Non-Intrusive Heat Flux Measurements using Ultrasound

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ABSTRACT

Heat flux values are needed in the field of fluid mechanics and heat transfer to quantify the transfer of heat within systems. Maximizing or minimizing the thermal energy transfer in many systems is crucial to their optimization. In this study, we demonstrate how heat flux measurements can be made using ultrasound. Tests have been conducted on a series of metals heated at one end using a calibrated infrared source. Using ultrasonic sensors located remotely from the heated surface the time-of-flight variations of heated surface echoes are used to calculate heat flux. The temporal variation of heat flux determined using ultrasonic data is identical to that derived from transient thermal models. In this study the value of ultrasonic-based heat flux estimates were found to be in good agreement with independent estimates computed from thermal transport models.

INTRODUCTION

Numerous heat flux measurement methods are available and have been employed in characterizing materials and components [1, 2]. These can be divided into two categories: 1) quasi-static direct read methods and 2) surface temperature measurement techniques. The most common direct methods are the Schmidt-Boelter gauge and the Gardon gauge. Both are quasi-steady state sensors which measure the temperature differential of appropriately configured thermocouple junctions in response to an imposed heat flux. The gauge output is directly proportional to heat flux. The Schmidt-Boelter gauge has good sensitivity, is robust and simple to use, but has poor temporal response and is limited to operation at relatively low temperatures (<300°C) [3]. The Gardon gauge is simple to use, inexpensive, but has poorer sensitivity and is less robust. This gauge is also limited in its operating temperature and temporal response.

Gauges that rely on surface temperature measurements provide indirect measurement of heat flux by processing time-resolved temperature data using various inverse numerical methods. The most popular surface temperature sensors are coaxial and thin film thermocouples. Surface temperature techniques can attain high temporal response, however they are less robust, more difficult to implement in an operational environment, have model dependence, and also have a limited operational temperature. The appropriate application of inverse equations often requires certain assumptions regarding the sensor environment and location. Some skill and experience are needed to ensure the integrity of test data [4, 5]. Both the surface temperature measurement methods and the quasi-static methods require that the active elements of the sensors and the electronic connections be located in close proximity of the heated zone. This is particularly the case if high bandwidth is needed. This often not only limits the detector reliability but also can alter thermal transport. Measuring the heat flux into a component is the measurement goal, not the heat flux into the sensor.

Ultrasonic-based sensors represent a significant departure from conventional approaches to the measurement of heat flux. This approach holds the promise of robust operation, high temperature/high enthalpy operation combined with excellent temporal response. Unlike traditional temperature sensors which provide single point temperature measurement, ultrasonic probes measure the entire temperature distribution sampled and integrated over the propagation path. This leads to several advantages such as rapid response and favourable response characteristics for heat flux measurements. It can be shown that under certain conditions, the time-of-flight (ToF) variation resulting from a heating event can be directly related to the incident heat flux [6, 10].

Ultrasonic thermometry is based on precise measurements of the variation in ToF of an echo in response to a heating event. Magnitude of the ToF variation is based on fundamental material properties; the elastic modulus, and the thermal expansion coefficient. Thus, probes can be fabricated from virtually any material and the maximum operating temperature is limited only by the melting temperature of the probe material. Because ultrasound can propagate over large distances and be reflected from heated surfaces the active sensing elements and associated electronics can be located remotely from the point of measurement, and thus can be isolated from extreme temperatures. Furthermore, measurements can be implemented without disrupting the flow field or thermal transport at the measurement point. Advances in high speed data acquisition, ultrasonic sensors and signal processing have made precise measurement of ultrasonic ToF both possible and affordable.

The present work describes the development and validation of ultrasonic-based techniques to measure heat flux. Sensors can be located remotely from the heated surface thus do not interfere with either the mechanical performance or the thermal transport. The reaction speed is ultimately limited by the speed of sound and not the thermal mass. Because the sensor can be isolated from the harsh environment of the heated zone, often conventional piezoelectric sensors can be used to measure extreme temperatures.

Similar to ultrasonic measurements of temperature, the ability to measure heat flux depends on the ability to measure variation in propagation times. The variation in the ToF of an ultrasonic wave propagating between two points is controlled by the length of the propagation path and the velocity of sound. The velocity variation stems from the dependence of the modulus on temperature while the latter is controlled by the thermal expansion of materials. For most solids both effects generally lead to increasing ToF with increasing temperature. These changes are small but readily measured with current instrumentation. As we shall see in the next section, heat flux is related to the time derivative of the variation in the ultrasonic ToF.

NOMENCLATURE

ToF	[s]	time of flight of sound wave
dG/G	[-]	fractional change in transit time
TC1	[-]	designation thermocouple 1
MS	[-]	mega sample

Special Characters

θ	[°C]	Temperature
T	[C]	Temperature
G	[s]	Time of flight of echo
z	[m]	Cartesian axis direction, the depth
x	[m]	Distance
v	[km/s]	Speed of sound
v_o	[km/s]	Initial speed of sound
α	[ppm/°C]	Thermal expansion coefficient
β	[–]	Velocity thermal coefficient
ξ	[ppm/°C]	Combined thermal-expansion and velocity-temperature coefficient
ρ	[g/cm^3]	Density
t	[s]	Clock time
ϕ	[W/m^2]	Heat flux
Q	[W/m^2* K]	Convection
L	[m]	Length
G	[s]	Time as related to transit time of sound
C_p	[J/kg*K]	Specific heat
A	[m^2]	Area
dG/G	[-]	Fractional ToF
TC1	[-]	Designation for thermocouple

Subscripts/Superscripts

o		Ambient or reference
i		Initial
′		Initial
q	[W/m^2]	Heat flux

METHOD

The heat flux estimation method is based on the thermal dependence of an ultrasound echo that accounts for two different physical phenomena: local change in speed of sound due to changes in temperature and thermal expansion of the propagating medium. The former produces an apparent shift in the location of an ultrasonic reflector, and the latter leads to a physical shift. The two effects lead to echo time shifts and are related to local change in temperature in the propagating medium. The basic equation which includes both thermal expansion and temperature-dependent velocity is given in equation (1).

$$G(z,t) = 2\int_0^z \frac{1+\alpha(z',t)}{V(\theta(z',t))} d\ ' \qquad (1)$$

Here, $G(z,t)$ is the ToF of the echo from a scatterer at depth z. $\theta(z',t)$ is the temperature at depth z', $V(\theta(z',t))$ represents the speed of sound at depth z' and $\alpha(z',t)$ is the thermal expansion coefficient. The parameter, t, is the clock time.

Equation (1) provides the basis for numerous studies in medical ultrasound where it has been used to non-invasively monitor tissue temperature changes due to heating fields using diagnostic ultrasound [11-13]. A similar method has been used by us to non-intrusively measure local temperature in industrial applications including large caliber Navy guns and wind tunnels used in hypersonic vehicle development [14, 16]. Because the variations in ToF are dependent on the temperature distribution integral along the 'line-of-sight' of the ultrasonic beam, heat flux and surface temperature can be determined using inverse computation methods [6, 10].

In order to understand the relationship between the heat flux and the ToF, the analysis of a simple one dimensional model is useful. Consider the experimental configuration shown in figure 1. The sensor probe consists of a long rod of high temperature material with cross-sectional area, A, with a piezoelectric sensor acoustically coupled to one end. In addition to the ultrasonic sensor, two thermocouples are attached to the rod. One is located near the piezoelectric sensor while the other is near the heated surface. These sensors are used for initialization. For isothermal initial condition, only one thermocouple is required. An unknown heat flux, ϕ_q, is applied to the top surface of the rod. In general this will be a time-dependent function. The heat loss on the side walls and end caps is designated by Q_i. As will become clear from the analysis below, it will be desirable to minimize the Q_i losses.

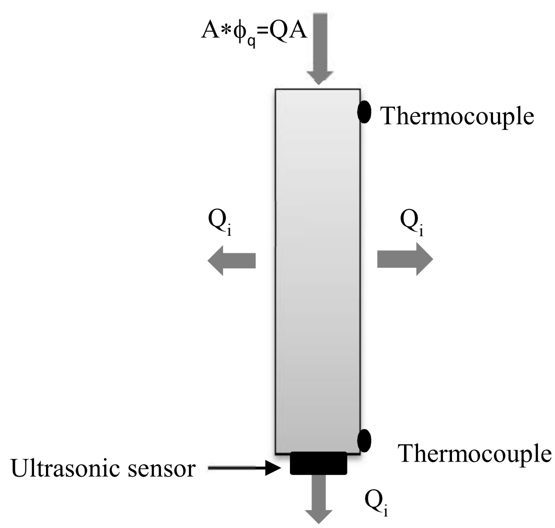

Figure 1 Simple conceptual design of ultrasonic-based heat flux probe.

Assume that the ultrasonic velocity (V) and the length (L) are dependent linearly on temperature as indicated in equation (2) and equation (3). Furthermore, if we assume that the temperature variations are small such that both $\beta\theta(x,t)$ and $\alpha\theta(x,t) \ll 1$, we can combine the contributions of α, and β into a single parameter, ξ, the velocity-expansion coefficient. It can be shown that $\xi = \beta - \alpha$. A simplified expression for the variation in ToF, ΔG from some initial starting point is shown in equation (4). The value of ΔG depends upon the integral of the unknown temperature distribution.

$$V = V_o(1 + \beta \;\; (x,t)) \tag{2}$$

$$L = L_o\big(1 + \alpha(\theta(x,t)\big) \tag{3}$$

$$\Delta \;\; = G - \frac{2L}{V_0} \cong \frac{2\xi}{V_0}\int_0^L \theta(x)d \tag{4}$$

Looking at this situation from a thermal transport perspective, we can arrive at a set of equations relating the unknown incident heat flux to the temperature distribution. Energy balance equation is shown in equation (5) where Q, is the unknown energy input to the rod as a function of time and the sum of the Q_i's is the heat flux lost from all of the other surfaces of the probe. In this equation ρ is the density and C_p is the specific heat. We recognize that the integral represents the total energy added to the rod over time relative to a reference.

$$\emptyset_q A = Q = \rho C_p A \int_0^L \frac{\partial \;\; (x)}{\delta} d \;\; + \sum Q_i \tag{5}$$

If the time interval, δt between successive temperature measurements is such that the spatial gradient can be considered stationary, the partial derivative can be removed from the integral. The Δt is controlled by the ultrasonic repetition rate. This rate can be set by the operator and can be as high as 50 kHz. Making this change we have:

$$\emptyset_q - {\sum Q_i}/{A} = \frac{\rho C_p}{\Delta t}\int_0^L \Delta\theta(x)d \tag{6}$$

In this expression we have divided both sides by the area, A to explicitly show the heat flux

The integral of the unknown temperature distribution occurs in both the ultrasonic and the energy balance equations. Combining the ultrasonic and thermal energy balance equations we have:

$$\emptyset_q - {\sum Q_i}/{A} = \frac{\rho C_p}{2\xi}\frac{V_0 \Delta G}{\Delta t} \tag{7}$$

Equation (7) is significant because it relates an unknown and presumably inaccessible heat flux, ϕ_q, to a measurable quantity ΔG. In the situations where the heat loss, Q_i is known or can be neglected, the unknown heat flux is simply proportional to the rate of change of the ToF. Change in the ToF from one pulse to the next is a measure of variation in the stored energy of the system. This equation indicates that the heat flux is proportional to the slope of the fractional ToF (ΔG) versus clock time (Δt) curve. Clearly this analysis is an oversimplification, but does serve to elucidate the relationship between the heat flux and the ultrasonic measureable, G.

For the configuration shown in figure 1 the spatial and temporal temperature distribution in the rod can be simulated for a given input heat flux, ϕ_q. Figure 2 shows the computed results for an uninsulated 80 mm long, 6.35 mm diameter copper rod with an incident heat flux of 1.85.0 x 10^5 W/m^2. The black dashed curve shows the heat is applied for a duration of 35 seconds commencing at 30 seconds and being removed at 65 seconds. The heat loss for the sidewalls and for the end cap as well as the net heat flux into the rod during both the heating and cooling cycle is plotted. As indicated in equation (7) the net heat flux is directly proportional to the time derivative of the ToF variation. In the absence of any losses the input heat flux is proportional to $\Delta G/\Delta t$.

From these calculations the convection coefficients for the sides of the rod and the thermal losses at the point of sensor attachment can be determined by laboratory heating experiments using a shuttered IR source. In these experiments five thermocouples were used to monitor the temperature during heating and cooling. The convection coefficients are adjusted to match the measured temperature at each position as a function of time. The temperature measured by the thermocouple located near the surface is the major factor in determining the best estimate of the incident heat flux for the IR source. The shape and magnitude of the cooling profiles was used to determine the convection coefficient.

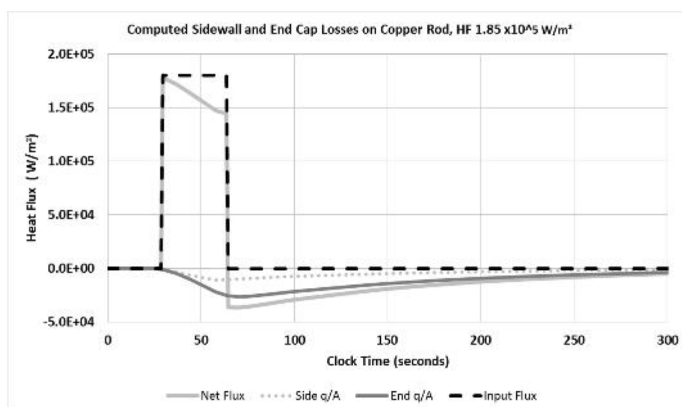

Figure 2 Computed sidewall and end cap losses for a stepwise heat flux input of 1.85 X10^5 W/m^2 (black dashed curve).

The net heat flux is energy per unit area per unit time entering or leaving the rod.

EXPERIMENTAL

A 10 MHz, 6mm diameter transducer was secured to an 80 mm long 6.25 mm diameter copper rod via pressure coupling. The rod was place inside of a Bakelite fixture to enable coupling. The rod and housing fixture were then placed on top of the insulation layer and centered 5 mm away from the IR heater. The purpose of this distance is to provide an efficient and uniform heating to the specimen surface. The tip of the rod was painted with black heat resistant paint to ensure unity absorbance of the infrared. An echo from the heated surface was recorded at a repetition rate of 4 Hz and the ToF measured using cross-correlation methods. Figure 3 shows the heating source and copper rod with attached sensor.

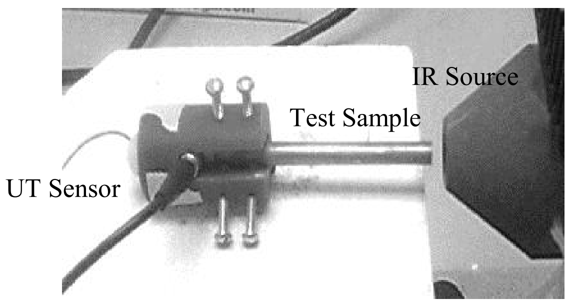

Figure 3 10 MHz, 6mm diameter transducer attached to a 6.25 mm diameter copper rod heated by IR source.

Fractional ToF data, dG as a function of clock time is shown in figure 4 along with temperature data measured by a thermocouple (TC1) near the ultrasonic sensor. After 30 seconds at ambient temperature the tip of the sample was heated with the IR source for 35 seconds (shaded area) and then allowed to cool. Ultrasonic ToF data was recorded continuously before the IR source was activated, during the heating and after the IR source was turned off. The ultrasonic echo data was recorded with a 200 MS/s 12-bit digitizer and processed using an IMS Inc. proprietary ToF determination algorithm.

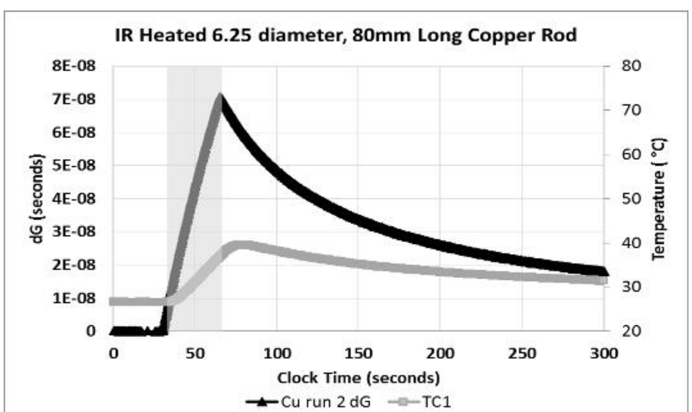

Figure 4 Fractional ToF data, dG as a function of clock time for an IR heated copper rod.

The thermocouple located near the ultrasonic sensor lags the heating event and the thermocouple temperature continues to rise once the IR heater is turned off. The ultrasonic response is more immediate in that there is no lag when the IR source is on and the signal drops immediately once the IR source is switched off. Note that the variation in the measure ToF is on the order of tens of nanoseconds. Figure 5 shows the results obtained from a similar on a 6.25 mm diameter titanium rod. The black curve shows the measured ToF data while the grey curve is the temperature measured using a thermocouple located at the ultrasonic sensor, 80 mm from the heated surface. In this case, due to the poorer thermal transport in the titanium the lag between the ultrasonic response and the thermocouple response is even greater.

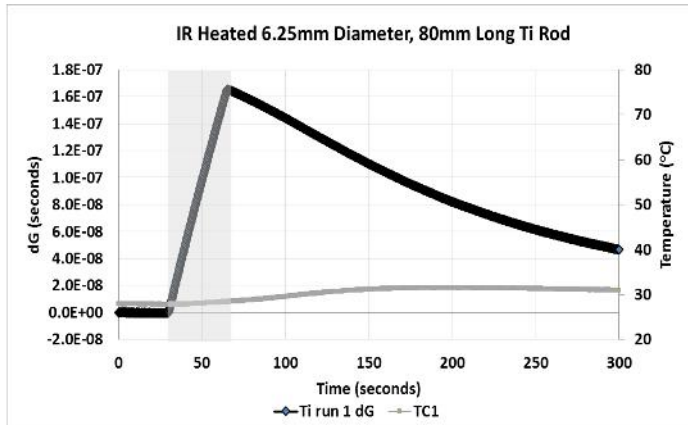

Figure 5 Fractional ToF data, dG as a function of clock time for an IR heated titanium rod.

Using the previously developed algebraic expression for heat flux and the time derivative of this curve we can obtain an estimate of the heat flux which is shown in figure 6. The model calculation, the dashed curve, is for an incident heat flux of 1.8 x 10^5 W/m^2 for a duration of 35 seconds. The grey curve follows from equation (7) using the properties shown in Table 1.

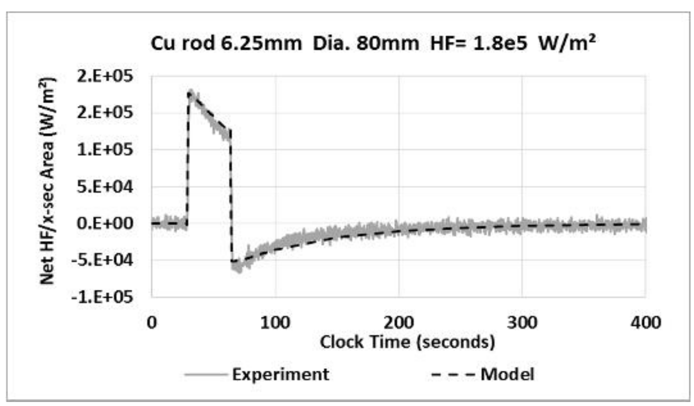

Figure 6 Comparison of experimental and model calculated heat flux on copper rod

Table 1 Properties used for heat flux calculations

Thermal Conductivity (k)=	400	W/m*K
Thickness (d) =	0.08	m
Velocity expansion change w/ Temp	-0.000110	
Specific Heat (Cp) =	400	J/kg K
Density (ρ) =	8940	kg/m^3
Velocity of Sound (c_o) =	4666	m/s

DISCUSSION AND CONCLUSIONS

Ultrasonic ToF data was continuously recorded during step-wise heating experiments on a series of metal rods. The ultrasonic response is compared with that of thermocouples co-located with the ultrasonic sensors. Whereas the thermocouple response shows significant time lag, the ultrasonic response for sensors located 80 mm from the heated surface is immediate. We find that the variation in ToF from one pulse to the next is a measure of the variation in the thermal energy stored in the system. The one dimensional analysis of both the ultrasonic response and the thermal response results in a simple algebraic equation for heat flux. Heat flux is found to be directly proportional to the rate of change of the ToF. Other physical parameters needed to convert variation of ToF to heat flux include specific heat, density, ultrasonic velocity, and ultrasonic velocity-expansion coefficient. To verify the ultrasonic-based heat flux estimates, transient thermal models have been developed using COMSOL. In order to calibrate the thermal models and determine the unknown heat transfer coefficients, additional heating experiments are carried out. In these experiments multiple thermocouples were used to measure the temperature profile during the heating and cooling of the rods. Heat flux estimates obtained on IR heated copper rods compare favourably with the model calculations. In these experiments the ultrasonic ToF data was acquired at a relatively slow rate of 4 Hz. However, this is determined by the pulse repetition rate of the instrumentation and in high heat flux experiments rates as high as 20 kHz are possible. Thus, the ultrasonic-based measurement has excellent temporal response and the operating temperature is limited only by the melting point of the probe material. Reliable and robust operation is possible because the active portion of the sensor is remote from the heated surface.

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