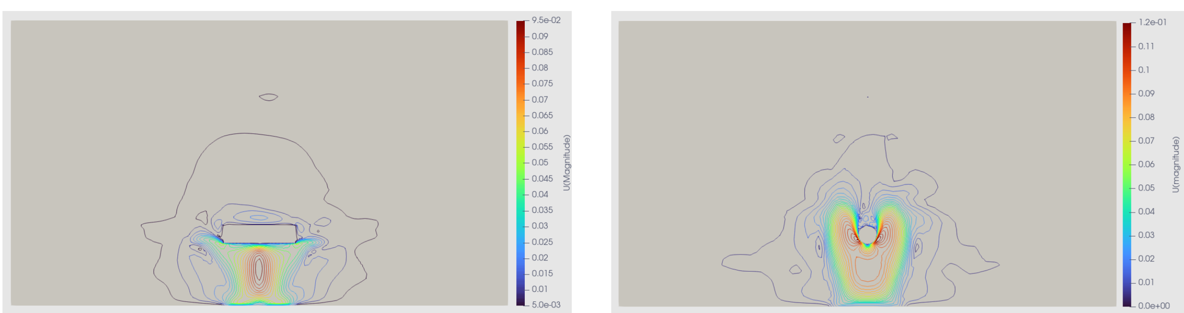
As seen from the temperature variation graph, albeit internal heat generation, the cooling rate is faster such that the temperature of the wire is constantly decreasing and has reached around 287K in the duration of 1 sec. The temperature profile now has variation along the y-axis (vertical axis) compared to variation in only the axial direction in the previous case. This is because the transducer is placed vertically below the wire.



(a) Pressure contour at $U = V_0$ (b) Pressure contour at $U = -V_0$

Figure 11: Water pressure

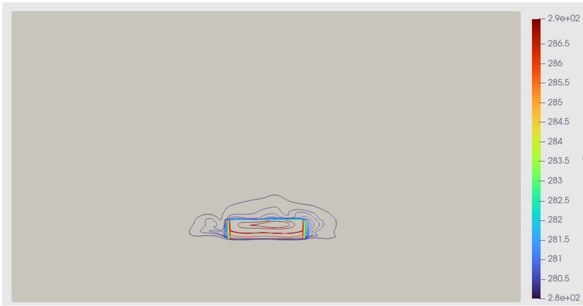
A large pressure variation (≈0.6 atm) is seen once the transducer is turned on. The pressure varies from ≈1.6 atm in -ve velocity cycle to ≈5 atm in +ve velocity cycle. The pressure variation amplitude in a wave increases with frequency. This was also qualitatively verified by running test simulations at low frequencies (10Hz and 100Hz). This pressure variation is the main cause of cavitation in ultrasonic waves.



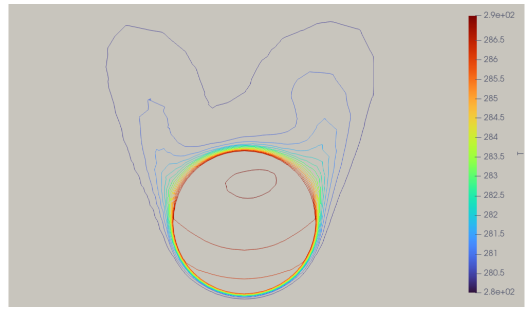
(a) Front View (b) Side view

Figure 12: Water velocity (magnitude) contours

Due to waves, flow is spread in the whole flask. Velocity has gone high up to 10cm/s in the flask. As the transducer is below the wire the waves hit the lower surface of the wire and reflect from there interfering with other waves and causing a random flow away from the wire.



(a) Front View



(b) Side view

Figure 13: Temperature contours

The temperature contours show that the energy is being diffused in all directions as compared to just the upward direction in natural convection. The time varying velocities carry away the heat more efficiently than natural convection. Also, as the velocity fluctuations are higher on the bottom side of the wire as compared to the upper side of the wire, this causes a higher heat transfer rate and lower temperature on the bottom of the wire in contrast with a low heat transfer rate and relatively higher temperature on the upper side of the wire.

References

Dehbani, M., Rahimi, M., Abolhasani, M., Maghsoodi, A., Afshar, P. G., Dodmantipi, A. R., & Alsairafi, A. A. (2014, Sep 01). Cfd modeling of convection heat transfer using 1.7 mhz and 24 khz ultrasonic waves: a comparative study. *Heat and Mass Transfer*, *50*(9), 1319-1333. Retrieved from `https://doi.org/10.1007/s00231-014-1346-9` doi: 10.1007/s00231-014-1346-9