Thermoacoustic Sensor for Nuclear Fuel Temperature Monitoring and Heat Transfer Enhancement

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Abstract

A new acoustical sensing system for the nuclear power industry has been developed at The Pennsylvania State University in collaboration with Idaho National Laboratories. This sensor uses the high temperatures of nuclear fuel to convert a nuclear fuel rod into a standing-wave thermoacoustic engine. When a standing wave is generated, the sound wave within the fuel rod will be propagated, by acoustic radiation, through the cooling fluid within the reactor or spent fuel pool and can be monitored from a remote location external to the reactor. The frequency of the sound can be correlated to an effective temperature of either the fuel or the surrounding coolant. We will present results for a thermoacoustic resonator built into a Nitonic-60 (stainless steel) fuel rod that requires only one passive component and no heat exchangers.

Keywords: acoustics, thermoacoustics, in-pile thermometry, self-powered temperature sensor

1. Introduction

In March 2011, the Fukushima Daiichi nuclear power plant experienced severe and irreversible damage due to an earthquake of magnitude 9.0 (Richter scale reading) that struck Japan. The tsunami, which soon followed, resulted in an influx of water that submerged the emergency diesel generators, the electrical switchgear, and dc batteries, resulting in the total loss of power to the reactors [1]. There was a loss of the sensors and instrumentation within the reactor that could have provided valuable information to guide the operators to make informed decisions and possibly reduce the magnitude of the unfortunate events that followed. In the light of these events, we have developed and tested a self-powered thermoacoustic system that could have the ability to serve as a temperature sensor and can transmit data outside the reactor vessel independently of electronic networks. Such a device is synergistic with the harsh environment of the nuclear reactor as it utilizes the heat from the nuclear fuel to provide the input power.

2. A thermoacoustic solution

2.1 Thermoacoustic Engine

The type of thermoacoustic engine utilized in this work produces an acoustic standing wave from heat flowing from a high temperature thermal reservoir to a colder one [2]. It is called a stack-based thermoacoustic engine [3], since the acoustic pressure and acoustic velocity are nearly 90° out-of-phase and it uses a material known as a “stack”, shown in Fig. 1 (Right), that has pore sizes that are on the order of the distance that heat can diffuse during one-half of an acoustic cycle. Such a device can utilize the high heat energy from a nuclear reactor and convert this into an acoustic oscillation, whose frequency can be correlated to the temperature within the reactor [4].
Figure 1. (Left) Half-wavelength resonator and the four step cycle of a gas particle within the stack. (Right) Celcor™ ceramic stack material developed by Corning Environmental Products [5] inside a test tube. (Photo courtesy of Reh-Lin Chen).

Figure 1 (Left) illustrates the operation of a stack-based thermoacoustic engine. It contains the porous stack material (Fig. 1 (Right)) and hot and cold heat exchangers in a closed-closed (half-wavelength) resonator. The stack used in our experiments is manufactured from a Celcor™ ceramic by Corning Environmental Products and consists of a regular array of parallel pores. These stacks are manufactured as the substrate for catalytic converters found in most automotive exhaust systems [5].

When heat is applied to the Hot Heat Exchanger end it creates a temperature gradient across the stack. The Cold Heat Exchanger maintains the temperature of the remainder of the engine at ambient or another desired value. As the gas moves to the left (step 1) its temperature is raised ($T_o \rightarrow T_{++}$) by (nearly) adiabatic compression and heat is transferred from the hot end of the stack to the gas during step 2, increasing the gas temperature ($T_{++} \rightarrow T_{+++}$) and its pressure. In step 2, the gas is at a constant high pressure. This increase in gas temperature causes an increase in volume of the parcel of the gas. Consequently, work ($p\Delta V$) is done to the gas by the flow of heat from the stack to the gas. The pressure increase pushes the gas back by a little more each cycle.

The gas then moves to the right (step 3) and is cooled ($T_{+++} \rightarrow T_+$) by (nearly) adiabatic expansion. Heat is transferred from the gas to the stack (step 4), lowering the gas temperature ($T_+ \rightarrow T_o$) and lowering its pressure. Since this removal of heat from the gas occurs at a constant low pressure, the volume of the parcel is decreased and work ($p\Delta V$) is done to the gas. This sucks the gas back toward the hot end of the stack by a little more each cycle. Eventually, the amplitude of the sound wave grows to a steady-state level when the acoustic power dissipated during each cycle is equal to the acoustic power generated by the thermoacoustic process. The result is that an acoustic pressure wave is sustained within the engine. This process of conversion of heat to sound was understood qualitatively by Lord Rayleigh near the end of the 19th century [6] when he stated that a “vibration is encouraged when heat is added during compression and removed during rarefaction.”
2.2 Thermoacoustic Fuel-Rod Resonator

A nuclear fuel-rod can be adapted to accommodate this same kind of stack-based thermoacoustic engine by inserting a stack with the correct dimensions at the correct position. Figure 2 illustrates the new thermoacoustic fuel-rod design.

![Figure 2. Nuclear fuel-rod adapted to a thermoacoustic sensor. The fuel (left) heats the hot end of the stack by electromagnetic radiation. The heat transfer from the ambient-temperature end of the stack is enhanced by the acoustically-driven streaming gas flow indicated by the oblong arrows. That streaming also increases the heat transfer from the gas to the surrounding coolant.](image)

The cylindrically shaped object in Fig. 2 represents a typical nuclear fuel rod, which contains a nuclear fuel source toward the left of the schematic. The heat source will be the nuclear fuel (although in these experiments electrical resistance heating was used) and electromagnetic radiation (E.M.R.) transports this heat to the hot end of the stack. The ambient side of the stack is initially kept cool by the surrounding cooling fluid and this temperature gradient across the stack will produce acoustic oscillations. When the acoustic wave is generated, a phenomenon known as acoustic streaming [7] will occur on the other side of the stack, i.e., the ambient end (right of Fig. 2). This acoustic streaming is a convective jet of gas, which will circulate hot gas away from the lower-temperature end of the stack, along the walls of the cylinder, then into the surrounding cooling fluid, as depicted by the arrows in Fig. 2. This will reduce the temperature of the ambient end of the stack, maintaining the temperature gradient needed for sustained acoustic oscillations. The sound wave that is produced in the nuclear fuel rod will be propagated by sound radiation throughout the cooling fluid in the reactor and can be monitored at a remote location away from the high temperatures of the nuclear fuel-rod. The frequency of this sound wave is representative of an effective temperature within the nuclear reactor.

In such a design, there are no heat exchangers required (such as those shown in Fig. 1) because the electromagnetic radiation and the acoustic streaming provide the heat transfer mechanisms necessary to maintain the required temperature gradient across the stack. Additionally, there are no physical moving parts to fatigue or fail, and no electrical cabling requirements inside the nuclear fuel-rod.

The Idaho National Laboratory (INL) manufactured two resonators of approximately the same dimensions and material (Nitronic-60 stainless steel) as those used to make nuclear fuel rods. Without access to nuclear fuel, the experiments to test the feasibility of the thermoacoustic fuel-rod sensor utilized different methods of electrical resistance heating. In the laboratory, we were able to fully instrument the resonator with conventional pressure and temperature sensors and then submerge this thermoacoustic fuel-rod resonator into a
thermally insulated container (calorimeter) filled with distilled water [8] (see Fig. 6). One of the modified resonators is shown in Fig. 3. Direct measurement of self-maintained acoustic oscillation pressure and temperatures at several locations within the resonator and calorimeter makes it possible to correlate the temperature-frequency dependence and quantify the effects of acoustic streaming on heat transfer [9].

3. Thermometry

3.1 Frequency-Temperature Invariant

The well-known equation relating the pressure-independent speed of sound, \( c \), in an ideal gas demonstrates that \( c \) is proportional to the square root of the absolute (Kelvin) temperature of the gas, \( T \). For a half-wavelength resonator, such as the thermoacoustic fuel-rod resonator described, the frequency of the first longitudinal mode of vibration, \( f \), is related to the speed of sound by \( c = 2Lf \), where \( L \) is the length of the resonator. Hence it is possible to derive an “invariant” expression from the ratio of this frequency to the square root of the temperature of the gas as shown in equation (1). In equation (1), \( R = 8.314471 \text{ J/mole-K} \) is the Universal Gas Constant, \( \gamma = c_p/c_v \) is the polytropic coefficient, which is the ratio of the specific heat at constant pressure to that at constant volume. For dry air \( \gamma = 1.403 \) and \( M = 0.02897 \text{ kg/mole} \) is the mean molecular mass [10].

\[
\frac{f}{\sqrt{T}} = \frac{1}{2L} \sqrt{\frac{\gamma R}{M}} \tag{1}
\]

An additional complexity is associated with equation (1) in its application to the thermoacoustic fuel-rod resonator since the thermoacoustic resonator does not have a spatially constant temperature. A substantial temperature gradient across the stack of approximately 400 °C to 450 °C is required for operation and there are no hot or cold heat exchangers so the temperature is less spatially uniform in the hot duct side of the stack or the ambient temperature duct on the other side of the stack. Hence if equation (1) were to be applied, the “invariant” quantity will actually be varying. For equation (1) to be applied in this more complicated situation, some effective sound speed \( c_{\text{eff}} \) must be defined, which is determined by an effective temperature \( T_{\text{eff}} \) of the gas at some location within the resonator. The thermoacoustic oscillation can be thought of as averaging the spatially-varying temperature throughout the resonator, thus determining its resonance frequency and the dependence of that frequency on an effective temperature. The following section is dedicated to a model that will arrive at this averaged temperature that the resonance frequency is “measuring”.

Figure 3. One of the fuel-rods manufactured from Nitronic-60 stainless steel by INL. The PVC section houses pressure and temperature instrumentation and protects the electronics when the device is submerged in water. The PVC housing also contains an electrically-actuated valve that can suppress the thermoacoustic oscillations remotely without making any other changes to the experiment.
3.2 Transfer Matrix Model

To investigate the relationship between the effective temperature in the resonator and the fundamental frequency, the temperature profile of the gas in the resonator was measured using four thermocouples and one integrated circuit temperature sensor (AD 592). A piezoresistive microphone was also included to measure the acoustic pressure and frequency. A transfer matrix network model was developed to characterize the temperature-frequency relationship of the thermoacoustic sensor that utilizes a concatenation of lumped elements to represent small sections or slices of the resonator to take into consideration the longitudinal variation in temperature in the gas in the resonator as well as changes in the cross sectional area due to the stack. These lumped elements are very short compared to the wavelength of sound and represent simple mechanical or electrical topologies, which can be used to analyze an acoustical system (or vice-versa). Acoustical inertances, $L_{acs}$ (masses/inductors), and acoustical compliances, $C_{acs}$ (springs/capacitors) are the lumped elements that were used for this transfer matrix network. $C_{acs}$ is not affected by temperature changes since it is dependent only upon the mean gas pressure. On the other hand, $L_{acs}$ is density dependent and in turn temperature dependent. Since the static pressure is spatially uniform within the resonator, the local temperature of the gas determines its local mass density.

Figure 4 shows the division of the resonator (with cross sectional area, $A$) into 31 slices. One slice represents the hot duct area from the hot end of the resonator (location of nuclear fuel) to the hot end of the stack, 10 slices represent the region of the stack, and the remaining 20 slices represent the length from the ambient end of the stack to the ambient rigid end of the resonator. Each slice is represented by a lumped element network, consisting of an inertance flanked by two half-compliances, as shown in Fig. 4. The average of the temperature of the nut (hot) end of the resonator and the hot end of the stack was used to represent the temperature of the hot duct. An exponential fit to the temperature profile was used to calculate the temperature of each of the remaining slices, and hence an inertance for each of those sections. The transfer matrix was solved [4] to find a modeled frequency for each temperature profile that was recorded (every two minutes during the operation of the resonator).

By logarithmic differentiation of Eq. (1), the sensitivity of the thermoacoustic sensor in this work can also be evaluated. The temperature uncertainty $\delta T$ is related to the uncertainty in the frequency $\delta f$ in Eq. (2).

$$\delta T = \frac{2T}{f} \delta f$$

(2)

In the experiments described in this section, the frequencies were measured to $\pm 0.01$ Hz, resulting in very small relative uncertainty in the temperature so an uncertainty in frequency of $\pm 0.01$ Hz corresponds to an uncertainty in temperature of about $\pm 0.01^\circ$C; a differential sensitivity of about $(dT/df) \approx 0.8$ K/Hz. Although small changes in temperature can be tracked very accurately, the relationship between the measured frequency and a temperature in a particular location within the resonator or the fluid surrounding the resonator can be difficult to establish to better than 5%.
Figure 4. The 31-slice model of the resonator to which the transfer matrix was applied. $A$ represents the cross-sectional area of the tube. $p_1$, $U_1$, $p_2$, and $U_2$ are pressures and volume velocities of the gas on either (rigid) end. The first slice represents the hot duct at a constant temperature. The exponential temperature profile was applied to the remaining slices, 10 of which are dedicated to the stack and 20 to the ambient end of the resonator. Each slice was represented by a lumped element network of an inertance, $L_{ac}$, flanked by two half compliances, $C_{ac}/2$.

4. Heat Transfer

The measurements presented thus far were made in the calorimeter shown in Fig. 7. The heat transfer paths are also important to recognize in this device, as they are required for keeping this sensor in continuous operation. Figs. 5 and 6 shows the different paths through which heat is transferred from the heat source (nuclear fuel) to the hot and ambient ends of the stack, into the water, and ultimately into the surrounding environment. The dominant method of heat transfer from the heat source to the hot end of the stack is electromagnetic radiation, $Q_{rad}$. $Q_{rew}$ is the conductive heat flow from the heat source that entirely bypasses the gas, but flows through the walls of the resonator and into the water. The heat from the hot end of the stack can be transported to the ambient end of the stack through a conductive path, $Q_{ha}$. Another conductive heat flow path also exists from the ambient end of the stack to the walls of the resonator and into the water, $Q_{aw}$.

With the thermoacoustic effect present within the resonator, there are two primary effects that contribute to the heat transfer: (i) enthalpy transport along the stack due to the “bucket brigade” effect [11] which acoustically transports heat through the stack and (ii) enhanced thermal contact between the acoustically-oscillating gas and the walls of the resonator due to acoustically-driven streaming ($Q_{sd}$ in Fig. 6) [12] [13]. The total power flowing through the stack, which includes $Q_{ha}$ is denoted by $H_2$ [4], hence, in Fig. 5, this enthalpy transport from the hot end of the stack to the ambient end of the stack due to thermoacoustics alone is $H_2 - Q_{ha}$. The remaining heat flow paths in Fig. 6, $Q_{henv}$ and $Q_{wenv}$ are the heat losses from the heat source and the water to the ambient environment.

To understand the thermoacoustic heat transfer effects, experiments were done using a linear actuator to suppress and reactivate acoustic oscillations within the fuel-rod resonator. Figure 7 (left) shows the temperature of the ambient end of the stack with and without the presence of acoustic oscillations. This corresponds to the introduction of the path $H_2 - Q_{ha}$ when there are acoustic oscillations in the resonator. $H_2 - Q_{ha}$ continuously drives more heat from the hot end of the stack to the ambient end of the stack, lowering the temperature at the hot end of the stack and increasing the temperature of the ambient end of the stack as shown in Fig. 7 (Left). Hence, there is a greater temperature difference between the heat source and the hot end of the stack.
Figure 7. (Left) Temperature of the ambient end of the stack with and without acoustic oscillations (ACS) demonstrating the enhancement of heat flux through the stack due to thermoacoustic effects. (Right) Temperature at the centre of the resonator and of the surrounding cooling water, with and without acoustic oscillations demonstrating an enhanced thermal contact between the gas and the water.

At the same time, the heat that is being accumulated on the ambient end of the stack is continuously being removed by the acoustically-driven streaming convection, $Q_{sd}$, and deposited onto the walls of the resonator and finally into the water. This maintains the temperature gradient across the stack for continued operation of the thermoacoustic sensor. Figure 7 (right) shows the temperature of the water (blue) and the temperature of the gas at the centre of the resonator, with and without acoustic oscillations (red). It is quite evident that there is an improved thermal contact as the temperature of the gas is reduced closer to the water temperature when there are sustained acoustic oscillations. It has also been demonstrated through these heat transfer experiments that the velocity of the acoustic streaming is proportional to the square of the acoustic pressure amplitude [8].
4. Conclusions

The thermoacoustic fuel rod sensor developed in this research has demonstrated a novel technique for monitoring the temperature within the core of a nuclear reactor that could use the heat from the nuclear fuel to generate sustained acoustic oscillations whose frequency will be indicative of the temperature. Converting a nuclear fuel rod into this type of thermoacoustic sensor simply requires the insertion of a porous material (stack) that has only minimal susceptibility to high-energy particle fluxes.

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