EEN035 Assignment 4

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October 2024

1 Part 1 - Comsol Tutorial

1.1 Q1

Focused ultrasound-induced heating is a therapeutic application of ultrasound that consist in increase the temperature of the tissue region that needs the treatment by directing the ultrasound energy into it.
Performing this simulation in a tissue phantom, as described in the tutorial, the following figures can be obtained:

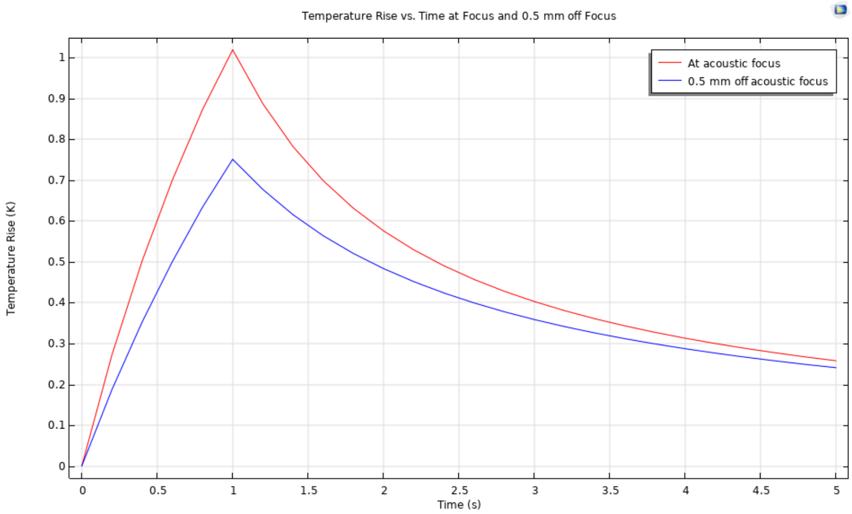


Figure 1: Heating and cooling curves at acoustic focus and 0.5 mm off-axis in the focal plane for 1 second of insonation with a focal pressure amplitude of 1.11 MPa.

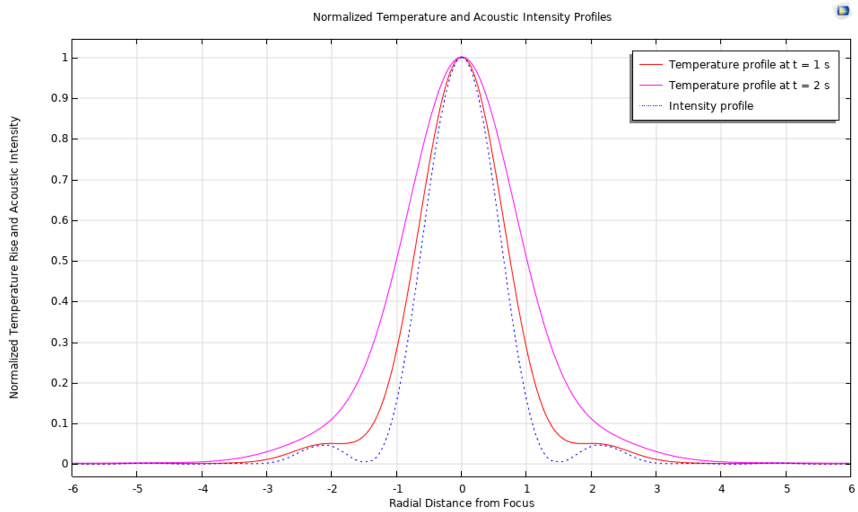


Figure 2: The temperature and intensity profiles show that the sidelobes in the intensity field are mitigated in the temperature response due to the smoothing effect of the thermal conduction.

The Figure 1 shows the temperature rise in the tissue phantom as a function of time. The red line describes the change in temperature at the point where the ultrasound energy is concentrated. Instead, the blue line describes the temperature rise at a point located 0.5 mm away from the focus.
The heat generated by the focused ultrasound dissipates over time, after reaching the maximum value at 1 s. As we can see from the figure, the red curve reaches a higher maximum value compared to the one reached by the blue curve. Specifically, at 0.5 mm away from the focal point, the increase in temperature is about 25% less than the one at the focal point.
These results are as we expected, since the aim of the treatment is to increase the temperature in the focal area, and not in the surroundings.

Figure 2 shows the temperature rise and the energy delivered by the ultrasound wave in the tissue phantom as a function of the spatial distance from the focal point. The red and the magenta lines describe the temperature rise at $t = 1s$ and $t = 2s$, respectively. Instead, the dotted blue line describes the acoustic intensity profile.
As we can see from the figure, the ultrasound energy is highly focused, resulting in a narrow main peak. However, because of the physics of ultrasound wave propagation, side lobes with lower intensity can be observed. Specifically, the ultrasound wave propagation is described by the Huygen's principle, for which each point of the wavefront acts as a source of secondary wave fronts. Therefore, the constructive interference at the focus creates the main lobe, while the interference outside the focus creates side lobes. The temperature profiles follow the bell shape of the acoustic intensity profile with a broader distribution. This wider profiles result because of the natural thermal conduction, since heat diffuses from the focal region to surrounding tissue over time. In support of that, we can also notice that the temperature profile at $t = 2s$ is broader than the one at $t = 1s$.

1.2 Q2

To numerically solve the equations, the domain of interest has to be discretised defining a mesh. In COMSOL it is common to divide the computational domain with triangular mesh elements for 2D-geometries, and with tetrahedral mesh elements for 3D-geometries.

When performing a simulation the mesh size influences both the accuracy of the results and the computational cost of the simulation. In general, a coarse mesh is characterised by large elements that will lead to reduced computation time, potentially losing accuracy in capturing details and rapid changes. Instead, a fine mesh has small elements that will lead to a finer resolution of the ge-

ometry which allows for higher accuracy but requires higher computation time and memory usage. In COMSOL it is possible to apply different mesh sizes locally. For example, in this simulation, it was suggested to define a finer mesh around the focal area and a coarser mesh away from the focal zone.
Therefore, by doubling the mesh size, the elements will be bigger and the mesh will be coarser. In this situation we expect the simulation to require lower computational time, but lower accuracy of the solutions. Conversely, by performing the simulation where the mesh size is halved as compared to the original one, the elements will be smaller and the mesh will be finer. In this situation we expect the simulation to require a longer time to compute the results, but improved accuracy of the solutions.

Performing this simulation with the new mesh sizes, we obtained the following heating and cooling curves at acoustic focus and 0.5 mm off-axis in the focal plane for 1 second of insonation with a focal pressure amplitude of 1.11 MPa:

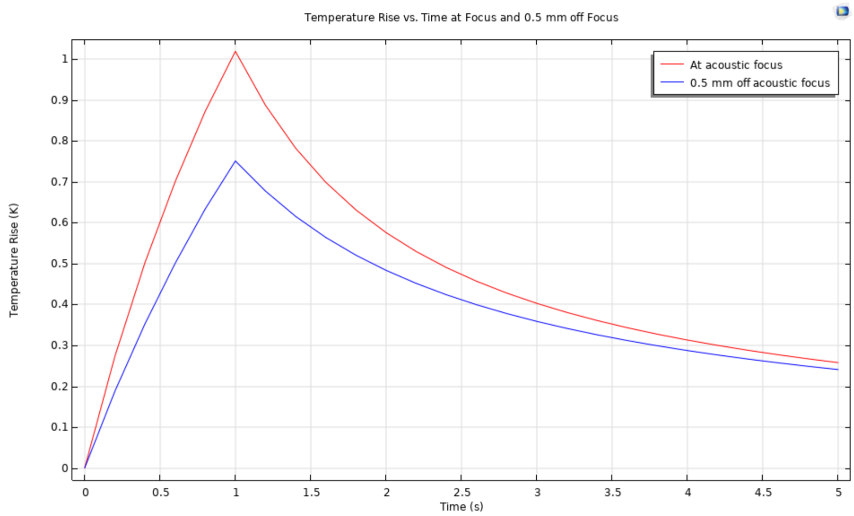


Figure 3: Heating and Cooling curves with doubled mesh size.

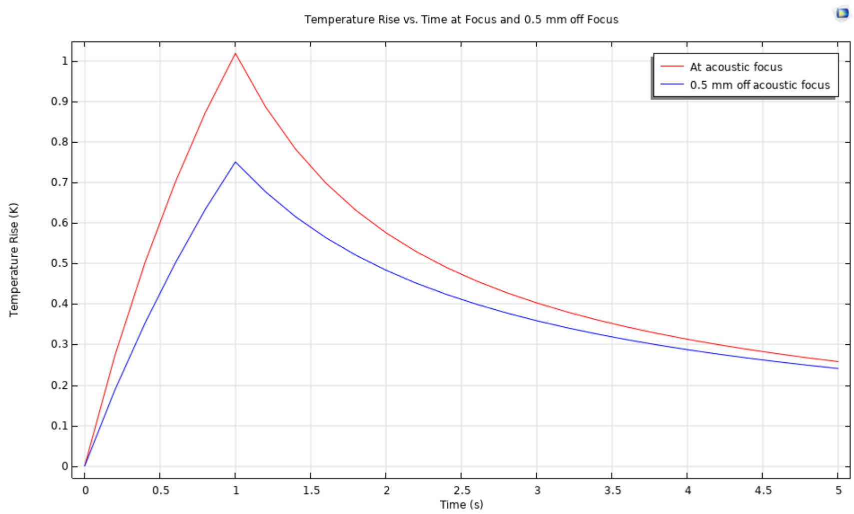


Figure 4: Heating and Cooling curves with halved mesh size.

Comparing Figure3 and Figure 4 with Figure 1, no differences can be noticed. Therefore, we can conclude that the original mesh size is adequate for capturing the effect of ultrasound energy

absorption, such as the temperature rise and the thermal conduction.
On one side, the natural thermal conduction led to a smooth temperature change over space and over time. Therefore, even a doubled mesh size can provide accurate results, as no rapid changes can be missed with the coarser mesh. On the other side, by halving the mesh size the accuracy of the solution does not improve, meaning that the original mesh already provides an accurate representation of both the temperature rise and the thermal conduction.

We also obtained the following temperature and intensity profiles with the new mesh sizes:

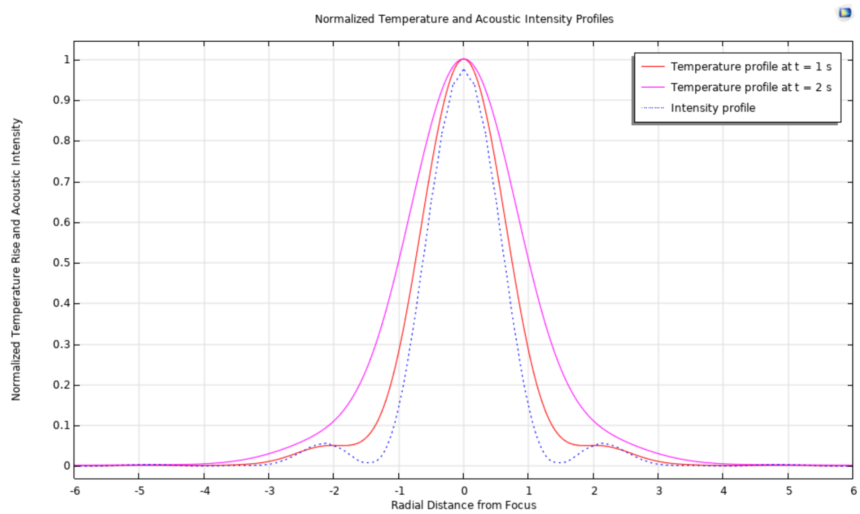


Figure 5: Temperature and Intensity profiles with doubled mesh size.

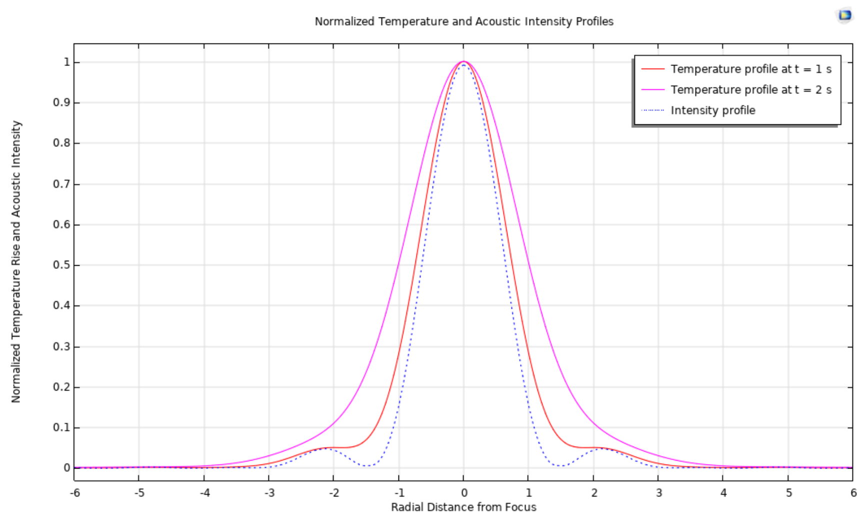
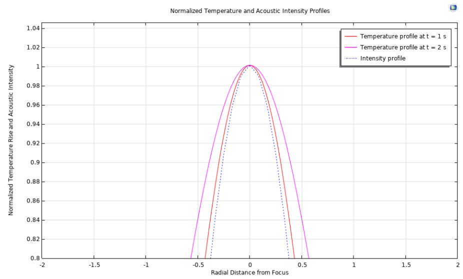
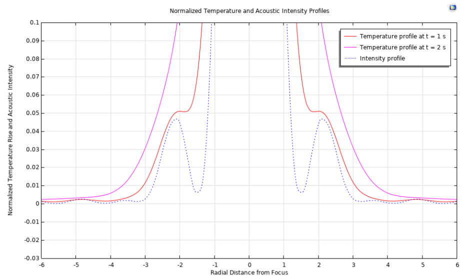


Figure 6: Temperature and Intensity profiles with halved mesh size.

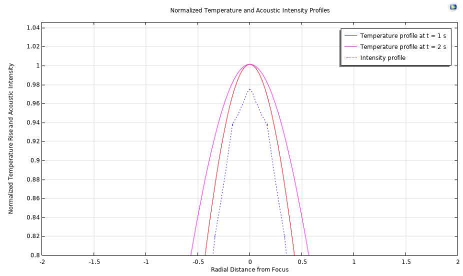
From a first analysis, it appears that Figure 5 and Figure 6 are the same as Figure 2. However, by zooming in on the peak and on the bottom some differences can be noticed.



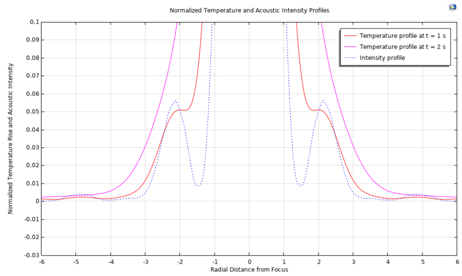
(a) Peak with original mesh size



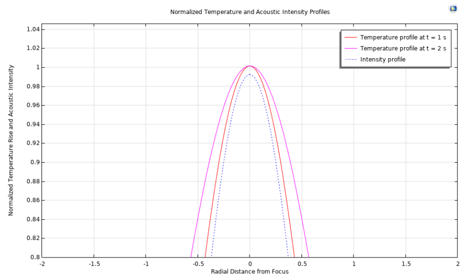
(b) Bottom with original mesh size



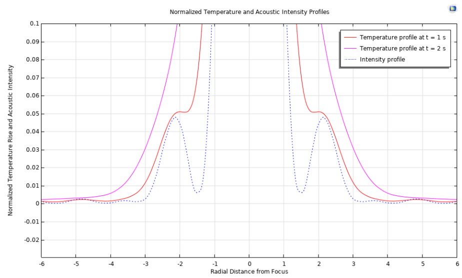
(c) Peak with doubled mesh size



(d) Bottom with doubled mesh size



(e) Peak with halved mesh size



(f) Bottom with halved mesh size

Figure 7: Zoom in on the peak and on the bottom of the Temperature and Intensity profiles

As we can see from Figure 7a, Figure 7c and Figure 7e, in the focal region, with all three mesh sizes, we obtain similar peaks. The temperature profiles at the peak remain unchanged, while the acoustic intensity profiles slightly deviate from the one obtained with the original mesh. More specifically, doubling the mesh size provides a less smooth intensity profile in the area close to the focus. Conversely, halving the mesh size provides a slightly smoother and more refined profile. However, the changes between the meshes are minimal because, as previously specified, the focus has relatively smooth changes in temperature and intensity that can be accurately approximated also with coarser meshes.

Comparing Figure 7d and Figure 7f with Figure 7b, we can notice that the temperature profiles at $t = 1s$ and at $t = 2s$ do not change, while side lobes of the acoustic intensity profile become slightly bigger. The increase in the intensity of the side lobes is small when we halved the mesh size, while it can more easily be noticed when doubling the mesh size. Hence, by increasing the mesh size, computational elements become bigger leading to insufficient mesh resolution and higher artifacts. However, in that case, too, the changes between the meshes are minimal.

2 Part 2 - Modification of the simulation model

In ultrasound imaging and focused ultrasound therapy, ensuring good contact between the ultrasound probe and the skin is essential for the efficient transmission of ultrasound waves into the body. Poor contact, often caused by the presence of air or other obstructions, can result in poor imaging quality or, in the case of focused ultrasound heating, insufficient heating of the target tissue. In this simulation, water serves as the coupling medium between the ultrasound probe and the tissue phantom. To explore the effects of poor contact, the model has been adjusted to include a 2 mm air gap between the water and the tissue phantom. This study investigates how the presence of air impacts both the temperature rise and acoustic intensity profiles in the tissue, with a focus on how air alters ultrasound wave propagation and heating patterns.

2.1 Q1

Performing the same simulation with an air gap, as described in the tutorial, the following heating and cooling curves can be obtained:

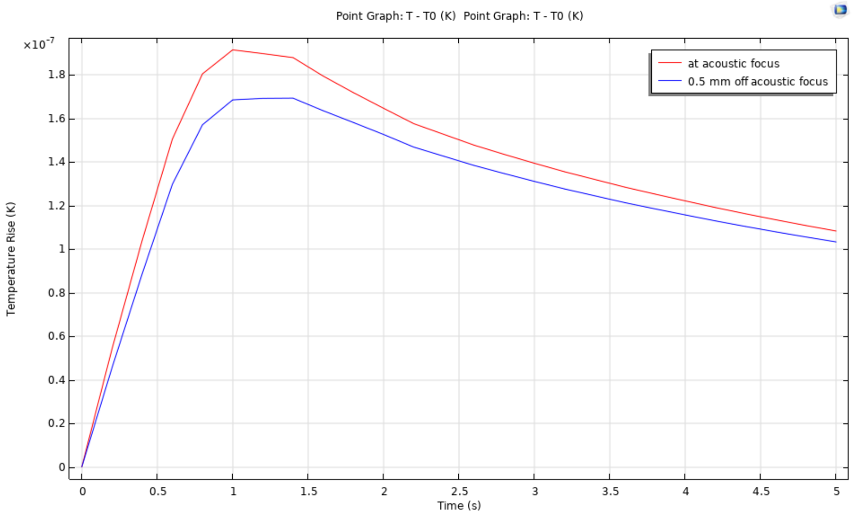
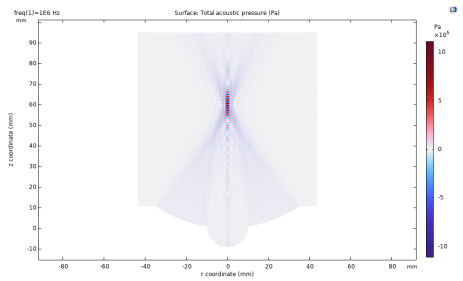
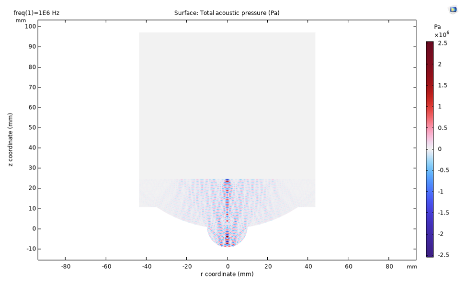


Figure 8: Heating and Cooling curves with air layer between water and tissue

In the model using an air gap between the tissue and water, the temperature rise in the tissue phantom as a function of time, which can be seen in Figure 8, presents much smaller and smoother curves compared to the one in Figure 1, i.e. a model without air gap.
In the model without the air gap, the ultrasound waves are tightly focused at the target, leading to a sharp temperature increase at the focal point (red curve) and a slightly lower, but still noticeable, rise 0.5 mm away from it (blue curve). However, as we can see in Figure 9, with the air gap, much of the ultrasound energy is either reflected or scattered, so far less energy reaches both the focal point and the surrounding tissue. This results in a much smaller temperature increase in both curves, that can only be barely perceived. As evidence of this, we can notice in Figure 8 and in the distribution of the temperature increase in Figure 10, that the temperature increase never exceeds the value of $2.0 \cdot 10^{-7}$.
Additionally, the temperature peak is also more rounded and spread out in the air gap model because the heat builds up and dissipates more slowly. With less focused energy, the tissue takes longer to reach its maximum temperature, and the cooling process is more gradual, creating a smoother temperature profile.



(a) Without air



(b) With air

Figure 9: The acoustic pressure field in the tissue domains. On the left, total acoustic pressure was obtained with water between the ultrasound probe and the tissue phantom. On the right, total acoustic pressure with a gap of air between the probe and the tissue phantom.

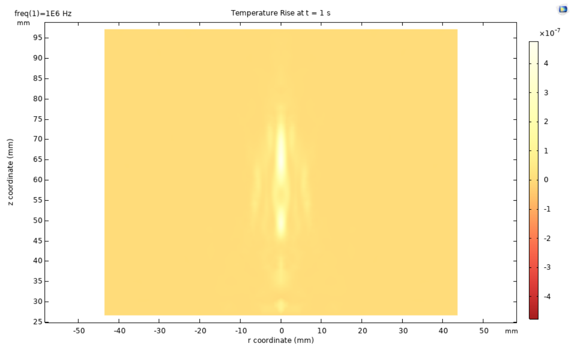


Figure 10: Surface plot of the temperature rise in the tissue phantom with an air gap after 1 second insonation for a focal pressure amplitude of 1.11 MPa

Performing the same simulation with an air gap, as described in the tutorial, we also obtained the following figure:

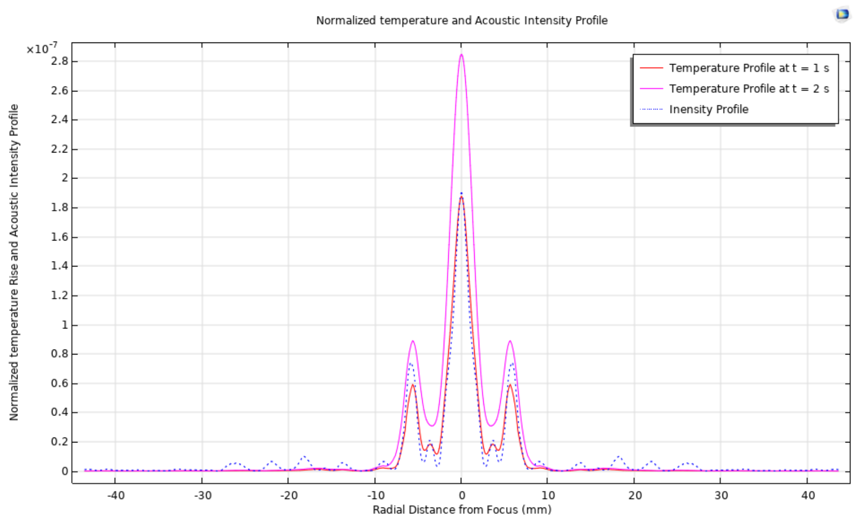
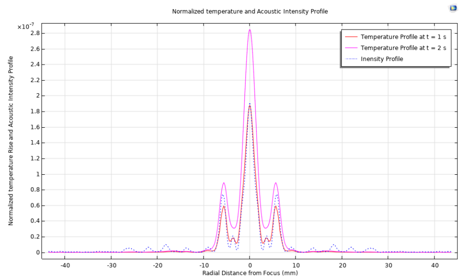


Figure 11: Temperature and Intensity profiles with air layer between water and tissue

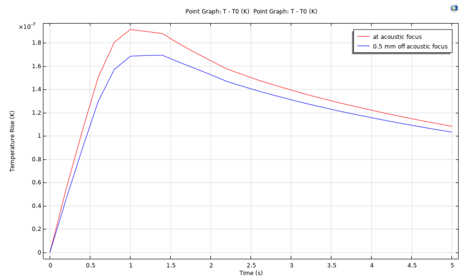
As previously mentioned and as shown in Figure 9, when there is an air gap, the ultrasound waves get scattered and reflected, so almost none of the energy reaches the focal point. This is apparent in Figure 11, making the main peak of the intensity profile (blue dotted line) much weaker in comparison to the main peak in Figure 2. Specifically, with air, the peak only reaches the value of $2.8 \cdot 10^{-7}$. Both acoustic intensity and temperature profiles maintain the bell shape as the one that can be observed in Figure 2. In Figure 11, additional side lobes of the acoustic intensity profile are noticeable, and side lobes appear in the temperature profiles too. However, it is important to remember that we are looking at a very small order of magnitude. Therefore, with an air gap between the probe and the tissue, both acoustic intensity and temperature profiles are almost zero.

2.2 Q2

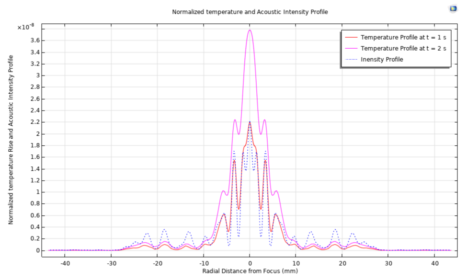
Changing the mesh size to the double and half size as in Part 1 but this time with the air gap, we obtained the following figures:



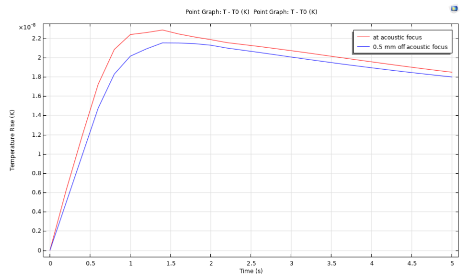
(a) Original mesh size



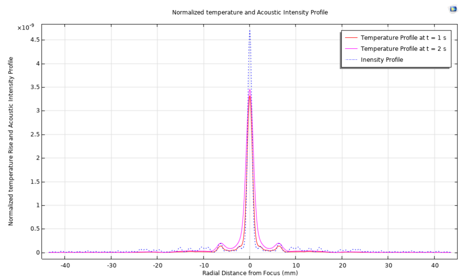
(b) Original mesh size



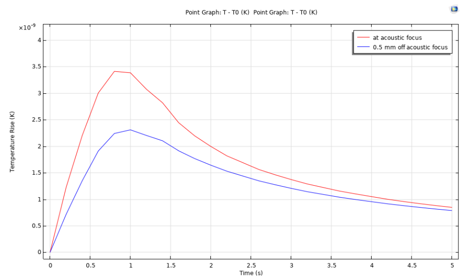
(c) Halved mesh size



(d) Halved mesh size



(e) Double mesh size



(f) Double mesh size

Figure 12: Temperature and Intensity profiles to the left and Heating and Cooling curves to the right, with different mesh sizes

As we can see in Figure 12 the size of the mesh has a significant impact on the results. Using a halved mesh size allows the simulation to capture finer details in the wave, which helps illustrate the constructive and destructive interference more clearly. This leads to the appearance of additional side lobes, which can be seen in Figure 12c. Moreover, the finer mesh causes temperature changes to occur more gradually, as we can see in Figure 12d. The cooling rates are slower due to better heat distribution throughout the tissue. As a result, the simulation reflects more subtle thermal dynamics, producing heating and cooling profiles that are less sharp and more spread out.
Instead, when the mesh size is doubled, the main lobes in the temperature and intensity profile become very narrow and small, with the side lobes almost disappearing, as shown in Figure 12e.

This is because the larger mesh oversimplifies the wave behaviour. In Figure 12f, the heating and cooling curves show higher heating and cooling rates, which are a result of the reduced resolution. The coarser mesh leads to less detailed heat transfer dynamics, causing faster heat absorption and dissipation.