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14. ABSTRACT
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# RPPR Final Report

## as of 13-Jul-2022

Agency Code: 21XD

Proposal Number: 75723EGRIP

Agreement Number: W911NF-20-1-0068

### INVESTIGATOR(S):

**Name:** Ronald Hanson  
**Email:** rkhanson@stanford.edu  
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**Principal:** Y

Organization: **Stanford University**

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Country: USA

DUNS Number: 009214214

EIN: 941156365

**Report Date:** 31-Jul-2022

Date Received: 12-Jul-2022

**Final Report** for Period Beginning 01-May-2020 and Ending 30-Apr-2022

**Title:** Laser and Imaging Systems for the Study of High-Temperature Laminar Flames in Shock Tubes

**Begin Performance Period:** 01-May-2020

**End Performance Period:** 30-Apr-2022

**Report Term:** 0-Other

Submitted By: Ronald Hanson

Email: rkhanson@stanford.edu

Phone: (650) 723-1745

**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

**STEM Degrees:** 1

**STEM Participants:**

**Major Goals:** The Hanson Research Group at Stanford University acquired the following laser and imaging equipment to enable transformational advances in state-of-the-art studies of the speed and structure of laminar flames at high-temperature, engine-relevant conditions:

1. High-Energy Pulsed Laser for Igniting Laminar Flames in a Shock Tube
2. Imaging and Laser Systems for Multi-Spectral, Multi-Species Imaging of Flame Structure

The equipment has had an immediate impact on the pace of combustion research by supporting the highest-ever-temperature studies of laminar flames, covering the entire engine-relevant regime of temperatures. Additionally, the equipment has helped refine the shock-tube flame speed method, enabling study of non-ideal flame behavior and confinement effects.

In order to address the dire lack of experimental flame data at elevated temperatures, the Hanson Research Group recently developed and validated a novel technique for measuring flame speeds in a shock tube. The nature of a shock tube, acting as an impulse heater, allows the study of flames at temperatures above which the mixture is spontaneously reactive, a criterion which has historically imposed an upper limit of around 550 K on flame speed measurements. Using the game-changing shock-tube technique, a demonstration of flame speed measurements in transportation-relevant fuels up to nearly 900 K was made for the first time. The combined value of the equipment acquired using this award has provided the Hanson Research Group in-house capabilities to continue the study of flames at high-temperature conditions and greatly advance the diagnostic capabilities available to characterize engine-relevant flame phenomena. The research facilitated through this award has greatly advanced the field of experimental combustion research by providing the first fundamental studies of flame dynamics at unexplored conditions of immediate relevance to advanced combustion systems (temperatures >1,100 K).

**Accomplishments:** The laser systems provided for in this DURIP established a critically important capability for generating and studying flames in our shock tube facility, greatly increasing both the quality and quantity of experimental data we can produce. In particular, an Nd:YAG ignition laser and laser attenuator provide significantly enhanced control of the ignition energies, an important capability for near-threshold flame studies relevant to over-driven and cool-flame phenomena, while a 355-nm laser provides the formaldehyde-PLIF capability that will be required to conclusively identify the presence of cool flames. To date, our studies using the shock-tube flame speed method, developed under ARO funding, have produced the highest-ever-temperature flame speed measurements (exceeding 1,100 K).

The new imaging system and highly optically accessible test section provided for in this grant have already begun providing critical and game-changing insights into shock-tube experiments. Our new shock tube is the first of its

## RPPR Final Report as of 13-Jul-2022

kind, utilizing cylindrical, cemented-doublet side-wall windows to provide schlieren-compatible optical access to the core of the shock tube. With this capability, along with end-wall imaging access, flexible ignition laser positioning, and line-of-sight absorption diagnostics, we are able to perform multi-diagnostic studies of both conventional ignition experiments and novel flame speed studies. The new imaging system is a force-multiplier when combined with the enhanced imaging access, allowing simultaneous multi-spectral, multi-perspective, or multi-diagnostic imaging where repeated experiments with each diagnostic would have previously been necessary. In this way, the cost, complexity, time requirement, and uncertainty of experiments are all simultaneously reduced, increasing the quality and quantity of the research outcomes that can be produced.

Multiple publications have resulted from this award, including work reporting laminar flame speed measurements of primary reference fuels at extreme temperatures, investigating end-wall effects on freely propagating flames in a shock tube, and a Ph.D. dissertation on high-speed imaging studies of flames in a shock tube.

**Training Opportunities:** Graduate students are performing the research portion of this project and are therefore directly learning the experimental skills related to acquiring and analyzing the relevant data, including use of shock tubes, laser absorption diagnostics, image processing algorithms, etc. Ph.D. students are responsible for presentations and publication of their research, with review by the PI. Graduate students involved in the current reporting period include:

- Adam Susa, Ph.D., graduated
- Lingzhi Zheng, Ph.D., current

**Results Dissemination:** Results have been disseminated through publications and conference presentations, including a presentation at the 2022 AIAA SciTech Forum in San Diego, California. A paper will also be presented at the upcoming ASME ICEF 2022 Internal Combustion Engine Division Fall Technical Conference in Indianapolis, IN.

Additionally, we have pursued collaborations with colleagues external to Stanford University to facilitate direct dissemination of results and collaboration:

Flame speed studies conducted using instrumentation acquired through this award are part of an ongoing collaboration with the ARO-supported lab of Prof. Yiguang Ju at Princeton University. The collaboration involves efforts to use numerical simulations to explain the negative temperature dependence of n-heptane flame speeds observed in our lab at high temperatures.

**Honors and Awards:** 2022 – R.K. Hanson, Distinguished Fellow of the International Shock Wave Institute (ISWI)

**Protocol Activity Status:**

**Technology Transfer:** Nothing to Report

### PARTICIPANTS:

**Participant Type:** PD/PI

**Participant:** Ronald Hanson

**Person Months Worked:** 1.00

Project Contribution:

National Academy Member: Y

**Funding Support:**

**Participant Type:** Graduate Student (research assistant)

**Participant:** Adam Susa

**Person Months Worked:** 2.00

Project Contribution:

National Academy Member: N

**Funding Support:**

**Participant Type:** Graduate Student (research assistant)

**RPPR Final Report**  
as of 13-Jul-2022

**Participant:** Lingzhi Zheng

**Person Months Worked:** 1.00

Project Contribution:

National Academy Member: N

**Funding Support:**

**CONFERENCE PAPERS:**

**Publication Type:** Conference Paper or Presentation

**Publication Status:** 1-Published

**Conference Name:** AIAA SCITECH 2022 Forum

Date Received: 12-Jul-2022

Conference Date: 03-Jan-2022

Date Published: 29-Dec-2021

Conference Location: San Diego, CA & Virtual

**Paper Title:** End-Wall Effects on Freely Propagating Flames in a Shock Tube

**Authors:** Adam Susa, Lingzhi Zheng, Zach Nygaard, Ronald Hanson

Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation

**Publication Status:** 3-Accepted

**Conference Name:** ASME Internal Combustion Engine Division Fall Technical Conference (ICEF 2022)

Date Received: 12-Jul-2022

Conference Date: 16-Oct-2022

Date Published:

Conference Location: Indianapolis, Indiana

**Paper Title:** Laminar flame speed measurements of primary reference fuels at extreme temperatures

**Authors:** Adam Susa, Lingzhi Zheng, Zach Nygaard, Alison Ferris, Ronald Hanson

Acknowledged Federal Support: **Y**

**DISSERTATIONS:**

**Publication Type:** Thesis or Dissertation

**Institution:** Leland Stanford Junior University

Date Received: 12-Jul-2022

Completion Date: 6/1/22 3:15AM

**Title:** High-speed imaging studies of flames in a shock tube: refined techniques and new applications

**Authors:** Adam Susa

Acknowledged Federal Support: **Y**

**Partners**

,

**RPPR Final Report**  
as of 13-Jul-2022

I certify that the information in the report is complete and accurate:

Signature: Ronald K. Hanson

Signature Date: 7/12/22 4:50PM

**Project Summary - Grant # W911NF2010068  
(Reporting Period: May 1, 2020 – April 30, 2022)**

**Laser and Imaging Systems for the Study of High-Temperature Laminar Flames in Shock Tubes**

Ronald K. Hanson  
Mechanical Engineering Department  
Stanford University, Stanford, CA, 94305

**Objective**

The Hanson Research Group at Stanford University acquired the following laser and imaging equipment to enable transformational advances in state-of-the-art studies of the speed and structure of laminar flames at high-temperature, engine-relevant conditions:

1. High-Energy Pulsed Laser for Igniting Laminar Flames in a Shock Tube
2. Imaging and Laser Systems for Multi-Spectral, Multi-Species Imaging of Flame Structure

The equipment has had an immediate impact on the pace of combustion research by supporting the highest-ever-temperature studies of laminar flames, covering the entire engine-relevant regime of temperatures. Additionally, the equipment has helped refine the shock-tube flame speed method, enabling study of non-ideal flame behavior and confinement effects.

**Approach**

In order to address the dire lack of experimental flame data at elevated temperatures, the Hanson Research Group recently developed and validated a novel technique for measuring flame speeds in a shock tube<sup>1</sup>. The nature of a shock tube, acting as an impulse heater, allows the study of flames at temperatures above which the mixture is spontaneously reactive, a criterion which has historically imposed an upper limit of around 550 K on flame speed measurements. Using the game-changing shock-tube technique, a demonstration of flame speed measurements in transportation-relevant fuels up to nearly 900 K was made for the first time<sup>2</sup>. The combined value of the equipment acquired using this award has provided the Hanson Research Group in-house capabilities to continue the study of flames at high-temperature conditions and greatly advance the diagnostic capabilities available to characterize engine-relevant flame phenomena. The research facilitated through this award has greatly advanced the field of experimental combustion research by providing the first fundamental studies of flame dynamics at unexplored conditions of immediate relevance to advanced combustion systems (temperatures >1,100 K).

**Relevance to Army**

Support from the ARO for the development of advanced shock-tube and diagnostic methods enables our laboratory to provide the ARO with the world's broadest capability and highest quality combustion kinetics and flame research. Flame speed measurements and study of abnormal flame behavior at engine-relevant temperatures will allow enhancement and validation of the predictive capability of engine models and are expected to aid in understanding the dominant physical processes inducing damaging, inadvertent ignition events in engines. Across these areas of study, the inclusion of both conventional, distillate fuels, and candidate alternative (e.g., bio-derived) fuels provides data to both improve current systems and inform next-generation solutions.

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<sup>1</sup> Alison M. Ferris et al., "High-Temperature Laminar Flame Speed Measurements in a Shock Tube," *Combustion and Flame* 205 (2019): 241–52, <https://doi.org/10.1016/j.combustflame.2019.04.007>.

<sup>2</sup> Adam J. Susa et al., "Flame Speed Measurements of Primary Reference Fuels at Elevated Temperatures in a Shock Tube, 2019-0460," in *AIAA Scitech 2019 Forum* (San Diego, California: American Institute of Aeronautics and Astronautics, 2019), <https://doi.org/10.2514/6.2019-0460>.

### **Accomplishments for Reporting Period**

The laser systems provided for in this DURIP established a critically important capability for generating and studying flames in our shock tube facility, greatly increasing both the quality and quantity of experimental data we can produce. In particular, an Nd:YAG ignition laser and laser attenuator provide significantly enhanced control of the ignition energies, an important capability for near-threshold flame studies relevant to over-driven and cool-flame phenomena, while a 355-nm laser provides the formaldehyde-PLIF capability that will be required to conclusively identify the presence of cool flames. To date, our studies using the shock-tube flame speed method, developed under ARO funding, have produced the highest-ever-temperature flame speed measurements (exceeding 1,100 K).

The new imaging system (high-speed camera and ultraviolet intensifier) and highly optically accessible test section provided for in this grant have already begun providing critical and game-changing insights into shock-tube experiments. Our new shock tube is the first of its kind, utilizing cylindrical, cemented-doublet side-wall windows to provide schlieren-compatible optical access to the core of the shock tube. With this capability, along with end-wall imaging access, flexible ignition laser positioning, and line-of-sight absorption diagnostics, we are able to perform multi-diagnostic studies of both conventional ignition experiments and novel flame speed studies. The new imaging system is a force-multiplier when combined with the enhanced imaging access, allowing simultaneous multi-spectral, multi-perspective, or multi-diagnostic imaging where repeated experiments with each diagnostic would have previously been necessary. In this way, the cost, complexity, time requirement, and uncertainty of experiments are all simultaneously reduced, increasing the quality and quantity of the research outcomes that can be produced.

Multiple publications have resulted from this award, including work reporting laminar flame speed measurements of primary reference fuels at extreme temperatures, investigating end-wall effects on freely propagating flames in a shock tube, and a Ph.D. dissertation on high-speed imaging studies of flames in a shock tube.

### **Collaborations and Technology Transfer**

Flame speed studies conducted using instrumentation acquired through this award are part of an ongoing collaboration with the ARO-supported lab of Prof. Yiguang Ju at Princeton University. The collaboration involves efforts to use numerical simulations to explain the negative temperature dependence of n-heptane flame speeds observed in our lab at high temperatures.

### **Research plans for next reporting period**

Nothing to report

### **Resulting Publications During Reporting Period**

1. Adam J. Susa, Lingzhi Zheng, Zach D. Nygaard, Alison M. Ferris, Ronald K. Hanson. Laminar flame speed measurements of primary reference fuels at extreme temperatures. Paper 90501 in *Internal Combustion Engine Division Fall Technical Conference, ICEF 2022* (accepted).
2. Adam J Susa, Lingzhi Zheng, Zach D Nygaard, Ronald K Hanson. End-wall effects on freely propagating flames in a shock tube. In *AIAA SciTech*, Paper 2346, 2022. doi: 10.2514/6.2022-2346.
3. A. J. Susa, "High-speed imaging studies of flames in a shock tube," Ph.D. Dissertation, Stanford University, 2022.

### **Graduate Students Involved During Reporting Period**

Graduate students are performing the research portion of this project and are therefore directly learning the experimental skills related to acquiring and analyzing the relevant data, including use of shock tubes, laser

absorption diagnostics, image processing algorithms, etc. Ph.D. students are responsible for presentations and publication of their research, with review by the PI. Graduate students involved in the current reporting period include:

- Adam Susa, Ph.D., graduated
- Lingzhi Zheng, Ph.D., current

### Awards, Honors and Appointments

- 2022 – R.K. Hanson, Distinguished Fellow of the International Shock Wave Institute (ISWI)

### Additional Figures:

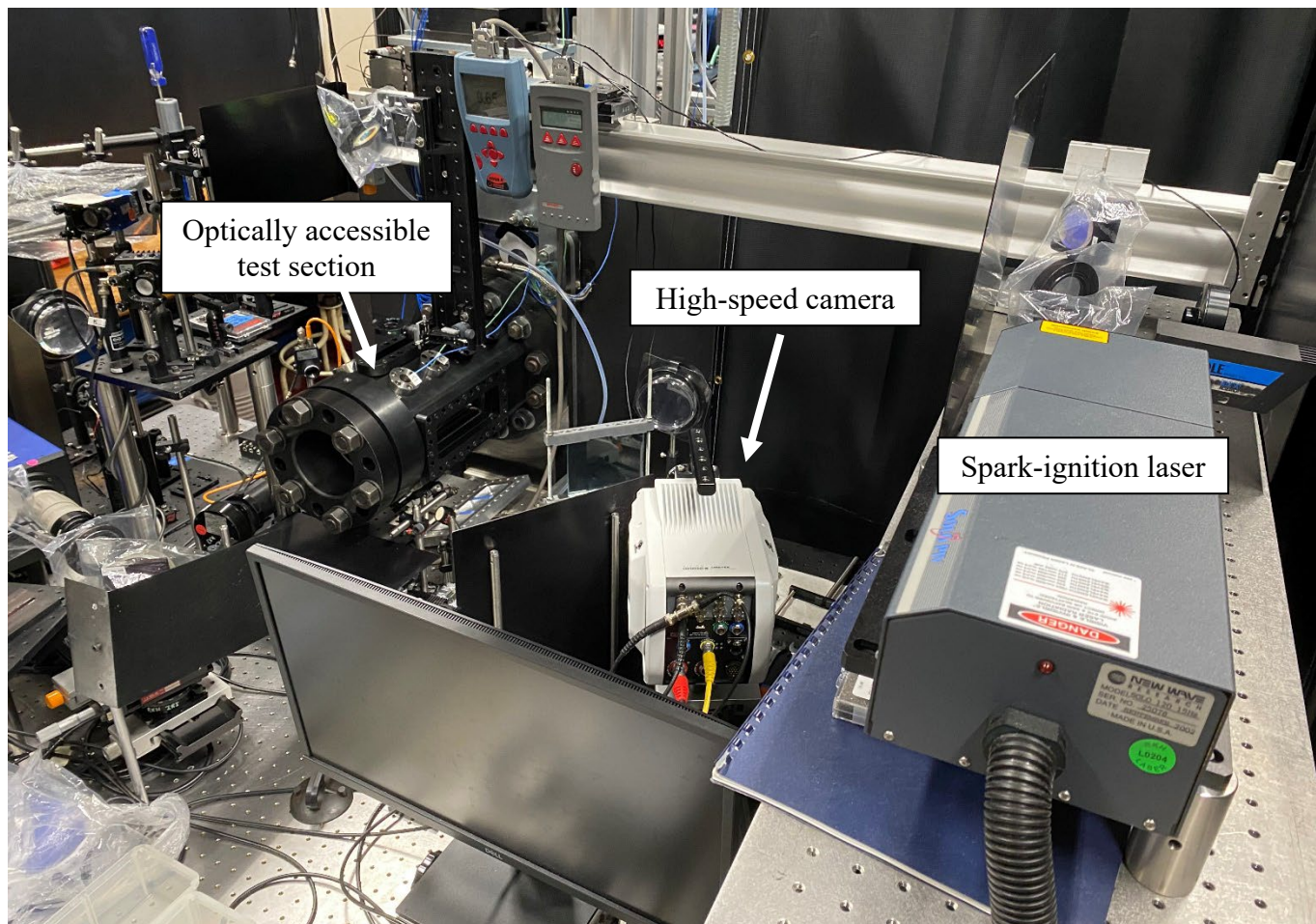


Figure 1. Image of shock tube setup and equipment purchased using this DURIP award

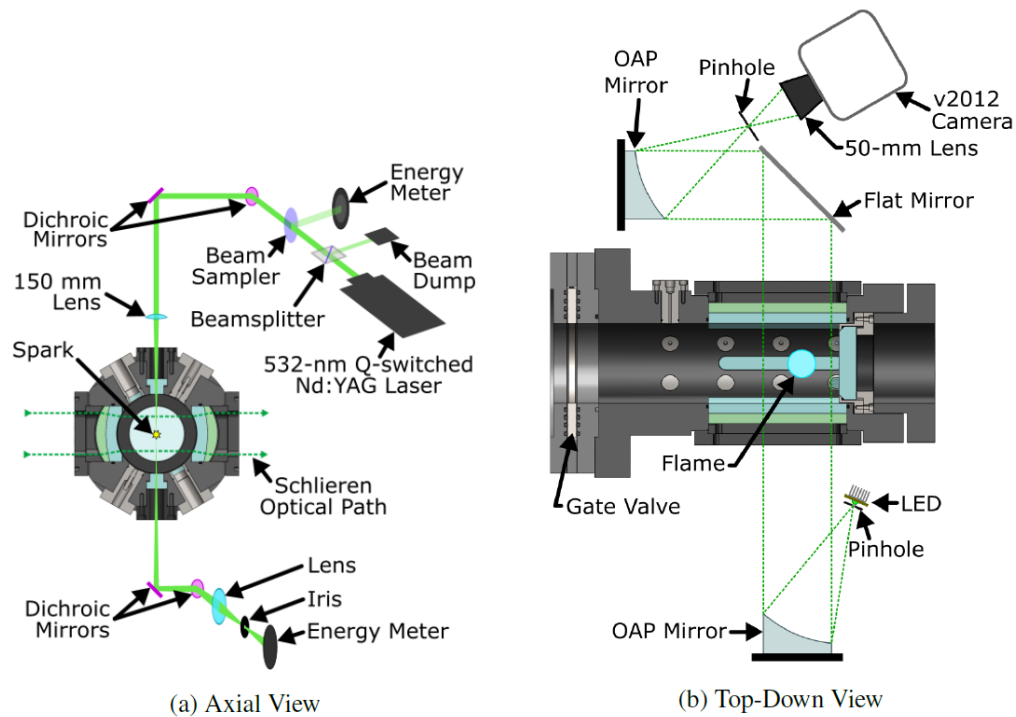


Figure 2. Cross-sectional views of the optically accessible shock tube setup

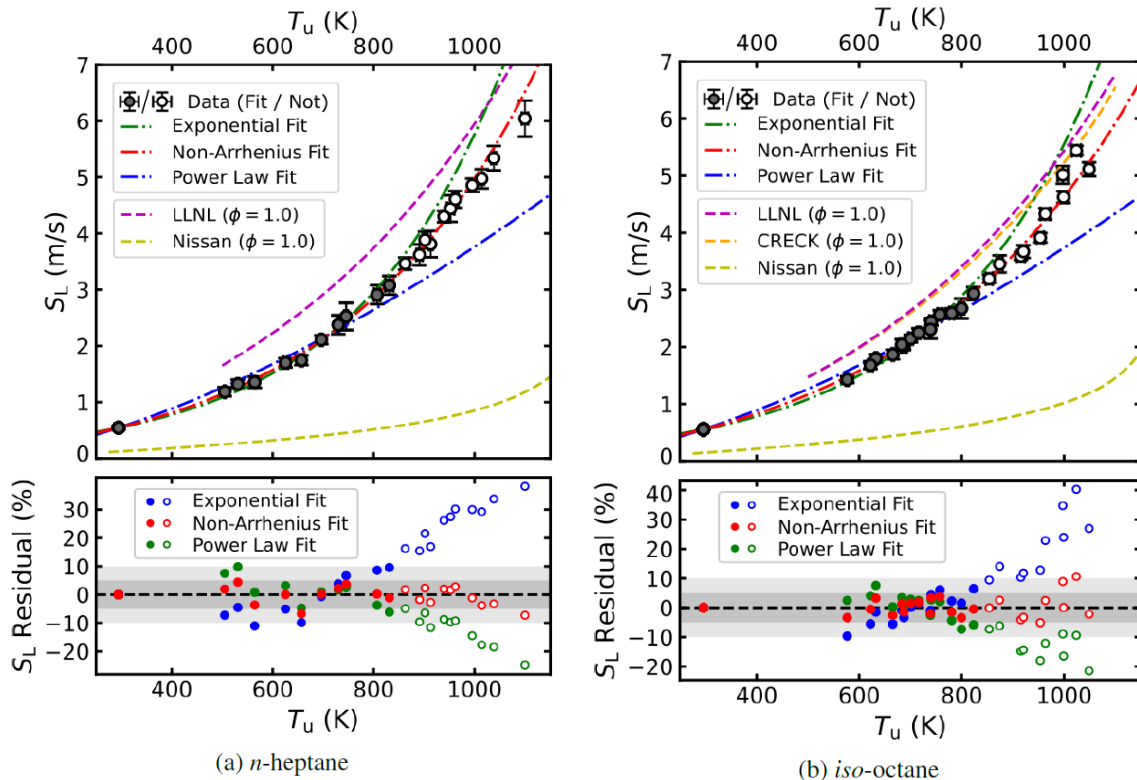


Figure 3. Measured laminar flame speeds, empirical fits, simulation results, and residuals for primary reference fuels *n*-heptane and *iso*-octane (Susa et al., ICEF 2022, *accepted*).