**1Pa4-6**

# Simulation of non-contact heating of a material surface under high-intensity aerial ultrasonic irradiation
高強度空中超音波照射による物体表面の非接触加熱シミュレーション

Masashi Hishinuma†, Ayumu Osumi[1], and Youichi Ito[1] ([1]Coll.Sci. and Tech., Nihon Univ.)
菱沼 真志 [1]†, 大隅 歩 [1], 伊藤 洋一 [1] ([1] 日大・理工)

## 1. Introduction

Cancer treatment using a high-intensity focused ultrasound and a nondestructive testing using the thermosonic method are among the technologies that use the irradiation energy of strong ultrasound. As one of these applied technologies, we have studied a non-contact heating technology that uses high-intensity airborne focused ultrasound (HIAFU) and have succeeded in raising the surface temperature of silicone rubber to ~60°C.[1]However, for this technology to be used in practice, it is essential to clarify in detail both experimentally and by simulations the relationships between the irradiation time and temperature rise and the irradiation range and temperature-rise distribution.

In this report, we propose a theoretical model that considers heating by HIAFU and heat dissipation by acoustic flow, and we present a numerical simulation of the surface temperature rise of silicone rubber by the proposed method.
be placed in appropriate positions within the text.

## 2. Numerical analysis method

We used the finite-difference time-domain (FDTD) method and equations (1) to simulate the sound-wave propagation numerically. The propagation of sound in a homogeneous medium and a three-dimensional domain is expressed in the linear domain by

$$\frac{\partial p}{\partial t} = -k\nabla\cdot v \qquad (1)$$

where $p$ is the sound pressure, $v$ is the particle velocity, $k$ is the bulk modulus, and $t$ is time.

We used the thermal diffusion equation for the thermal analysis of the silicone rubber surface, and we analyzed the heat conduction and convective heat transfer due to fluid flow by adding an advection term to the thermal diffusion equation:

$$\rho C\left\{\frac{\partial T}{\partial t} - \left(\overrightarrow{v_f}\cdot grad\right)T\right\} = \lambda\nabla^2 T + Q, \qquad (2)$$

where $v_f$ is the velocity in the fluid, $T$ is the temperature, $\lambda$ is the thermal conductivity, and $C$ is the specific heat. The amount of heat $Q$ generated by the absorption and attenuation of ultrasonic waves was obtained from the absorption coefficient $\alpha$ of the medium and the sound wave intensity $I$.

The above two analyses (sound field and thermal) were performed by discretizing the space temporally and spatially in a two-dimensional region and applying the central finite-difference method.

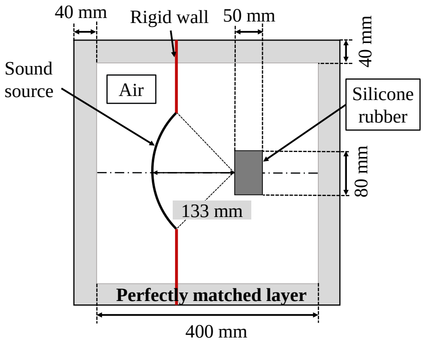

Fig. 1 Schematic of analysis model.

## 3. Analysis conditions

The numerical analysis was limited to a two-dimensional plane, and the model was set up as shown in **Fig. 1**, where silicone rubber with dimensions of 50 mm × 80 mm was placed in an air medium with dimensions of 400 mm × 400 mm. To reproduce the sound waves emitted from the point-focused ultrasonic source[2] that was actually used, the point source was placed in an arc with a radius of 133 mm. The focusing position of the radiated sound waves was set as the boundary between the silicone rubber and the air. The air flow generated during the focused sound-wave irradiation was considered in the area indicated by the red frame near the silicone-rubber surface.

---

Email: osumi.ayumu@nihon-u.ac.jp

**Table 1** lists the parameters used in the analysis. The sampling intervals in space and time for the FDTD method were $\Delta x = \Delta y$ = 2.551 mm and $\Delta t$ = 1.786 µs, and the attenuation coefficient was set to $3.814\times10^{-6}$ m$^{-1}$ for air and $3.073\times10^{-6}$ m$^{-1}$ for silicone rubber. In the simulation, the sound pressure at the convergence point was set to be about 50000 [Pa] based on the time constant of the radiation characteristics of the real source. In the region where air flow was considered, the air flow characteristics were given corresponding to the time constant of the radiated sound wave, and the flow was saturated at a maximum velocity of 5 cm/s.

Table 1 Parameter of analysis

| Parameter | air | water |
|---|---|---|
| Speed of sound[m/s] | 343.5 | 1500 |
| Density[kg/m$^3$] | 1.205 | 997.2 |
| Attenuation coefficient[dB/m/kHz] | 16.4 | 0.022 |
| Specific heat[J/kg/K] | 1005 | 4186 |
| Thermal conductivity[W/m/K] | 0.0241 | 0.582 |

## 4. Simulation results

**Fig. 2** shows the sound pressure distribution in free space, and the measured values are shown for comparison; the results are normalized to their respective maximum values. From the results, the sound pressure distributions are in good agreement throughout.

**Fig. 3** shows the analysis results and the measured values of the temperature distribution on the surface of the silicone rubber surface. The results show that both temperature distributions are similar, with the highest temperature at the sound-wave focusing point.

**Fig. 4** shows the temperature-rise history from the start time of sound-wave irradiation to 2.0 s at the hottest point on the silicone-rubber surface. The analytical and experimental results show similar trends.

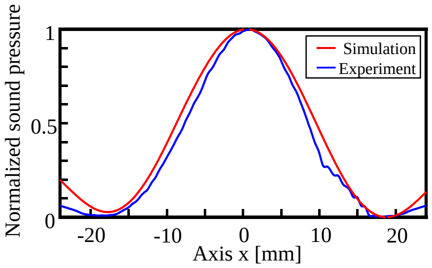

Fig. 2. Sound pressure distribution (normalized values).

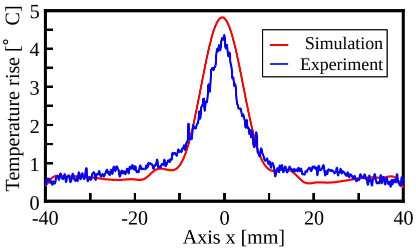

Fig. 3. Temperature-rise distribution along silicone-rubber surface.

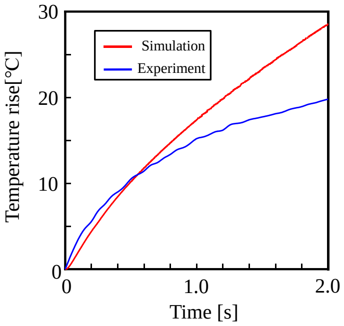

Fig. 4. Temperature rise at sound-wave focusing point.

## 5. Conclusion

We proposed a theoretical model that considers heating by HIAFU and heat dissipation by acoustic flow, and we performed a numerical simulation of the surface temperature rise of silicone rubber by irradiation with high-intensity aerial focused sound waves. In doing do, we confirmed that the simulation results and the experimental results by the theoretical model considering the heating by HIAFU and the heat dissipation by the acoustic flow have almost the same trends.

**Acknowledgment**

This work was partly supported by JSPS KAKENHI Grant number 19K04931.

## References

1. H.Sato, et al: Proc. 36th Symp. UltraSonic Electronics, 2015 3P4-3.
2. I. Solodov, et al., Ultrasonics 60 (2015) 1–5.