MEMS Jet Fuel Atomizer

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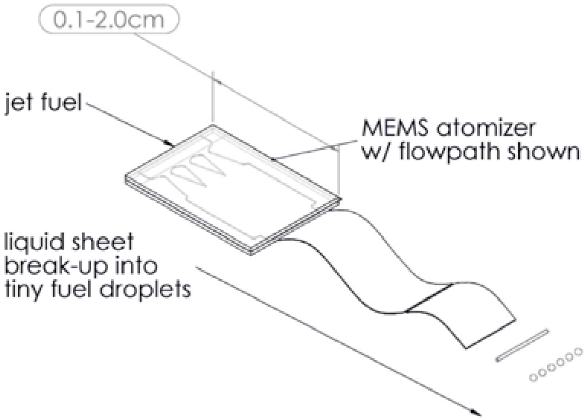


Figure 1. Silicon MEMS fuel atomizer sketch.

PROBLEM STATEMENT

Operational requirements documents express a need for high speed and long-range standoff missiles against mobile targets. Further, the ability to penetrate deeply buried and hardened targets is also needed. Of the air breathing propulsion cycles that could enable this missile, the pulse detonation engine (PDE) is most efficient and has great potential for improved range and thrust. (See the schematic representation of an engine in Figure 2.) Most research has been performed with low energy-density gaseous fuels, so demonstrating rapid deflagration-to-detonation using storable, liquid hydrocarbon fuels is essential to successful development and widespread application of this engine. Unfortunately, liquid fuels require atomization, which introduces the challenge of detonating a liquid droplet spray. Recent research shows that droplet Sauter-mean diameters (SMD or $d_{3,2}$) as small as 3mm may be required to achieve detonation under cold-start conditions [Figure 3 Brophy et al. 2000].

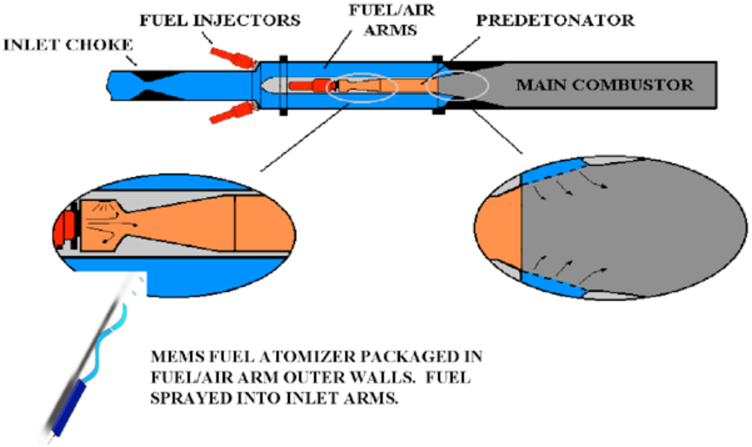


Figure 2. Typical PDE configuration (Naval Postgraduate School Rig).

Such small droplets cannot be easily produced.

Micro-electro-mechanical systems (MEMS) are novel technologies well suited to the micro-scale. TDA Research has teamed with the University of Colorado at Boulder to develop a MEMS based atomizer that can produce these small droplets and still meet the Navy's practical requirements of high temperature operability (500 °F), low pressure drop (< 50 psid), high-speed on/off pulsing with zero-drip closure and high fuel flow rate (0.5 lbm/s).

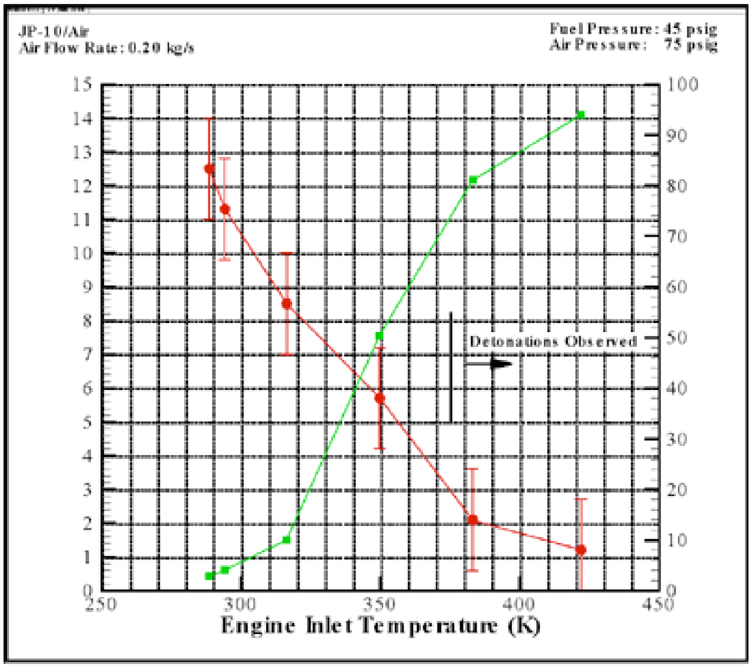


Figure 3. Liquid fuel spray detonability.

WHO CAN BENEFIT?

This PhII MEMS Liquid Fuel Atomizer project has been funded by ONR. Dr. Chris Brophy (Naval Postgraduate School, Monterey, CA) provides technical oversight. Atomizer development will enable efficient liquid fueled PDEs for high-speed missiles. In addition Pratt & Whitney Seattle Aerosciences Center and General Electric have been developing PDEs for high-speed missiles, manned/unmanned aircraft and access to space applications. All need liquid fuel atomizers and would immediately transition TDA's MEMS atomizer into their technology programs if available. TDA's MEMS atomizer will be sufficiently developed by the end of Phase II for direct insertion into these programs. One of the option phases specifically addresses thermal issues associated with direct injection into GE's PDE combustor.

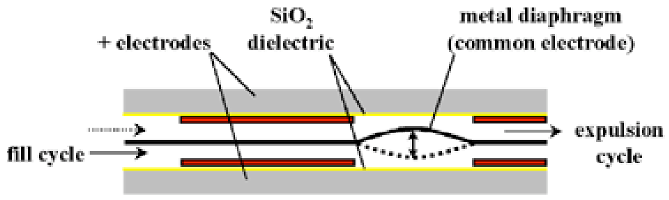
TDA's MEMS atomizer can also improve small power plant and portable power generation unit performance. For example, multi-service UAVs require very efficient propulsive power plants to achieve the desired range and loiter goals. Furthermore, the engines must run on available logistic fuels. Unfortunately, since these fuels have very low vapor pressure, a uniform distribution of finely atomized droplets may be required for engine startup and efficient operation.

Future Army portable power generation units must also be fueled with readily available logistic fuels. Again, these fuels are difficult to vaporize and burn, unless a uniform distribution of finely atomized liquid droplets can be created. Since small portable heaters and stoves have little power available for fuel delivery and atomization, conventional atomization technologies cannot be used. TDA's MEMS atomizer can provide a solution.

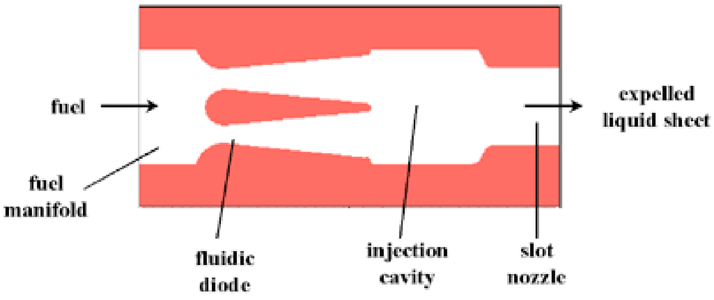
BASELINE TECHNOLOGY

Current atomization techniques include the orifice (simple, dual, swirl, pulse-width modulated, etc.), poppet-type, air atomizing, ultrasonic, electrostatic, and inkjet atomization technologies. Of these the orifice type injectors are the most widely used, but their minimum droplet SMD is limited to about 20mm for an orifice diameter of <250mm with a feed pressure of 1000 psi. The droplet size is roughly proportional to the square root of the orifice diameter and to $Dp^{-0.4}$. They also require a high-pressure drop to achieve the needed fuel flow rate. This is particularly true of diesel direct fuel injectors, which pressurize the fuel to tens of thousands of psi in order to produce very small droplets and inject a relatively large slug of fuel in a very short time. Poppet-type injectors operate at 100’s of psi and the spring pre-load provides a limited shut-off capability. Ultrasonic injectors use low ultrasonic vibrational energy to atomize a thin fluid film. Although they operate with low supply pressure, they are costly, have limited flow capacity and do not work well with viscous fluids. None of the above technologies though can cyclically atomize jet fuels at high flow rate to produce micron-size droplets with little pressure and power. In fact, most droplets are larger than 3mm and some droplets can be as large as 200mm. These large droplets need up to 40 milliseconds to vaporize, whereas typical engine residence times are only a few milliseconds. Therefore, they prevent detonations and cause inefficiencies in combustion.

The inkjet, a relatively recent innovation in atomization technology, can be characterized by its ability to deliver small droplets at an affordable cost. Analytical and experimental results show the effectiveness of low-cost, commercially available inkjets to produce small monodisperse droplets (~ 30mm). However, even smaller droplets are required for successful detonation of liquid sprays in the PDE. Thus, design innovations are required to reduce droplet size even further, increase the mass flow rate and assure compatibility with JP-10 fuel. Table 1 compares commercially available atomizers with TDA’s MEMS Atomizer.



a) side view



b) top view

Figure 4. Double acting diaphragm pump configuration and flowpath details.

Table 1. Comparison of commercially available atomizers to the Navy specifications.

Type	**<10 mm SMD**	**Dp <50 psid**	**$\dot{m}$ >0.5 lbm/s**	**f_{MAX} >100 Hz**	**fuel compatibility**	**positive shut-off capability**	**manufacturers**
Simple orifice	no	no	yes	no	yes	no	Delavan, BETE, Mee, Spraying Systems, BEX
Dual orifice	no	no	yes	no	yes	no	
Swirl orifice	no	no	yes	no	yes	no	BETE, Mee, Spraying Systems, BEX
Poppet-type	no	no	yes	no	yes	yes	Delavan, Hago
Air blast	no	no	yes	no	yes	no	Delavan, BETE, Spraying Systems
Ultrasonic	no	yes	no	yes	a	no	Sono-Tek
Electrostatic Spray	yes[b]	yes	no	yes	no	a	Charged Injection
Inkjet	no	yes[d]	no	yes[c]	no	yes	Hewlett-Packard, Seiko Epson, Aprion Digital
MEMS Atomizer	yes[e]	yes[e]	yes[e]	yes[e]	yes	TBD	TDA prototype development

a. Data not available.
b. High voltage extraction.
c. Potential for 100 kHz multi-droplet operation has been demonstrated.
d. Usually self-aspirating with almost no pressure drop.
e. By analysis

TECHNOLOGY DESCRIPTION

The MEMS Jet Fuel Atomizer has been designed to atomize logistic fuels into droplets smaller than 10mm SMD with little supply pressure or external power and can operate at greater than 100Hz cycle speed. This will enable new engine cycles like the pulse detonation engine to operate with liquid fuels. Our design has morphed from its initial conception based on electrostatic inkjet technologies into a dual-acting single stage diaphragm atomizing micropump for fuel delivery and atomization (see Figure 4). The atomizer draws fuel from a reservoir into one chamber, while simultaneously expelling the fuel out of the opposing chamber through the nozzle. The micropump diaphragm is alternately actuated in direction by periodic switching of the actuation voltage. [Nabity et al. 2003] The atomizer is self-aspirating, since the diaphragm or pressure plate serves as a pump to bring fluid into the injector and eject fluid through the nozzle. Therefore, in contrast to conventional atomizers the demand on supply pressure is small (no more than several psi).

Individual nozzles can be separately addressed (as is the case in printers) using very simple electronics. That means that one could build an injector in the form of an array with spatial and temporal control of the fuel injection pattern to optimize system performance and avoid forming fuel-rich, high temperature zones responsible for high NOx and CO emission levels. Further, injector arrays are easily scalable and configurable to multiple engine concepts. We have micro-machined atomizers from about 0.1 cm to 2.0 cm in size using photolithography.

CURRENT STATE OF DEVELOPMENT

Development of a conformal array MEMS atomizer based on inkjet technologies (electrostatic actuation, MEMS devices and micro-surface machining) continues with the ultimate goal of prototype fabrication for Navy PDE testing. Extensive modeling and simulation of the coupled multi-physics problem led to our current atomizer designs, which we are currently fabricating for laboratory investigations to characterize atomization, operability and reliability. Later, we will conduct shock tube testing to verify adequacy of spray injection for rapid detonation and to determine the robustness of the atomizer under the environmental loading typical of PDE operation. We expect to demonstrate performance that meets the Navy specifications. A MEMS atomizer with digital control electronics will be supplied to the Naval Postgraduate School at the end of Phase II.

REFERENCES

Dr. Chris Brophy, project technical point of contact (TPOC) at the Naval Postgraduate School in Monterey, CA, will conduct independent tests of our atomizer in a multi-tube pulse detonation engine test rig at the end of Phase II. Dr. Brophy may be reached at (831) 656-2327 or cmbrophy@nps.navy.mil.

C.M. Brophy, D.W. Netzer, J. Sinibaldi, and R. Johnson, “Detonation of a JP-10/Aerosol for Pulse Detonation Applications,” ONR PDE Workshop, Russia, July 2000.
C.M. Brophy, J.O. Sinibaldi, D.W. Netzer, and R.G. Johnson, “Operation of a JP-10/Air Pulse Detonation Engine,” 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 17-19 July 2000, Huntsville, Alabama. AIAA Paper 2000-3591.
J. Nabity, G. Balducci, and J. Daily, “Electrostatically Actuated Fuel Atomizer Design for the Pulse Detonation Engine” AIAA-2003-4861 was presented at the Joint Propulsion Conference in Huntsville, AL, July 2003.
Robert Wall, “Where Next? Pentagon turns focus to ‘smarter’ weapons and ways to counter suicide bombers,” Aviation Week & Space Technologies, October 20, 2003, p.32.

TDA Research can provide copies of its SBIR Phase I and Phase II reports to qualified parties.

TECHNOLOGY AVAILABILITY

The earliest opportunity for introduction of MEMS based liquid fuel atomizer technology into Navy systems would be in the form of a high-speed missile. Unfortunately, there is no acquisition program in place at this time, although the AF/DARPA recently awarded contracts for Falcon high-speed missile design studies [Schactman 2003] and the pentagon plans to formulate language in its FY06 Defense Planning Guidance for support of high-speed weapons. [Wall 2003]

Developmental prototypes will be available by Dec 2004 for insertion into ONR and industry PDE developmental programs, which have an unfulfilled need for fine droplet atomizers. TDA has several non-disclosure agreements with potential customers awaiting prototype demonstration results expected first quarter 2004. Additional technology development to improve atomizer performance, miniaturize the control electronics and improve packaging will be required as a minimum to mature the technology to TRL 6 (readiness for flight demo). At that point we envision transitioning the atomizer into an ongoing Advanced Technology flight Demonstration (ATD) program on or about FY08. A high-speed PDE missile ATD could be initiated as early as FY05. An engineering, manufacturing and development program could be initiated no sooner than about FY09 culminating in an initial operational capability (IOC) in FY14.

ABOUT THE COMPANY

TDA Research, Inc. (TDA), founded in 1987, is an established company with 65 employees and 2002 revenues of $9.3 million. TDA develops and commercializes innovative technologies in its core competency areas of aerospace components, catalysts and sorbents, polymers, carbons, ceramics, and aerospace components. Our strategy is then to market and license these technologies to an industry leading prime company best suited to commercialize our products.

Our aerospace technology development in high energy and endothermic fuels and high temperature components leverages TDA's expertise in ceramics and nanoscale materials. Aerospace components have been under development at TDA for many years and we recently expanded into the MEMS arena in 2000. TDA works with the major aerospace and propulsion primes as consultants and for the transfer of our technologies. An example of this is related below. Our major collaborators are General Electric Aircraft Engines, United Technologies Pratt & Whitney, Rolls-Royce Allison, Boeing Phantom Works, Alliant Technologies and Lockheed-Martin.

In February 1997, the emergency oxygen generator onboard Mir (which decomposed (burned) a perchlorate oxygen candle) malfunctioned, sending a three foot metal/pure oxygen flame into the astronaut's cabin, threatening to force them to abandon the space station but simultaneously cutting off their escape route. Although the fire was brought under control, NASA embarked on a search for a safer backup oxygen generation system. Building on previous life support experience for NASA, TDA proposed a new design, built it, tested it and flight qualified the hardware. We delivered a ground test unit and two flight qualified units of the system nine months after the start of the project; normally designing, building and flight qualifying even the simplest space hardware is a three to five year job. The Backup Oxygen Canister System (BOCS) was entirely passive, and exploited the oxygen produced by the chemical decomposition to pull cool cabin air though a shroud around the canister, cooling the device (the reaction temperature is 820ºC) and keeping the touch temperature of the shroud below 45ºC. [Graf, et al, "Development of a Solid Chlorate Backup Oxygen Delivery System for the International Space Station," SAE ES28D – 233, 2000.]

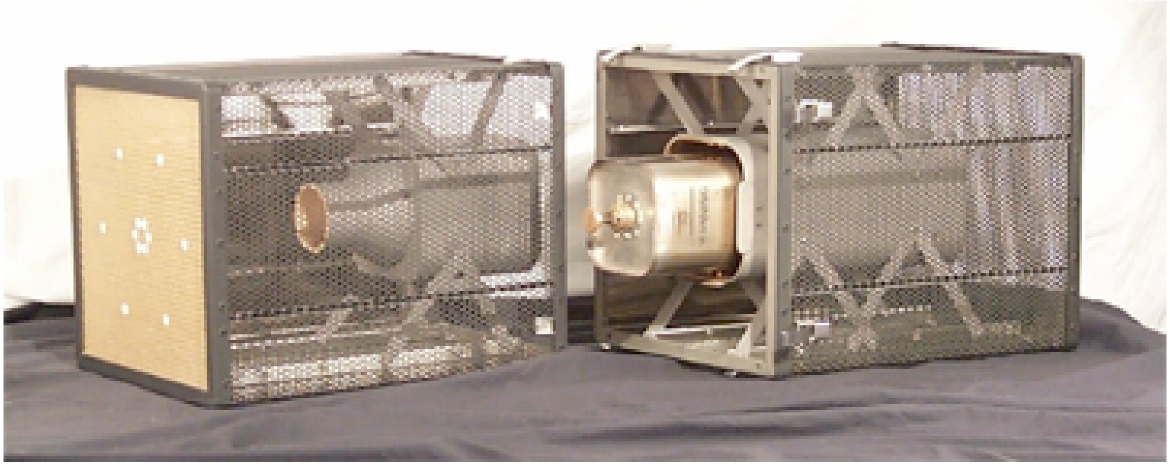


Figure 5. Photo of the TCA with candle in place: assembled envelope dimension 14" by 14" by 36".

Our catalyst and sorbent expertise are largely in sulfur processing for the oil and gas industry and hydrocarbon reforming to produce hydrogen and syngas. We also synthesize new polymers and nanoparticle additives for plastics, coatings (paints) and conducting polymers. TDA funds its research activities largely through government contracts in order to develop enabling technologies. We also formulate and/or develop processes to make specialty carbons, particularly carbons with nanoscale features, including fullerenes and carbon-based electrode materials.