Simulation of Convection in Water Phantom Induced by Periodic Radiation Heating

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Introduction

Water calorimetry is employed to establish a primary reference standard for radiation dosimetry by measuring the temperature rises in a water phantom (a cube of about 30 cm x 30 cm x 30 cm) subjected to a beam of ionizing radiation (cross section of 10 cm x 10 cm). At the cancer therapy level, radiation dose rate of the order of Gy/min corresponds to a temperature rise of about 0.24 mK/min at room temperature. To overcome the difficulty of low signal to noise, prolonged radiation periods are required to boost experimental statistics, but come at the cost of introducing distortions due to heat transfer resulting from the non-uniform radiation heating. We have developed a technique using a modulated periodic incident radiation to establish a steady state, and measure the system response in the frequency domain [1]. The radiation on/off periods range from 15 s to 300 s. The detection for such a small temperature rise traditionally could only be done with a sensitive thermistor in an arm of a Wheatstone bridge [2] by measuring the temperature at a given point in space. We use a recently developed ultrasonic technique [3] that has a comparable sensitivity to thermistor-based techniques but without the excess heat associated with non-water materials introduced into the radiation beam. However, the effect of heat transfer due to temperature gradients remains. Moreover, unlike a thermistor that can be enclosed in a small volume with a convection barrier, the ultrasound path is open and is subject to convective movement of water. Experimentally we have observed this movement in a stable periodic fashion in response to the varying periods of the incident radiation using a heat lamp controlled by an electrical relay. Time waveforms are recorded for hours and Fourier transforms are performed to study the oscillation amplitudes.

Use of COMSOL Multiphysics

We use COMSOL Multiphysics to model the system using the Heat Transfer module and the Incompressible Navier-Stokes module with a geometry of 2D-axial symmetry (while we are still trying to get a full 3D model to work). Temperature waveform is calculated by putting a periodic heat source that is spatially non-uniform both in r and z directions. A body force is defined by the Boussinesq approximation.

Expected Results

Experimentally, we observe at short periods (15 s) the response is what is expected with the conduction effect. As the period increases, the convection effect enters, causing oscillations on the temperature waveform, In the simulation, the body force, $\rho g \alpha \Delta T$, is insufficient to cause noticeable convections due to the small temperature changes. It needs to be increased artificially 100 times higher to trigger convective oscillations observed in the experiment (Fig. 1). We intend to investigate the influence on the coupling mechanism of this parameter. The features of the oscillations are qualitatively matched for the 120 s on/off cycles. Other periods have also been simulated to produce a response curve in the frequency domain. The velocity of this system is in the sub-mm/s range, and the temperature changes are in the few mK range.

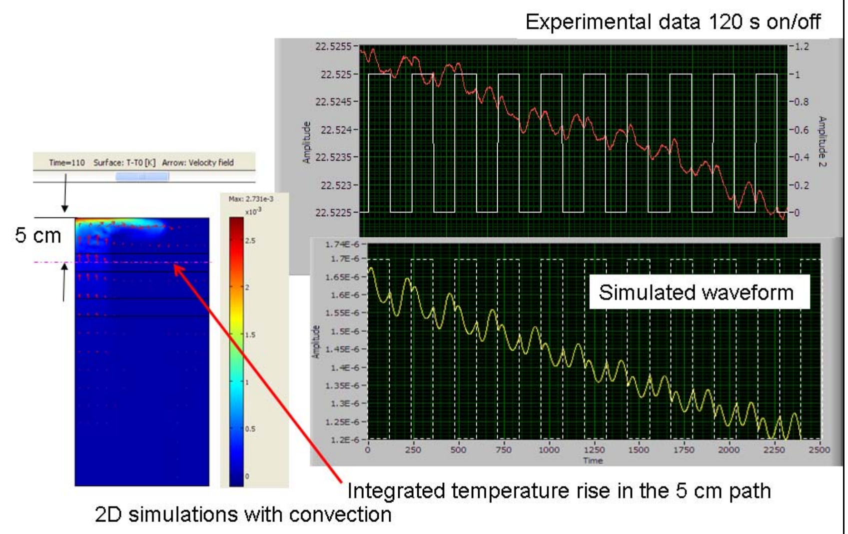

Figure 1. Comparing simulated temperature response to a periodic radiation heating with 120 s on/off cycles, represented by the square waveform. The upper panel is the experimental data obtained with the ultrasonic thermometry technique with the transducer at 5 cm below the water surface, and lower panel is the simulated temperature response averaged over the 1 cm wide path at the same depth. Both waveforms show similar oscillations attributed to convection established in a periodic fashion.

Conclusion

Convection caused by temperature gradients in a radiation beam in the water phantom has been observed with ultrasonic thermometry and simulated by a simple model. We will use the results and analysis from this study to understand the pattern and implement a correction factor for the system, an important step toward establishing a primary standard for therapy level radiation dosimetry.

Reference

1. R. E. Tosh and H. H. Chen-Mayer, “A transfer-function approach to characterizing heat transport in water calorimeters used in radiation dosimetry,” *Proceedings of the International Thermal Conductivity Conference,* **(ITCC29)** 24–27 (2007)
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