



Effects of Spent Cooling and Swirler Angle on a 9-Point Swirl-Venturi Injector

*Zhuohui J. He, Kathleen M. Tacina, and Chi-Ming Lee
Glenn Research Center, Cleveland, Ohio*

*Robert R. Tacina
Glenn Research Center, Cleveland, Ohio*

*Phil Lee
Woodward FST, Inc., Zeeland, Michigan*

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Fax your question to the NASA STI Information Desk at 443-757-5803
- Phone the NASA STI Information Desk at 443-757-5802
- Write to:
STI Information Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320



Effects of Spent Cooling and Swirler Angle on a 9-Point Swirl-Venturi Injector

*Zhuohui J. He, Kathleen M. Tacina, and Chi-Ming Lee
Glenn Research Center, Cleveland, Ohio*

*Robert R. Tacina
Glenn Research Center, Cleveland, Ohio*

*Phil Lee
Woodward FST, Inc., Zeeland, Michigan*

Prepared for the
8th U.S. National Combustion Meeting
sponsored by the Western State Section, Combustion Institute
Park City, Utah, May 19–22, 2013

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

This research was funded by NASA's High Speed Research (HSR) Fundamental Aeronautics/Aeronautical Sciences programs.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

This work was sponsored by the Fundamental Aeronautics Program at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at <http://www.sti.nasa.gov>

Effects of Spent Cooling and Swirler Angle on a 9-Point Swirl-Venturi Injector

Zhuohui J. He, Kathleen M. Tacina, and Chi-Ming Lee
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Robert R. Tacina*
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Phil Lee
Woodward FST, Inc.
Zeeland, Michigan 49464

Abstract

This paper presents multipoint Lean-Direct-Injection (LDI) emissions results for flame tube combustion tests at an inlet pressure of 1034 kPa and inlet temperatures between 835 and 865 K; these are the combustor inlet conditions that the High Speed Research (HSR) program used for supersonic cruise. It focuses on one class of LDI geometry, 9-point swirl-venturi LDI (SV-LDI). Two parameters are compared in this paper: the use of dome cooling air and the swirler blade angle. Dome cooling air is called “spent cooling” and is at combustor inlet conditions. Three cooling variations are studied: cooling at the venturi throat, cooling at the dome face, and no cooling at all. Two swirler blade angles are studied: 45° and 60°. The HSR 9-point SV-LDI emissions are also compared to a similar 9-point SV-LDI design which was used in the later ultra-efficient engine technology (UEET) program. The HSR and UEET designs cannot be compared directly due to different UEET combustor conditions. Therefore, this paper uses previously published UEET correlation equations to make comparisons. Results show that using a 45° swirler produces lower NO_x emissions than using a 60° swirler. This is consistent with the later UEET results. The effects of spent cooling depend on swirler angle, spent cooling location, and the test conditions. For the configuration with 45° swirlers, spent cooling delivers lower NO_x emissions when it is injected at the throat. For the 60° swirler, spent cooling does not have much effect on NO_x emissions. These results might be caused by the location and the intensity of the flame recirculation zone.

Introduction

Burning hydrocarbon fuel produces many effects on the environment. One of the major pollutants is nitrogen oxides (NO_x). Through several complex chemical reactions, nitrogen oxides emissions have caused problems like photochemical smog, greenhouse gas generation, as well as depletion of the protective ozone layer in the stratosphere (Ref. 1). In aircraft engines, nitrogen oxides reduction relies on advanced combustor design. Low-NO_x combustor designs have been investigated by NASA in collaboration with engine and fuel injector companies since the 1970s; since the 1990s, NASA has investigated Lean Direct Injection (LDI) combustion concepts. The LDI concept is designed to burn fuel as lean as possible to avoid high flame temperatures because NO_x emissions are an exponential function of combustion flame temperature. To avoid local hot spots, fuel is mixed with air as quickly as possible.

* Retired.

In order to avoid the problems of flashback and premature autoignition that plague premixed lean combustion concepts at high temperatures and pressures, in LDI fuel is injected directly into the combustion zone.

The LDI geometry that is studied in this paper is called 9-point Swirl-Venturi. With this geometry, fuel is injected into the combustor through nine small fuel injectors. Each injector is accompanied by an air swirler that generates highly turbulent air to break up the fuel and promote quick mixing. Throughout this paper the fuel injector and air swirler will be referred to as an “element” or a “fuel/air mixer.”

These experiments were conducted in a flame-tube combustor at high-speed-research (HSR) supersonic cruise conditions. Two parameters were investigated in this study: the use of cooling air and the swirler blade angle. The cooling air is called “spent cooling” and is injected at combustor inlet conditions. Flame produced by this LDI geometry has a very short flame length (~25-mm) (Ref. 2). To address the concern that the flame would be too close to the dome and damage the hardware, spent cooling air is applied. There are two spent cooling variations and a configuration with no spent cooling. The effects of these spent cooling methods on NO_x emissions were studied with injectors that configured of either 45° or 60° blade angle swirlers.

Four configurations were compared in this report: 45° blade angle swirlers with both types of spent cooling, 60° blade angle swirlers with one type of spent cooling, and 60° blade angle swirlers with no spent cooling. These HSR 9-point SV-LDI emission results were also compared to those from a similar 9-point SV-LDI design which was used in the later ultra-efficient engine technology (UEET) program. The HSR and UEET designs could not be compared directly due to different UEET combustor conditions. Instead, two previously published UEET correlation equations were used to predict the NO_x values at HSR conditions, and then both results were compared with each other.

Experimental Setup and Procedure

All the tests were conducted in CE-5, a flame-tube combustion test facility at the NASA Glenn Research Center (Ref. 3). A drawing of the CE-5 flame-tube is shown on Figure 1. Nonvitiated air was pre-heated to a maximum temperature of 865 K and a maximum pressure of 1380 kPa. Commercial Jet-A aviation fuel was used. The fuel flow rate was measured by a turbine meter, and air flow rate was measured by a venturi meter. The fuel-air mixture was injected into a flame tube that contains ceramic

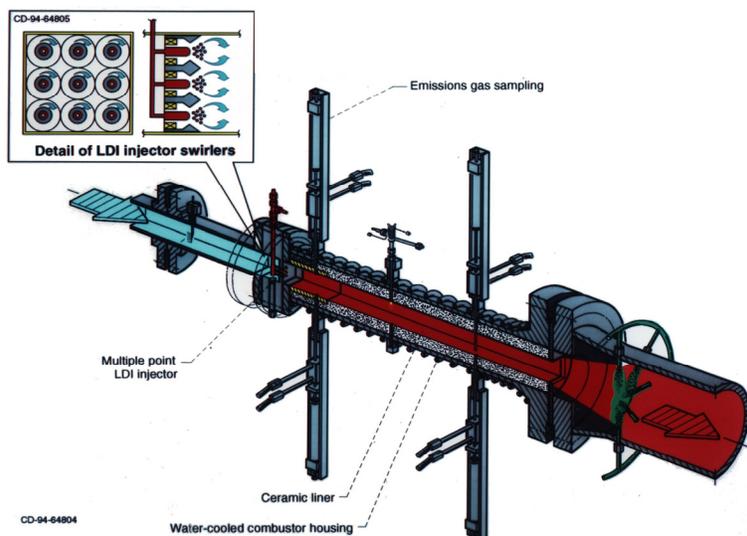


Figure 1.—Drawing of CE-5 flame tube.

liners with no liner cooling. A gas probe was placed downstream of the injector to collect combustion products for analysis. The rest of the combustion products were cooled down to 450 K by mixing with sprayed water before exiting to a low pressure exhaust system. The combusted gas samples were analyzed according to the standard gas-analysis procedure, SAE-ARP1256 (Ref. 4). As for NO and NO₂, the simultaneous chemiluminescence method was used.

The SV-LDI module described here contains nine identical fuel/air mixers in a 3 by 3 array occupying a 76.2 by 76.2-mm square area, as shown in Figure 2. The nine fuel/air mixers replace a single conventional fuel injector. Each fuel/air mixer consists of an air passage with a helical axial air swirler followed by a converging-diverging venturi section (Fig. 2(a)). For the HSR SV-LDI configurations, the swirlers have five blades; for the UEET configurations, the swirlers have six blades. A simplex fuel injector is inserted through the center of the air swirler; the fuel injector tip is at the venturi throat.

Two types of spent cooling are used in the HSR SV-LDI configurations: cooling at the dome face (“straight through”) and cooling at the venturi throat (“at throat”). For both types of spent cooling, the cooling air was at the combustor inlet conditions. Figure 2(b) shows straight through spent cooling (ST). For straight-through spent cooling, four holes were drilled straight-through the dome plate in between the nine elements. Figure 2(c) and (d) show spent cooling at the throat (AT). For cooling at the venturi throat, the cooling air was split among the nine elements. Four small holes were used to cool the center element, and one larger hole was applied in the venturi throat for other eight elements.

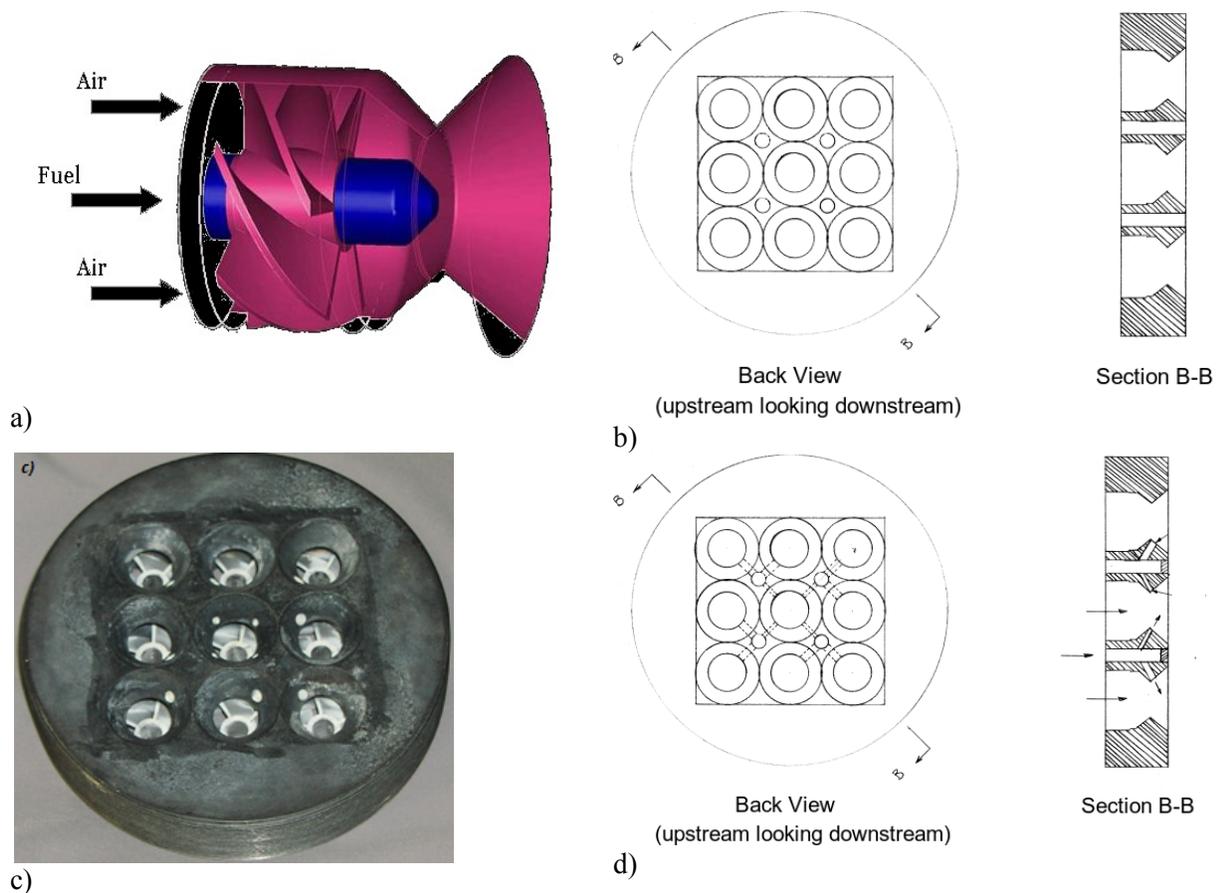


Figure 2.—Experimental hardware: (a) drawing of a fuel/air mixer, (b) drawing of a 9-point injector with straight through spent cooling, (c) and (d) picture and drawing of a 9-point injector with spent cooling at the throat.

No spent cooling was used in any of the UEET 9-point configurations. The correlations that were used to calculate the UEET NOx emissions are given in Equations (1) and (2). For the UEET configuration with 45° swirlers (Ref. 5):

$$E_{\text{INOx}} = 0.11 * P_3^{0.59} * e^{\frac{T_3}{194}} * \Phi^{5.07} * \left(\frac{\Delta P}{P} \% \right)^{-0.56} \quad (1)$$

For the configuration with 60° swirlers:

$$E_{\text{INOx}} = 0.013 * P_3^{0.59} * e^{\frac{T_3}{194}} * \Phi^{1.69} * \left(\frac{\Delta P}{P} \% \right)^{-0.56} \quad (2)$$

Equations (1) and (2) were used to predict the UEET 9-point NOx emissions at the HSR inlet temperatures, inlet pressures, equivalence ratios, and mass flow rates.

Results and Discussion

Testing of the HSR configurations showed that the spent cooling was not needed at HSR conditions: a post-testing visual inspection of the 60° configuration with no spent cooling showed no damage. In the testing with the UEET configurations, post-testing inspections also showed no damage, and thermocouple measurements showed acceptable dome temperatures. Nevertheless, spent cooling might be needed at the higher inlet pressures of next generation aircraft engines, especially when burning alternative fuels with a shorter ignition delay time. Therefore, understanding the effects of spent cooling may be important for future SV-LDI designs.

Air and fuel pressure drops are important parameters in designing the aircraft combustor. For the simplex fuel nozzle, fuel pressure drop across the injector affects the fuel drop size (Ref. 6). Higher the fuel pressure drops, the smaller is the fuel-drop size, which results in a better fuel-air mixture. The same type of simplex fuel injector was used in all four HSR configurations. As shown in Table 1, the flow numbers for these four configurations were about the same, which were around eighteen. The flow number is a function of fuel pressure drop across the injector and fuel mass flow rate and is defined as $FN = \text{fuel mass rate}/\sqrt{\Delta P}$. Therefore, fuel drop sizes at a given fuel flow rate should be similar among the four HSR configurations. However, the flow numbers for the UEET configurations were about forty percent higher than these four HSR configurations. According to the correlations found in Lefebvre (Ref. 6), this 40 percent higher flow number will result in the UEET fuel drop sizes being about 30 percent higher than the HSR fuel drop sizes at a given mass flow rate.

TABLE 1.—AVERAGE ACD AND FLOW NUMBER FOR EACH CONFIGURATION OF THE 9-POINT INJECTORS

	45°/ST	45°/AT	60°/ST	60°/no cooling	UEET 45°	UEET 60°
ACd	1.745	1.644	1.477	1.37	1.48	1.35
FN(total)	17.9	17.16	18.49	18.24	26.1	26.1

Figure 3 compares the effects of mass flow rate and two types of spent cooling methods on the NOx emission for mixers configured with 45° swirlers at various equivalence ratios (Φ) (Fig. 3(a)) or adiabatic flame temperature (Fig. 3(b)). For a typical fuel/air mixer configuration, NOx emissions mainly depend on fuel-air ratio, combustion inlet air temperature and pressure, as well as the air pressure drop across the dome. When NOx data was plotted against the adiabatic flame temperature, the effect of the combustion inlet temperature was minimized, allowing for easier comparison. Comparing the NOx emissions of the two spent cooling methods, the straight-through spent cooling produced higher NOx than spent cooling at the throat (at least 25 percent higher). This is consistent with the result expected from the UEET NOx correlations. At a given air mass flow rate, the straight through configuration's larger effective area (ACd) decreased the air pressure drop across the dome. Based on the UEET correlations, NOx emissions decrease

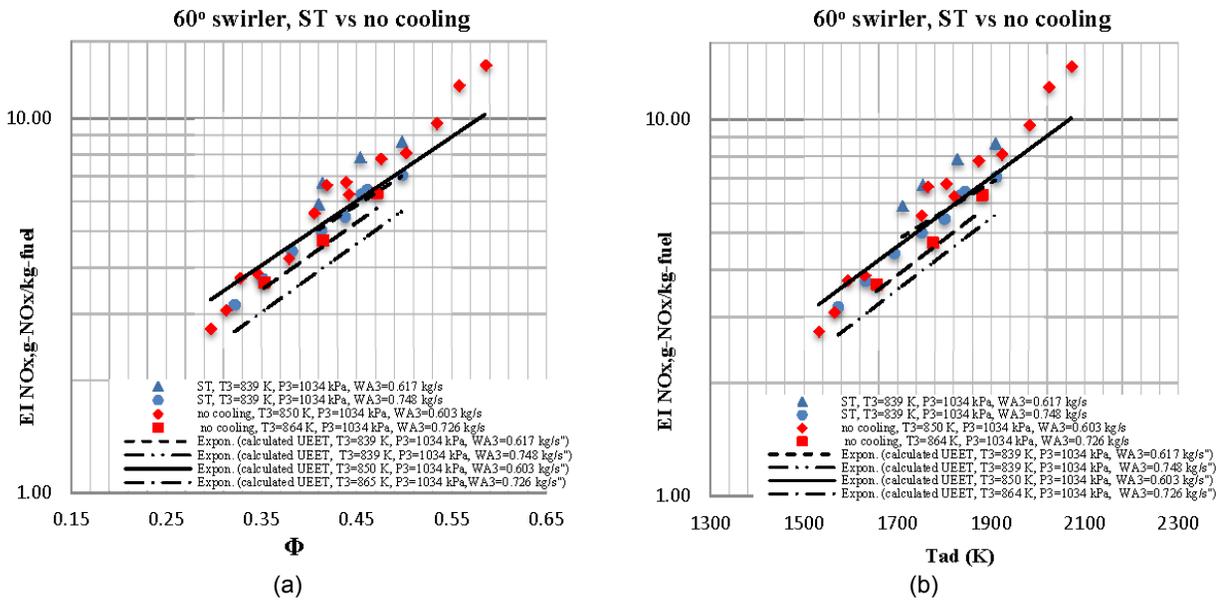


Figure 4.—Straight-through spent cooling vs. no spent cooling for a 9 point injector with a 60° swirl angle. (a) EI NOx vs. Φ , (b) EI NOx vs. T_{ad} (K).

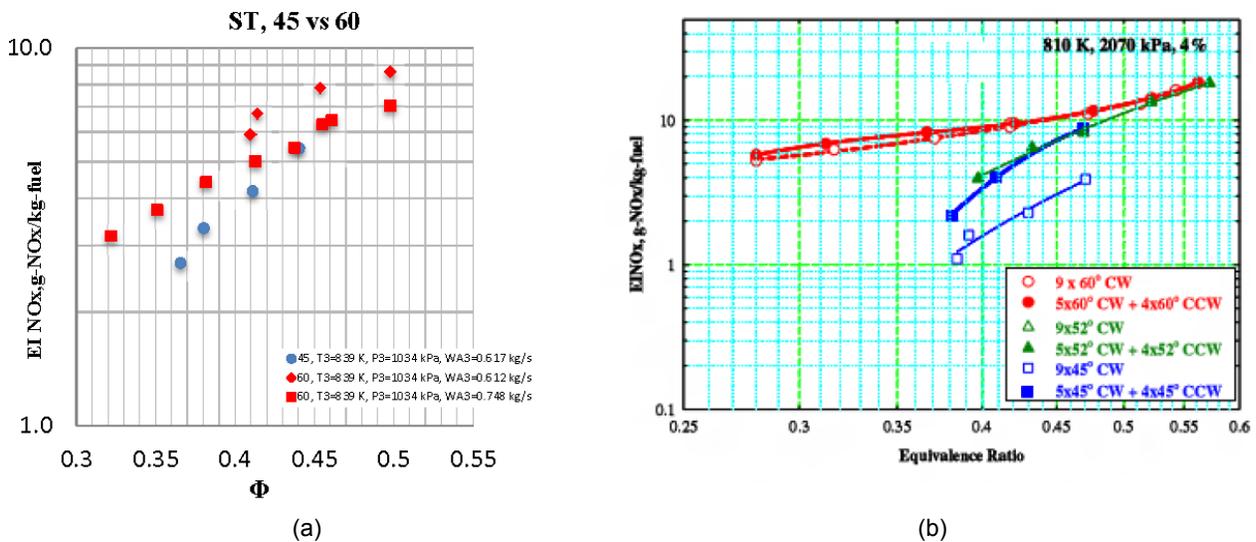


Figure 5.—(a) Comparison of the HSR straight through spent cooling configurations with 45° and 60° swirlers, and (b) Comparison of UEET configurations with 45°, 52°, and 60° swirler angles (Ref. 6).

The effects of spent cooling depend on spent cooling location, swirler angle, and test conditions. By applying spent cooling at the venturi throat, the cooling air is coming out at the same location as the swirled air (or combustion air). It will change the swirl number, and thus affect the air flow dynamic inside the combustor. The straight-through spent cooling method applied cooling air through the dome plate at the locations between the fuel injectors. These locations were at the same location of the circulation zones that the 45° swirlers produced. Since the recirculation zones were relatively weak, applying straight-through spent cooling at the dome plate might change the location of the recirculation zone and lead to the change in NOx emission. For configuration with 60° swirlers, the recirculation zone was strong and it was located on the axis of the swirlers in the gas stream. As a result, straight-through spent cooling did not show much effect on this configuration.

Conclusions

This paper explores the effects of dome cooling and swirler angle on SV-LDI low NO_x combustion configurations. This dome cooling is called “spent cooling” and its original intent was to protect the fuel/air mixer hardware from the flame burning too close to the dome plate. However, testing and thermocouple measurements at the dome plate showed that the spent cooling was not needed at HSR or UEET conditions studied here. But spent cooling might be needed at the higher inlet pressures of next generation aircraft, especially when burning alternative fuels with a lower ignition delay time. Therefore, understanding the effects of spent cooling may be important for future SV-LDI designs.

The data presented in this paper showed the effect of applying spent cooling at two locations. The first location was at the dome face in between fuel/air mixers and the second location was at the venturi throat. The effects of spent cooling depend on spent cooling location, swirler angle, and test conditions. For fuel/air mixers configured with 45° swirlers, NO_x emissions were significantly higher when the cooling was applied at the dome face than when it was applied at the venturi throat. For the fuel/air mixers configured with 60° swirlers, NO_x emissions when spent cooling was applied at the dome face were not significantly different from NO_x emissions when no spent cooling was used.

HSR results also indicate that decreasing the swirler angle from 60° to 45° decreases NO_x emissions: the straight through spent cooling configuration with 45° swirlers had lower NO_x emissions. This is consistent with results from the UEET configurations, which had no spent cooling.

References

1. Wey, Chowen, C., and Maurice, Lourdes Q., Exploring Aviation’s Environmental Impact, AIAA-2003-5993, 1st International Energy Conversion Engineering Conference (IECEC).
2. Hicks, Yolanda R., Heath, Christopher M., Anderson, Robert C., and Tacina, Kathleen M. *Investigations of a Combustor Using A 9-Point Swirl-Venturi Fuel Injector: Recent Experimental Result*, ISABE-2011-1106, 2011.
3. Bianco, J., *NASA Lewis Research Center’s combustor test facilities and capabilities*, AIAA-1995-2681, 1995.
4. SAE ARP1256-2006, Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines.
5. Tacina, Robert, Lee, Phil, and Wey, Changlie, *A lean-direct-injection combustor using a 9 point swirl-venturi fuel injector*, ISABE-2005-1106, 2005.
6. Lefebvre, Arthur H, *Gas Turbine Combustion*, Taylor and Francis, Philadelphia, 2nd edition, 1998.
7. Ajmani, Kumud, Mongia, Hukam, Lee, Phil, *CEF Best Practices To Predict NO_x, CO and Lean Blowout for Combustor Design*, ASME Turbo Expo 2013, San Antonio, Texas, USA.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-04-2014	2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)		
4. TITLE AND SUBTITLE Effects of Spent Cooling and Swirler Angle on a 9-Point Swirl-Venturi Injector			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) He, Zhuohui, J.; Tacina, Kathleen, M.; Lee, Chi-Ming; Tacina, Robert, R.; Lee, Phil			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER WBS 794072.02.03.05.02		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-18859		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2014-218117		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 7 and 5 Available electronically at http://www.sti.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES Robert R. Tacina, retired.					
14. ABSTRACT This paper presents multipoint Lean-Direct-Injection (LDI) emissions results for flame tube combustion tests at an inlet pressure of 1034 kPa and inlet temperatures between 835 and 865 K; these are the combustor inlet conditions that the High Speed Research (HSR) program used for supersonic cruise. It focuses on one class of LDI geometry, 9-point swirl-venturi LDI (SV-LDI). Two parameters are compared in this paper: the use of dome cooling air and the swirler blade angle. Dome cooling air is called "spent cooling" and is at combustor inlet conditions. Three cooling variations are studied: cooling at the venturi throat, cooling at the dome face, and no cooling at all. Two swirler blade angles are studied: 45° and 60°. The HSR 9-point SV-LDI emissions are also compared to a similar 9-point SV-LDI design which was used in the later ultra-efficient engine technology (UEET) program. The HSR and UEET designs cannot be compared directly due to different UEET combustor conditions. Therefore, this paper uses previously published UEET correlation equations to make comparisons. Results show that using a 45° swirler produces lower NOx emissions than using a 60° swirler. This is consistent with the later UEET results. The effects of spent cooling depend on swirler angle, spent cooling location, and the test conditions. For the configuration with 45° swirlers, spent cooling delivers lower NOx emissions when it is injected at the throat. For the 60° swirler, spent cooling does not have much effect on NOx emissions. These results might be caused by the location and the intensity of the flame recirculation zone.					
15. SUBJECT TERMS Nitrogen Oxide emission; Lean-Direct-Injection (LDI); Aircraft engine combustions					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 443-757-5802

