Technion – Israel Institute of Technology
Faculty of Mechanical Engineering
Internal Combustion Engines Lab

Ministry of National Infrastructures,
Energy and Water Resources

Association of Engineers, Architects and Graduates in Technological Sciences in Israel

MAFAT
Directorate of Defense Research & Development (DDR&D)
Aeronautical Division

טכנולוגיות הנעת כלי טייס בלתי מאוישים

הכנס הארצי הרביעי

חוברת תקצירים

הפקולטה להנדסת מכונות, הטכניון
חיפה
ט' שבט תשע"ה
29 בינואר 2015

Conference Program

4th Conference on Propulsion Technologies for Unmanned Aerial Vehicles

Thursday, January 29, 2015
Shirley and Manny Ravet Auditorium, D. Dan and Betty Kahn Building
Faculty of Mechanical Engineering, Technion, Haifa

8:30 – 9:00	**Welcome and Registration**
Opening session	**Chairperson: Leonid Tartakovsky,** Technion
9:00 – 9:30	**Welcome:** **Wayne D. Kaplan**, Executive Vice President for Research, Technion **Yoram Halevi,** Dean, Faculty of Mechanical Engineering, Technion **Uri Zvikel,** Head Propulsion Branch, Directorate of Defense Research & Development, MAFAT **Emanuel Liban,** Chairman, Israeli Society of Mechanical Engineers
9:30 – 10:00	**Keynote address:** **Internal combustion engines for UAV** **Wai Cheng,** Director, Sloan Automotive Lab, MIT, USA
Morning plenary session	**Chairperson: Yitzhak (Itche) Hochmann,** Edmatech
10:00 – 10:30	**UAS Operational Evaluation, Integration and Aging Challenges in the Israeli Air Force** **Col. Erez Kabariti,** Israeli Air Force
10:30 – 11:00	**UAV Engines in Operational Environments – Lessons Learnt and Technical Implications** **Hemi Oron,** Senior Director, UAV Engines Plant, Elbit Systems - UAS
11:00 – 11:30	**Coffee break**
Noon plenary session	**Chairperson: Kobi Feldman,** Israeli Aerospace Industries
11:30 – 12:00	**Automotive Technology in UAV Propulsion Systems** **Emanuel Liban,** Edmatech Ltd. – CEO
12:00 – 12:25	**Progress in Development of a Small Rotary SI Engine** **N. Shkolnik, A. Shkolnik, D. Littera and M. Nickerson,** LiquidPiston, Inc., USA
12:25 – 12:50	**UAV Engine Control Development Using a Model-Based Design Environment** **Yonathan Nassau, Menachem Lerer**, UAS Division, Elbit Systems

12:50 – 14:00	**Lunch**
Afternoon session "New Concepts"	**Chairperson: Nir Geva,** Elbit Systems
14:00 – 14:25	**Development of a PCM-based engine for Micro Aerial Vehicles (MAV)** **J. Fuchs, A. Lidor, E. Sher and D. Weihs**, Technion
14:25 – 14:50	**Solar High Altitude Unmanned Vehicle Propulsion System Feasibility Analysis** **D. Weihs and M. Harmatz**, Technion
14:50 – 15:15	**Common-rail fuel injection systems for diesel engines with piezo-injectors** **Erez Mosafi,** Ledico – Bosch Israel
15:15 – 15:40	**Experimental study of burning velocities of hydrogen-rich gaseous fuels** **Ahmad Omari and Leonid Tartakovsky,** Technion
Afternoon session "Engine Design & Performance"	**Chairperson: Gil Finder,** Israel Defense Forces
14:00 – 14:25	**Supercharging of UAV engines – benefits and challenges** **Yehuda Fass,** Israeli Aerospace Industries
14:25 – 14:50	**Engine design and performance optimization through advanced simulation tools** **Arnon Poran and Leonid Tartakovsky,** Technion
14:50 – 15:15	**Knock and surface ignition problems in UAV spark-ignition engines and ways of their prevention** **Ran Amiel**[1], **Kobi Cohen**[2] **and Leonid Tartakovsky**[1] 1 – Technion; 2 – Israeli Air Force
15:15 – 15:40	**Four-Stroke Engine with a Port in the Cylinder Sleeve** **A.L. Zhmudyak, L.M. Zhmudyak**
Closing remarks 15:40 – 15:50	**Leonid Tartakovsky**, Chairman Organizing Committee

Organizing Committee

- *Leonid Tartakovsky*, Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, **Conference Chairman.** Email: tartak@technion.ac.il
- *Kobi Feldman*, Israeli Aerospace Industries
- *Gil Finder*, Israel Defense Forces
- *Yitzhak (Itche) Hochmann*, Edmatech Advanced Engineering Consultants Ltd.
- *Emanuel Liban*, Chairman of Israeli Association of Mechanical Engineers
- *Amihai Magal*, Israel Defense Forces
- *Hemi Oron*, Elbit Systems
- *Michael Shapiro*, Faculty of Mechanical Engineering, Technion – Israel Institute of Technology

Conference Secretary:

Mrs. Ruthie Bouscher, meruthi@tx.technion.ac.il *Phone: +972-4-8292065, Fax: +972-4-8295711*

Keynote address

IC Engines for Unmanned Airborne Vehicles

Wai Cheng[1]*

[1]Department of Mechanical Engineering, MIT, Cambridge, Massachusetts, USA
* Presenting author email: wkcheng@mit.edu

Keywords: UAV; IC engines

Unmanned Airborne Vehicles (UAV) requires engines of high power, low weight, good specific fuel consumption and reliability. The power requirement for different size vehicles ranges over orders of magnitude, from ~10^2 to 10^5W. The positive displacement internal combustion engines (ICE) are the workhorse of choice. This talk gives an overview of ICE for UAV. The conventional spark ignition engines are attractive because it is well developed and continued to be developed by the automotive industry. The recent development of turbo-downsizing for automotive engines offers improved power density and efficiency for bigger engines. Because of the relatively small UAV market, there is the opportunity of custom fuel blending to mitigate knocking and further improve efficiency. For military applications in which heavy fuel is used, stratified-charge SI engines are employed to mitigate the knock constrain of these fuels. The opposed piston engines and rotary engines have potential for better power to weight ratio than the conventional SI engines. Further developments are needed to improve their combustion characteristics and durability.

UAS Operational Evaluation, Integration and Aging Challenges in the Israeli Air Force

Col. Erez Kabariti

Israeli Air Force, IDF

Keywords: Unmanned aerial vehicle; UAV Operational requirements; UAV Monitoring and diagnostics; Requirements for UAV

UAV Air Systems plays important role and continuously emerging its volume and capabilities in the operational doctrine of the Israeli Air Force. This trend which dates back 10 years ago, as a result of the modern warfare challenges requires adaptable solutions for versatile and rapidly changing operational requirements. In parallel to the research and development effort of new Unmanned Air System, significant challenges flourish in the area of aging Unmanned Aircraft operational evaluation, integration and maintenance.

The challenges are pretty known in the life cycle of weapon system; starting from the **Development**, continue with **Certification** by the airworthiness agency (Air Force Material Directorate) which depicts inherent dilemma of balancing operational requirements, safety and budget, throughout the **Evaluation Phase**, performed during high-tempo operations. This delicate balance requires large investments in **Monitoring and Diagnostics**, an emerging vector in recent years, which is based on the capability to predict the UAV status in real-time and provides an early warning on forthcoming failure.

An additional evolving challenge is focused on the integrated debriefing capability, overarching technical and engineering through operational aspects. The presentation will provide an insight into the integrated debriefing capability, embedding the Air Force legacy holistic debriefing methodology. Moreover, questions on the technical professions and knowledge required to operate and maintain those systems will be answered.

The Israeli Air Force is the Lead of the Fleet and operates aging UAVs. Common methods for maintaining manned aircraft are delicately adapted to composite materials-made UAVs. The presentation will provide insight into advanced non-destructive tests and complex engineering activity which enable today air vehicle life extension, where international standards were not in hand when those aging UAVs were developed. Finally, advanced maintenance concepts and contracts will be discussed, which are based on performance and outputs, complementing the aging advanced fleet in the Air Force.

UAV Engines in Operational Environments – Lessons Learnt and Technical Implications

Hemi Oron

Senior Director, UAV Engines Plant, Elbit Systems – UAS, Nes-Ziyona, Israel
Presenting author email: Nehemia.Oron@elbitsystems.com

Keywords: UAV Engines; Wankel; Piston

The study is based on several hundreds of thousands of flight hours performed by UAV's worldwide in operational service. The areas of operations covered by this paper were: Iraq and Afghanistan (British Artillery), Gaza Strip (Israel IDF), Rio de Janeiro – Maracana (Brazilian Forces) and others. Due to the nature of these operations, the information provided herein refers only to technical aspects, and does not point specifically on specific operations.

UAV's in operational and combat zones are subject to enhanced requirements, as their operation is usually referred to as "lifesaving missions". This means they will fly in almost any condition, and be used to the extreme limits.

UAV engines were originally built for leisure and hobbies, or in better cases for motorcycles and light sport aviation. They were not intended for a continuous full power operation for long durations, nor for performance at high altitudes.

Operation areas are not defined by where it is good to fly, but on where the threat is. And the threat can be in a remote desert, in a heavy populated hostile area, or in the vicinities of a football stadium jammed with 100,000 fans.

Engines of strenuous operational missions are modified to provide solutions to such environments. Several challenges and solutions are presented. Among them:

- Acoustic signature attenuation
- Air (for combustion and cooling) filtration
- Shortening the TBS (Time Between Sorties)
- Rain and Hale protection
- Icing conditions protection
- Very Cold environments
- Increased Altitude operation
- Multi Fuel requirements
- Semi-prepared runways
- Engine Certification requirements
- Engine Health Monitoring
- "Get Home capabilities"
- Engines' mishaps

Short term and long term solution to such requirements will be discussed and presented.

Automotive Technology in UAV Propulsion Systems

E. Liban

EDMATECH Advanced Engineering Consulting Ltd, Tel-Aviv, Israel
Presenting author email: edmatech@netvision.net.il

Keywords: Internal Combustion Engine; Unmanned Aerial Vehicle; Engine technology; Hybrid propulsion; Fuel cell

The driving force behind the developments in IC (Internal Combustion) propulsion in the last four decades is the Automotive Industry.

The high and unpredictable fuel prices, environmental regulations and fierce competition in the Global Market Place lead to a steep reduction in fuel consumption and weight and increase in reliability and customer satisfaction in spite of the enormous complexity of presents Power Train Systems.

The Automotive Industries invested double digit, Billions of U.S in R&D, manufacture and testing. Among the most outstanding achievements are:

- "Common Rail" system for Diesel engines.
- Direct Injection (High Pressure Fuel System) in Otto Cycle engines.
- Increase of pressure ratio in Otto Cycle engines .
- New generation of Injectors
- Electronic Controls with Multiple Sensors (FADEC –Full Authority digital Electronic Control or EFI – Electronic Fuel Injection).
- Real Time Control of the Thermodynamic Cycle.
- Turbo charging (Single and Multistage).
- Emissions Reduction.
- Multi-fuel Capability.
- Higher Power to Weight and Volume Ratio engines
- Increase in usage of light materials such as Aluminium Alloys and Hi-Temp Plastics.
- Reduction in Friction losses and wear due to new materials, coatings, advanced bearings, and new low viscosity lubricants
- Smaller engines with fewer numbers of cylinders .

- "Piston Deactivation"
- Starter – Alternator
- Powerful and Reliable rechargeable batteries
- Hybrid propulsion
- "Fuel Cells" (Hydrogen Fuel)

During this period the Aircraft I/C engines industries were in stagnation and even suffered a set back due do the shrinking market of piston engine powered aircrafts, Turbofan– engines competition and lack of R&D funds.

The few developments that happened in Europe and USA were based on derivatives and ideas from automotive technology .

The typical Mission Profile of UAV consist of Take –off , Climb, Cruise and Loiter and is very different from the automotive regime and requirements. Therefore the A/C Engines do not need all the new features of advanced automotive engine but on the other hand they have to meet Airworthiness Specifications.

In the lecture the main automotive technologies will be described with an emphasis on their possible application in A/C propulsion and the characteristic of ideal UAV engine will be described.

Progress in Development of a Small Rotary SI Engine

Nikolay Shkolnik*, Mark Nickerson, Daniele Littera and Alexander Shkolnik

LiquidPiston, Inc. Bloomfield, CT, USA.
* Presenting author email: ns@liquidpiston.com

Keywords: Rotary Engine; High Power Density, High Efficiency, Low Vibration

This paper builds on prior work presented by Shkolnik *et al* [1], and describes progress in development of "XMv3" – an innovative, 4-stroke, small, rotary internal combustion engine designed to operate on the Spark Ignition (SI) version of the patented High Efficiency Hybrid Cycle (SI-HEHC). The HEHC was originally developed for application to larger engines using heavy fuel, compression ignition (CI), including high compression ratio (CR), constant-volume (isochoric) combustion, and overexpansion. First law analysis using air-standard assumptions shows that the HEHC has a theoretical efficiency of 75% [2]. The XMv3 rotary engine, in its current form, is being developed to operate in SI mode (SI-HEHC), albeit at lower efficiencies than predicted for CI-HEHC. Predicted efficiencies are still higher than those for conventional piston and other rotary engines. As this engine does not have poppet valves, and the gas may be fully expanded before the exhaust stroke begins, it is relatively quiet and may not require a muffler. Similar to the Wankel rotary engine, the XMv3 engine contains only two primary moving parts – a shaft and rotor, resulting in compact size and low-vibration operation. Unlike the Wankel, however, the XMv3 engine is uniquely configured to adopt the HEHC with its associated efficiency and NVH benefits, as well as a unique direct seal lubrication method. The result is an engine which is compact, lightweight, low-vibration, quiet, and fuel-efficient. The above mentioned advantages, along with XMv3's favorable form factor and ability to operate in both horizontal and vertical directions, could be of special interest for the UAV applications.

XMv3 is a 70cc, 1 rotor / 3 chamber rotary engine, expected to produce 3-5 HP, with up to 2.7 kW/kg specific power, with efficiencies up to 20% higher than conventional piston engines. Building a small rotary engine presents unique challenges in sealing, thermal management, and tribology. Further tuning and optimization is necessary and is currently underway to fully exploit the advantages of HEHC with the X architecture engines. This paper will review the HEHC as well as XMv3's design, challenges encountered, and provide an overview of recent experimental results.

High Efficiency Hybrid Cycle (HEHC)

As the name implies, the HEHC attempts to combine (hybridize) the best features of several thermodynamic cycles, including the Diesel, Otto, and Atkinson cycles to create a highly efficient engine. In its purest form, the HEHC combines the following features:

- High CR of air (e.g. Diesel cycle)
- Constant-volume (isochoric) combustion (e.g. Otto cycle) achieved by long-duration burn, through a dwell in volume near Top Dead Center (TDC).

- Overexpansion to atmospheric pressure (E.g. Atkinson cycle)

The patented [3, 4] X architecture, described below, is designed to implement this cycle. In the Compression-Ignition (CI) version of the HEHC, fresh air (without fuel) is compressed to a high CR in a combustion chamber of the engine. Fuel is injected into the chamber just prior to TDC and CI takes place. The majority of combustion occurs under a relatively constant volume condition, achieved through a long duration dwell in chamber volume near TDC. The combustion gas then expands to a larger volume than the initial intake volume. Fig. 1 shows Pressure-Volume (P-V) diagrams, and indicates a much larger area encompassed by the HEHC curve, when compared to the diesel and Otto cycles, thus indicating higher efficiency.

The HEHC cycle can also operate with SI, albeit with lower resulting efficiencies. In this case, an air fuel mixture is compressed to a lower compression ratio, as in standard Otto cycle engines. The reduction in CR causes a reduction in efficiency compared to CI, but the dwell in combustion volume near TDC results in higher peak pressure and efficiency than piston-engines operating with SI. The dwell in volume at TDC allows the engine to more closely achieve true constant-volume combustion (isochoric head addition), compared to a piston implementation of the Otto cycle. Overexpansion further increases efficiency, similar to the Atkinson cycle.

The HEHC is compatible with boosting techniques, primarily by the addition of a supercharger. This will effectively raise the entire curve of the pressure PV diagram. Supercharging is preferable to turbocharging because of the overexpansion feature- the exhaust gas will naturally contain less energy in HEHC as compared to Otto or Diesel cycles. In this paper we focus on naturally aspirated cases.

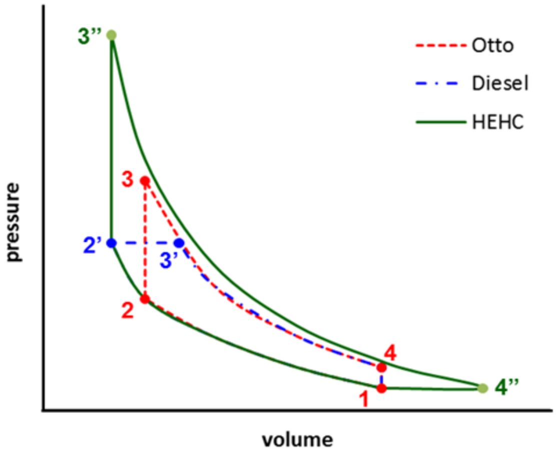


Figure 1 P-V diagram comparing ideal air-standard cycles

The ideal gas standard HEHC thermodynamic model is presented for the purpose of comparison with ideal gas-standard Otto (constant volume heat addition) and Diesel (constant pressure heat addition) cycles [5]. Fig. 1 shows the qualitative comparison of the pressure-volume (P-V) diagram for each cycle. Analysis of ideal gas standard Otto and Diesel cycles is useful for theoretical purposes to illustrate trends in efficiency, and is a common discussion in most internal combustion engine textbooks. A more in depth review of the HEHC cycle and efficiency comparison may be found in [1]. The thermodynamic ideal cycle efficiency of HEHC assuming moderate diesel compression ratio of 18:1 is 74%, approximately 30% higher than comparable Otto or Diesel ideal cycles.

Figure 2 XMv3 engine in comparison to an iPhone for scaling

XMv3

A small, air cooled, 70cc engine, the XMv3 is currently undergoing initial testing by LiquidPiston. This engine (shown in

Fig. 2) has potential applications in the lawn and garden industry, as well as moped, watercraft, UAV, and small generator markets. The engine executes a 4-stroke HEHC cycle. As this engine is designed for lower-cost markets, the first version developed is a SI engine with a lower compression ratio of 9:1. For development, a PFI injector is used to modulate fuel into the intake, however the engine is designed to accommodate a carburetor. Three spark plugs are used to ignite the fuel air mixture (one for each chamber). The engine utilizes a near-constant volume combustion process and over-expansion of gas products to improve efficiency and reduce noise output.

The engine architecture and operation is shown in Figure 3. The intake charge is drawn in axially through the shaft, then enters an intake passageway within the rotor, before entering the chamber. The charge is compressed by the rotor, and is spark ignited. Expansion proceeds until an exhaust port opens. The side plates have three windows, configured for cooling air to flow through the rotor, driven by a fan on the shaft). Exhaust gas is allowed to enter into the rotor through the exhaust port, but is immediately diluted and blown out of the engine by the cooling fan. Notably for military applications, this results in a lower heat signature. The intake channel is insulated from the exhaust. The long pathway for intake serves as a plenum to allow mixing of air and fuel and absorbs the intake air pulses (an effect of the early or late closing of the intake port). The interested reader can view the assembly and operation of the XMv3 in this video [6].

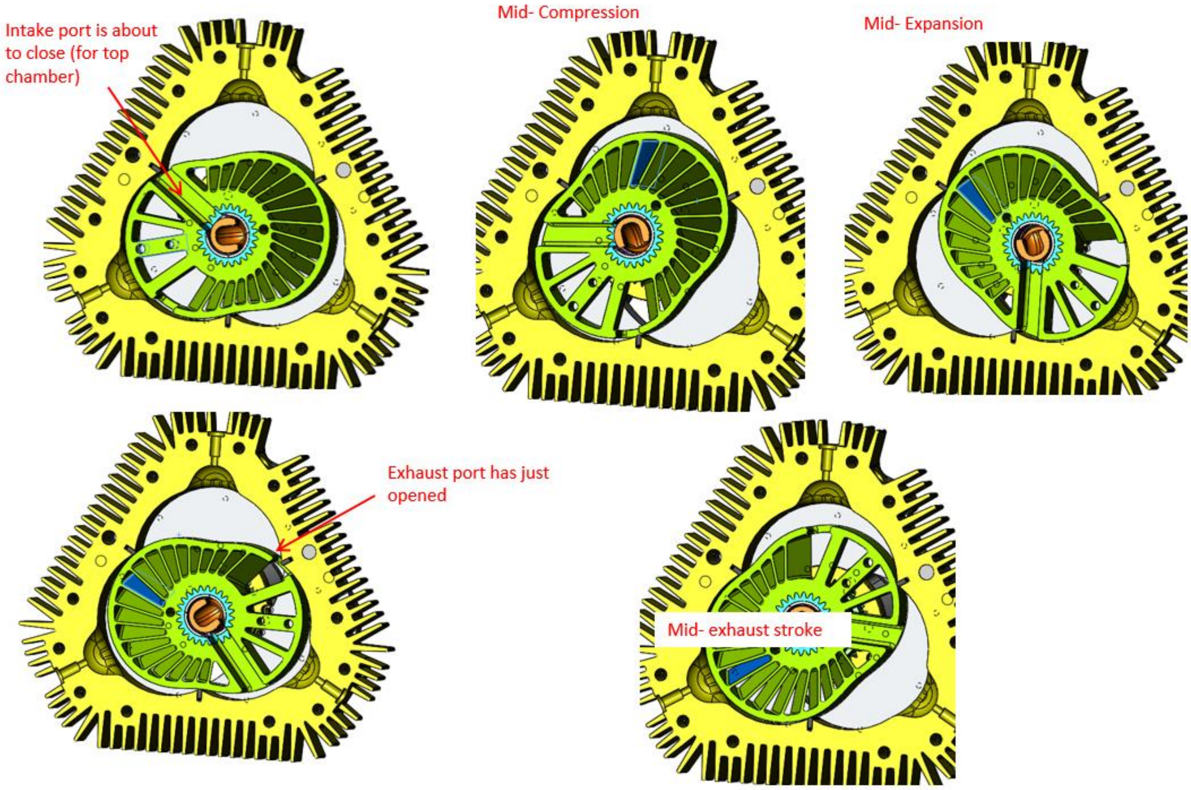


Figure 3 Operation of XMv3 engine

The XMV3 has approx. 40% larger intake area than a comparable SI single cylinder 30cc 4-stroke lawn and garden engine measured as a baseline. It is important to remark that the XMv3 has three chambers, with a displacement of 23cc each (23.3 x 3 = 70cc total). A single set of intake and exhaust ports operates for all the three chambers. Furthermore, the ports open and close rapidly as they are not cam-driven. A great advantage of rotary engines is the lack of reciprocating motion. XMv3 has the potential to be almost vibration-free, which would be especially useful in hand-held, UAV, and mobile power applications, where the weight of mounting brackets and frame can be reduced. Analysis results indicate a reduction of two orders of magnitude on the shaking forces and moments.

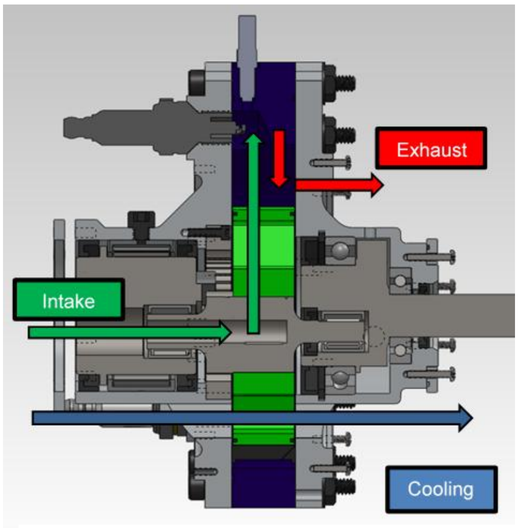


Figure 4 XMv3 section view and flow configuration

The XMv3 engine is a proof of concept engine designed to demonstrate the scalability of the HEHC and X engine geometry, as well as operation at steady-state with air cooling. Initial motoring results show good motoring pressures (>16 bar peak), indicating that sealing is less of an issue, especially at higher RPM. Leakage problems are still significant for XMv3 at low speed, and improvements to sealing are in progress. At higher RPM, the pressures are notably higher than in the piston engine due to improved breathing, and a slight ramming effect from the delayed intake-port closing.

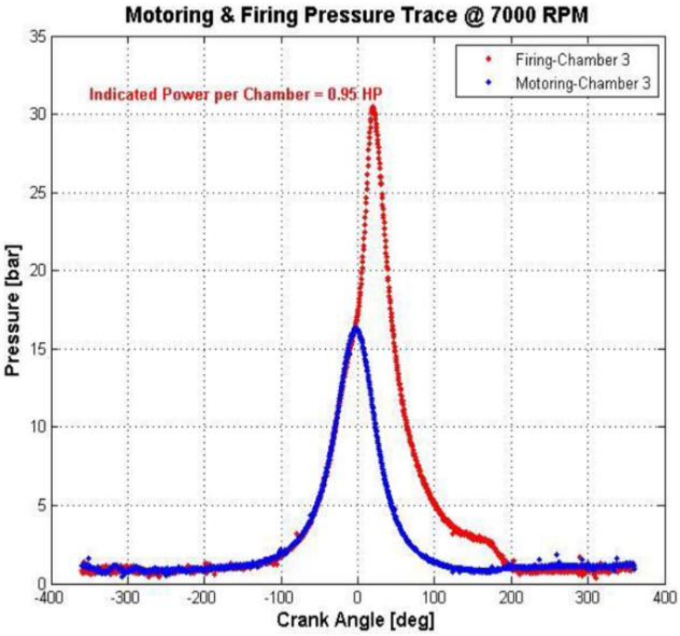


Figure 5 Motoring and Firing traces for XMv3

The newly developed engine has demonstrated 3.5 HP (indicated) at 7000rpm with 25 BTDC spark advance. Indicated efficiency is 10%. With continued development, this engine, weighing 3.5 lbs., is expected to produce 3-5 HP brake at up to 14,000 RPM.

Further development of the engine will focus on improving sealing and volumetric efficiency, as well as finer engine calibration. The goal for the XMv3 is to achieve high power density (3-5hp for an engine that weighs 3 lb.) with higher efficiency (20% to 25%) than a 4-stroke SI piston engine of the same displacement, with the added advantages of low vibration and low noise.

Conclusions

In this paper we reviewed the HEHC and the XMv3 rotary engine architecture, which together allow for high power density, low NVH, a reduction in number of moving parts, fuel flexibility, and scalability, making this engine architecture particularly suitable for UAV applications. While the engine is in the early stages of development, its initial performance (3.5 indicated HP at 10,000 RPM) is supporting of our analytical models. A good agreement between 0D/1D models and the initial test results indicate that the target efficiency and power levels are achievable.

Acknowledgement

The authors wish to thank Northwater Capital Management and Adams Capital Management for funding this development as well as members of the engineering / technical team which helped in the design and testing of the X engines, including especially: Alexander Kopache, Chuankai Sun, Ganapathy Machamada, Kyle Becker, Nicholas Medeiros, Ryan Leary, Jamael Velasquez, Len Louthan; the team at Davinci engineering: Dave Gruenwald, Bryan Danner, Eddie Phillips; the team at Century Tool, especially Lee Sroczenski.

References

1. Development of a Small Rotary SI/CI Combustion Engine, Alexander Shkolnik, Daniele Littera, Mark Nickerson, and Nikolay Shkolnik, Kukwon Cho, SAE 2014-32-0104
2. Shkolnik, N. and Shkolnik, A., “High Efficiency Hybrid Cycle Engine”, proceedings of the ASME Fall Conference on Internal Combustion Engines, ICEF2005-1221, 2005, doi:10.1115/ICEF2005-1221
3. Shkolnik, N., and Shkolnik, A. (2013) Cycloid rotor engine, US Patent # 8,523,546.
4. Shkolnik, N., and Shkolnik, A. (2014) Hybrid Cycle Combustion Engine and Methods, US Patent # 8,794,211.
5. Heywood, J. (1988) Internal Combustion Engine Fundamentals, McGraw-Hill, New York.
6. LiquidPiston (2014) ‘X’ Engine animation. Website URL: http://liquidpiston.com/technology/how-it-works/

UAV Engine Control Development Using a Model-Based Design Environment

Yonathan Nassau, Menachem Lerer
Elbit Systems LTD - UAS – UEP

* Presenting author email: menachem.lerer@elbitsystems.com, Yonatan.nassau@elbitsystems.com

Keywords: ECU; Model Based Design; Simulink; Hardware-In-Loop (HIL)

The growing number of UAV applications in military and civil applications led to stringent requirements for compliance with formal international design and development standards. The design and development process of an engine control unit (ECU) cannot readily therefore be adopted from existing off-the-shelf automotive or aerospace systems. The Model-Based Design process described here can offer significant advantages in cost, performance and mainly, time to market.

The development environment is based on the Matlab and Simulink platform with the applicable tools for the selected target machine (this paper describes a target device based on a Freescale Power PC processor). The entire ECU model may be developed as a set of building blocks for all the sensors, actuators, engine management strategies and control logic. All unique UAV requirements such as dual or triple redundancy on sensors and actuators, health monitoring, fail-safe strategies, limp-home capability, logging and host computer communication, can be readily designed and tested.

The next step of machine code generation can be performed both in the traditional methods of manual coding, testing and documentation, or by using the Matlab Embedded Coder that provides automatic code generation with provisions for full documentation. The embedded coder offers a highly efficient development process that can save a lot of time and cost. Once the target machine is loaded with the code, the design verification process may be performed by using the actual target ECU as the hardware-in-the loop (HIL) device coupled to a suitable test environment system that simulates all engine components. The test system should be capable to run automated scripts, fault injections, events capture and logging. The test system described here is based on the National Instruments Compact-RIO FPGA system.

The ECU can now be integrated with the engine installation and start operating in the calibration process. The calibration process may be performed by using the CCP (CAN based) or XCP (Ethernet based) communication protocols and a suitable software application such as ETAS INCA, Vector CANape, or ATI Vision. The engine can now be operated in the test cell through the entire operational envelope while optimizing the ECU maps and lookup tables.

This development process was initially demonstrated at UEP on a small single-cylinder 2-stroke engine. The entire process that started by building the Simulink model and ended in the test cell with a fully configured engine and ECU, took less than 10 days.

This paper describes the development process of an ECU for a 4-cylinder 4-stroke engine with full redundancy on sensors, logic and ignition. The ECU also provides turbocharger control, wide-range Lambda control at sea-level to 30K Ft altitude, and knock control.

Development of a PCM-based engine for Micro Aerial Vehicles (MAV)

J. Fuchs[1], A. Lidor[2], E. Sher[2]* and D. Weihs[2]

[1]Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, Haifa, 3200003, Israel
[2]Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa, 3200003, Israel
* Presenting author email: sher@technion.ac.il

Keywords: Phase Change Materials; Micro Aerial Vehicles; MAV; Energy Source;

There has recently been an increased effort in research and development of remotely-controlled and autonomous micro aerial vehicles (MAV). While there are many different challenges in the development of MAVs, one of the severe limiting factors in terms of weight is the energy source/storage (Lidor, Weihs, & Sher, 2013). We have examined several potential alternative energy storage: carbon nano-tubes (CNT), fuel cells, shape memory alloys (SMA), synthetic muscles, flywheels, elastic elements, pneumatics, thermal systems, radioisotope thermoelectric generators, and phase change materials (PCM). We have concluded that PCM-based energy source currently offers the best alternative. A novel PCM-based cycle (Lidor, Sher, & Weihs, 2014) - Fig. 1, has been systematically analyzed, designed and constructed.

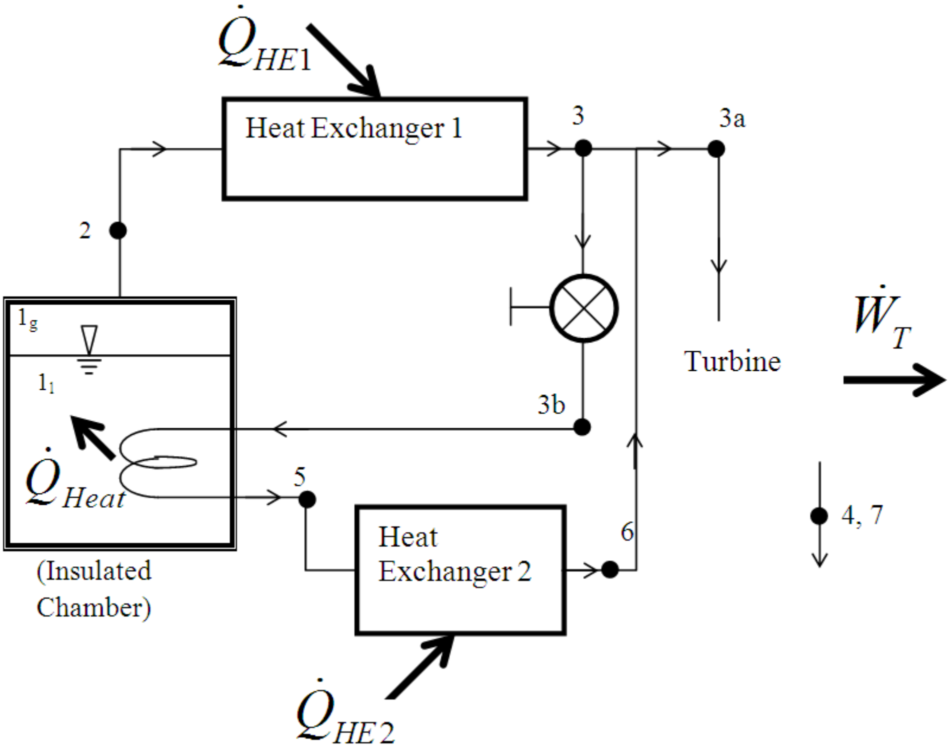


Figure 1. Conceptual cycle design of the PCM-based engine

Since a major challenge in the implementation of this cycle is the miniature turbine, an off-the-shelf turbine was chosen, with performance characteristics as close as possible to our requirements. The method for sustaining the boiling in the storage tank was also examined, with several options in mind. We came into the conclusion that the original proposed solution of using a portion of the superheated vapors benefits significant advantages over the alternatives (injection of a portion of the superheated fluids, electrical heating or using air ducts through the insulation). We have also reevaluated the system properties for the different possible PCM fluids, in regards to our working pressure limitation (as required by our purchased turbine, an Air Turbine Tools 201SV model, designed for 40,000rpm and 700kPa), with the results presented in Table 1.

Table 1. Comparison of the system properties for different PCM fluids

Properties at working pressure of 700kPa						Optimal conditions	
Fluid	**Initial mass**	**Final mass**	**Mass flow**	**Tank volume**	**Tank temp.**	**Optimal pressure (for minimum mass)**	**Optimal pressure initial mass**
	[kg]	[g]	[g/s]	[L]	[°C]	[kPa]	[kg]
Nitrogen	0.9548	39.26	1.367	1.367	-174.7	1746	0.8057
Helium	~above critical pressure (227.5kPa)~					190	0.5425
Methane	0.5236	15.48	0.4234	1.401	-131.4	2163	0.4211
Argon	1.487	42.18	1.204	1.202	-162.4	2161	1.252
Oxygen	1.076	28.82	0.8727	1.062	-159.3	2339	0.8577
CO2	1.44	22.97	1.181	1.25	-49.37	2950	1.079
Ethane	0.9469	24.93	0.7683	1.967	-43.16	1988	0.7806
Fluorine	1.261	32.68	1.023	0.9436	-166.6	2453	0.9947

To properly measure the output and to characterize the system, a custom made testing bench was also designed and fabricated. The experimental system is already partially assembled, with the turbine and test bench completed, and the PCM storage tank undergoing design. The first stage of the experiments, aimed at characterising the turbine under pressurized air (without the complexity of the PCM system), is currently underway.

References

Lidor, A., Sher, E. & Weihs, D. (2014). Phase-change-materials as energy source for micro aerial vehicles (MAV). *Applied Thermal Engineering*, *65*(1), 185–193.

Lidor, A., Weihs, D. & Sher, E. (2013). Alternative power-plants for micro aerial vehicles (MAV). *53rd Israel Annual Conference on Aerospace Sciences 2013*, *1*, 600–619.

Solar High Altitude Unmanned Vehicle Propulsion System Feasibility Analysis

D. Weihs* and M. Harmatz
Faculty of Aerospace Engineering and Autonomous Systems Program, Technion, Haifa
*Presenting author email: dweihs@tx.technion.ac.il

Keywords: Solar propulsion; HALE UAV

The promise of solar energy for propulsion of High Altitude, Long Endurance unmanned aerial vehicles has long attracted interest as a possible unlimited endurance configuration. However, limitations of energy conversion and storage and the fact that at the altitudes considered (around 20km) there are eternal winds of over 20 m/s have prevented these vehicles from becoming practical, and therefore hybrid solutions have been proposed in the past (Harmatz & Weihs,1996).
Existing solar UAVs come in two types – ones for HALE observation use which have the advantage of being above the weather and very low atmospheric attenuation but have to deal with the high west winds mentioned above, and ground-covering low altitude UAVs, which suffer weather and attenuation, but under some constraints can move much more slowly and thus reach balance of energy input and requirements.

Table 1 shows three existing configurations, none of which is free of all the constraints above.

Name	Altitude [km]	Velocity [m/sec]	Wing Span [m]	Wing Aspect Ratio	Solar Cells Eff. [%]	Total Weight [kg]	Battery/ Fuel Cell Weight [kg]	Battery/ Fuel Cell Specific Energy [w-hr/kg]	Engines Max. Power [kw]	Cruise Power [kw]
Helios HP03	15	12	75	31	19	1050	385	450	21	18
Solar Impulse	8.5-1.5	33-19	63.4	20	22	1600	430	220	30	10
Zephyr 7	21.5	25[1]	22.5	20	10	53	21	350	1.5	0.5[2]

Recent developments in solar cell efficiencies, aerodynamic efficiency and fuel cell storage capacities, as well as advanced design of flight trajectories have changed the situation. This has encouraged us to perform a reevaluation of the feasibility of fully solar powered, unlimited endurance UAVs. Thus, efficiencies of solar cells have increased from about 15-18% to about 30% in the last decade. Rechargeable closed circuit fuel cells have reached capacities of around 500 W*hr/kg, wing designs with stable lift coefficients of up to 1.7, i.e. an improvement of over 40%, better conversion to electric energy and a new flight mechanics approach that can save up to 20% in the storage requirements is presented here. The combination of these changes have made the flight based on solar energy alone (within limitation of middle-east latitudes) possible, and the present paper includes the analysis and configurations that give a positive energy balance.

Flying at altitudes of above 18000 m, which is above regular air corridors releases the UAV from regulatory problems, while allowing a full use of solar energy, as atmospheric attenuation is essentially negligible and no clouds reach that altitude. However, this altitude is out of the atmospheric boundary layer, and thus constant west to east winds of up to 80 m/s are blowing there. This requires the UAV to move at least at the wind speed in order to be able to keep station above a certain area. We will utilize a “window”, of average velocities of about 20 m/s that exists at between 18-24 Km.

The major issue in solar-powered vehicles is the fact that the sun only shines for part of the 24 hr cycle, so that excess energy must be stored, and used during the dark hours. The present paper will show two techniques for reducing the amount of electrical energy stored, first by using some of the excess energy to climb during daytime and slowly descend during the dark to initial height. The second technique is flying into the wind and using biomimetic soaring techniques.

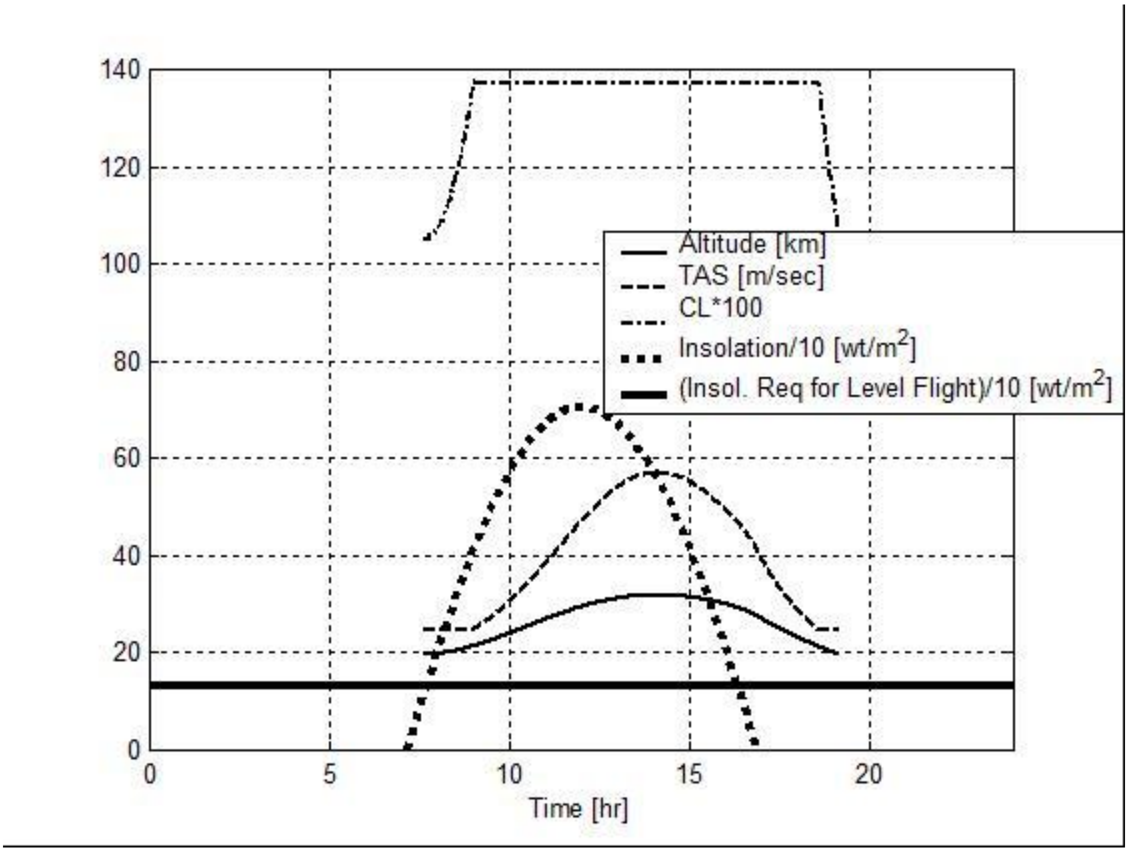


Fig 1. Potential battery type trajectory

Table 2. HALE UAV with minimal wingspan , for all-year use. WPL=100kg, PPL=1000w, F.C. Spec. Energy=600w-hr/kg, Design for winter, With Maneuver Max. Aero. Eff.=40, PV Cells Eff.=30%, Structure Part=0.25, Propulsion Spec.Weight=2.5kg/kw

Flight Season	Base Altitude [km]	Base Velocity [m/sec]	Cells Cover. Ratio	Span [m]	Total Weight [Kg]	Fuel Cell Weight [Kg]	Part of Daylight Excess Energy Stored in Fuel Cell [%]	Mean Day Excess Power [kw]	Required Power [Kw]	Lift Coeff.
Winter	20.6	28	1.0	62.2	650	280	80	0	6.4	1.05
Summer	20.6	28	1.0	62.2	650	280	32	0.76	6.4	1.05
Summer	17.0	31	1.0	62.2	650	280	33	0.21	7.4	0.48

Conclusions

With present capabilities a large (>60 m) wingspan HALE UAV with a practical payload is close to being feasible , and if no power is required for the payload can be built. One interesting conclusion was that there exists an optimum covering of the wing, i/e/ full covering may be suboptimal. Two original energy sparing techniques are presented.

1. The potential energy “battery”, i.e. converting part of the excess energy during sunlight hours to altitude, instead of storing in fuel cells/batteries.
2. For station keeping- flying into the wind.

Acknowledgments

We thank R. Gordana, Zwickel and E. Liban for support and useful discussions.

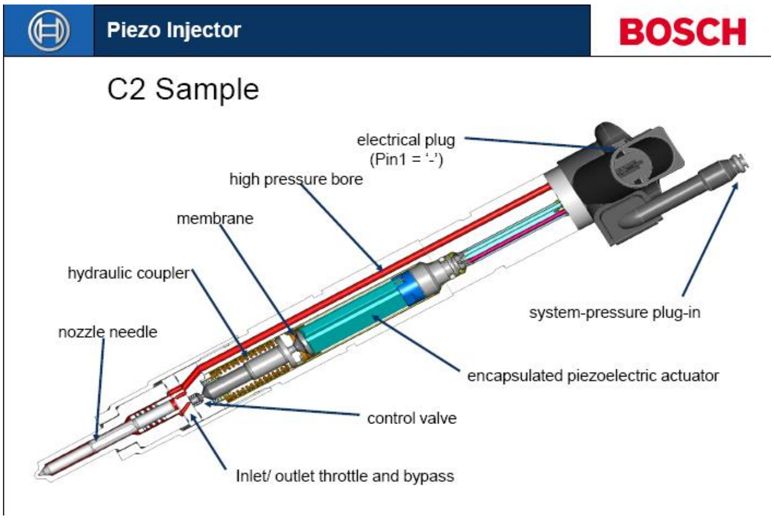
Common-rail fuel injection systems for diesel engines with piezo-injectors

Erez Mosafi

Bosch – Ledico, Rishon-le-Zion, Israel
* Presenting author email: mosafie@zahav.net.il

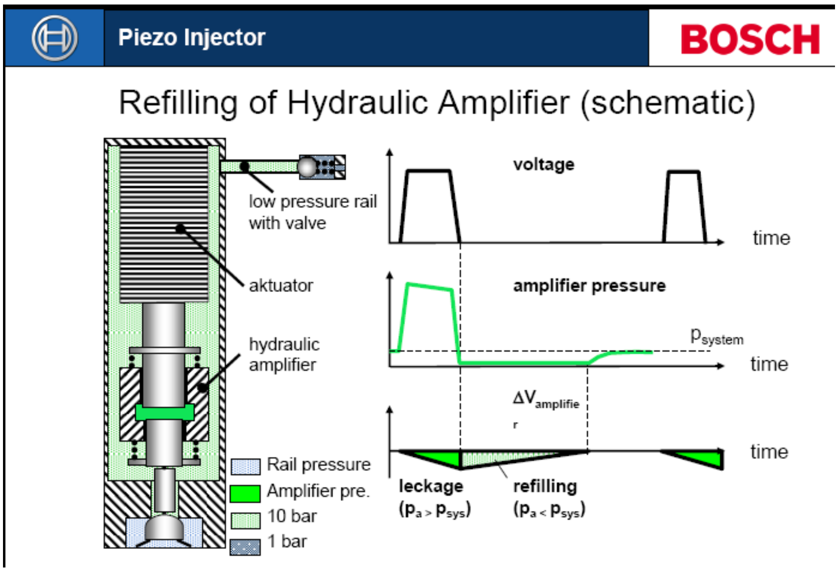
Keywords: Diesel engine; Fuel injection; Common-rail system; Piezo injector

The presentation will focus on latest developments of fuel injection systems for diesel engines. Benefits of common-rail injection systems and piezo injectors will be widely discussed.



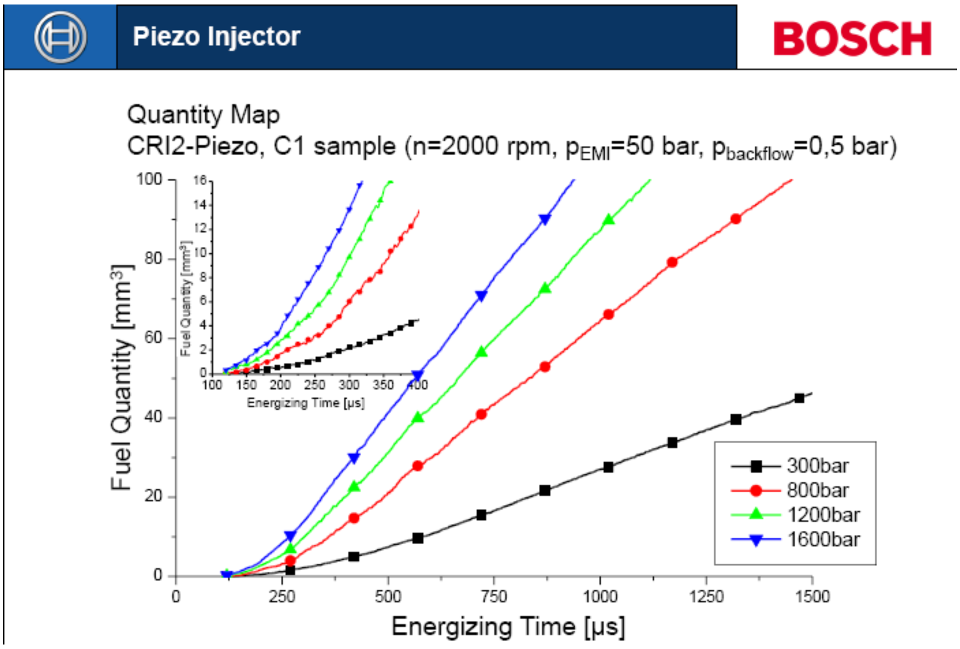
Piezo Injector BOSCH

C2 Sample



Piezo Injector BOSCH

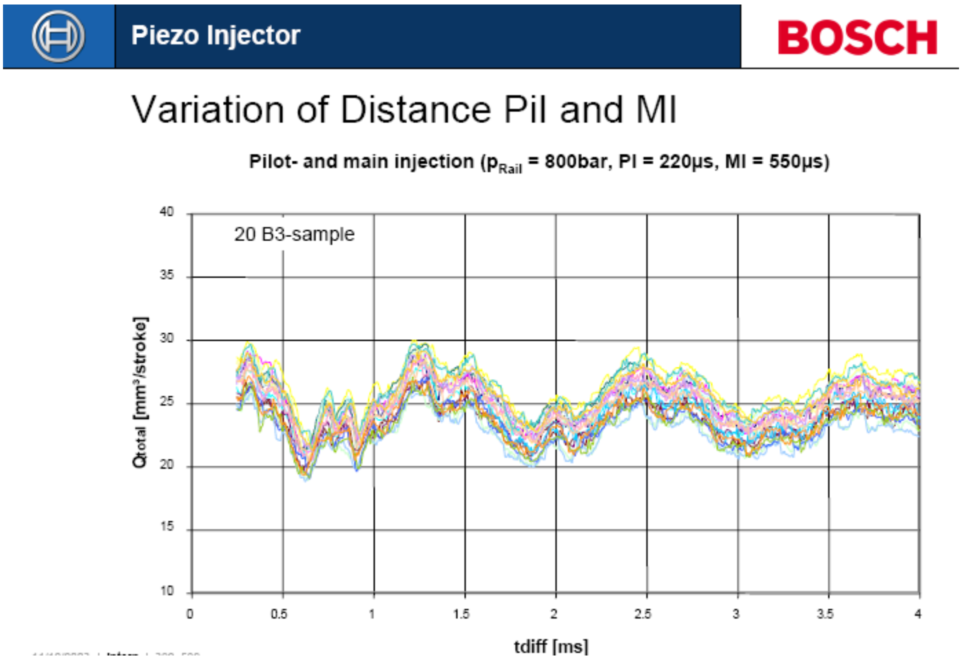
Refilling of Hydraulic Amplifier (schematic)



Piezo Injector

Quantity Map

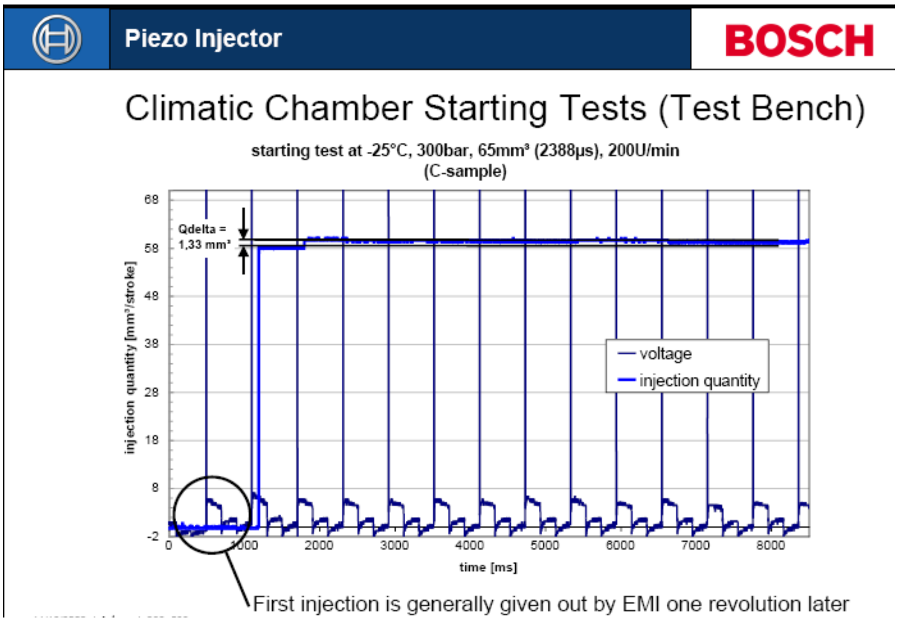
CRI2-Piezo, C1 sample (n=2000 rpm, p_{EMI}=50 bar, $p_{backflow}$=0,5 bar)



Piezo Injector

Variation of Distance PiI and MI

Pilot- and main injection (p_{Rail} = 800bar, PI = 220µs, MI = 550µs)

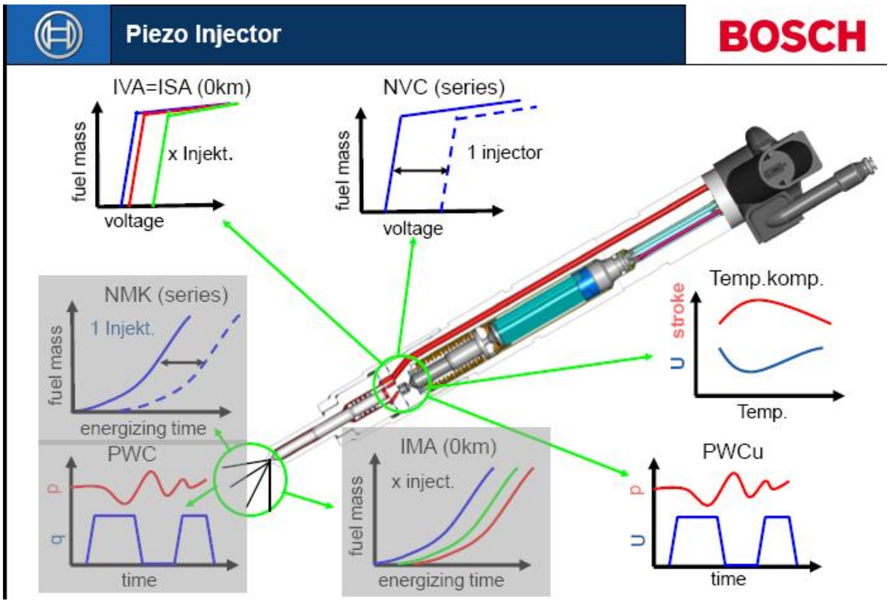


Piezo Injector BOSCH

Climatic Chamber Starting Tests (Test Bench)

starting test at -25°C, 300bar, 65mm³ (2388µs), 200U/min
(C-sample)

First injection is generally given out by EMI one revolution later



Piezo Injector BOSCH

Laminar burning velocity of alcohol reforming products and effects of cellularity on flame propagation

A. Omari*, M. Shapiro and L. Tartakovsky

Faculty of Mechanical Engineering, Technion, Haifa, Technion City, 32000, Israel

* Presenting author email: winterhalter.a@gmail.com

Keywords: Laminar burning velocity; cellularity; steam reforming; hydrogen;

Utilizing exhaust gas heat emitted from an internal combustion engines (ICE) for an on-board alcohol reforming is a promising way to produce hydrogen-rich syngas, while recovering part of the otherwise totally wasted exhaust gas energy. Feeding the engine with these gases contributes to a higher flame speed, higher knock resistance and wider lean flammability limits, all of which result in an increased overall efficiency as well as in mitigation of hazardous emissions. Moreover, utilizing on-board alcohol reforming will combine the distribution and storage advantages of liquid fuels with the combustion benefits of hydrogen.

Various alcohol reforming processes may contribute to different compositions of the produced reforming products (syngas). Among the parameters that determine this composition are: alcohol type, water-alcohol ratio, reforming temperature and catalyst selectivity. Different reformate compositions in turn have different combustion properties. High hydrogen containing reformates have wide flammability limits; high burning velocities and cellular flame structure which further contributes to a faster flame propagation. Contrary, increased CO and CH_4 fractions in the reformates result in a higher energy density and better pre-ignition resistance. On the other hand, the above not fully oxidised carbon products can enhance coke formation in the reformer which badly affects its operation and hence the systems reliability.

Simulating the joint reformer-ICE operation using computer software is considered a powerful and cost-effective initiative for providing better insight when determining the optimal reforming process and the resulting reformate composition. The knowledge of the laminar burning velocity for various alcohol reforming products is a key factor allowing the determination of the actual in cylinder heat release rate necessary for the above mentioned simulations.

This research investigates the laminar burning velocities of H_2, CO, CO_2 and CH_4 mixtures that simulate methanol and ethanol steam reforming products for various water-alcohol ratios. The influence of flame cellularity on the flame propagation speed was studied as well. A spherical constant volume combustion vessel was designed for this purpose (Fig.1). The flame propagation was filmed using a high-speed camera along with a Schlieren system and the pressure rise during flame propagation was monitored. From the latter data, both the laminar burning velocity and the apparent cellular burning velocity were derived. The change in burning velocity with respect to the change in heating value of the different air-fuel mixtures were considered and conclusions regarding Reformer-ICE performance where made.

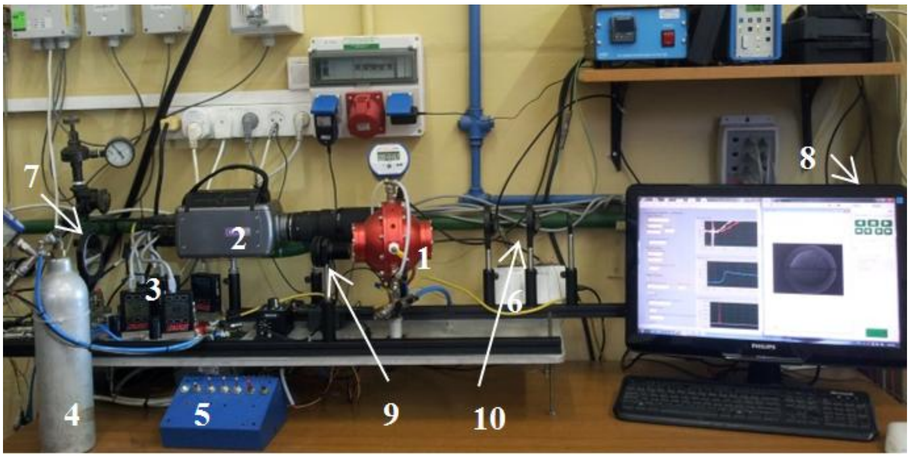


Figure 1. Experimental setup. (1) Vessel; (2) High-speed camera; (3) Mass-flow controllers; (4) Mixing Chamber; (5) Control panel; (6) Data acquisition device; (7) First parabolic mirror; (8) Second parabolic mirror; (9) LED point light source; (10) Aspheric lenses

The results showed maximal burning velocities up to 140cm/sec for mixtures simulating either an ethanol or methanol steam reforming process with zero CH_4 and CO selectivity. For stoichiometric mixtures, the burning velocity was found to be not affected by the increase in CO selectivity. In contrast, for lean mixtures, an increase in CO selectivity showed a slight decrease in burning velocity. Higher CH_4 selectivity resulted in a strong decrease in burning velocities for both stoichiometric and lean mixtures. Flame cellularity was found to accelerate the flame propagation and thus contributing to a faster pressure rise i.e. higher heat release rate. The effect of cellularity was quantified by an apparent cellular burning velocity which exceeded the laminar one up to 90%.

Acknowledgement

The financial support of the Israel Science Foundation is highly appreciated. The authors acknowledge the support from the Nancy and Stephen Grand Technion Energy Program (GTEP). We are grateful to Mr. Magdi Gazal for his help in carrying out the experiments.

Supercharging of UAV engines – benefits and challenges

Y. Fass[1]*, J. Feldman[1]

[1]Israel Aerospace Industries, Ben-Gurion Airport, Israel
* Presenting author email: yfass@iai.co.il

Keywords: Turbocharger; UAV; supercharger; altitude;

UAV industry uses internal combustion engines (IC) engines for propulsion, converting the engine work to thrust using a propeller. The main disadvantage for using IC engine in UAV's is based on their operation principle. A naturally aspirated engine will produce power in direct proportion to the density of the intake air. At sea level, air has a density of 1.225 kg/m^3. At 10,000ft altitude, the density drops to 0.904 kg/m^3. This means an engine that delivers 100HP at sea level will deliver 100*0.904/1.225=73.8HP at 10,000ft.

A UAV engine that uses turbocharger to regain the power loss at high altitude is referred to as a *normalized engine*. A normalized engine usually has a waste-gate to pass all of the exhaust gas at sea level. Consequently, no turbocharging takes place at sea level. As the engine starts to lose power with increased altitude, the waste-gate gradually closes by an automatic control. The turbocharger then compresses the inlet air to sea level pressure. This allows the engine to deliver essentially sea-level horsepower.

The engine continues to develop sea-level horsepower up to an altitude where the waste-gate is completely closed. At this point, called *critical altitude*, all the exhaust gases pass through the turbine. When the UAV climbs above critical altitude, the engine will start to lose power. The turbocharger can no longer deliver air at sea-level pressure. Illustration of engine power, with/without a turbocharger, versus altitude is shown in Figure 6.

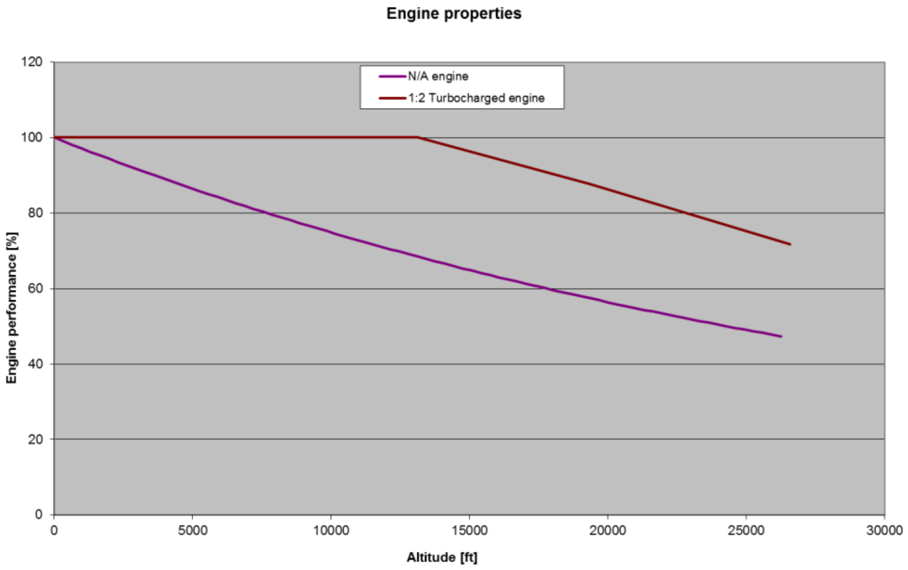


Figure 6. Engine performance VS altitude, with/without turbocharger

The operation line of turbochargers in UAV's is different than in automotive industry. In automotive, the main reason to use turbocharging system is to produce more power from given engine displacement while in aviation the usage of the turbocharger is to maintain SL power at high altitude .In automotive, the boost pressure is set to produce the power required by the engine manufacturer and the pressure ratio will remain constant for a range of engine RPM's. In UAV's, the pressure ratio gradually rise as the UAV climb. The difference between operation lines is described in Figure 7.

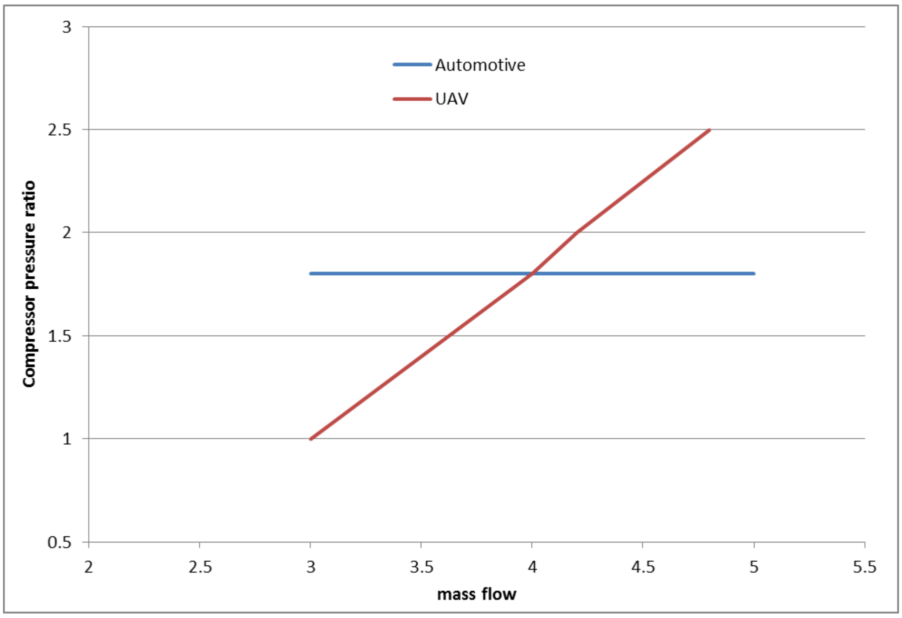


Figure 7. UAV vs. automotive operation lines

In our work we show the variety of turbochargers on the market and the unique modification and installation process for turbocharging UAV's engines. This process includes charge air cooling, operation line calculations, boost control, exhaust gas management and piping.

Design and Performance Optimization through Advanced Simulation Tools

A. Poran[1]*, L. Tartakovsky[1]

[1]Faculty of Mechanical Engineering, Technion, Haifa, 32000, Israel
* Presenting author email: arnonp@campus.technion.ac.il

Keywords: Simulations; computer aided engineering; internal combustion engines

The recent increase in computational power has enabled the creation of detailed computerized models of various engine components as well as construction of comprehensive vehicle models out of numerous system mechanisms. Thus, in the last couple of decades computer-aided engineering (CAE) tools have become prevalent in the competitive automotive industry (Shi *et al*, 2011, Sher & Bar-Kohany, 2002). Companies report that extensive usage of CAE tools significantly reduces the number of prototypes produced in the development processes and to a substantial decrease in development time and cost (Thomke, 1998, Whitfield, 2001). Other benefits of software modelling originate from the fact that virtual experiments and modifications are much faster and cheaper to perform compared to physical ones; therefore, more modifications and experiments are conducted and engineers can gain a more profound understanding of the effects of different parameters on the system's behaviour (Thomke, 1998). The same qualities also make software simulations a good tool for concept proofing.

The broad usage of CAE tools has led to development of many modelling methods suitable for different cases. To fit a method to a model, it is important first to specify the model goals and required accuracy; these specifications together with experimental data already available on the system will determine the right model to be used.

The presentation examines and describes different projects performed at the Technion Internal Combustion Engines (TICEL) laboratory and demonstrates how different goals and available experimental data lead to creation of different models.

The first example model was derived to examine a novel concept of a direct-injection internal combustion engine with exhaust gas waste heat recovery through methanol steam-reforming (Fig. 1).

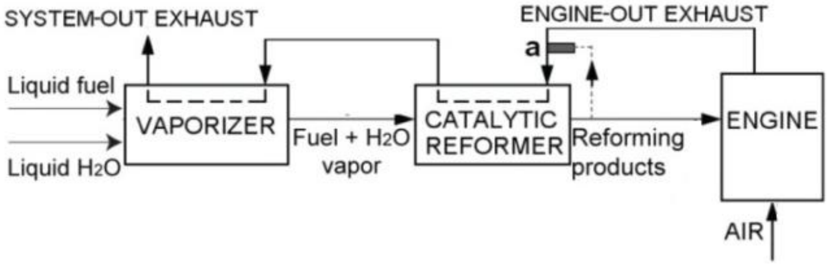


Figure 8. Direct injection internal combustion engine with thermo-chemical recuperation through methanol steam reforming.

The main goals of the model aimed to prove that the exhaust gas contains enough available energy to sustain the endothermic methanol steam reforming process and to estimate the size of the reforming system. According to these goals and the fact that at the time of the model creation there was no experimental data available, the created model utilized a 1-D gas exchange semi-predictive combustion model, Woschni heat transfer correlation for the in-cylinder heat transfer, and detailed chemical kinetics for the reformer (Poran *et al*, 2014). In addition to the achievement of simulation goals, the model also showed that lean combustion possibilities, enabled due to the reforming process, have greater contribution to the overall system efficiency than the waste heat recovery (Fig 2.).

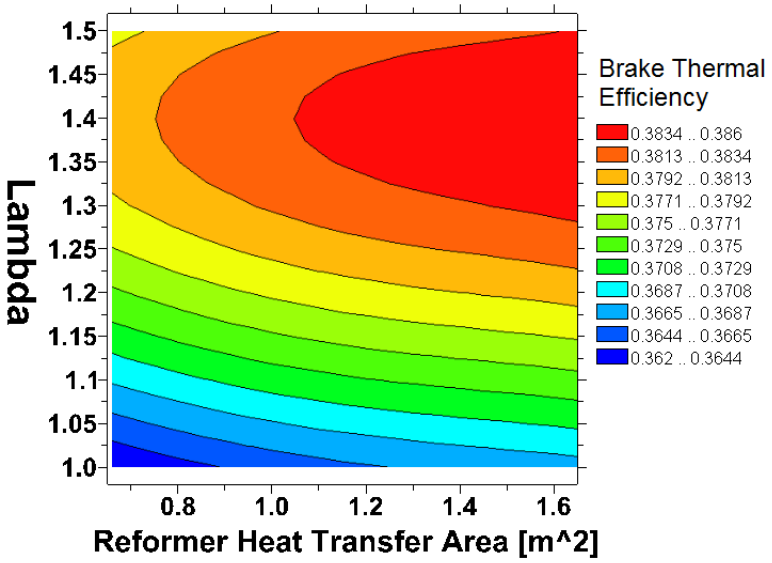


Figure 9. Brake thermal efficiency as a function of reformer heat transfer area and Lambda.

The second project studies knock in a turbo-charged Rotax 914 engine. The project goals aim first to identify when and where the knock phenomenon occurs and then propose several ways of preventing it. These goals required utilization of a fully predictive combustion model calibrated with experimentally obtained indicated pressure measurements. Available CAD files were used to create detailed intake system. The generated model predicts the air-flow and fuel consumption with maximal error of 3% and can also predict knocking.

Even though the model has reached good agreement with the experimental data, acquirement of experimental information such as motoring test, and temperature measurements at various locations will further improve this model and hence its knock predictions.

The last example examines the use of commercial reciprocating piston software to model a rotary Wankel engine (Tartakovsky *et al*, 2012). Since there was no experimental regarding intake and exhaust discharge coefficients, CFD simulation was used to calculate them. The results of this simulation where then inserted to 1-D gas exchange model. Heat transfer and combustion coefficients were calculated using available traditional models. The model used experimentally obtained combustion chamber temperatures. Even though the rotary engine was simulated through a virtual reciprocating piston, simulations performed predicted engine performance parameters with high accuracy (Fig. 3).

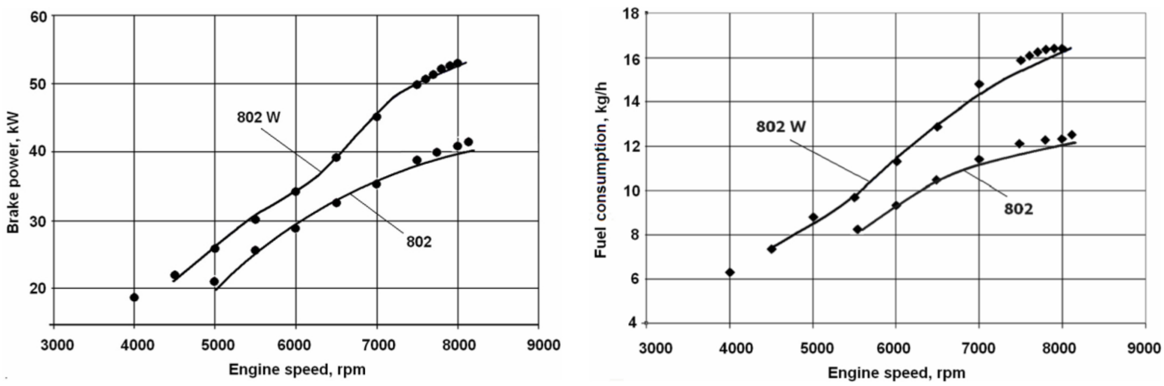


Figure 3. Wankel engines 802 and 802W: predicted (lines) and measured (dots) values of the brake power (left) and fuel consumption (right) over full load curve.

The given examples show that difference in data availability and project requirements lead to creation of different models; each model requires detailed modelling of a different part of the system. Yet, all models provide sufficient simulation results.

Acknowledgement

The financial support of the Israel Science Foundation is highly appreciated. The authors acknowledge the support from the Nancy and Stephen Grand Technion Energy Program (GTEP).

References

Poran, A., Artoul, M., Sheintuch, M., & Tartakovsky, L. (2014). Modeling Internal Combustion Engine with Thermo-Chemical Recuperation of the Waste Heat by Methanol Steam Reforming. *SAE International Journal of Engines.*, 7(1):234-242, 2014, doi:10.4271/2014-01-1101.

Sher, E., & Bar-Kohany, T. (2002). Optimization of variable valve timing for maximizing performance of an unthrottled SI engine—a theoretical study. *Energy*, 27(8), 757-775.

Shi, Y., Hai-Wen, G., & Rolf Deneys, R. (2011). *Computational optimization of internal combustion engines.* London: Springer.

Tartakovsky, L., Baibikov, V., Gutman, M., Veinblat, M. et al., "Simulation of Wankel Engine Performance Using Commercial Software for Piston Engines," SAE Technical Paper 2012-32-0098, 2012, doi:10.4271/2012-32-0098.

Thomke, S. H. (1998). Simulation, learning and R&D performance: Evidence from automotive development. *Research Policy* , 27.1: 55-74.

Whitfield, K. (2001). Toyota Pursues the Elusive'Triple WOW'. *Automotive Manufacturing and Production*, 113.9:58

Knock and surface ignition problems in UAV spark-ignition engines and ways of their prevention

R.AMIEL.[1]*, K.COHEN.[2]

[1]Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, Haifa, 32000, Israel
[2]I.D.F, Air Force, Tel Aviv, Israel
* Presenting author email: Ran@amiel.biz

Keywords: Knock; Detonation; surface ignition; SI engine

The knock phenomenon in spark ignition (SI) internal combustion engines (ICE) has been a limiting factor in power generation since the invention of the Otto cycle in the mid-19th century. Knock (or detonation) is an abnormal combustion in the ICE cylinder, caused by an undesired flame front formed inside the cylinder in addition to the flame initiated from the spark ignition. Two main phenomena that cause this are surface ignition and/or mixture ignition due to the increased pressure and temperature during the progress of the flame through the cylinder.

Abnormal combustion is called "knock" because of the noise generated by the colliding of the multiple flame fronts and the increased cylinder pressure that causes the piston, connecting rod and bearings to resonate. The presence of multiple flame fronts can have serious effects on the ICE: decrease in engine power output and longevity, increase in pollutant emissions and total destruction of the engine in the worst cases. (Heywood, 1988, Zhen *et al, 2011*).

IAF's Rotax 914 engines have undergone a number of detonations which caused engine damage, mission aborts and even severe accidents. As a result, the IAF has initiated a stricter engine operational policy; it has also improved the detonation identification algorithm, and started using fuels of better quality. Despite the measures taken, the problem still exists and requires attention.

The main goal of our research is to study the causes of knocks in the Rotax 914 engine, find the methods to identify their start and prevent them. During normal operation of the Rotax 914 engine, the knock phenomenon occurred and forced the platform operators to stop its work. The knock phenomenon results in significant damage to the designated tasks of the platform and causes economic losses due to mechanical destruction of the engine.

The first step in our research is to build a computer model of the engine in the GT-SUITE software. The most important feature in the model is the combustion profile inside the cylinder, which is designed to predict combustion and flame behavior in various conditions as similar as possible to the real ones in the engine. The model will be used to test a variety of knock treatments, which in turn will be applied on the Rotax 914 engine in real experiments.

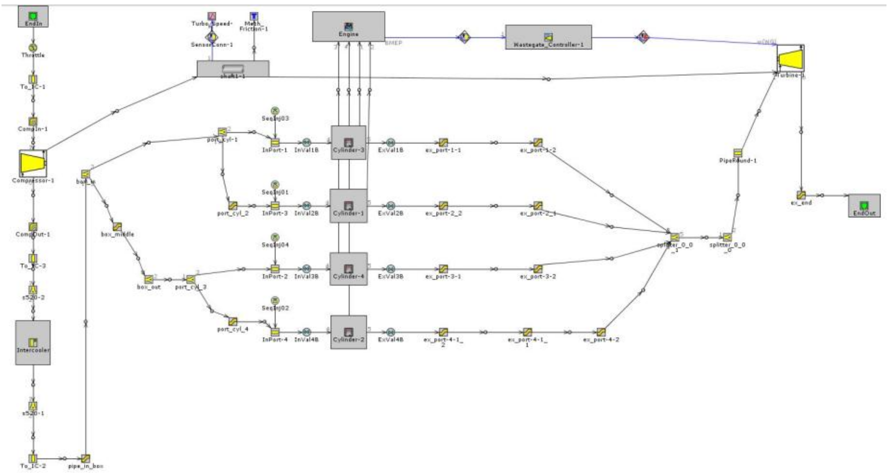


Figure 1. Model of the engine Rotax 914 in the GT-Power software

	experimental measurements			model measurements		
RPM	**5800**	**5500**	**3500**	**5800**	**5500**	**3500**
P [kW]	**80.9**	**68.8**	**36.6**	**80.9**	**68.9**	**36.7**
BSFC g/kWh	**300.2**	**297.6**	**356.1**	**308.1**	**303.5**	**362.8**
Air flow kg/h	**297.1**	**255.3**	**139.7**	**300.2**	**257.7**	**141.2**

Table 1. Comparison between experimental measurements and model performance.

There are many methods available to detect engine knocks, which can be classified into direct and indirect methods. Direct methods are based on the direct measurement and study of inside cylinder parameters, which are influenced by knock. Other methods are based on indirect measurements such as sound pressure, cylinder block vibration, exhaust temperature, etc.

Many solutions have been proposed and investigated over the years for the knock suppression:

- Optimization of the cooling system. (Towers and Hoekstra, 1998, Russ, 1996)
- Spark advance. (*idem*)
- Increase of the inert gases, e.g. EGR. (Grandin *et al*, 1998)
- Increase of the fuel octane number by introducing antiknock additives to the fuel (Heywood, 1988)
- Use of direct injection of a second fuel. (Blumberg *et al*, 2008)
- Water injection. (Lanzafame, 1999)
- Lowering the oil reactivity. (Amann and Alger, 2012)

The above methods are going to be simulated on the GT-SUITE model and the relevant ones will then be implemented on the engine.

Acknowledgement

The financial support of MAFAT is highly appreciated.

References

Heywood, J.B., *Internal Combustion Engine Fundamentals*, McGraw-Hill, New York, 1988.

Zhen X., Wang, Y., Xu, S., Zhu, Y., Tao, C., Xu, T., Song M. (2011) *The engine knock analysis – An overview. Applied Energy.*

Lanzafame R. (1999) *Water injection effects in a single-cylinder CFR Engine*. SAE Technical Paper no. 1999-01-0568.

Towers J.M, Hoekstra R.L. (1998) *Engine knock, a renewed concern in motorsports – a literature review*. SAE technical paper no. 983026.

Russ S. (1996) *A review of the effect of engine operating conditions on borderline knock*. SAE technical paper no. 960497.

Amann, M. and Alger, T., (2012) *Lubricant Reactivity Effects on Gasoline Spark Ignition Engine Knock, SAE Int. J.*
Fuels Lubr.

Grandin B., Angstrom H.E., Stalhammar P., Olofsson E. (1998) Knock *suppression in a turbocharged SI engine by using cooled EGR*. SAE Technical Paper no. 982476

Blumberg P.N, Bromberg L, Kang H, Tai C. (2008) *Simulation of high efficiency heavy duty SI engines using direct injection of alcohol for knock avoidance*, SAE Technical Paper no. 2008-01-2447

Four-Stroke Engine with a Port in the Cylinder Sleeve

A.L. Zhmudyak[1], L.M. Zhmudyak[2*]

[1]R&D, Panaya, Raanana, 43657, Israel
[2] Rehovot, 7645501, Israel
* Presenting author email: l_jmoudiak@hotmail.com

Keywords: four-stroke engine; port; cylinder; sleeve

1. Introduction

We propose a new four-stroke engine, where the exhaust gas from the cylinder flows out through the valves and through the port in the cylinder sleeve.

In naturally aspirated engines, pressure in the intake manifold is lower than in the exhaust manifold. Out-dated turbo-supercharging engines also have this pressure correlation. In these conventional 4-stroke internal combustion engines, intake and exhaust is realized through valves in the cylinder head only. Use of a constantly open port in the cylinder sleeve for gas exchange was impossible in these engines for the following reason. At the end of admission when the piston is located near bottom dead centre (BDC) and the cylinder sleeve port is open (see Figure 1), a portion of the hot exhaust gases returns to the cylinder through this port. This is because the pressure inside the cylinder is lower than the exhaust manifold pressure. Such back flow of exhaust gases is illustrated by the black arrows in Figure 1.

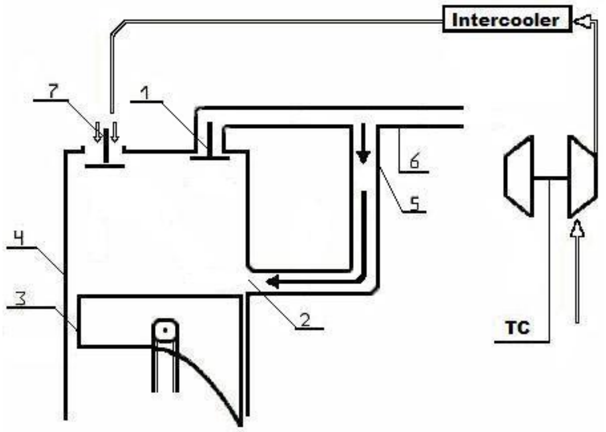


Figure 1. $p_{int} / p_g < 1$, the end of intake stroke

Back flow of combustion products reduces the cylinder filling with fresh charge, and consequently reduces the engine power. In spark ignition engines, hot combustion products can even cause early ignition of the air-fuel mixture in the cylinder. This is all inadmissible for full loads, so the cylinder sleeve port could not be used for gas exchange.

In modern engines with turbo-supercharging, boost pressure and pressure after intercooler, p_{int}, is higher than the pressure in the exhaust manifold, p_g (i.e. the pressure after the exhaust valve, before the turbocharger turbine). Due to this favourable pressure ratio, in addition to valves, a constantly open port in the cylinder sleeve can be used for gas exchange. Back flow of combustion products to the cylinder will not take place, since $p_{int} / p_g > 1$. In this paper, we present a new method for gas exchange in 4-stroke internal combustion engines. To realize the proposed gas exchange method, a constantly open port in the cylinder sleeve should be made in addition to the valves in the cylinder head. We term such an engine as an “A-engine”.

2. Method of Work of the Proposed Engine

Let us consider the working processes of the A-engine at full load, as well as maximum and nominal loads. At these loads $p_{int} / p_g > 1$.

At the last stage of a combustion stroke (near BDC) and at the first stage of an exhaust stroke (Figure 2), the exhaust gas flows from cylinder 4 through both exhaust valve 1 and port 2, into the exhaust manifold 6 and then to the turbine of turbocharger. Exhaust is facilitated since gases flowing out through both port 2 and valve 1. This in turn increases efficiency.

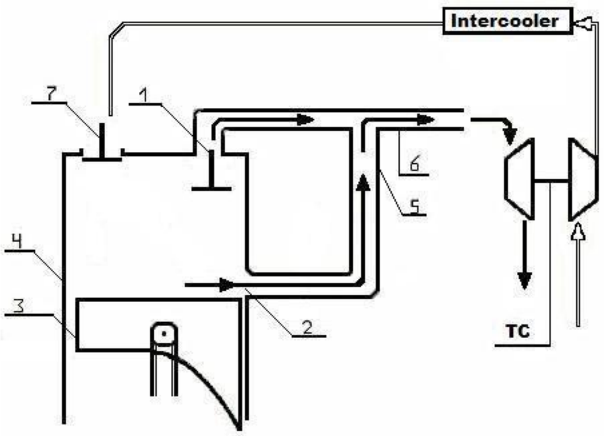


Figure 2. Exhaust.

As only half of the gases flow through valve 1, the temperature of the exhaust valve and cylinder head is lower than in conventional designs. Thus, in spark ignition engines, the boost pressure and/or compression ratio may be increased.

The air from the compressor of the turbocharger is supplied to cylinder 4 through intake valve 7. At the last stage of the intake stroke (Figure 3) the piston again opens port 2 in the cylinder sleeve. At full load, pressure in the cylinder is higher than the pressure in exhaust manifold 6. Thus, air flows away from the cylinder through port 2 and pipe 5 into manifold 6 and then to the turbine. The airflow in figure 3 is indicated by the arrows.

The airflow through the cylinder cools the internal cylinder walls, reducing the temperature of the piston, the cylinder sleeve, and the turbine of the turbocharger, and therefore reduces the predisposition for detonation. Due to this intrinsic air cooling, the cooling system of an A-engine may be reduced.

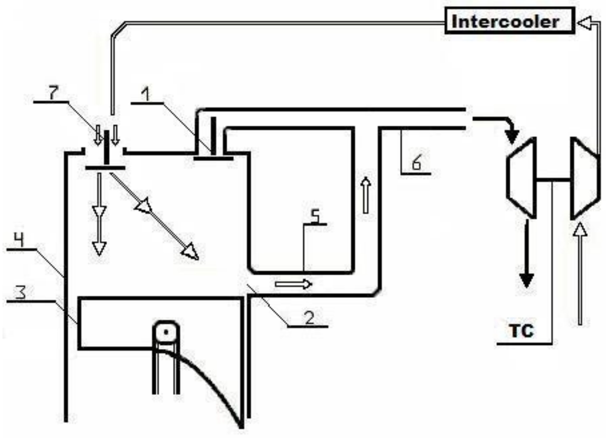


Figure 3. Intake, $p_{int} / p_g > 1$

At low loads, in idle running and in starting the cylinder pressure at the last stage of the intake stroke (when port 2 opens, Figure 4) is lower that p_g (the pressure before the turbine and the pressure in pipes 6 and 5). Therefore, when the piston is near BDC and port 2 is open (Figure 4), exhaust gases from exhaust pipe 5 flow into the cylinder. The mass, pressure, and temperature of the gas inside the cylinder are increased. As a result, starting is improved and operation at low loads and in idle running mode is more stable. The ecological characteristics of these regimes are superior to those of typical engine designs.

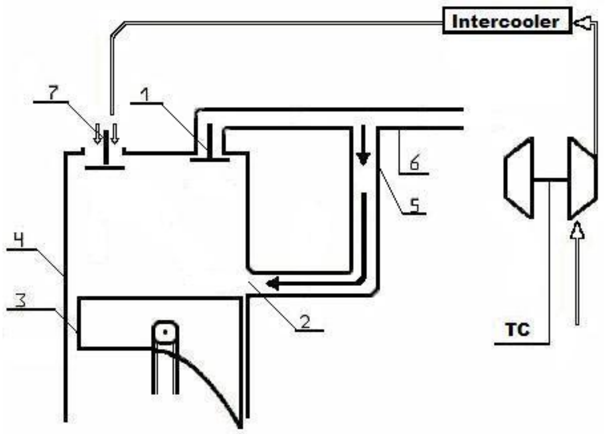


Figure 4. Intake at low loads, idle running, and starting; $p_{int} / p_g < 1$

The A-engine has the combined advantages of both the 4-stroke and 2-stroke internal combustion engines, since gas flows out of the cylinder through both the valves and port, resulting in an increase in efficiency at high engine revolutions. This easy exhaust through the valves and port in the sleeve allows the engine to augment crankshaft rpm, and thus a proportional increase of power. Due to the ability to increase boost pressure without detonation, power increases too.

3. Conclusion

In modern engines with turbo-supercharges, the air boost pressure and after intercooler pressure is higher than the exhaust manifold pressure. In such 4-stroke engines, a constantly open port in the cylinder sleeve may be used (together with valves) for gas exchange. The easy exhaust through the valves and the port in the sleeve allows an increase of rotation frequency of the crankshaft, resulting in a proportional power increase. Nearly half of the exhaust gases flow out through the exhaust valve, while the other half flows out through the port in the cylinder sleeve. That’s why the exhaust valve and cylinder head temperature is lower than in typical engines. The proposed A-engine is characterized by unique high airflow. In consequence of airflow and decreasing mass of exhaust gases flowing out through exhaust valve, temperatures of fresh charge, piston, turbine, and other parts have been reduced. Low temperatures permit boost pressure and/or compression ratio increasing and hence power and efficiency increasing at full loads.

References

A. Zhmudyak, L. Zhmudyak. Method of Gas Distribution of Internal Combustion Engine. Nonprovisional application for US patent. Application number 13/684,169.