

Mechanical and Combustion Performance of Multi-Walled Carbon Nanotubes as an Additive to Paraffin-Based Solid Fuels for Hybrid Rockets

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Paraffin-based solid fuels for hybrid rocket motor applications are recognized as a fast-burning alternative to other fuel binders such as HTPB, but efforts to further improve the burning rate and mechanical properties of paraffin are still necessary. One approach that is considered in this study is to use multi-walled carbon nanotubes (MWNT) as an additive to paraffin wax. Carbon nanotubes provide increased electrical and thermal conductivity to the solid-fuel grains to which they are added, which can improve the mass burning rate. Furthermore, the addition of ultra-fine aluminum particles to the paraffin/MWNT fuel grains can enhance regression rate of the solid fuel and the density impulse of the hybrid rocket. The multi-walled carbon nanotubes also present the possibility of greatly improving the mechanical properties (e.g., tensile strength) of the paraffin-based solid-fuel grains.

For casting these solid-fuel grains, various percentages of MWNT and aluminum particles will be added to the paraffin wax. Previous work has been published about the dispersion and mixing of carbon nanotubes.¹ Another manufacturing method has been used for mixing the MWNT with a phenolic resin for ablative applications, and the manufacturing and mixing processes are well-documented in the literature.² The cost of MWNT is a small fraction of single-walled nanotubes. This is a scale-up advantage as future applications and projects will require low cost additives to maintain cost effectiveness.

Testing of the solid-fuel grains will be conducted in several steps. Dog bone samples will be cast and prepared for tensile testing. The fuel samples will also be analyzed using thermogravimetric analysis and a high-resolution scanning electron microscope (SEM). The SEM will allow for examination of the solid fuel grain for uniformity and consistency. The paraffin-based fuel grains will also be tested using two hybrid rocket test motors located at the Pennsylvania State University's High Pressure Combustion Lab.

The first motor, the Long-Grain Center-Perforated (LGCP) hybrid rocket motor, is for baseline characterization of the solid-fuel grains. The LGCP employs a cartridge-loaded fuel grain with fast turnaround times and high experimental repeatability. The motor is capable of pressures up to 12 MPa (1,750 psig) and can hold fuel cartridges 38 mm in diameter with lengths up to 406 mm. Because of its small size, the LGCP requires minimum amounts of solid fuel to be cast for basic fuel regression rate characterization, limiting the need for large samples of MWNT or other additives (i.e., ultra-fine aluminum). The second motor, the X-ray Translucent Center-perforated (XTC) motor, uses a paper phenolic fuel cartridge that holds the fuel and acts as the pressure vessel. The heavy-walled phenolic tube is capable of operating pressures up to 4.2 MPa (600 psig). The XTC (shown in Figure 1) allows for instantaneous regression rate characterization via X-ray radiography. Both systems operate on the same oxidizer feed system which can deliver oxygen mass flow rates up to 0.36 kg/s. Both the LGCP and XTC have been used for performance characterization of several hybrid rocket fuel formulations.^{3,4}

The anticipated results from this study are an increase in regression rate and improved mechanical properties over pure paraffin fuel. Detailed observations and calculations will be given in the full manuscript.

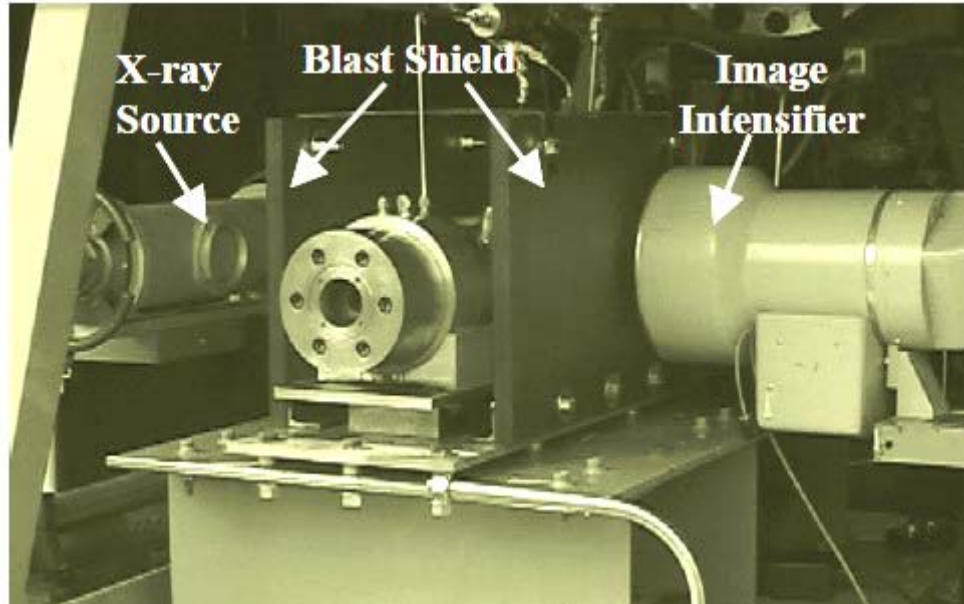


Figure 1. Photograph of XTC hybrid rocket motor with real-time X-ray radiography system installed to measure solid fuel regression rate

¹ Luo, Z.P., Koo, J.H., "Quantitative Study of the Dispersion Degree in Carbon Nanofiber/Polymer and Carbon Nanotube/Polymer Nanocomposites," *Materials Letters*, Volume 62, Issue 20, pp 3493-3496, July 31, 2008.

² Tate, J.S., Kabakov, D., Koo, J.H., "Carbon/Phenolic Nanocomposites: Ablative Applications," *SAMPE Journal*, Volume 47, Issue 3, pp 36-43, May-June, 2011.

³ Evans, B., Favorito, N., Risha, G., Boyer, E., Wehrman, R., Kuo, K. K., "Characterization of Nano-Sized Energetic Particle Enhancement of Solid-Fuel Burning Rates in an X-Ray Transparent Hybrid Rocket Engine," *AIAA-2004-3821*, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, Florida, July 11-14, 2004.

⁴ Risha, G., Boyer, E., Wehrman, R., and Kuo, K. K., "Performance Comparison of HTPB-Based Solid Fuels Containing Nano-Sized Energetic Powder in a Cylindrical Hybrid Rocket Motor," *AIAA-2002-3576*, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Indianapolis, Indiana, July 7-10, 2002.