

Spatio-Temporally Resolved Experimental Characterization of Rotating Detonation Rocket Engine Heat Transfer

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Reliable prediction of Rotating Detonation Rocket Engine (RDRE) heat transfer presents a critical on-going challenge for developing flight ready hardware. Traditional spatial and temporally averaged techniques for measuring RDRE heat flux hinder the development of convective heat transfer correlations that capture the multidimensional, complex detonation wave and oblique shock structures. In the following paper, detailed analysis on a series of experimental techniques to capture temporally and spatially resolved heat transfer measurements within RDREs is presented. First the Atomic Layer Thermopile (ALTP) is applied as a method to temporally and spatially resolve the heat flux in the RDRE. An additional technique is then presented with the Coaxial Surface Junction Thermocouple (CSJT) to enhance spatial resolution for heat transfer measurements with greater temporal accuracy than traditional low speed thermocouples. Finally, heat conduction within the instruments is modeled with numerical Finite Difference Method (FDM) to evaluate measurement performance and identify suitable practices. Prior instantaneous heat flux and wall temperature measurements and calculations from the gaseous hydrogen-air Turbine-integrated High-pressure Optical RDE (THOR) at Purdue University are used as references for the evaluation of sensors.

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I. Nomenclature

α	= Thermal diffusivity
Bi	= Biot number
c_p	= Specific Heat (constant pressure)
d	= ALTP film/ CSJT junction thickness
f	= Sampling rate
F	= Integrated Seebeck coefficient formula
Fo	= Fourier number
h	= Convective heat transfer coefficient into sensor
k	= Thermal conductivity
L	= ALTP substrate/CSJT leg length
l	= ALTP film width
q''	= Heat flux
r	= Radial coordinate
S	= Seebeck coefficient
s	= Sensitivity coefficient
T	= Temperature
t	= Time
V	= Voltage
z	= Sensor normal coordinate
β	= Thermal product
ε	= Convergence criteria
θ	= Film tilt/Azimuthal coordinate
ρ	= Density
τ	= Wave period
ϕ	= Equivalence ratio

Subscripts

$ALTP$	= Thermal characteristics of Atomic Layer Thermopile (ALTP) sensor
$film$	= Thermal properties evaluated for ALTP film
i	= Start of wave cycle
n	= Timestep number
ref	= Cold junction reference temperature
sub	= Thermal properties evaluated for ALTP substrate
1	= First thermocouple leg material
2	= Second thermocouple leg material

II. Introduction

Pressure gain combustion devices such as rotating detonation rocket engines (RDREs) have attracted significant attention in the last decade as methods to extract additional enthalpy from the same propellant mass. The performance advantages of RDREs are driven by an azimuthally revolving detonation wave that compresses the injected fuel and oxidizer prior to combustion. This continuous detonation combustion process increases combustion efficiency and lowers entropy generation compared to traditional deflagrative rocket engines [1]. Within rocket engine applications, the RDRE is expected to greatly reduce combustor size and weight and has the potential to increase Isp by 6-8% [2]. Despite the promising benefits of applying RDREs to future launch missions, the high heat load generated by the detonation wave has resulted in substantial difficulties in designing flight applicable hardware [3]. The revolving detonation wave releases a substantial amount of concentrated thermal energy in the combustor and provides a strong pressure gradient which compresses the temperature and velocity boundary layer thicknesses and results in a high heat flux into the annular walls [4]. The increased heat flux from the detonation wave provides an additional engineering

challenge that will require future experimental and numerical characterization to effectively design cooling hardware [5].

The highly complex and transient combustion environment has historically limited experimental characterization to gaseous RDREs with propellants such as hydrogen-air [6] and methane-oxygen [7,8]. In general, hydrogen-air detonation waves have been observed to travel at speeds of 1500 to 2000 m/s [9]. Inside of an RDRE annulus, these wave speeds would require sensors on the order of ~ 100 KHz to temporally resolve periodic oscillations in combustor static properties and heat transfer quantities. Despite the requirement in high-frequency, previous attempts at calculating heat flux in RDREs have relied on low-frequency sensor technology within the rapidly evolving transient combustor environment [4,5,10]. Within these same experiments, results indicated low-frequency pressure transducer measurements of static pressure inadequately estimated average heat flux measurements by the 0.8 mass flux scaling law in Bartz Equation [11]. However, this finding is expected since the boundary layer integral equations governing the Bartz equation are derived for a steady boundary layer representing a system without significant temporal variations static properties. At the same time, the Bartz correlation was scaled with reference to the nozzle throat without the consideration that the combustor contains large spatial variations in heat flux [11]. Furthermore, the application of low-speed pressure measurements does not accurately represent the boundary layer thinning by the Von Neumann pressure spike in the detonation structure [12] which drives an increase in heat flux. Together, these findings indicate that new correlations are necessary for application to RDREs.

In past experiments, embedded low-speed thermocouples with inverse heat conduction calculations have been applied within heat-sink RDRE hardware to determine heat flux [4,10]. This technique has extensively been utilized in applications for traditional deflagration rocket engines where the absence of strong temporal oscillations in heat flux allowed for a steady estimate of heat loads to develop engine cooling hardware [13]. Following this process, a cluster of thermocouples at different radial locations in the combustor wall provides discrete temperature measurements which are then used in an inverse solution of the heat diffusion equation to determine the hot-gas heat flux. These techniques are often iterative and strive to minimize the error between the calculated and experimental temperature profiles. However, without placing embedded thermocouples at precise locations immediately near the surface, heat flux oscillations are not captured with the inverse calculation which are required to compare with analytical models. More recently, calorimetric hardware has been applied to measure the average heat flux and bulk heating in RDREs during longer duration tests for evaluating steady state behavior [5,14,15]. For these experiments, the combustor hardware contains azimuthal or axial cooling passages where water at known conditions enters the hardware and exits at higher temperature to calculate the thermal energy gain. This thermal energy increase in the water is then related to the average heat flux through the combustor wall. However, calorimetric combustor bodies that contain axial cooling passages effectively eliminate the ability to correlate heat flux differences at different axial positions which is essential for characterizing the effects of detonation structure on RDRE heat flux. On the other hand, azimuthal cooling passages within calorimetry bodies can capture general trends of detonation structure on combustor heat flux but are limited in their resolution to the size of the cooling passages and provide no temporal description of heat flux behavior to correlate with theoretical heat convection models.

With the increase in demand for thermal characterization in high enthalpy and transient environments, new developments of high-frequency heat flux and temperature sensors have been developed for applications to measure both spatial and temporally accurate heat transfer quantities. One such sensor, the Atomic Layer Thermopile (ALTP), is a high-frequency heat flux sensor that was developed for hypersonic wind tunnel and shock tube applications with a 1 MHz sampling rate [16]. Recently, this sensor was utilized in the Purdue THOR gaseous hydrogen-air RDE to evaluate the instantaneous heat flux at different axial locations of the combustor outer body. From the data gathered, the high resolution of the sensor captured the Azimuthal Reflected Shock Combustion (ARSC) trailing the main detonation wave [6,17]. For evaluating wall temperatures in highly transient combustion environments, the high-speed coaxial surface junction thermocouple (CSJT) provides an alternative method to embedded thermocouples to capture the high-frequency oscillations in wall temperature with rise times less than 100 microseconds [18]. When flush mounted inside a combustion chamber, the device can return the inner wall temperature when the thermocouple metals have similar thermal properties to the combustor wall. Within this paper, the ALTP and CSJT will be evaluated at different operating conditions to demonstrate best practices and sources of error when resolving both the spatial and temporal variations of heat flux within a gaseous hydrogen-air RDE.

III. ALTP Background

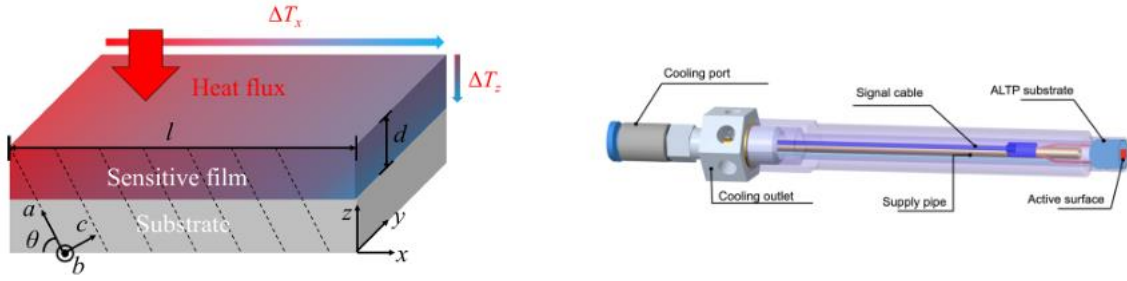


Fig. 1 Diagram of ALTP film and substrate configuration (Left) [19] and design of ALTP probe for RDRE experiments (Right) [17].

The Atomic Layer Thermopile is a high frequency heat flux sensor that creates an electric field based on the transverse Seebeck effect when a temperature gradient forms between the upper and lower surfaces of a 500 nm crystal film [20,21]. The film comprises of interchanging CuO₂ and YBa₂Cu₃O₇ (YBCO) tilted layers that form a series of atomic thermocouples that serve as the active surface of the instrument. The thermoelectric field that is produced creates an electromotive force along the film length, perpendicular to the temperature gradient and allows for measurement [21]. With knowledge of the thermoelectric behavior and geometry, the voltage measured from the sensor is:

$$V = \frac{l}{2d} \sin(2\theta) \Delta S \Delta T_z \quad (1)$$

For thin films where thermal conduction dominates over energy storage, the thermal gradient becomes nearly linear. For sampling rates where the Fourier number in the film remains much greater than 1, the measured voltage output from the sensor is related to the temperature gradient and heat flux into the film by combining Eqn. (1) and (3):

$$Fo = \frac{\alpha}{fd^2} \gg 1 \quad (2)$$

$$|q''| = k \left. \frac{\partial T}{\partial z} \right|_{z=0} \approx k \frac{\Delta T_z}{d} \quad (3)$$

$$V = \left(\frac{l \sin(2\theta) \Delta S}{2k} \right) |q''| = s |q''| \quad (4)$$

The above Eq. (4) presents the concept of the sensor sensitivity coefficient. When the mean temperature in the film is close to room temperature during short duration tests, the change in Seebeck coefficients and thermal conductivity due to temperature becomes negligible. As a result, the measured voltage is linearly proportional to heat flux over 11 orders of magnitude using the sensitivity coefficient [23].

Underneath the film lies a substrate where the crystal is grown and serves a heat sink to conduct heat away. Common substrate materials for ALPTs consist of MgO, SrTiO₃ and LaAlO₃ [17,22]. For high heat and long duration experiments where the substrate begins to rise in temperature appreciably, mean temperature of the film increases, and temperature dependency of Seebeck coefficient and thermal conductivity becomes important for consideration [24-26]. At elevated temperatures, stability of the sensor becomes compromised as oxygen atoms begin to escape from the film. At lower oxygen concentrations in the film, the Seebeck Coefficient and uncertainty in heat flux measurements increase [24]. Simultaneously, thermal conductivity of YBCO films increases at higher temperatures. Both effects contribute to an increase in sensor sensitivity coefficient and results in higher voltages returned for the same heat flux [26]. Consensus from researchers developing YBCO film ALTPs indicate that prolonged operations of more than 300°C could produce irreversible damage to the sensor film [22,26,27]. Once reaching temperatures near 450°C, a phase transition from orthorhombic to tetragonal occurs within the YBCO film that greatly affects the electric properties and provides even greater uncertainty of heat flux measurements [19]. For this reason, studies have not

been conducted to characterize the changes in YBCO ALTP sensitivity at the elevated film temperatures that are expected to occur with RDE environments. Recently however, research into the development of CCO and LCMO films for use in ALTPs provides a possible future opportunity for operations up to 800°C due to their enhanced stability of physical properties at elevated temperatures [22,27].

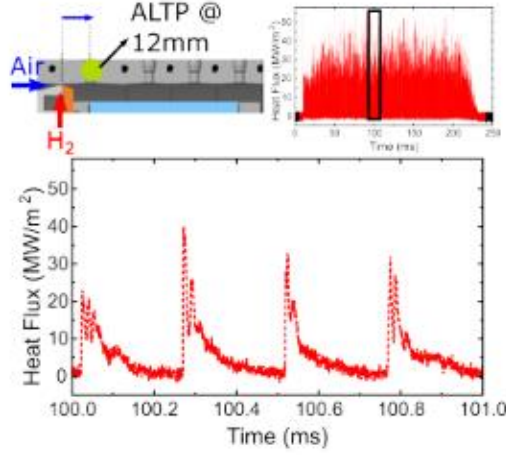


Fig. 2 Purdue THOR RDE heat flux experimental hardware and set-up with temporally resolved heat flux data from ALTP sensor [17].

The exceptionally fast response time of the ALTP allows the sensor to resolve highly transient oscillations in convective heat transfer between detonation wave passings in an RDE. At the same time, high spatial resolution is achieved due to the small active surface area and provides an effective point measurement. To measure heat flux into the inner walls of an RDRE combustor, the ALTP sensor is flush mounted and exposed to the combustion environment. At each pass of a detonation wave, the heat released by the combustion reaction is transferred to the active surface of the sensor before conducting into the underlying substrate. By conducting heat away from the film, the substrate prevents overheating and maintains a low temperature for consistent heat flux measurements. As a result, the sensor's temperature behaves like a semi-infinite wall rather than a lumped capacitance model despite the low Biot number of the active film.

$$Bi_{film} = \frac{hd}{k_{film}} \ll 0.1 \quad (5)$$

$$Bi_{ALTP} = \frac{hL}{k_{sub}} \gg 0.1 \quad (6)$$

IV. CSJT Background

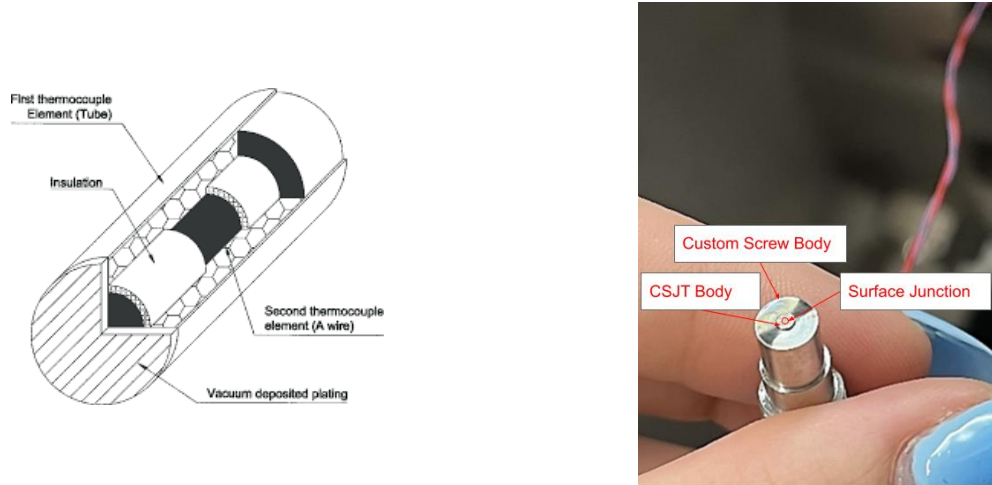


Fig. 3 Coaxial Surface Junction Thermocouple (CSJT) high level design [28] (Left). CSJT press fit into custom screw body for mounting in THOR RDE (Right).

The Coaxial Surface Junction Thermocouple (CSJT) is a high frequency temperature measurement device that relies on a heat sink design to measure temperature changes in the environment. When mounted flush with the inside of an RDE body, this sensor measures the temperature of the surface junction due to the applied heat flux. Unlike a traditional thermocouple, this design allows for the instrument to be installed through a geometry and thermally behave as the wall when the thermal properties match the combustor. For this reason, the thermocouple type with material properties most like the combustor wall should be selected to measure inner wall temperature [29]. This technique allows for a direct measurement of inner wall temperature without inverse computations. These inverse calculations often carry uncertainties associated with contact resistance and slow time constant when using traditional embedded thermocouple methods in rocket engines. However, current sensor designs are limited to short duration tests to maintain ambient temperature on the opposite side of the sensor. Although the primary use of a CJST is to measure temperature, a 1-D transient conduction analysis can be used to calculate the heat flux at the junction surface. Instead of determining the heat flux with the use of an inverse heat conduction analysis with embedded thermocouples, the temperature gathered by the CJST provides the inner wall boundary condition to solve the heat diffusion equation directly. From the temperature profile, the heat flux is then calculated by the temperature gradient at the surface junction.

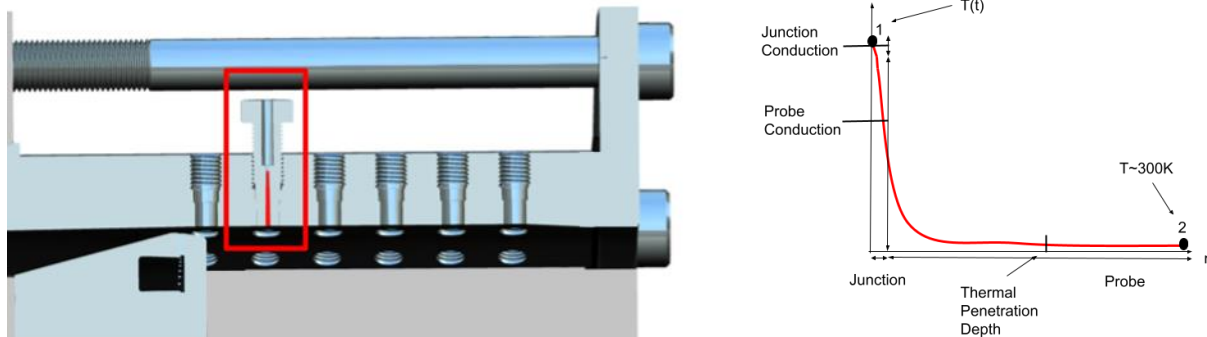


Fig. 4 Example nearfield placement of custom CSJT screw body into THOR RDE, CSJT seen in red (Left). 1D temperature profile of CJST shortly after RDRE ignition (Right).

Inside of the device, two dissimilar metals are organized in a coaxial/annular configuration with a thin electrical insulation separating both elements. At one end, a junction is formed by a thin vapor deposited plating that connects both dissimilar metals. When a temperature gradient is in the thermocouple legs, an electromotive force (EMF) is produced by the Seebeck Effect along their length [30]. The voltage measured from the coaxial thermocouple is presented as:

$$V = \int_{T_{ref}}^T (S_1(T') - S_2(T')) dT' = F(T) - F(T_{ref}) \quad (7)$$

Within this equation, the measured voltage can be related to temperature difference when the nonlinear relationship between Seebeck coefficient and temperature is known for the two thermocouple legs. To allow for a direct calculation of junction temperature, a cold junction must be provided at a known reference temperature. After evaluating the integral and rearranging, the measured temperature is iteratively solved based on the measured voltage, reference temperature and Seebeck coefficients.

$$F(T) = V + F(T_{ref}) \rightarrow T \quad (8)$$

Like the ALTP film, the CJST surface junction responds quickly to temperature/heat flux changes due to a low Biot number with a response time on the order of a few microseconds [30]. Unlike traditional thermocouples, the heat transferred out of the junction surface is nearly equal to the heat conducted into the dissimilar coaxial metals. As a result, the CJST also behaves as a semi-infinite body rather than a lumped capacitance model like Eqn. (5) and (6). To properly select an ALTP and CSJT for measuring heat flux in an RDRE, the thermal properties of the substrate and thermocouple elements must be selected to closely match the thermal product of the combustor walls. From the heat sink design, if the thermal product of the sensors is exceptionally lower than the combustor walls, the sensor temperature increases at a faster rate than the wall and results in measuring a lower heat flux. The thermal product of the wall, substrate and thermocouple elements are described by the Eq. (9):

$$\beta = \sqrt{\rho c_p k} \quad \left[\frac{KJ}{m^2 \sqrt{sec-K}} \right] \quad (9)$$

V. THOR RDE Heat Flux Experimentation

At Purdue University, a series of heat flux experiments using SrTiO₃ ALTPs and Medtherm E-type CSJTs were conducted on the H₂-air Turbine-Integrated High-Pressure Optical RDE (THOR) to assist in development of theoretical heat transfer correlations as part of a NASA STTR. The THOR RDE uses an axial supersonic injection of air through a converging-diverging nozzle where gaseous hydrogen is injected radially downstream of the nozzle in a crossflow configuration. Downstream of the injector, a Backwards Facing Step (BFS) provides additional room for radial expansion of combustion products and recirculation between wave cycles. Encompassing the combustion chamber is a cylindrical stainless-steel 304 outer body used to house instruments for conducting heat transfer and performance studies.

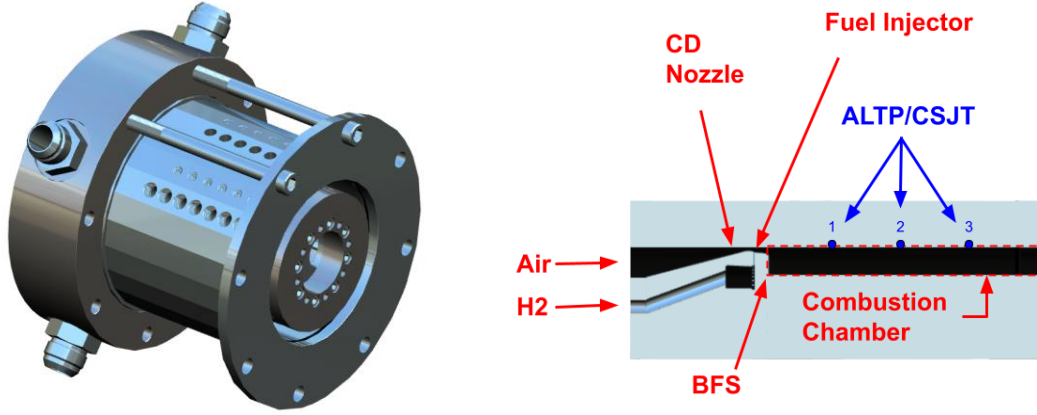


Fig. 5 THOR RDE with 304 SS Instrumented Outer body (Left). Diagram of annular RDE cross-section with sensor locations (Right)

For these experiments, a single geometry configuration without a nozzle was used to remove additional area change effects on heat transfer. At the same time, a single equivalence ratio was used to produce a single detonation wave to evaluate the performance of these high-speed sensors and compare theoretical models over a limited range of operating conditions. For the tests, a single sensor was placed at one of three axial locations within the combustor for a hot-fire duration of 300 milliseconds. Each axial location was selected to represent a different region of the RDE detonation wave structure. The dimensions provided are relative to the BFS. The first location represented the nearfield inside the detonation wave where injection refill provided film cooling between wave cycles (16.45 mm). Further downstream, a second sensor location near the end of the detonation wave provided an evaluation of the expected location of maximum heating (41.85 mm). Finally, a third sensor location was placed inside the oblique shock region to evaluate the heat transfer characteristics outside of the detonation wave where no refill film cooling occurred (67.25 mm).

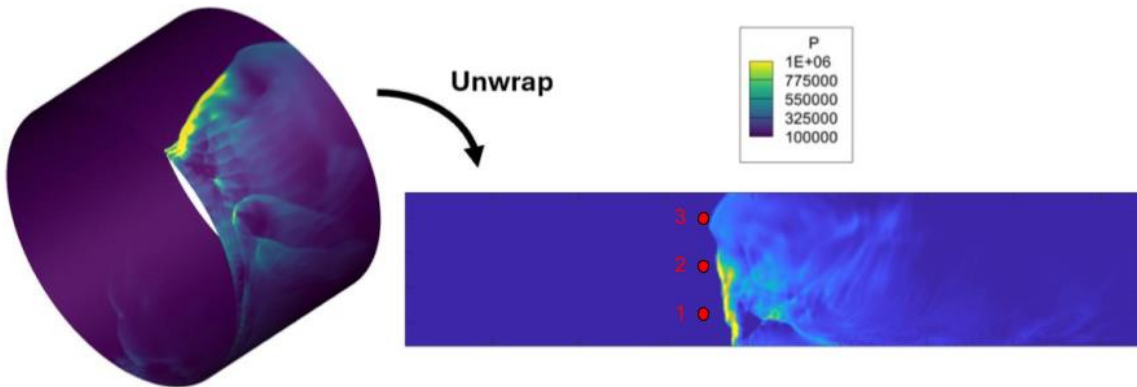


Fig. 6 THOR RDE Unsteady Reynolds Averaged Navier Stokes (URANS) CFD simulation from NCSU BEFAST lab with nearfield (1), midfield (2) and farfield (3) sensor locations relative to detonation wave

For each sensor, three trials at each location starting from the nearfield were completed before the mass flow rate was increased. Table 1 provides a summary below of the test conditions for reviewed experiments. Additional injector data was made available by CFD simulations from the NCSU BEFAST lab at the 1 and 2 lbm/s cases. Although simulation data was not available for the 1.5 lbm/s case, static property estimates half-way between the 1 and 2 lbm/s cases were used. To determine the static properties for injection, CFD data was averaged radially and azimuthally at the exit of the diverging injection nozzle while centered at one of the fuel orifices.

Sensor Type	Sensor Location [mm]	Air Mass flow rate [lbm/s]	Equivalence ratio	Injection Mach Number	Injection Temperature [K]	Injection Static Pressure [kPa]
ALTP & CSJT	16.45, 41.85, 67.25	1	1	1.68	185.3	57.58
CSJT	16.45, 41.85, 67.25	1.5	1	Unknown	Unknown	Unknown
CSJT	16.45, 41.85, 67.25	2	1	1.72	186.4	109.26

Table. 1 THOR RDE ALTP & CSJT experimental operating conditions

To measure the RDE inner wall heat flux, the ALTP film and CSJT junctions were aligned flush with the inside of the RDE outer body as shown in Fig. 4. The ALTP contained an M8 threadable probe and was inserted directly into combustor wall and sealed with a rubber O-ring. Next, CSJT probes were press fit into a custom threaded screw that accommodated a brass O-ring for sealing into the combustor outer body. To collect sensor voltage data, a HBK Highspeed Genesis Data Acquisition Center (DAQ) was set to 2.5 MHz to provide sufficient temporal resolution of the ALTP. For the CSJT, a 1-G089 HBK digit cold junction with the Genesis DAQ was used to convert the raw voltage signal to temperature measurements but required a lowpass filter of 15 KHz.

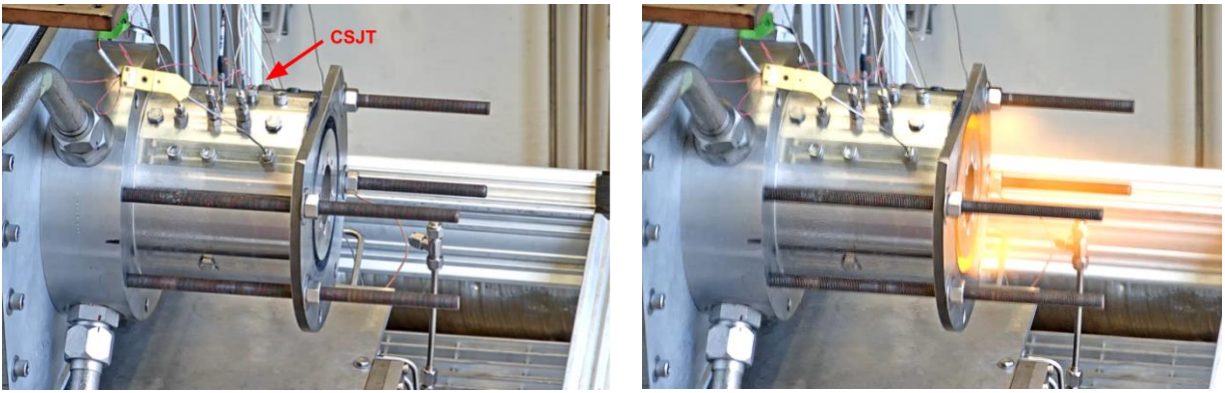


Fig. 7 CSJT installed in THOR outer body midfield (Left). 300 ms hot fire with CSJT directly measuring inner wall temperature (Right).

Following completion of experiments with the CSJT, temperature data was analyzed to ensure response time was low enough to capture the passing of detonation wave. Although the temporal resolution was not comparable to the ALTP due to the lowpass filter and larger junction time constant, the distinct oscillations in wall temperature due to the passing detonation wave ensured that the sensor was sufficient for spatially accurate but time averaged wall temperature. Following an approach outlined in Section VI, the heat flux into the CSJT was calculated to provide an additional reference to ALTP measurements.

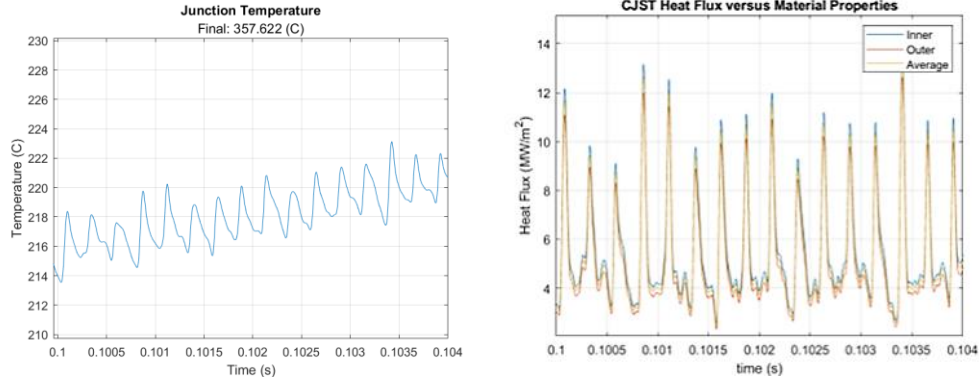
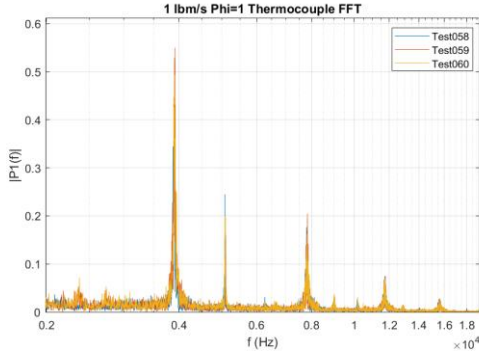


Fig. 8 Medtherm E-Type CSJT temperature measurements (Left) and heat flux calculation with 1-D transient conduction model (Right) in farfield at 1 lbm/s & $\phi=1$ (Test 058)

Next, Fast Fourier Transforms (FFT) were performed on the CSJT data and averaged between all the trials at the same operating conditions to measure wave speed. As the mass flow rate increased in the experiments, the detonation wave speed began to approach the ideal CJ velocity. For this size of RDE, the average wave period was determined to range between 215 to 255 microseconds for 3915 to 4466 revolutions per second.



Mass Flow Rate (lbm/s)	Average wave speed (ft/s)	% CJ velocity
1	5,474.4 [1,668.6 m/s]	84.6
1.5	5,867.8 [1,788.5 m/s]	90.6
2	6,244.8 [1,903.4 m/s]	96.4
Theoretical	6,473.8 [1,973.2 m/s]	100

Fig. 9 E-Type CSJT FFT (Left) and respective detonation wave velocities (Right)

In post-processing, the temperature data from the CSJT experiments was plotted to demonstrate the impact of detonation wave structure and mass flow rate on heat transfer at different axial positions. At the 1 lbm/s, the mid and far field inner wall temperatures were nearly identical, indicating a nearly uniform and less sensitive heating rate in the oblique shock region. Inside the refill region, additional film cooling was provided significantly lowering the average heat flux. As the injection mass flow rate increased, the refill height also increased and shifted the location of maximum heat release axially downstream. Although further experimental investigation through chemiluminescence imaging is required to confirm the refill height relative to midfield CSJT, downstream shifts in the average location of the wave height at higher propellant flow rates would provide greater heat releases further downstream in the combustor and result in a higher midfield wall temperature.

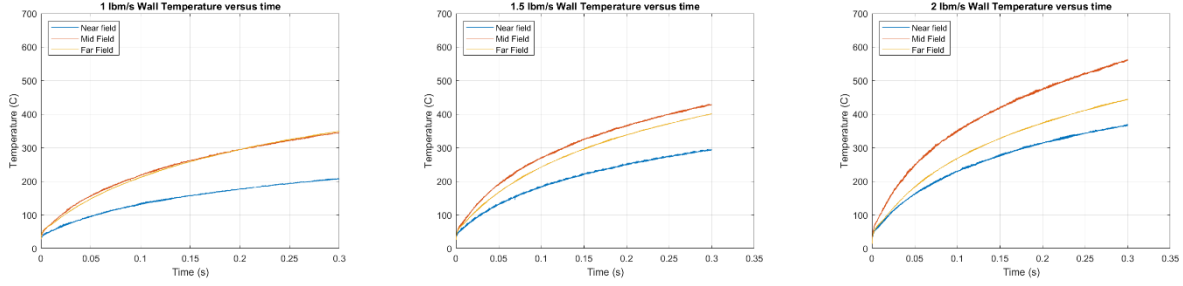


Fig. 10 CSJT measured RDE inner wall temperature versus time compared at different axial stations. 1 lbm/s (Left), 1.5 lbm/s (Middle) and 2 lbm/s (Right)

The focus on collecting heat flux data using the ALTP was originally intended to understand the order of magnitude of heat fluxes experienced in the RDE and to understand the trends in the time-resolved heat flux profile [17]. To compute the heat flux from measured sensor voltage, a single sensitivity coefficient was used for the film at room temperature as provided by the sensor manufacturer. However, the experimental data shows that heat flux increases with time as the sensor heats up. This trend does not satisfy Newton's law of cooling and indicates that there may be an increase in the sensitivity coefficient as the YBCO film temperature increases. For the experiments, a protective film from the manufacturer was placed on top of the active surface to help reduce oxygen loss and sensitivity coefficient uncertainty at higher film temperatures. Other than the errors associated with the average heat flux trend, the instantaneous heat flux demonstrates a quick rise in heat flux at the detonation wave followed by a fast decrease as combustion products expand and cool. Between wave cycles, the heat flux drops to near zero as the fresh reactants are injected near the combustor wall with a film cooling effect.

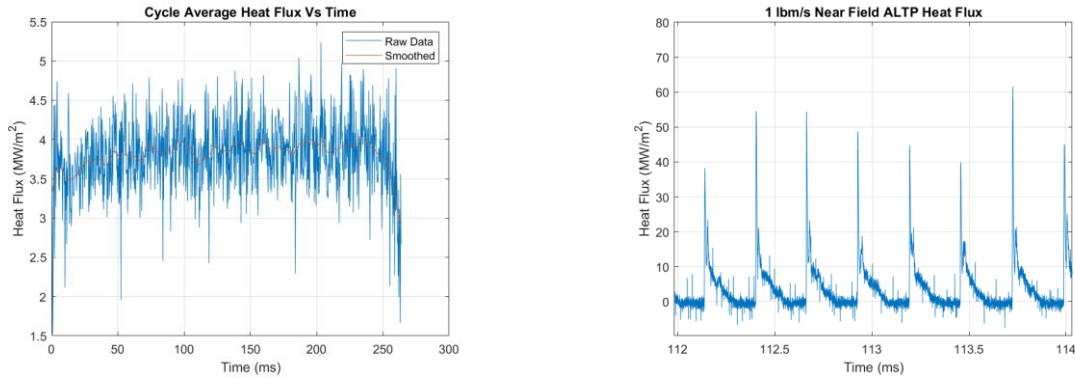


Fig. 11 1 lbm/s nearfield RDE cycle averaged heat flux versus time measured with SrTiO₃ ALTP during test 018 (Left) [17]. Instantaneous heat flux from same sensor and test (Right)

Following completion of the CSJT test campaign, experimental data was post-processed in MATLAB and compared to theoretical models. The Method of Characteristics (MOC) model developed by North Carolina State University was used to estimate the freestream conditions within the H₂-air RDE [31,32]. The solver represents a 2D, reduced order approximation of the freestream flow field of an unwrapped, symmetrical, premixed gaseous RDE. The solver operates by solving the 2D compressible and irrotational RDE flow field within the frame of reference of the detonation wave by assuming steady cyclic operation at ideal Chapman-Jouguet (CJ) wave conditions [32]. The process for calculating heat flux and wall temperatures follows internally developed equations and methodologies that are considered proprietary. The theory and equations that have undergone both validation from experimental data presented in this paper and CFD [17] are not available for publication at this time.

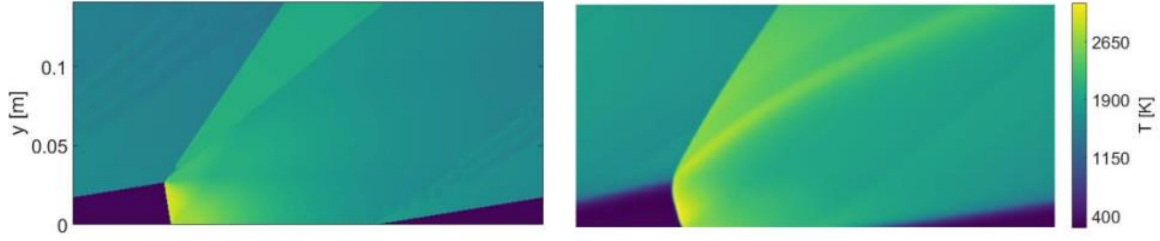


Fig. 12: Premixed RDE MOC static temperature field versus CFD simulation as viewed from steady detonation wave reference frame [32]

Within the detonation wave, the nearfield demonstrated a close agreement between calculations and experiment. Starting with the lower 1 lbm/s case, the methodology provided a reasonable over-prediction in wall temperature within the 200 ms operating window. Additionally, the similar shape in the temperature versus time demonstrates that the time evolution of heat flux predicted in the model is very similar to the experiment and would likely replicate a similar over-prediction at longer hot-fire durations. Moving over to the 1.5 lbm/s and 2 lbm/s cases, the wall temperatures between experiments and models are closer but the transition from over to under prediction at the end of the 200 ms simulation time indicates that there are some minor errors in heat flux prediction. The decrease in over-prediction at higher mass flow rates is likely attributed to the experimental increase in detonation wave speed while the wave speed in the calculations remained constant for ideal CJ conditions.

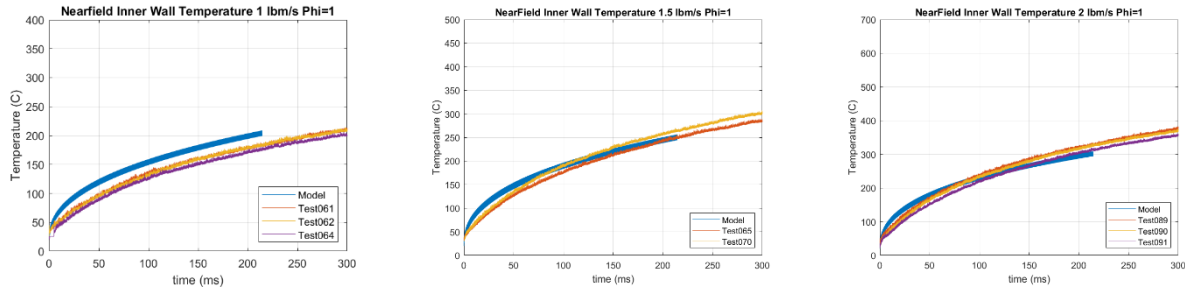


Fig. 13: Experimental RDE wall temperature measurements by CSJT compared with in-house RDRE heat transfer model

VI. Theoretical Sensor Performance Evaluation (FDM)

To properly evaluate how well the ALTP and CSJTs measure the combustor wall heat flux, and inner wall temperature respectively, 1-D transient heat conduction analyses were performed on the sensor bodies and stainless-steel combustor wall with the cell-centered Finite Difference Method (FDM). In these calculations, the same heat flux formula with dependency on wall temperature is applied to ensure each sensor is evaluated independently from one another. To estimate freestream properties for the RDE, the MOC model was used to assume a periodic ideal CJ velocity detonation wave [32]. For these calculations, the RDRE heat flux correlation for the nearfield location was used to represent a transient heat flux Boundary Condition (BC) on the sensor faces. On the opposite end for the CSJT and wall calculations, an isothermal or adiabatic boundary condition was applied due to the short penetration depth of the heat. For the ALTP, the much smaller thickness of the substrate did not allow pure semi-infinite conditions for the test duration and instead included an adiabatic boundary condition since cooling effects by natural convection had a negligible effect. For this simplified analysis, no conduction between the sensors and the walls were considered or axial conduction within the RDE for short duration.

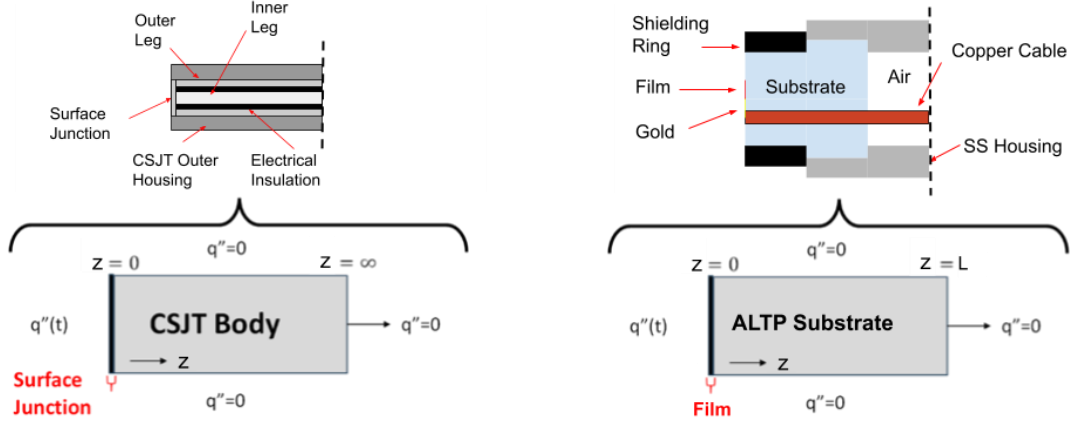


Fig. 14 1-D FDM physic domain simplification of E-Type CJST (Left) and SrTiO3 substrate ALTP (Right). Thickness of Electrical insulation in CSJT exaggerated for clarity.

To perform a 1-D heat transfer analysis, the geometry of both the CSJT and ALTP were simplified. For the CSJT, the annular configuration of materials means that the heat conduction is inherently multi-dimensional. However, the outer chromel P* and inner constantan legs share a very similar thermal product. By neglecting the thin electrical insulation and taking an average of the material properties between the thermocouple legs, the CSJT body is then approximately representative of 1-D heat transfer. On top of the simplified CSJT body is a uniform and thin vapor-deposited chromium junction.

Due to the sub micrometer thickness, the temperature history in the substrate is nearly identical without the active film. For this reason, a multi-dimensional conduction calculation within the ALTP is nearly the same as if the active surface spans the entire substrate surface. By neglecting the gold, thin copper cable and focusing on the conduction near the center of the sensor, a geometry simplification is made to proceed with analysis. The 100-500 nm protective film was also not included in the modeling due to negligible impact on thermal conduction from its size and unavailability of specified materials used. The modeled ALTP dimensions of interest were estimated based on published data from the ALTP manufacturer [33]. To compare results directly to a combustor wall experiencing the same freestream conditions, the heat conduction was performed for a transient 1-D radial coordinate system.

	RDE Wall	ALTP/CSJT
Internal Cells	$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) \quad \{r_i < r < r_o\}$	$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) \quad \{0 < z < L\}$
Hot-side BC	$q''(t)$	
Cold-side BC	$q'' = 0$	
Initial Condition	$T = 20^\circ C$	

Table 2. 1-D FDM Governing equations for simplified combustor wall and sensors

Material	$k \left[\frac{W}{m-K} \right]$	$c_p \left[\frac{J}{kg-K} \right]$	$\rho \left[\frac{kg}{m^3} \right]$	$\beta \left[\frac{KJ}{m^2 \sqrt{sec-K}} \right]$
Stainless Steel 304	16.2	490	7930	7.93
SrTiO3 [34,35]	12	594	5100	6.03
ALTP Film (YBCO) [33,36,37]	1.5	370	6680	1.93
Chromel	17.2	448	8730	8.2
Chromium	69.1	461	7190	15.13
Constantan	22.6	393	8860	8.87

Table 3. Room temperature properties of analyzed materials

A preliminary sensitivity analysis was performed by applying experimental CSJT temperature measurements as a transient temperature boundary condition within the solver. Here the percent difference in cycle averaged heat flux was compared by evaluating material properties at the different thermocouple legs and their average. From the results, the resulting heat flux is nearly identical for evaluating the material properties at either of the thermocouple legs and their average. This result indicates that the previous analysis simplifications are sufficient to follow for the E-type CSJT.

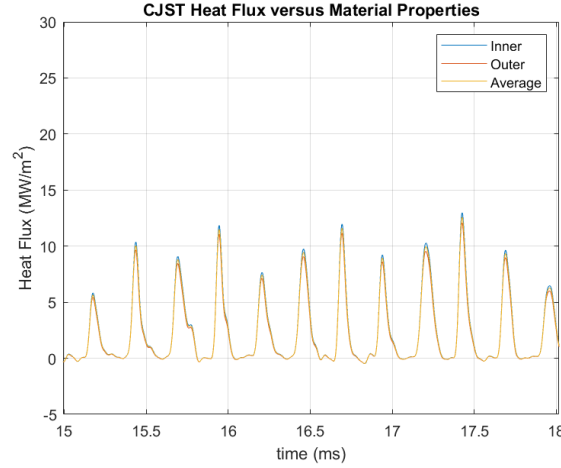


Fig. 15 Calculated CSJT Heat flux from test 061 (1 lbm/s nearfield) using simplified 1-D domain

To resolve high temperature gradients, a non-uniform grid was used to concentrate elements near the surface with an exponential increase in element size after. At the same time, a dynamic time stepping technique based on the hot-side heat flux was used to ensure accuracy of capturing the heat flux by the detonation wave. The timestep was calculated to ensure that the relative increase in heat flux did not exceed the criterion in Eq. 10.

$$\left| \frac{q''(t_{n+1}) - q''(t_n)}{q''(t_n)} \right| \leq \varepsilon \quad (10)$$

Due to the periodic nature of the heat flux boundary condition, the heat flux profile was first computed at the IC and used to evaluate timesteps within a single wave period. This profile was then repeated until reaching the target simulation time. To provide unconditional stability under variations in timestep and large heat fluxes, the Crank-Nicolson method for second order temporal accuracy was used. To account for changes in material properties due to temperature, thermal properties for the future timestep were evaluated at the current temperature and underwent a convergence loop to linearize the discretized PDE at each iteration. Below, the solution process for the 1-D transient conduction code is presented in Fig. 16.

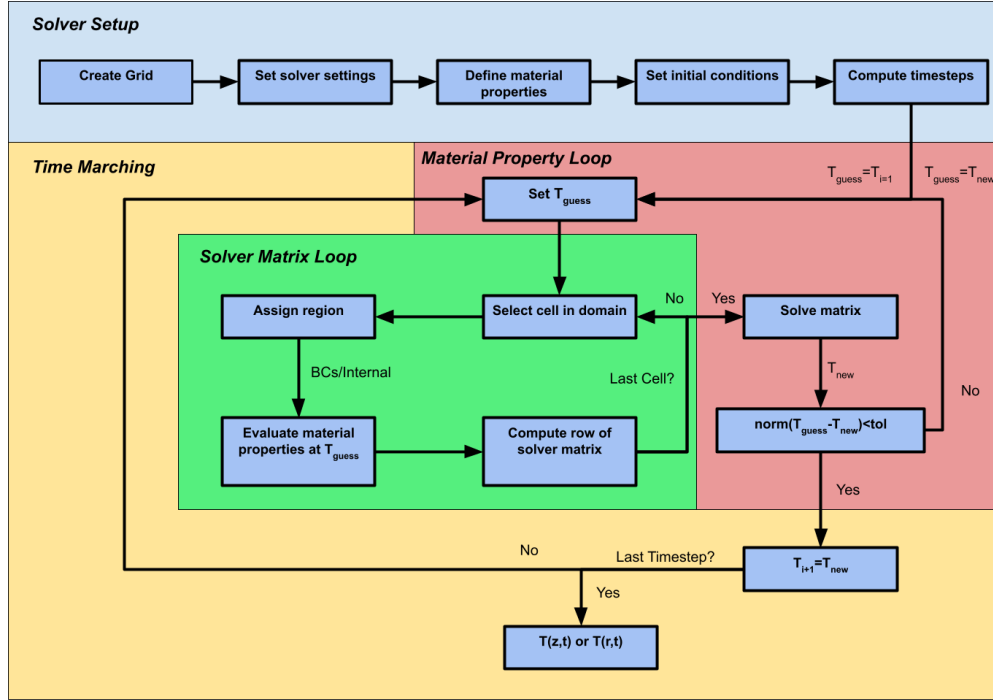


Fig. 16 Solution process of 1-D transient conduction code

For the short duration hot fires, the theoretical sensor surface temperatures were compared to the calculated inner wall temperatures. In each temperature plot, temporal oscillations of surface temperature due to the passing detonation wave are visible. Due to the low thermal conductivity of the YBCO film in the ALTP, the magnitude of temperature oscillation is much greater than the stainless-steel combustor wall and CSJT junction. At each wave passing, the temperature profile follows a similar shape with a slight shift upwards as the internal temperature rises in the sensors and combustor wall.

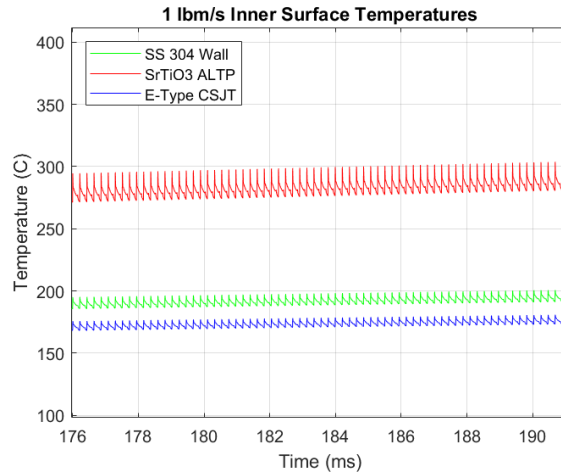


Fig. 17 Temporally resolved oscillations in calculated wall and sensor surface temperatures due to detonation wave

Across all RDE flow rates, the ALTP film temperature was much greater than the wall as seen in Fig. 18. This result was expected due to the much lower thermal product of the ALTP substrate. On the other hand, the E-type CSJT matched closely with the wall for the entire duration due to the thermal product being similar between the average thermocouple materials. For the CSJT, the percent error increased quickly at the start before reaching a maximum just below 10% and steadily decreasing thereafter. The percent error for the ALTP on the other hand continued to increase

without hitting a maximum within the simulated test duration due to the lower thermal product. Although the thermal product is not much lower at room temperature, SrTiO₃ thermal conductivity drops rapidly with increases in temperature [34]. This results in greater discrepancies due to the increase in thermal product of stainless steel with higher temperatures. As the mass flow rate increased, greater heating rates were experienced in the RDE nearfield and resulted in greater discrepancies for the ALTP at the end of the 300 ms hot-fire duration. The CSJT on the other hand reached its same maximum percent error sooner than the 1 lbm/s case and again decreased thereafter. Without any active cooling on the RDE this error is expected to increase over time but represents a reasonable estimate for preliminary design of stainless steel RDE hardware. If another material was used in the combustor outer body, a different thermocouple type would need to be selected to match the thermal product for similar results.

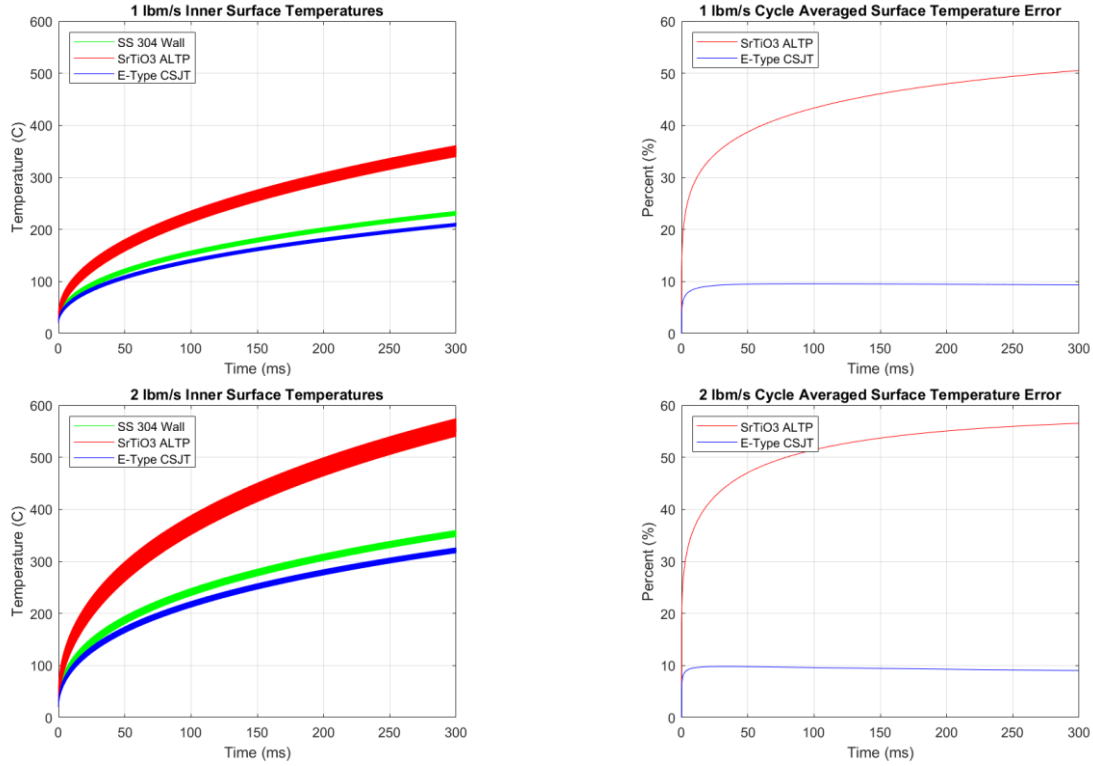


Fig. 18 Calculated wall and sensor surface temperatures in RDE nearfields (Left). Calculated percent errors sensors would exhibit if attempting to measure cycle average wall surface temperature due to thermal properties differences (Right).

Next, the heat flux into each sensor was determined from the 1-D transient heat conduction calculation to understand their errors in predicting the heat flux into the RDE combustor wall. Although time-resolved heat flux is the focus of this paper and efforts towards development of RDE heat transfer correlations, the time response characteristics of the ALTP have already been experimentally demonstrated to provide greater temporal resolution than the CSJT. To eliminate the dependency of time constant for comparing sensor performance, the cyclic averaged heat flux values were instead calculated to focus on the importance of matching thermal properties with the wall.

$$\bar{q}'' = \frac{1}{\tau} \int_{t_i}^{t_i+\tau} q''(t') dt' \quad (11)$$

As expected from the sensor surface temperature results in Fig. 18, the cycle averaged heat flux into the E-type CSJT was closer to the combustor than ALTP heat flux in Fig. 19. Although clear asymptotic behavior was not observed in either of the sensors at either flow rate, the CSJT was observed to nearly asymptote under 3% and 4% error for 1 and 2 lbm/s respectively. On the other hand, the heat flux into the ALTP sensor experienced errors up to 11% and 19% for the 1 and 2 lbm/s cases with clear indication of greater percent errors during longer hot-fire durations.

This large increase in error ALTP heat flux was expected as the surface temperature continued to climb higher than the combustor wall and CSJT surface temperatures.

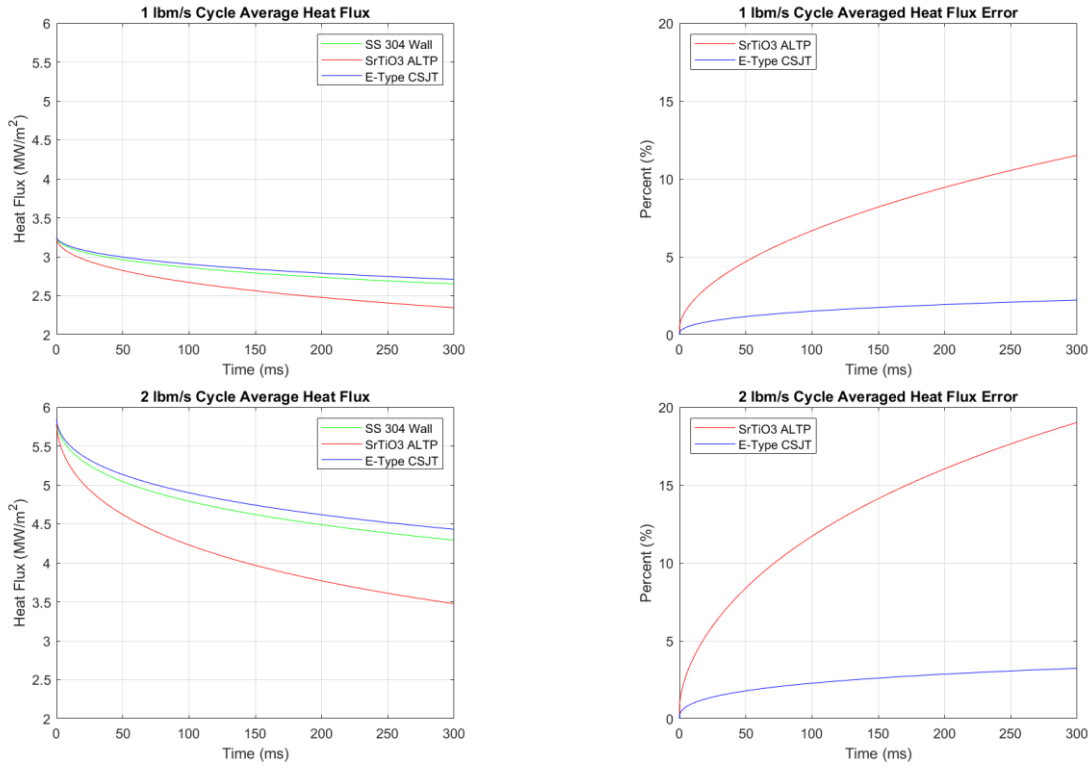


Fig. 19 Calculated wall and sensor surface cycle averaged heat flux in RDE nearfields (Left). Calculated percent errors sensors would exhibit if attempting to measure cycle average wall surface heat flux due to different evolution of surface temperatures (Right).

By conducting these calculations on the ALTP, additional information has also been provided for interpreting experimental data. Even at lower flow rates in the refill region of the RDE, the ALTP film reaches upwards of 350-550°C. These temperatures are beyond the recommended continuous operating range for YBCO films due to possible oxygen loss and large variations in physical properties. In Fig. 19, the heat flux measured by the sensor was predicted to decrease with time as the temperature difference between the RDE hot gas and the film temperature also decreased. However, the experimental data collected in the nearfield ALTP showed a slight increase in heat flux with time in Fig. 11. When compared with experimental data, it becomes evident that the increase in heat flux measured by the ALTP with time was likely attributed to the increase in sensitivity coefficient with temperature. Due to the large difference in experimental and theoretical cyclic averaged heat fluxes, the unaccounted changes in sensitivity coefficient were observed to have a strong and non-negligible effect. When compared directly to experimental data in Fig. 20, the cycle averaged heat flux begins nearly the same, but the unaccounted-for increase in sensitivity coefficient of the sensor results in a growing error from the calculated heat flux. Future studies will seek to characterize the ALTP sensitivity coefficient increase with film temperature and any impacts due to protective films.

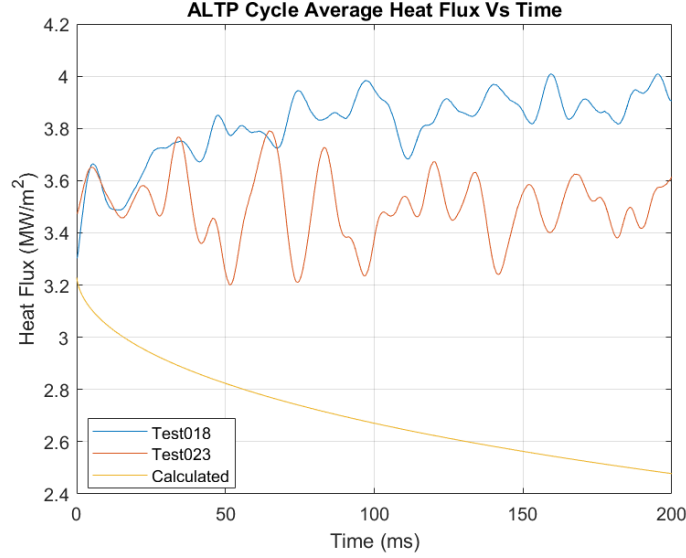


Fig. 20 Discrepancies in calculated versus experimental ALTP cycle averaged heat flux (smoothed) due to differing thermal products and assumption of constant sensitivity coefficient

VII. Conclusion

From this project, combined analysis between ALTP and CSJT experiments in a gaseous RDE has provided new insight into the temporally and spatially resolved diagnostic techniques needed for further development of analytical heat transfer models. To validate these models, a series of CSJT experiments were able to measure the THOR RDE wall temperature during a series of 300 ms hot fire experiments for comparison back to proprietary RDRE heat transfer correlations. Within this paper, the finite difference method was then used to solve the 1-D transient conduction within the CSJT sensors and demonstrate its close approximation to combustor wall temperature. From the analysis, the SrTiO₃ ALTP was demonstrated to have experienced non-negligible under-prediction errors up to 19% in heat flux measurement due to the differences in thermal products and surface temperature with the combustor wall. Furthermore, the experimental over-prediction during conversion between ALTP voltage and heat flux was further troubled by the unaccounted-for increase in sensitivity coefficient with film temperature due to a lack of publicly available data. Together, these two findings indicate that a correct measurement of temporally and spatially resolved RDRE heat flux with an ALTP must be done with understanding of the film temperature and its relationship to sensitivity coefficient.

The ALTP sensor within the experiments contains cooling ports that provide future opportunities for the study of temporally and spatially resolved heat flux of an RDE at steady state. If the ALTP film temperature is set to match the combustor wall temperature by varying the cooling heat flux, then the discrepancies in heat flux into the sensor by differences in material properties would be eliminated. To achieve the cooling effect, a higher thermal conductivity substrate such as MgO, should be selected to maintain the film temperature below the damage threshold. By focusing on the development of a methodology for spatially and temporally resolved heat flux measurements in steady state operation, validation of heat transfer correlations will become simplified and no longer encounter uncertainties due to start-up transients.

VIII. References

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