Studies of Heat Transport from a Point Source in the NIST Domen Water Calorimeter

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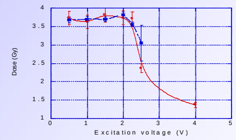
Abstract

In water calorimetry, conduction effects complicate measurements of the true temperature rise at a point in space from direct radiation heating. In general, the effects are removed by correction factors obtained from finite-element simulations under carefully prescribed experimental conditions. We have developed a set of spectral methods for identifying heat conduction artifacts that may lead to a more systematic correction for these artifacts. In order to refine this work, we have sought to isolate the artifacts by stimulating heat conduction in the calorimeter without a radiation beam. In particular, we have devised a thermal point source in the calorimeter vessel by using one of the two small thermistors in the cylindrical Domen detector vessel as a heat source, with the remaining thermistor as a sensor to measure the temperature rise. By modulating the source-thermistor power, we are able to observe conduction-related attenuation and phase shifting of the resulting temperature signal. Finite element simulation is also employed to understand the experimental findings. This study can be used to assess the system response function to processes such as thermistor self-heating, external stirring in the outer phantom, and the onset of convection in the detector vessel, all of which affect corrections to the absorbed dose, but can be quantified.

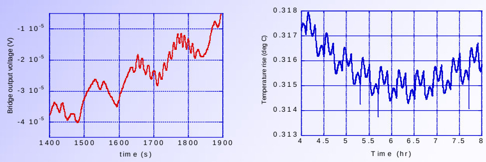
Motivation

Previous questions regarding convection inside the vessel in literature [1]

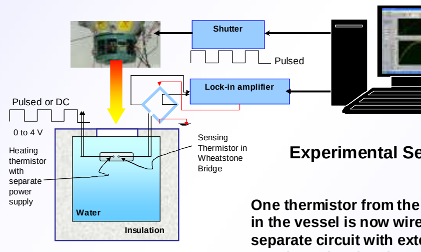
Measured dose decreases as excitation voltage increases (Clinac data)



Experimental observations of oscillations at elevated voltage (rapid) and prolonged exposure (slow)



Thermistor "Cross Heating"



Experimental Setup

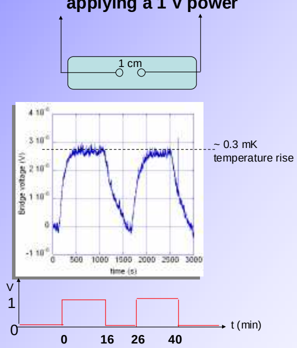
Point source heating

- **Conduction**
- **Onset of convection**
- **Influence on radiation measurement**

One thermistor from the original pair in the vessel is now wired in a separate circuit with external power supply as the "heating" thermistor. A 10K fixed resistor replaces that thermistor and forms a Wheatstone bridge with the remaining thermistor for normal temperature measurements. The heating can be due to the adjacent thermistor or from radiation, or both.

Results and Discussion

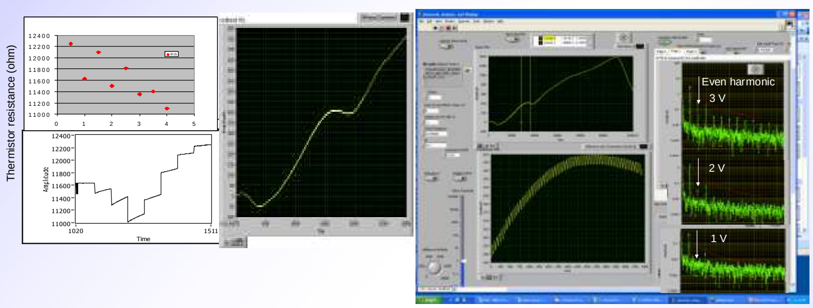
Temperature rise of water measured by thermistor 2 due to the heating of thermistor 1 by applying a 1 V power



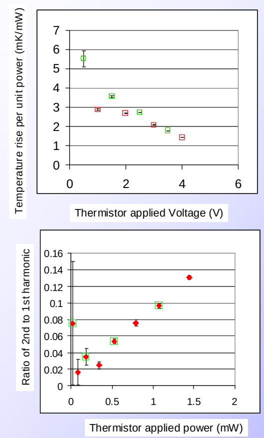
Rising time constant ~ 133 s
Sqrt(4κt) = 9 mm

Modulating heating thermistor voltage (30 s on 30 s off) at 1 to 4 V range

Onset of convection

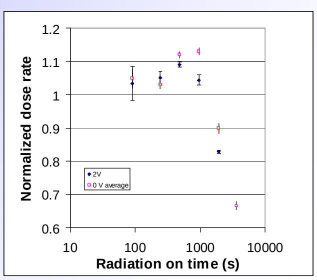


As applied voltage increases from 0 to 4 V (thermistor heating power up to 1.6 mW, max rating 9 mW). Convection has been observed by others at around 0.05 to 0.1 mW [1,2] in a similar geometry and irradiation conditions. Experimental signature suggests reduced temperature rise may be associated with convection.



Temperature rise caused by the adjacent thermistor heating normalized to the input electric power (upper panel), indicating a decreased "sensitivity", likely caused by convection. The lower panel shows the ratio of 2nd to 1st harmonics as a function of heating power, indicating increased convection as increased heating power. The heating thermistor experienced irreversible change in resistance, shown in green.

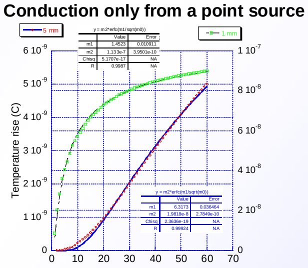
Dose measurement in the presence (or absence) of the adjacent heat source



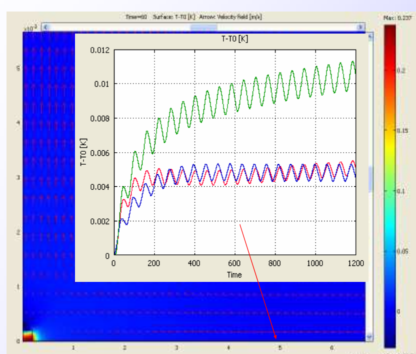
A series of measurements performed at various shutter opening times (90 s to 1920 s). With a steady 2 V applied voltage, at shorter irradiation times there are no measurable difference; but at longer times it gives a lower dose.

Finite Element Simulation

Conduction only from a point source

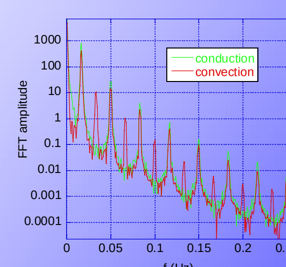


Simulation based on a simple 2D model with a point heating source with conduction only shows that the temperature rise at a given distance has a erfc[r/sqrt(4κt)] dependence.



Model simulation of point source heating with convection enabled. Temperature (red) and velocity field (1e-2 m/s) (blue) at 5 mm from the point source as a function of time; the point source is modulated in 30 s on/off cycles in time domain. Without convection, the temperature rise is shown in green.

Simulation shows convection vs. conduction Emergence of even harmonics



Simulation with a point heat source periodic in time gives rise to even harmonics in the frequency spectrum when convection is enabled, as observed in experimental data.

Summary

- One of the original pair of thermistors inside a sealed core is used as a point heat source to study convection and its influence on temperature measurements in water calorimetry. The heating can be modulated in time to enable frequency domain analysis developed earlier [3].
- Even harmonics emerge at elevated heating power, and are also observed in revisiting data from prolonged broad beam radiation heating where convection-causing excess heat in glass vessel wall is suspected. Therefore, the simpler Ohmic heating scheme can be used to understand the more complicated and possibly more subtle convection effect due to radiation heating.
- Finite element simulations of heat transport agree with analytical formulae for heat conduction [4]. When convection is enabled in the model, a coupling term involving the velocity field and the temperature gradient gives rise to the normally missing even harmonics in the frequency domain representation.
- The frequency domain technique can be used to discern signs of convection. Convection in a controlled fashion may be characterized, and may be formulated into a correction to allow measurement of dose at prolonged irradiation times to boost signal to noise ratio.

References

[1] J. P. Seuntjens, I. Kawrakow, and C. K. Ross, Revisiting Convective motion in Stagnant Water Calorimeters Operated at Room Temperature, Proceedings of NPL workshop on recent advances in calorimetric absorbed dose standards, NPL Report CIRM 42, National Physical Laboratory, Teddington, United Kingdom (1999).
[2] J. K. Domen and S. R. Domen, Studies of excess heat and convection in a water calorimeter, J. Res. NIST 106, 846-856 (2001).
[3] R. E. Tosh and H. H. Chen-Mayer, Frequency-domain Characterization of Heat Conduction in Sealed Water Calorimeters, Nucl. Instrum. Meth. A, 2007, in press
[4] H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Oxford University Press, 1978.