Temperature and Heat-Flux Measurements in a Thin-Wall RDE.

Christopher A. Stevens, Matthew L. Fotia, and John L. Hoke
Innovative Scientific Solutions Inc., Dayton, Ohio, USA 45459

and

S. Alex Schumaker and Garth B. Wilks
Air Force Research Laboratory, Wright-Patterson AFB, Ohio, USA 45433

1 Thermal Management in Rotating Detonation Engines

Thermal management remains one of the more difficult challenges facing the development of practical Rotating Detonation Engines (RDEs). Data on the heat transfer environment within an RDE remains limited. Published results so far have focused on cold wall or transient heat transfer [1-7]. The results have shown some interesting phenomena such as circumferential and axial variation of the wall temperature [8] and produced an accurate if poorly resolved estimate of the bulk heat transfer in both the center-body and outer-body of a hydrogen fueled RDE. Despite prior efforts, data at higher wall temperatures remains sparse.

In this work, a thin-walled, stainless steel RDE was constructed to fill in some to the gap. The walls of the RDE were 3.18 mm thick. This reduced the temperature difference between the inner and outer walls and reduced the thermal mass of the center-body and outer-body. However there was sufficient thickness to prevent prompt failure (bursting) until well after erosion commenced on the inner wall of the outer body which allowed for safe shutdown after erosion began.

Correspondence to: christopher.stevens.17.ctr@us.af.mil

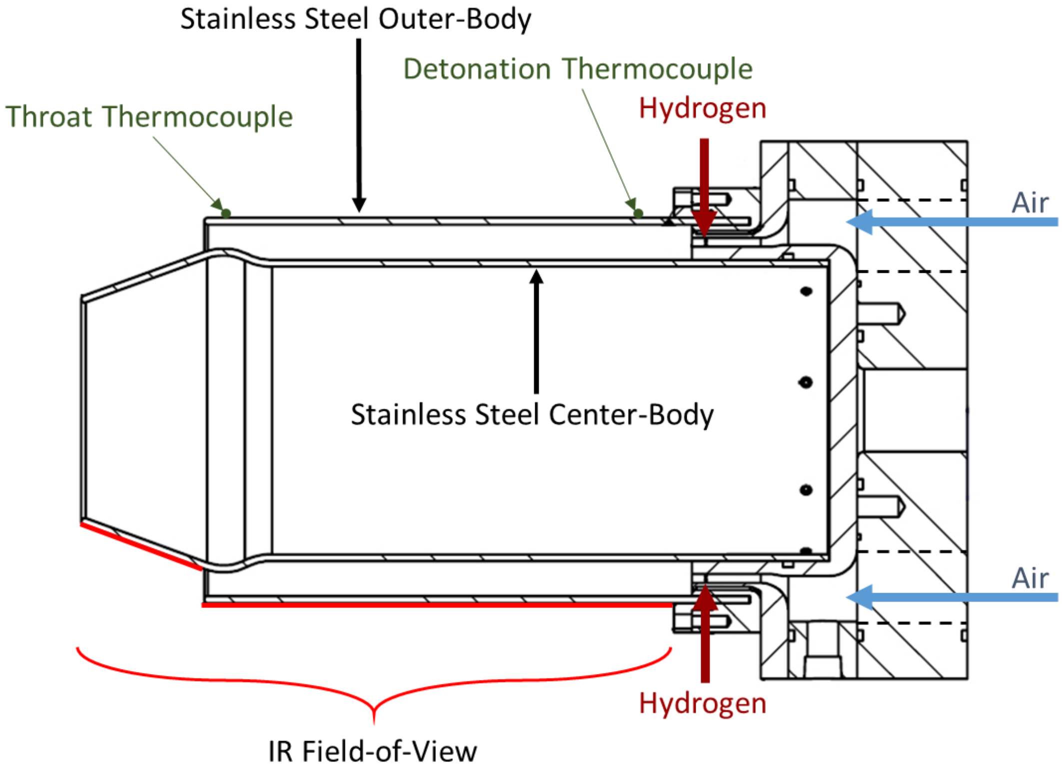


Figure 1. Section View of Thin-Walled RDE.

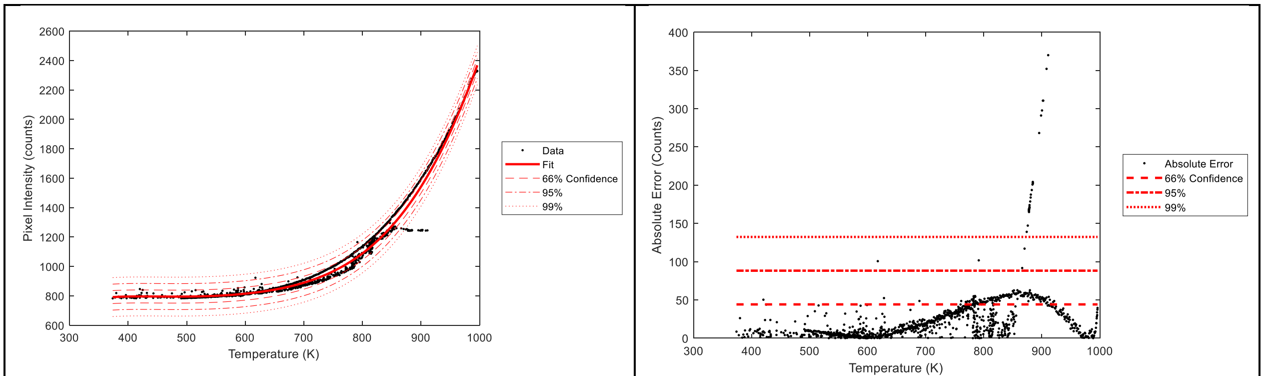
The RDE was operated on a hydrogen/air mixture at independently controlled flowrate and equivalence ratio. The flow rate was between 0.5 lbm/s (0.23 kg/s) and 3.0 lbm/s (1.36 kg/s), and the equivalence ratio was between 0.67 and 1.0. In most cases, the run was terminated automatically before reaching either the damage threshold of the walls, or steady state. One steady state run was conducted, and one run resulted in damage to the RDE due to a computer failure.

The data show that the heat fluxes are smaller compared to cooled walls while the temperatures are predictably higher. The result is less energy loss from the combustion products, and reduced need for active cooling at the cost of reduced damage margin. Thermal imaging showed both circumferential and axial variation in the wall temperature. The hottest spots occurred about 25 mm downstream of the fuel injection, and a cooler hot spot near the trailing edge of the outer-body. The locations of the two hot spots did not change significantly with flow rate in either the axial or circumferential directions which suggests a geometry dependence. But without data from multiple wave-number modes, it is impossible to say that the hot spots are fixed.

The results of this work imply that hotter channel walls are preferred in RDEs so long as the chance of failure remains low. Energy loss the walls of the detonation channel was less than in previous cooled wall tests. The observed failure mechanism was erosion of the channel wall. This is likely due to melting of the stainless steel similar to that observed in prior work. A 3.17 mm wall thickness was sufficient to allow shutdown between the onset of erosion and the prompt failure of the outer-body. An unwelcome, but expected result was plastic deformation of the outer-body and center-body at their respective attachment points due to the vast difference in temperature between the two parts.

2 Temperature Imaging Technique

Measurements of the temperature and heat flux were obtained via thermocouples and infra-red imaging. Two thermocouples were welded to the outer body one located 25 mm downstream of the beginning of the channel, and one 25 mm upstream of the trailing edge of the outer-body. The infra-red camera was placed to capture an unimpeded view of one side of the outer-body with as little spatial distortion as possible, and was employed for some of the higher flow rates to examine the spatial variation of temperature and heat flux. The camera was calibrated in-situ using both of the thermocouples to produce a single calibration curve (Figure 2a). The curve fit agrees well with the thermocouple data with a 95% confidence interval of 88 counts. The infra-red camera was not used at low flows and short run-times because the outer-body was not hot enough to exceed the noise floor of the camera.



(a) (b)

Figure 2. Curve Fit (a) and Absolute Error (b) of Sample Thermographic Data

Using the thermographic technique, the temperature of roughly half of the outer body was captured in each frame of the infra-red video. This allows both spatial and temporal analysis of the heat flux with spatial resolution of 0.05 cm and temporal resolution of 0.5 seconds. In Figure 3, there are clear regions of higher temperature near the base of the outer-body and near the training edge. These correspond to the detonation and nozzle throat respectively.

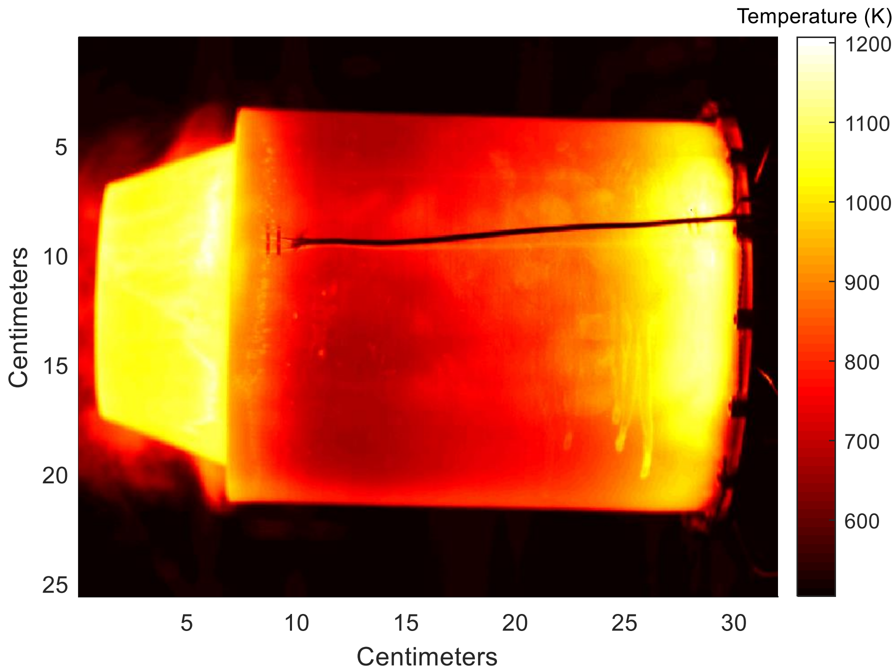
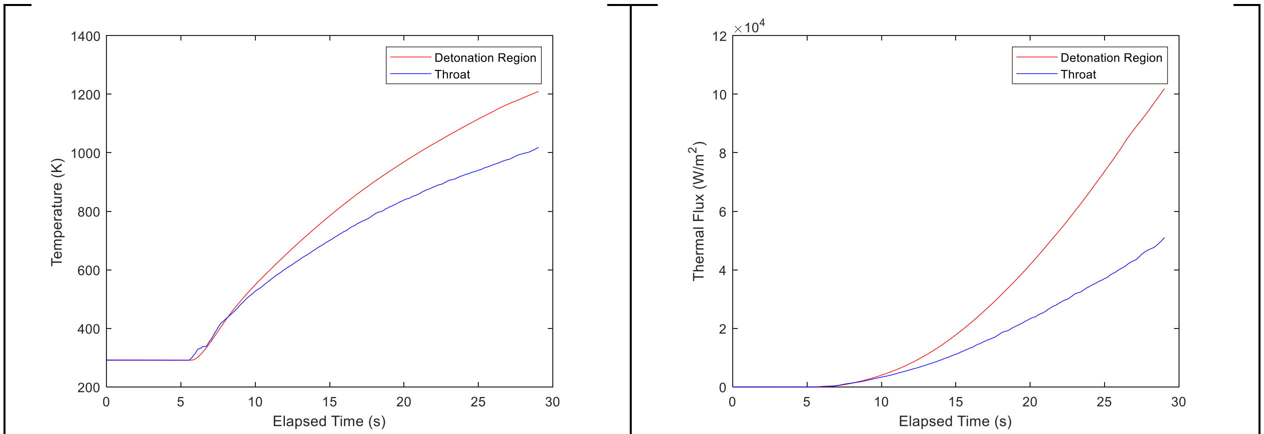


Figure 3. Sample Surface Temperature Image.

3 Heat Transfer

The thermocouple measurements of outer-body temperature were place where higher temperatures were expected. This gave better accuracy when calibrating the thermographic imaging. The thermocouple histories are also useful for studying the temporal changes in heat temperature and heat flux. Figure 4 shows that over the 20 seconds of operation of the RDE, the temperatures at both the detonation and nozzle throat begin to approach asymptotes, but do achieve equilibrium. The detonation region was 16% hotter than the nozzle at 1206K. Longer run durations were avoided to prevent damage to the hardware.



(s)	(b)

Figure 4. Histories of Temperature and Thermal Flux.

The temperature image in Figure 3 shows that the detonation region thermocouple was very close to a hot spot on the outer body. In good agreement with prior work [8] the temperature varies around the circumference of the outer-body. The high and low temperature differ by 180 K and there will be significant impacts on thermal stress and oxidation due to the variation.

The heat fluxes were calculated from a one-dimensional radiation model for each image pixel. The trends are identical to the temperature trends with higher fluxes associated with the nozzle throat and the detonation region. The peak flux was 102 kW/m^2 while the average was 25 kW/m^2. The environment surrounding the RDE contains significant entrained air flow which was not accounted for in this effort. As a result the true thermal flux is larger than indicated by the radiation calculation alone.

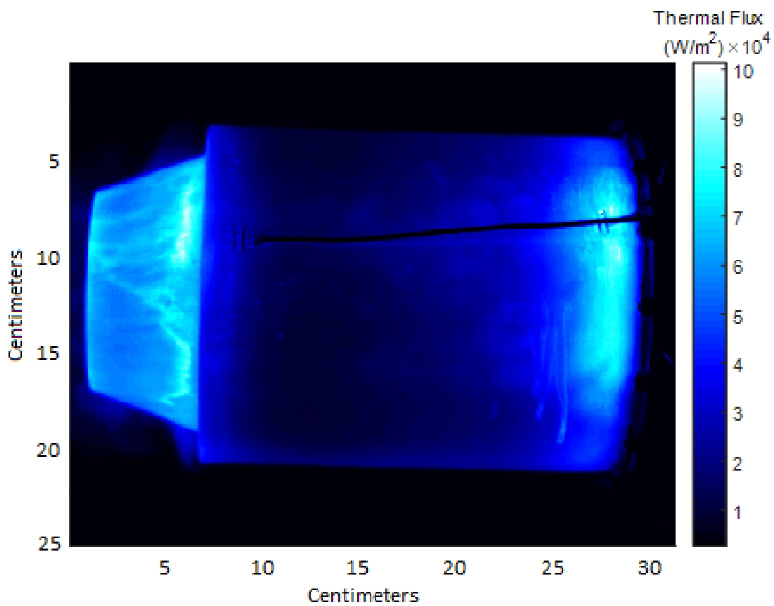


Figure 5. Thermal Flux of the Outer-Body at 24.66s.

4 Future Steps

In this work, a thermography technique was developed using a calibrated infra-red camera. Temperatures were measured over half of the outer-body or an RDE and thermal fluxes were calculated with good spatial and temporal resolution. In the future, further development of the flux model will yield an estimate of the convection coefficient inside the detonation channel, and further testing over a suite of mass flow and equivalence ratio will establish a larger data set of convection coefficient for elevated wall temperatures.

References

[1] Stevens, C., Fotia, M., Hoke, J., Schauer, F., "Quasi-Steady Heat Transfer Measurements in an RDE." 2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, Kissimmee, FL, January, 2018, AIAA 2018-1884.

[2] Naples, A., Hoke, J., Battelle, R., Wagner, M., Schauer, F. "RDE Implementation into an Open-Loop T63 Gas Turbine Engine." 53rd AIAA Aerospace Sciences Meeting, Grapevine, TX, January 2017, AIAA 2017-1747.

[3] Theuerkauf, S.W., King, P.I., Schauer, F.R., and Hoke, J.L. "Thermal Management for a Modular Rotating Detonation Engine." 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, January 2013, AIAA 2013-1176.

[4] Theuerkauf, S.W., Schauer, F.R. Anthony, R. and Hoke, J.L. "Average and Instantaneous Heat Flux to the Wall of an RDE." 52nd Aerospace Sciences Meeting, National Harbor, MD, January 2014, AIAA 2014-1503.

[5] Theuerkauf, S.W., Schauer, F.R., Anthony, R., Paxson D.E., Stevens, C.A., and Hoke, J.L. "Comparison of Simulated and Measured Instantaneous Heat Flux in a Rotating Detonation Engine." 54th AIAA Aerospace Sciences Meeting, San Diego, CA, January 2016, AIAA 2016-1200.

[6] Meyer, S.J., Polanka, M.D., Schauer, F.R., Anthony, R.J., Stevens, C.A., Hoke, J.L., and Rein, K.D. "Experimental Characterization of Heat Transfer Coefficients in a Rotating Detonation Engine." 55th AIAA Aerospace Sciences Meeting, Grapevine, TX, January 2017, AIAA 2017-1285.

[7]. Ishihara, K., Nishimura, J., Goto, K., Nakagami, S., Matsuoka, K., Kasahara, J., Matsuo, A., Funaki, I., Moriai, H., Mukae, H., Yasuda, K., Nakata, D., and Higashino, K. "Study on a Long-Time Operation Towards Rotating Detonation Rocket Engine Flight Demonstration." 55th AIAA Aerospace Sciences Meeting, Grapevine, TX, January 2017. AIAA 2017-1062.

[8] Stevens, C.A., Fotia, M.L., Hoke, J.L., Schauer, F.R., "An Experimental Comparison of Inner and Outer Wall Heat Flux in an RDE." 2019 AIAA SciTech Forum, San Diego, CA January 2019, AIAA 2019-1252.