Check for updates

Bao Yang
Department of Mechanical Engineering,
University of Maryland,
College Park, MD 20742
e-mail: baoyang@umd.edu

Liangbing Hu
Department of Material Science and Engineering,
University of Maryland,
College Park, MD 20742
e-mail: binghu@umd.edu

Weiwei Ping
Department of Material Science and Engineering,
University of Maryland,
College Park, MD 20742
e-mail: m18392456236@163.com

Rishi Roy
Department of Mechanical Engineering,
University of Maryland,
College Park, MD 20742
e-mail: rroy1235@umd.edu

Ashwani K. Gupta[1]
Department of Mechanical Engineering,
University of Maryland,
College Park, MD 20742
e-mail: akgupta@umd.edu

Boron-Nitride Nanosheet-Based Thermal Barrier Coating for Micro-Combustor Performance Improvement

One of the major challenges in the development of micro-combustors is heat losses that result in flame quenching, and reduced combustion efficiency and performance. In this work, a novel thermal barrier coating (TBC) using hexagonal boron nitride (h-BN) nanosheets as building blocks was developed and applied to a Swiss roll micro-combustor for determining its heat losses with increased temperatures inside the combustor that contributes to improved performance. It was found that by using the h-BN TBC, the combustion temperature of the micro-combustor increased from 850 K to 970 K under the same thermal loading and operational conditions. This remarkable temperature increase using the BN TBC originated from its low cross-plane thermal conductivity of 0.4 W m^{-1} K^{-1} to mitigate the heat loss from the micro-combustor plates. Such a low thermal conductivity in the h-BN TBC is attributed to its interfacial resistance between the nanosheets. The development of h-BN TBC provides an effective approach to improve thermal management for performance improvements of gas turbine engines, rocket engines, and all various kinds of micro-combustors. [DOI: 10.1115/1.4052734]

Keywords: air emissions from fossil fuel combustion, alternative energy sources, energy conversion/systems, energy extraction of energy from its natural resource, fuel combustion, hydrogen energy, natural gas technology

Downloaded from http://asmedigitalcollection.asme.org/energyresources/article-pdf/144/6/062106/6799295/jert_144_6_062106.pdf by University of Maryland Libraries user on 24 June 2022

Introduction

Micro-combustors are critical components in micro-power systems for small and portable electronics, small robots, small aerial vehicles, and small satellites [1–5]. One big challenge in micro-combustors is to reduce their heat loss for stable combustor operation over a large range of fuel/air ratios and thermal loadings. It is well known that combustion systems are adversely sensitive to scaling since the heat loss to heat generation ratio (surface area to volume) induces flame quenching and shifts flame stability to fuel-rich zone when the combustor is made sufficiently small [3,6]. In the micro- and meso-scale combustors, with physical size around or less than 10 mm, the time scale of thermal diffusion in the chamber walls is comparable to the combustion time scale, which results in strong thermal coupling between the flame and chamber walls. Advanced thermal management must be developed in order to minimize the heat losses from the micro-combustors, to enhance the combustion sustainability, thermal efficiency, and reliability.

One approach to reduce the heat loss is to apply thermal barrier coating (TBC) to the walls of the micro-combustors. Research on TBCs has been driven by the desire to reduce thermal conductivity and heat loss, as well as improving durability at high temperatures [7–9]. Current TBC technology is largely based on the ceramic material, yttria-stabilized zirconia (YSZ). 7YSZ, zirconia ZrO2 partially stabilized with 7 wt% Y2O3, is the most popular composition of YSZ due to its combined thermal and mechanical properties. 7YSZ has a relatively low thermal conductivity, 1–2 W/mK, and its phase can be stable at temperatures up to 1200 °C [9]. This type of TBCs contains precious rare earth elements.

In this work, a TBC that is composed of layer-by-layer laminated hexagonal boron nitride (h-BN) nanosheets has been developed to mitigate heat loss issues from the micro-combustor. The h-BN TBC possesses a low thermal conductivity, about 0.4 W/mK in the cross-plane direction, and can significantly increase the combustion temperature of the Swiss-roll micro-combustor, from 850 K to 970 K to result in increased performance of the micro-engine device.

Preparation of Thermal Barrier Coating and Micro-Combustor

h-BN nanosheets, consisting of equal numbers of boron and nitrogen atoms and possessing a similar crystalline structure to grapheme, can be fabricated by exfoliating the bulk hexagonal boron nitride [10]. Within each atomic layer, boron and nitrogen atoms are bound by strong covalent bonds, whereas the layers are held together by weak van der Waals forces. This disparity causes superior chemical, thermal, and mechanical properties in h-BN nanosheets [11,12], which are desired for TBC applications.

The h-BN nanosheets were produced by sonication-assisted liquid-phase exfoliation of bulk h-BN flakes in powder [10,13]. Excess h-BN powder flakes at an initial concentration of 3 mg mL^{-1} were put in isopropyl alcohol (IPA) and sonicated for 10 h. They were then followed by a centrifugation procedure (3000 rpm, 15 min) that yielded in a white, dilute, and saturated suspension (h-BN ink) dispersed with h-BN nanosheets. The glass particles were added to the h-BN ink as a binder. The h-BN coating was produced by the spray-coating technique using ink of dispersed h-BN nanosheets with glass particles (Fig. 1(*a*)). The thickness of the h-BN coating can be controlled by adjusting the spray-coating time and/or the concentration of the h-BN ink. A rapid high-temperature (HT) heating process was also developed to quickly sinter the coating layer on the combustor plate with strong adhesion and good mechanical properties (Figs. 1(*b*) and 1(*c*)). The BN

[1]Corresponding author.

Contributed by the Advanced Energy Systems Division of ASME for publication in the Journal of Energy Resources Technology. Manuscript received September 30, 2021; final manuscript received October 9, 2021; published online October 28, 2021. Editor: Hameed Metghalchi.

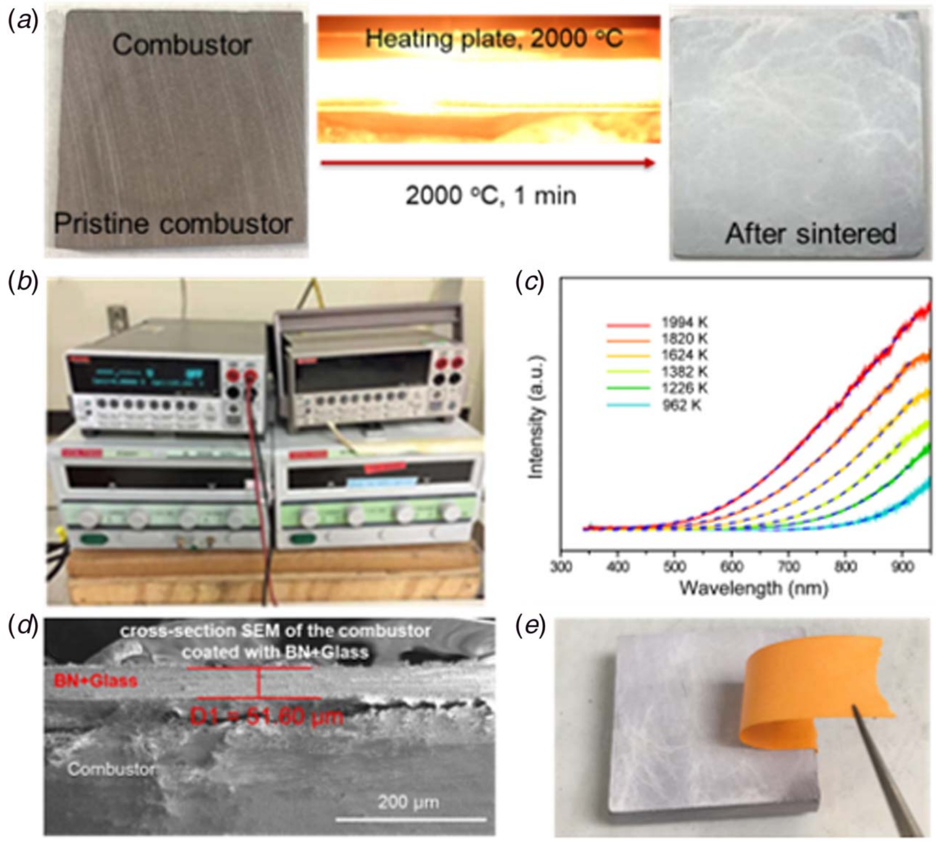

Fig. 1 The fabrication process of coating using rapid high-temperature (HT) technique: (*a*) the h-BN coating produced from the fabricated HT technique using a temperature of 2000 °C, (*b*) setup of the HT machine, (c) fitting curve of the HT plate, (*d*) cross section of the h-BN coating sintered by HT providing a thickness of about 50 μm, and (*e*) the digital photo of the tape testing process. The coating cannot be peel off by the tape, suggesting strong adhesion of the h-BN coating on the combustor plate.

coatings fabricated with this HT method showed good adhesion and mechanical properties (Figs. 1(*b*) and 1(*c*)). With the glass particle addition, the thickness of the h-BN coating layer can be more than 50 μm (Fig. 1(*d*)). The initial tape test showed that coating could not be peeled off from the micro-combustor (Fig. 1(*e*)).

The TBCs need to have a low thermal conductivity in the direction perpendicular to the surface to minimize the conductive heat loss. Due to the multilayer structure of the h-BN TBC, its cross-plane thermal conductivity can be significantly reduced by interfacial resistance between the nanosheets. The interface disorder and gap scatter phonons impede the transfer of vibrational energy across interfaces between the nanosheets [14]. The cross-plane thermal conductivity of the h-BN TBC was measured to be 0.4 W/m K using a time-domain thermo-reflectance (TDTR)

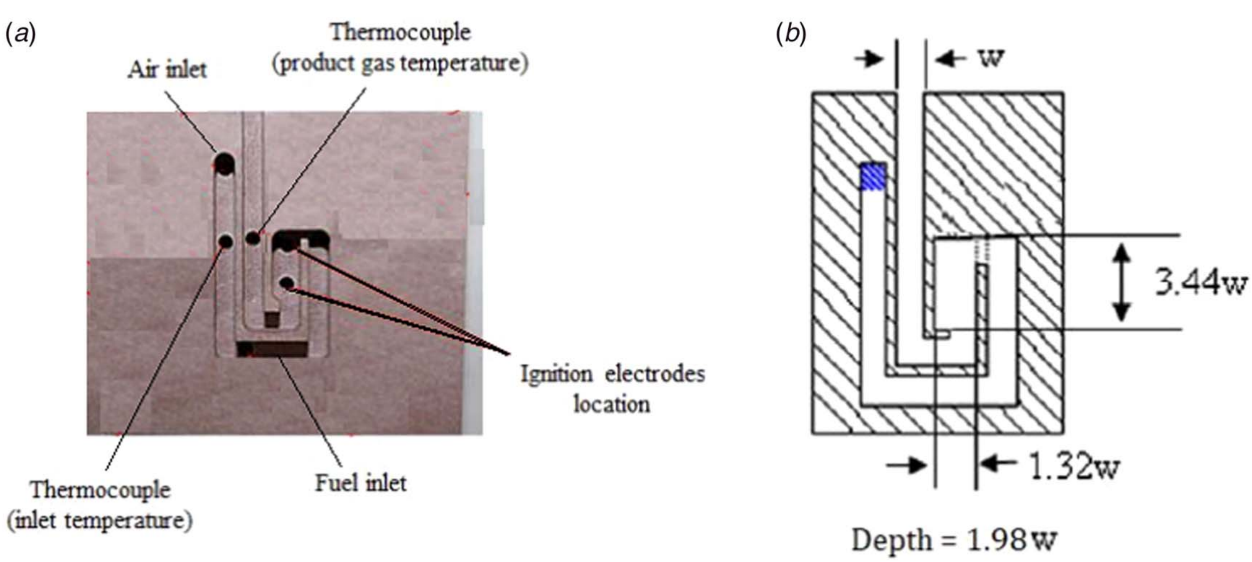

Fig. 2 (*a*) Image of the Swiss-roll micro-combustor and (*b*) cross section

Downloaded from http://asmedigitalcollection.asme.org/energyresources/article-pdf/144/6/062106/6799295/jert_144_6_062106.pdf by University of Maryland Libraries user on 24 June 2022

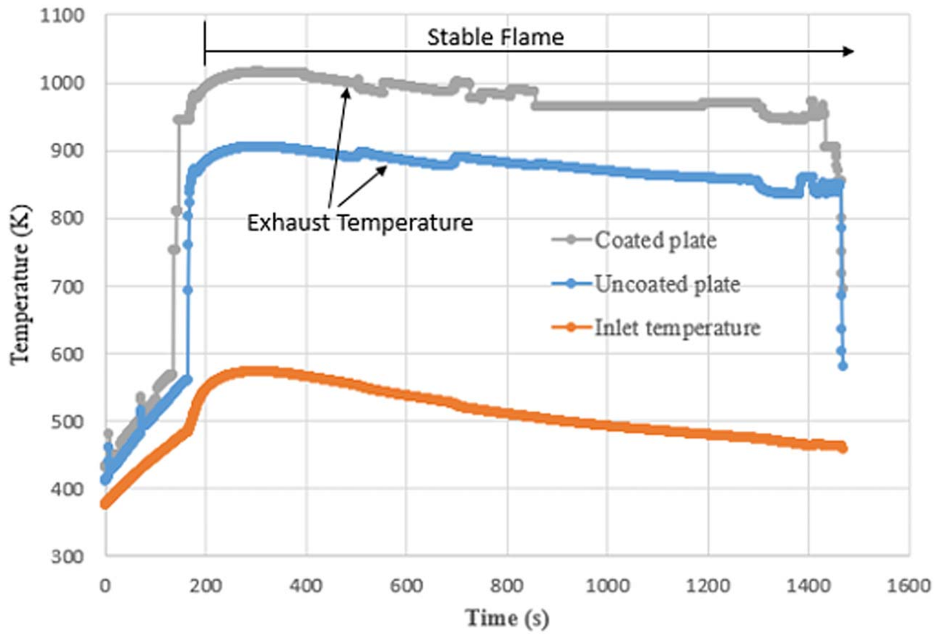

Fig. 3 Temporal evolution of inlet and exhaust temperature from the micro-combustors with and without the h-BN TBC

method [15]. This thermal conductivity is lower than that of monolith alumina silicate (1.98 W/mK), which was used for the top plate of the micro-combustor for the work presented here. In comparison, the thermal conductivity of the state-of-the-art TBC, YSZ has a thermal conductivity of 1–2 W/m K [9]. The BN micro-combustor showed significant improvements as compared to normal combustors [16–21].

Two identical Swill roll micro-combustors were fabricated in this work, one without the h-BN TBC, and the other with h-BN coating. Figure 2 shows the geometry of the combustor as well as the locations of fuel and air inlets, thermocouples, and ignition electrodes. The channel width (w) was 1.59 mm that produced a combustion volume of 35 mm^3. The non-premixed mode was adopted to avoid any adverse effects associated with flame flashback into the supplying tubes located at the back of the combustor. Sealing was introduced around the tubes to ensure that no fuel or air lacked from the combustor. The combustor was fabricated from a 38-mm square monolith alumina silicate block. The top cover plate made of the same material as the combustor was used to cover and seal the combustor. Such material primarily minimized heat loss from the combustor to the ambient due to its lower thermal conductivity (of 1.98 *W/mK*). The material has low porosity relative to other ceramic compounds having lower thermal conductivity and high porosity. The porosity plays an important role as some of the reactants may otherwise diffuse into the porous walls of the reactor, thus altering the fuel–air mixture equivalence ratio. Heat treatment (for 45 min at 1050 °C) allowed for the combustor to operate at higher temperatures with less possibility of cracking due to the elimination of thermal stresses.

Results and Discussion

The experiments were carried out using two identical Swiss roll combustors so that one combustor had a cover plate coated with the h-BN TBC while the other combustor was without the TBC. The single turn Swiss roll combustor involves a step entrance to the combustion unit which created a local recirculation zone within the combustion volume to enhance the flame stability.

Measurement of the inlet and exhaust temperature from the micro-combustor was performed using two K-type thermocouples

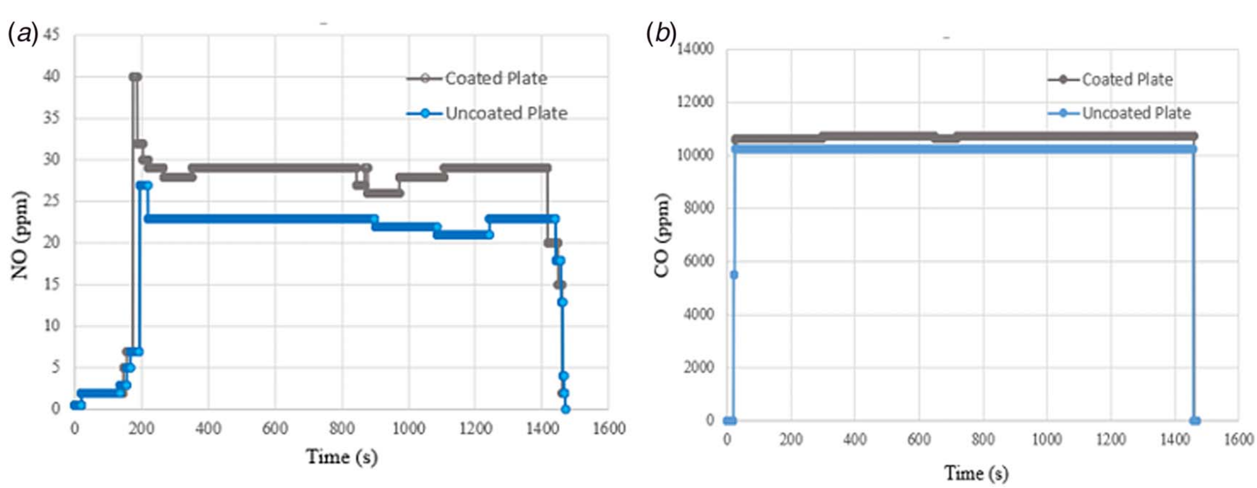

Fig. 4 (*a*) Variation in exhaust NO concertation with time and (*b*) variation in exhaust CO concertation with time in the micro-combustors with and without the h-BN TBC

Downloaded from http://asmedigitalcollection.asme.org/energyresources/article-pdf/144/6/062106/6799295/jert_144_6_062106.pdf by University of Maryland Libraries user on 24 June 2022

attached to the combustor. Experiments were performed under the non-premixed propane-air flame condition at an equivalence ratio of 1.2 (i.e., fuel rich). Flames at lower equivalence ratios suffered from difficulties of ignition and stability within the combustor. Temperature measurements were made for the top cover plate with and without the h-BN TBC. Figure 3 shows the temporal evolutionary behavior of inlet and exhaust temperature of the micro-combustor both without and with the top cover plate coated with the h-BN TBC. The difference in exhaust temperature with the coated and uncoated plates remained small before the stable flame was established. The steady exhaust temperature with the h-BN TBC was observed to be around 970 K while it was only 850 K without h-BN TBC of the top plate. These remarkable temperature increases in the combustion temperature are directly attributed to low cross-plane thermal conductivity associated with the h-BN TBC (0.4 $W m^{-1} K^{-1}$), which helped to reduce the heat loss from the micro-combustor to the surrounding environment. Slight fluctuations in temperature could be observed during steady operation. We attribute this to the small intermittent fluctuation of air and fuel flows to the micro-combustor. Despite the difference in magnitude, the temperature profiles were similar for both cases. The rise of inlet flow temperature was not significant throughout the micro-combustor operation. However, a small peak was observed when the flame was stabilized within the combustor. The experiments were performed for approximately 20 min, and after this time, a decrease in temperature was observed as the flame got extinguished.

The pollutants (nitrogen oxide and carbon monoxide) concentration at the exit of the micro-combustor was also measured simultaneously in conjunction with the gas temperature using a lab-based Horiba gas analyzer. Figures 3 and 4 show the variation in NO and CO concentration with time from the micro-combustor, both with and without the h-BN TBC. The micro-combustor with the h-BN TBC showed a slightly increased NO emission (~27 ppm) than that without the h-BN TBC (having NO concentration of ~ 22 ppm). Such an increase in NO concentration was attributed to the higher exhaust temperature from the combustor with the h-BN TBC. The spike in NO observed near 200s was due to the ignition and establishment of a stable flame within the combustor. The NO emission remained fairly constant with the stable flame for both cases.

The analysis of exhaust gas revealed high CO emission (>10,000 ppm) from the combustor for both the cases. Such observation can be attributed to low residence time within the combustor that is hampered to allow complete combustion. The difference in CO concentration for the coated and uncoated top plate cases was not remarkable (~200 ppm). The CO emission was also consistent, similar to NO concentration, during the stable flame operation. A rapid drop in CO concentration observed after 1400 s indicated a globally extinguished flame in the combustor.

Conclusions

This study demonstrated that h-BN TBC can effectively reduce the heat losses from the combustor that resulted in increased combustion temperature, from 850 K to 970 K, in the Swiss roll micro-combustor. This increase in temperature offers significant improvement in combustor performance. The improved performance of the micro-combustor was due to the low cross-plane thermal conductivity (0.4 $W m^{-1} K^{-1}$), of the h-BN TBC. Such a low thermal conductivity associated with the h-BN TBC was from its multilayer structure, wherein the interface disorder and gap scatter phonons impede the heat transfer across interfaces between the nanosheets. The h-BN thermal barrier coating was composed of earth-abundant elements of boron and nitrogen, and is unlike the conventional YSZ coating. It did not contain any rare earth elements. This work not only provides an effective approach to resolving heat loss issues in micro-combustors, but also offers significant benefits for other thermal management applications, including gas turbine and rocket engines, and thrust vector control units. It also offers low plume signatures making them suitable for many applications where mitigation of thermal signatures is important.

Acknowledgment

This research was supported by the Office of Naval Research (ONR), USA and also the US National Science Foundation (NSF). Their support is gratefully acknowledged by the authors.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The data sets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper. No data, models, or code were generated or used for this paper.

References

[1] Vijayan, V., and Gupta, A. K., 2010, "Combustion and Heat Transfer at Meso-Scale With Thermal Recuperation," Appl. Energy, **87**(4), pp. 2628–2639.
[2] Shirsat, V., and Gupta, A. K., 2011, "A Review of Progress in Heat Recirculating Meso-Scale Combustors," Appl. Energy, **88**(12), pp. 4294–4309.
[3] Maruta, K., 2011, "Micro and Mesoscale Combustion," Proc. Combust. Inst., **33**(1), pp. 125–150.
[4] Fernandez-Pello, A. C., 2003, "Micropower Generation Using Combustion: Issues and Approaches," Proc. Combust. Inst., **29**(1), pp. 883–899.
[5] Vetter, R., Yang, V., Wang, Z., Wang, V., Milius, D., and Peluse, M., 2003, "Development of Meso and Micro Scale Liquid Propellant Thrusters," AIAA-2003-676.
[6] Aghalayam, P., Bui, P. A., and Vlachos, D. G., 1998, "The Role of Radical Wall Quenching in Flame Stability and Wall Heat Flux: Hydrogen-Air Mixtures," Combust. Theory Modell., **2**(4), pp. 515–530.
[7] Miller, R. A., 1997, "Thermal Barrier Coatings for Aircraft Engines: History and Directions," J. Therm. Spray Technol., **6**(1), pp. 35–42.
[8] Padture, N. P., Gell, M., and Jordan, E. H., 2002, "Materials Science—Thermal Barrier Coatings for Gas-Turbine Engine Applications," Science, **296**(5566), pp. 280–284.
[9] Levi, C. G., 2004, "Emerging Materials and Processes for Thermal Barrier Systems," Curr. Opin. Solid State Mater. Sci., **8**(1), pp. 77–91.
[10] Zhu, H., Li, Y., Fang, Z., Xu, J., Cao, F., Wan, J., Preston, C., Yang, B., and Hu, L., 2014, "Highly Thermally Conductive Papers With Percolative Layered Boron Nitride Nanosheets," ACS Nano, **8**(4), pp. 3606–3613.
[11] Beiss, P., Ruthardt, R., and Warlimont, H., 2002, *Powder Metallurgy Data. Refractory, Hard and Intermetallic Materials*, Springer, New York.
[12] Luo, W., Zhou, L., Yang, Z., Dai, J., Hitz, E., Kuang, Y., Han, X., Yang, B., and Hu, L., 2017, "Protection of Boron Nitride Nanosheets by Atomic Layer Deposition Toward Thermal Energy Management Applications," Nano Energy, **40**(1), pp. 149–154.
[13] Zheng, J.-C., Zhang, L., Kretinin, A. V., Morozov, S. V., Wang, Y. B., Wang, T., Li, X., et al., 2016, "High Thermal Conductivity Hexagonal Boron Nitride Laminates," 2D Materials, **3**(1), p. 011004.
[14] Chen, G., Borca-Tasciuc, T., Yang, B., Song, D., Liu, W. L., Zeng, T., and Achimov, D., 1999, "Heat Conduction Mechanisms and Phonon Engineering in Superlattice Structures," Therm. Sci. Eng., **7**(1), pp. 43–51.
[15] Jiang, P., Qian, X., and Yang, R., 2017, "Time-Domain Thermoreflectance (TDTR) Measurements of Anisotropic Thermal Conductivity Using a Variable Spot Size Approach," Rev. Sci. Instrum., **88**(7), p. 074901.
[16] Feser, J., and Gupta, A. K., 2021, "Performance and Emissions of Drop-In Aviation Biofuels in a Lab Scale Gas Turbine Combustor," ASME J. Energy Resour. Technol., **143**(4), p. 042103.
[17] Singh, P., Chuhan, S. R., Goel, V., and Gupta, A. K., 2019, "Impact of Biodiesel Blend on Lubricating Oil Degradation in a Compression Ignition Engine," ASME J. Energy Resour. Technol., **141**(3), p. 032203.
[18] Scenna, R., and Gupta, A. K., 2018, "The Influence of the Distributed Reaction Regime on Fuel Reforming Conditions," ASME J. Energy Resour. Technol., **140**(12), p. 122002.
[19] Said, A. O., Khalil, A. E., and Gupta, A. K., 2016, "Dual Location Fuel Injection Effects on Emissions and NO/OH Chemiluminescence in a High Intensity Combustor," ASME J. Energy Resour. Technol., **138**(4), p. 042208.
[20] Said, A. O., and Gupta, A. K., 2015, "Oxygen Enriched Air Effects on Combustion, Emission and Distributed Reaction," ASME J. Energy Resour. Technol., **137**(4), p. 042203.
[21] Kekec, K. B., Karyeyen, S., and Ilbas, M., 2022, "Colorless Distributed Combustion of Diffusion Methane Flame Using Two Cyclone Burners," Int. J. Energy Clean Environ., **23**(1), pp. 1–17.

Downloaded from http://asmedigitalcollection.asme.org/energyresources/article-pdf/144/6/062106/6799295/jert_144_6_062106.pdf by University of Maryland Libraries user on 24 June 2022