LOX/Methane In-Space Propulsion Systems Technology Status and Gaps

Mark D. Klem
NASA GRC
Southwest Emerging Technology Symposium (SETS) 2017
Background

• Human exploration architecture studies have identified liquid oxygen (LOX)/Methane (LCH4) as a strong candidate for both interplanetary and descent/ascent propulsion solutions

• Significant research efforts into methane propulsion have been conducted for over 50 years, ranging from fundamental combustion & mixing efforts to rocket chamber and system level demonstrations

• Over the past 15 years NASA and its partners have built upon these early activities that have demonstrated practical components and sub-systems needed to field future methane space transportation elements

• These advanced development efforts have formed a foundation of LOX/LCH4 propulsion knowledge that has significantly reduced the development risks of future methane based in-space transportation
LOx/Methane Propellants Advantages and Disadvantages

• As a bipropellant propulsion system, LOX/LCH4 has some favorable characteristics for long life and reusability, which are critical to lunar and Mars missions
  – Non-toxic, non-corrosive, self-venting, and simple to purge
  – No extensive decontamination process required as with toxic propellants
  – High vapor pressure provides for excellent vacuum ignition characteristics
  – Performance is better than current earth storable propellants for human scale spacecraft

• Provides the capability for future Mars exploration missions to use propellants that are produced in-situ on Mars

• Liquid Methane is thermally similar to O\textsubscript{2} as a cryogenic propellant, 90,111 K (LO2, LCH4 respectively) instead of the 23 K of LH\textsubscript{2}
  – Allows for common components and thus providing cost savings as compared to liquid hydrogen (LH\textsubscript{2})
  – Due to liquid methane having a 6x higher density than hydrogen, it can be stored in much smaller volumes

• Cryogenic storage aspect of these propellants needs to be addressed
  – Passive techniques using shielding and orientations to deep space
  – Refrigeration may be required to maintain both oxygen and methane in liquid forms
Needs for Beyond Earth Orbit Human Exploration

• Some architecture studies have identified the potential for commonality between interplanetary and descent/ascent propulsion solutions using LOX/LCH4

• Meeting these functions (interplanetary, descent, and ascent propulsion) will require many or all of the following subsystems, components, and capabilities:
  • Reaction Control Propulsion: ~ 100 to 880 N (25 lbf – 200 lbf) class
  • Pressure fed engine: ~ 25 KN (6000 lbf) class
  • Pump fed engine system~ 100 KN (25,000 lbf) class
  • Long Duration Cryogenic Fluid Management and Distribution
    • Including high performance pressurization systems
    • Including thermal management with high performance Multilayer insulation and 90K class cryo-cooler systems integrated with CFM&D
    • Including management of propellant losses due to boil-off and component leakage
<table>
<thead>
<tr>
<th>Lox/Methane Propulsion System Technology</th>
<th>Performance needs for a Deep space based lander or other vehicles (service)</th>
<th>Goals</th>
<th>Technology Solutions</th>
</tr>
</thead>
</table>
| Integrated System                      | High Reliability - several usages of the same vehicle, Low cost, High delta-v, long life reusable, High mass fraction, quality and origin of methane | 1. Reliability > 0.995  
2. Life > 10 operating cycles  
3. Mass Fraction > 0.85 (Prop dry+structure) | 1. Design for re-usability |
| Pressurization System                  | High density light weight storage | 50% reduction in volume and mass over ambient temperature storage | 1. Ghe cold storage with heat exchanger  
2. partial autogenous systems |
| Pressure vessel                        | Lightweight | 1. PV/W > [Tank Pressure*volume/Tank Mass] | 1. Metallic (aluminum lithium)  
2. Composite Overwrap  
3. All Composite |
| Thermal Management                     | low boiloff, thermodynamical management of propellants during launcher phase from Earth ground | 1. deep space Zero boil-off (0 W/m²) storage at EML1  
2. lunar surface surface heat leak 0.25 Watts/m² | 1. Passive  
2. active |
| Liquid Acquisition in zero/low g       | zero-g start, refueling capability, slosh damping, and anti vortex | 1. 2% residuals | 1. Screens channel  
2. Vanes  
3. Sponges |
| Feedsystem                             | Redundancy management, propellant distribution | 1. Lightweight  
2. Low Pressure drop  
3. low heat leak | 1. Cryogenic Feedsystem for LOx/LCH4 main engine and RCS |
| Reaction Control Engines               | Provide Min. Impulse Bit, Thrust, and high cycle life | 1. Min Ibit TBD  
2. Thrust Range  
3. Cycle Life > TBD | |
| Main Engines                           | Throttle capability including idle mode, High Isp, High reliability, Thrust / Weight ratio | 1. > 4:1 throttle depending on T/W  
2. Isp > 355 sec  
3. Thrust >30 KN  
4. Helium free design | 1. Pump-fed,  
2. Pressure-fed Ablative  
3. Pressure-fed regen |
STATUS OF TECHNOLOGY
Italy - Agenzia Spaziale Italiana (ASI)

- Tested MIRA Demonstrator, a 100-kN (10-tonne) thrust class, expander cycle LOx/LCH4 engine, for the a new upper stage of Vega, in cooperation with Roscosmos
  - Successfully tested at the complete engine level
    - More than 11 tests performed up to full operating condition
    - Accumulating more than 600 s of firing.
  - Development and testing of liquid methane fuel turbo-pump bearings

- With JAXA, ASI is investigating the methane thermal behavior, characterizing bearings working in liquid methane, and designing a regenerative thrust chamber in the 100-kN (10-tonne) class which is to be tested in Italy

- Designing small methane thrusters to be applied as a potential reaction control system of the launcher stage

- The Italian Aerospace Research Center, CIRA, is developing the ‘Hyprob’ research program, specifically dedicated to combustion phenomena studies and breadboard testing, up to the design of a medium scale
  - 30-kN (3-tonne thrust class) regenerative thrust chamber
  - Program developing test facilities at both laboratory level and thrust chamber assembly (up to 100-kN (10-tonne class)
France

CNES *(Centre national d’études spatiales)*

- Engine tests on KVD1 Russian engine during a French – Russian cooperation

- Research & Development activities are being performed in parallel with several designs, manufacturing and testing at subsystem level (combustion tests and simulation capabilities including high-frequency -HF- instability analysis, pump and inducer performances, for example)

- French capabilities are currently being developed for cryogenic propellant management

- Current main objective for CNES with French industry support is to prepare a LOX/LCH4 low cost, gas-generator engine demonstration at 1000-kN (100 t) thrust level before 2023
  - 10-kN scale – bleed expander cycle
  - Capability of current LOx/LH2 engines to operate with LOX/LCH4 is also being addressed
Germany
DLR (Deutsches Zentrum für Luft- und Raumfahrt)

- Investigated flame visualization in optically accessible chambers
  OH* and CH* visualization for sub and super-critical pressures
- Investigated injector behavior
  - Flame stabilization of coaxial and porous injectors was investigated
  - Combustion efficiency investigations are planned
- Investigated combustion stability with a single coax injector
- Ignition of LOX/CH4 multi-injector configurations
  - Chemical igniters (LOX/H2 flame)
  - Laser ignition
- High-altitude ignition of LOX/GCH4
  - Laser ignition of a full-scale 200-400 N RCS chamber was performed to determine the minimal ignition energy and demonstrate the feasibility of laser ignition.
  - Pre-ignition flow conditions in the chamber were visualized
- LOX/Methane pre-burner applications
  - Film cooling and Regenerative cooling with methane
JAXA (Japanese Aerospace Exploration Agency)

- 100-kN class LNG rocket engine, named LE-8, developed by (JAXA) and IHI Aerospace Co., Ltd. (IA)
  - Completed more than 2000 seconds of its firing tests
- 30 KN LNG engine for the purpose of obtaining performance data with a high altitude test stand (HATS)
  - Five firing tests with a total of 122 seconds at altitude conditions
- The LE-8 and the 30-kN class engines consist of an ablative chamber and a liquid-liquid impinging type injector – simpler engine and reduced cost
- LNG engine with regenerative cooling chamber was designed and demonstrated in a sea level test facility
  - Equivalent I_sp reached to approximately 350 sec
- To achieve higher performance, JAXA is carrying out a research activity on LNG engines focusing on a regenerative cooling type engine

<table>
<thead>
<tr>
<th></th>
<th>LE-8 engine</th>
<th>30 kN-class engine</th>
<th>IHI in-house engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust(Vacuum)(kN)</td>
<td>107</td>
<td>30</td>
<td>98.0</td>
</tr>
<tr>
<td>Isp(Vacuum)(sec)</td>
<td>314</td>
<td>335</td>
<td>354</td>
</tr>
<tr>
<td>Combustion chamber pressure(Pc)(MPa)</td>
<td>1.2</td>
<td>1.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Mixture ratio(Thrust chamber)</td>
<td>3.2</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Chamber cooling</td>
<td>Ablative</td>
<td>Ablative</td>
<td>Regenerative</td>
</tr>
<tr>
<td>Nozzle expansion ratio</td>
<td>42</td>
<td>49</td>
<td>150</td>
</tr>
</tbody>
</table>
Recent activities (10 years)

- **CFM:**
  - 1.2 m diameter spherical tank was used to demonstrate insulation
  - Zero-boil-off (ZBO) system for LO2 was demonstrated using a flight-like cryocooler
  - Radio Frequency Mass Gauge (RFMG) for mass gauging in micro-gravity
  - Cryogenic feed systems for multiple RCS engines and main engine in a vacuum

- **Engines:**
  - RCS engines at thrust levels of 88 N (25 lbf), 444 N (100 lbf), and 3.8 kN (870 lbf)
  - 24.5 kN (5.5 klbf) ablative engine for lunar ascent - 2% of target 355 s Isp @ 150:1
  - Throttling 24 kN (5 klbf) and 8.8 kN (2 klbf) with ablative/film-cooling

- **System:**
  - Integrated feed system, RCS, main engine at altitude
  - Flight testing of an integrated LOx/Methane system on terrestrial lander

Current Activities

- **CFM - Evolvable Cryogenics project is developing**
  - RFMG for cryogenic subsystem of the Robotic Refueling Mission 3
  - Zero Boil-off Transfer (ZBOT) payload for the ISS Microgravity Science Glovebox
  - Sub-scale Laboratory Investigation of Cooling Enhancements (SLICE) - welded vs. bolted design for skirt designs

- **Engines:**
  - Currently, small-scale pressure fed (17 kN (4 klbf)) and large-scale pump fed (111 kN (25 klbf)) engine components are being built using Advanced Manufacturing
Other Activities

• SpaceX – Raptor Development (738 Klb, full flow staged combustion)

• Blue Origin – BE-4 (550 Klb oxygen rich staged combustion)

• Air Force Research Lab
  – Third Generation Reusable Booster (3GRB)

• Other smaller companies – Masten, TGV, Wask, Exquadrum, Sierra Nevada, etc.

• Universities – UTEP, Purdue, etc.
GAPS
GAPS

• Develop a throttle-able regenerative-cooled pump-fed and/or pressure-fed engines to address gap for throttling (5:1 – 10:1), 360-365 sec, and for regenerative-cooled engines in the 25 – 100 kN range

• Develop 100 to 880-N RCS thrusters with integrated cryogenic feed systems to address gap for thruster size/cost and then to evaluate GNC impulse bit and thrust requirements

• Develop long duration reliable cryogenic refrigeration systems capable of maintaining zero-boil-off and performing liquefaction of in-situ produced propellants (several hundred watts at ~90 K)

• Develop composite cryogenic tanks with focus on spherical geometry to addresses gap in propellant tank technology
GAPS

• Develop high performance pressurization systems that improve storage density and reduce mass to address gap for use with cryogenic propellants

• Develop low-leakage, long-duration cryogenic valves and leak detection

• Develop automated fluid couplings

• Conduct extended duration thermal vacuum testing of integrated system to address gap of integrated system testing in thermal vacuum environment

• Fly a zero-g cryogenic liquid acquisition experiment in space, such as on the ISS or in a cis-lunar location to address gap of lack of demonstration of LOX/LCH4 in these conditions

• Fly a test vehicle in space as a technology infusion mission to demonstrate integrated LOX/LCH4 propulsion systems to address gap of no in-space flight experience
Overall References

Dig into references within references


Summary and Conclusions

• LOX/LCH4 is an enabler for future exploration with in-situ propellant production

• Offers improved performance, improved reusability and elimination of toxicity issues for surface operations, and fluid commonality

• Foundational R&D activities conducted multiple LOX Methane advanced development efforts and hardware demonstrations over the last 15 years

• While focused on different ultimate applications these efforts combine to significantly reduce the development risks associated with future methane propulsion systems for human exploration

• Future system level testbed demonstrations (ground) leading to a potential risk reduction flight demonstration is a recommended path forward