Turbomachinery and Heat Transfer Laboratory

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Increasing Efficiency of UAV Internal Combustion Engines via Inverted Brayton Cycle

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Introduction

- Worldwide spending on UAVs expected to reach $70 billion by 2020
- UAVs comprises about 1/3 of USAF aircraft
- MALE (medium altitude, long endurance) UAVs tend to be powered by IC engines

Elbit Systems Hermes 900

General Atomics MQ1 Predator

ROTAX 914
4-cyl. 4 stroke w/ turbocharger

State of the art and problem definition

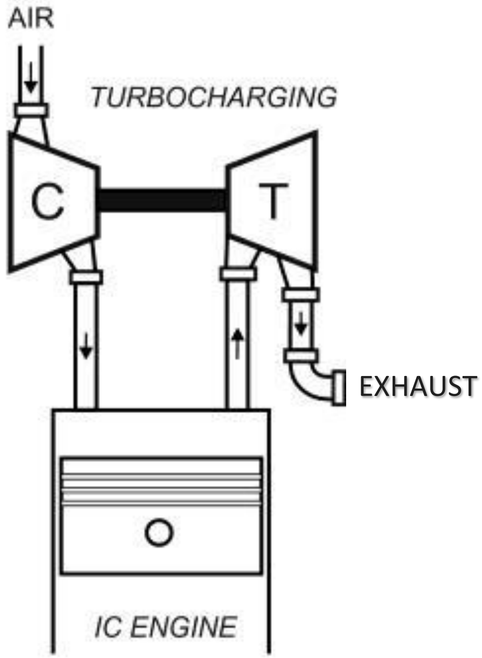
MALE UAV propulsion:

- GT efficiencies drop at smaller scales
- IC engines have greater efficiency, but suffer relatively low power-to-weight ratios
- Thus, methods to improve engine cycle efficiencies have significant impact potential in the global UAV market
- Considering 30% of thermal energy in IC engine combustion is expelled in waste gas, bottoming cycles can be implemented to utilize this heat and boost overall efficiency

State of the art and problem definition

Turbocharging:

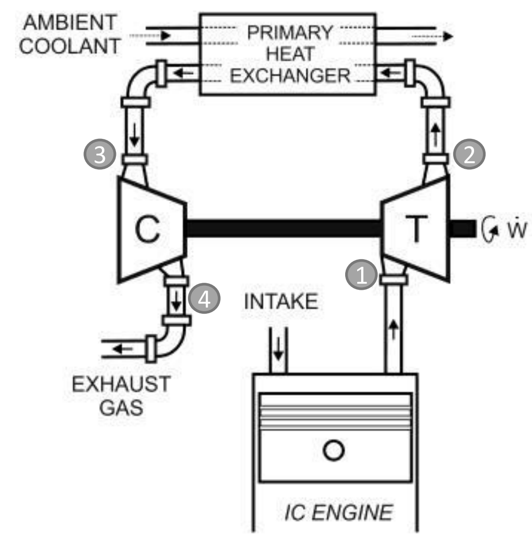
- Draws exhaust energy towards compressing inlet flow
- Boosts engine performance
- Turbine exhaust is open to atmosphere directly
- Turbine imposes backpressure on exhaust stroke
- Engine inlet and outlet conditions are manipulated by turbo components

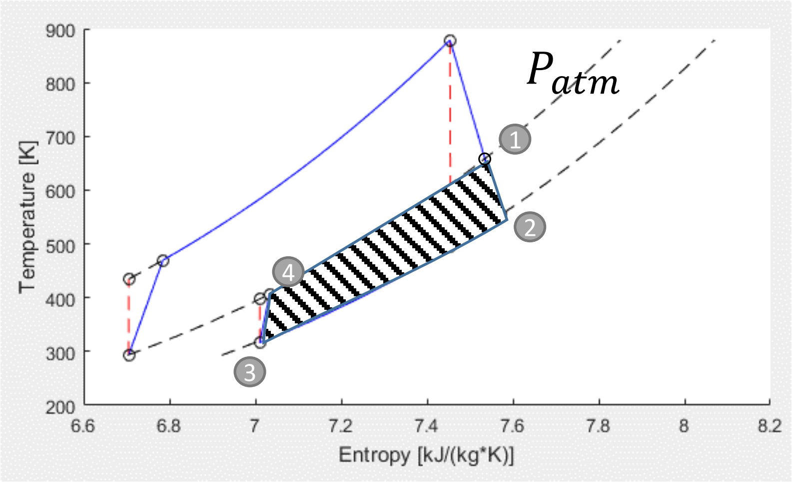


Inverted Brayton cycle

Inverted Brayton Cycle:

- Secondary shaft for additional power
- Turbine expands into sub atmospheric pressures set by compressor
- Low backpressure on the exhaust stroke
- Heat recovery not limited by atmospheric conditions
- Engine inlet and outlet conditions remain the same





Inverted Brayton cycle – state of the art

Thermodynamic Simulations

- IBC with **recuperated combustion** for CHP application
- IBC as bottoming cycle **for micro turbines**
- IBC as bottoming cycle **for automotive IC engines**

Experimental Prototypes

- **Kawasaki Heavy Industries** (2006): functionable 3 kW_{el} prototype (recuperated combustion chamber)
- **DLR Stuttgart** (2017): experimental setup using an ENERTWIN micro turbine to establish the IBC

Market Maturity

- Current efficiencies are not sufficient

Inverted Brayton cycle – Research objective

Component Selection

- Turbomachinery
- Heat exchanger

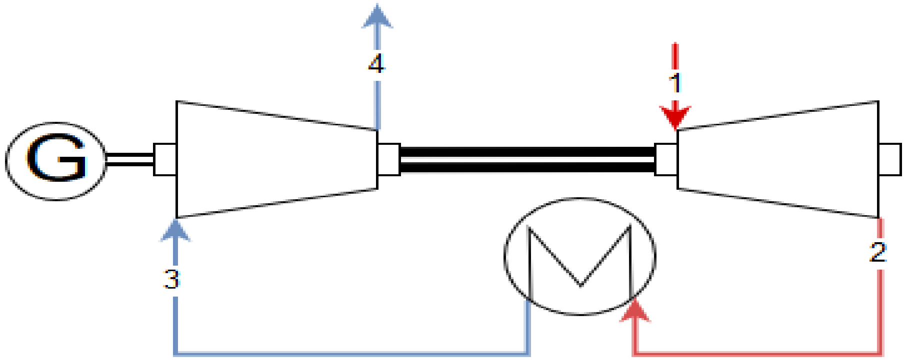
Thermodynamic Simulation in MATLAB

- Development of component models
- Preliminary and detailed simulations

Experimental Set-up

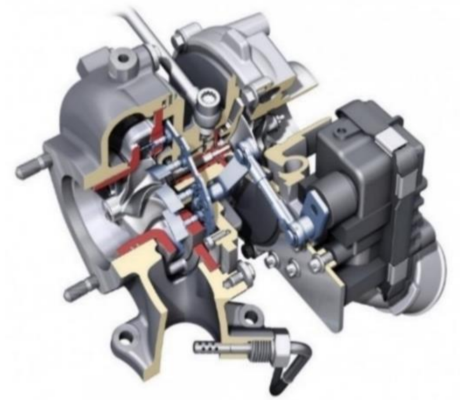
- CAD design
- Assembly and commissioning

IBC Components



Turbomachinery

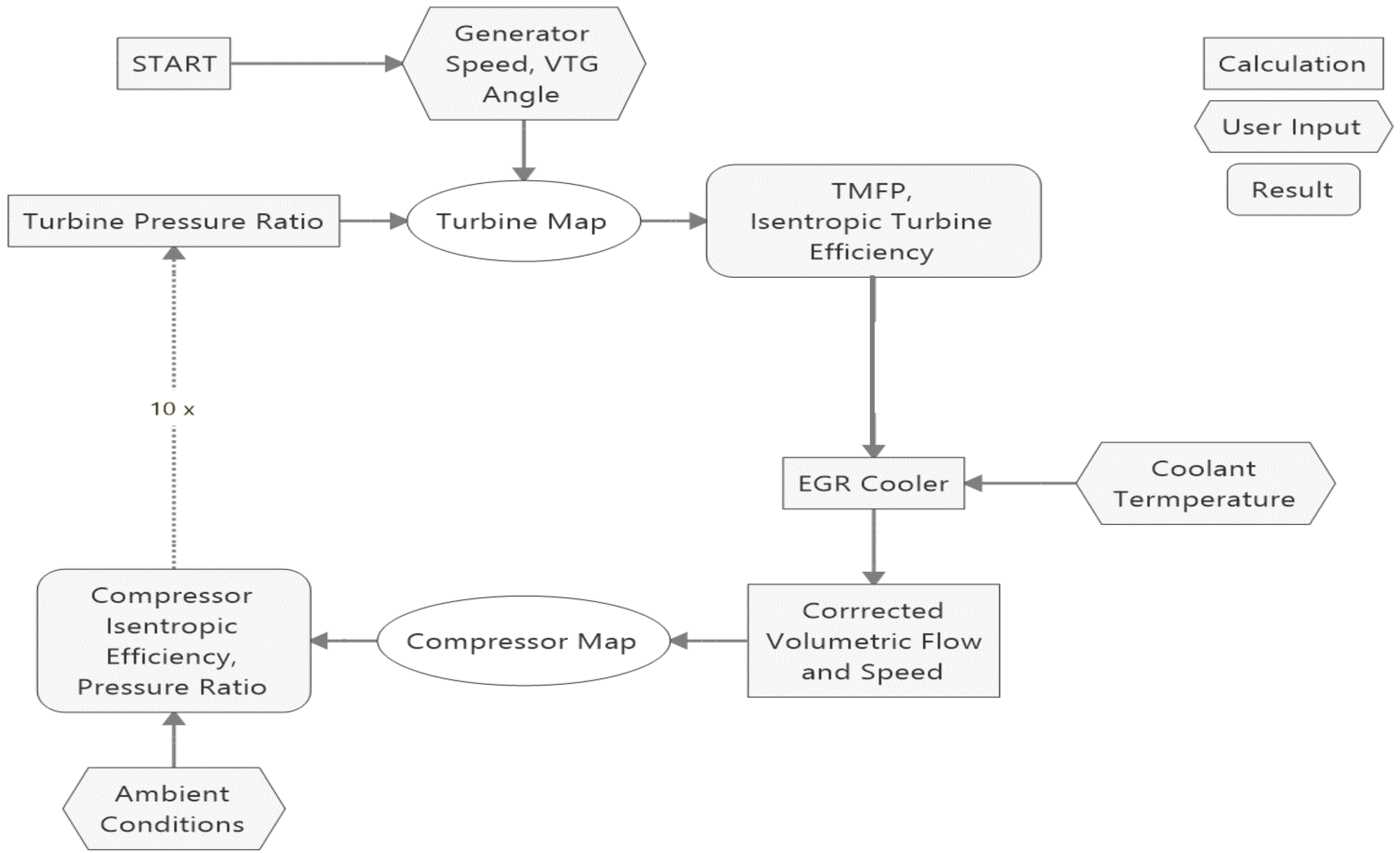
- Turbocharger components (BorgWarner)
- Selection by preliminary estimations
- VTG turbine



Gas to liquid heat exchanger

- EGR coolers (high availability, low cost)
- Shell-and-tube type

IBC Main Program – Iterative Calculation Algorithm

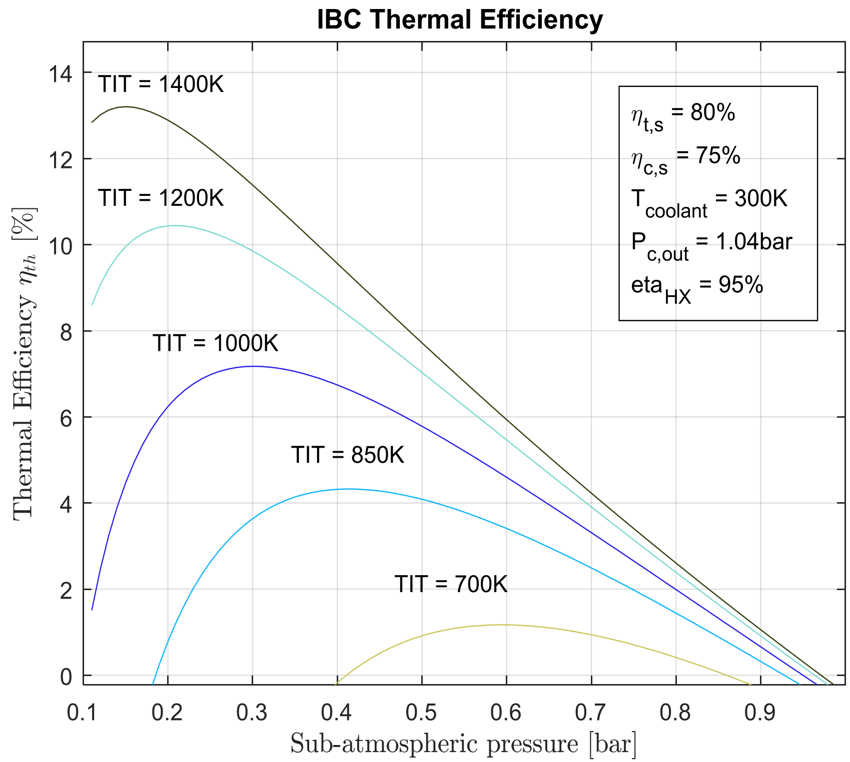


Thermodynamic Cycle Analysis: Simulation results

Non-Recuperated Cycle

- **Simplified model** for validation and *preliminary estimations*
- IBC shows an **optimum sub-atmospheric pressure** for different TIT
- **Heat exchanger and turbomachinery** efficiency highly significant

$$\eta_{th} = \frac{|w_t| - |w_c|}{q_{fuel}}$$



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Thermodynamic Cycle Analysis: Lambert T15 rig

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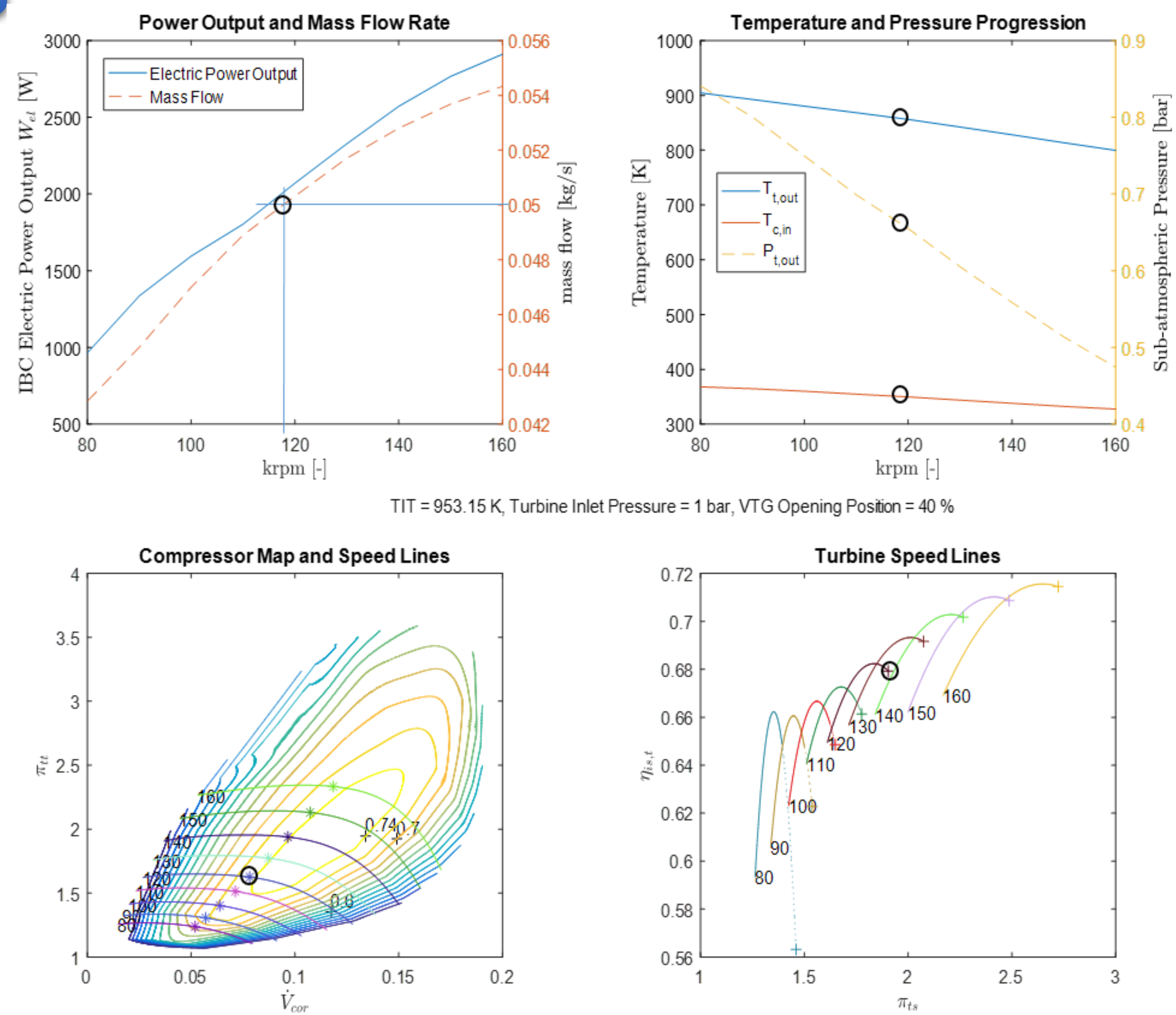
Non-Recuperated Cycle

- **Gas turbine** serves as gas generator (1.2 bar, 950 K)
- Turbocharger **VTG angle and rpm** are alternated
- Operating point: **120,000 rpm, 2 kW electric power output from IBC**

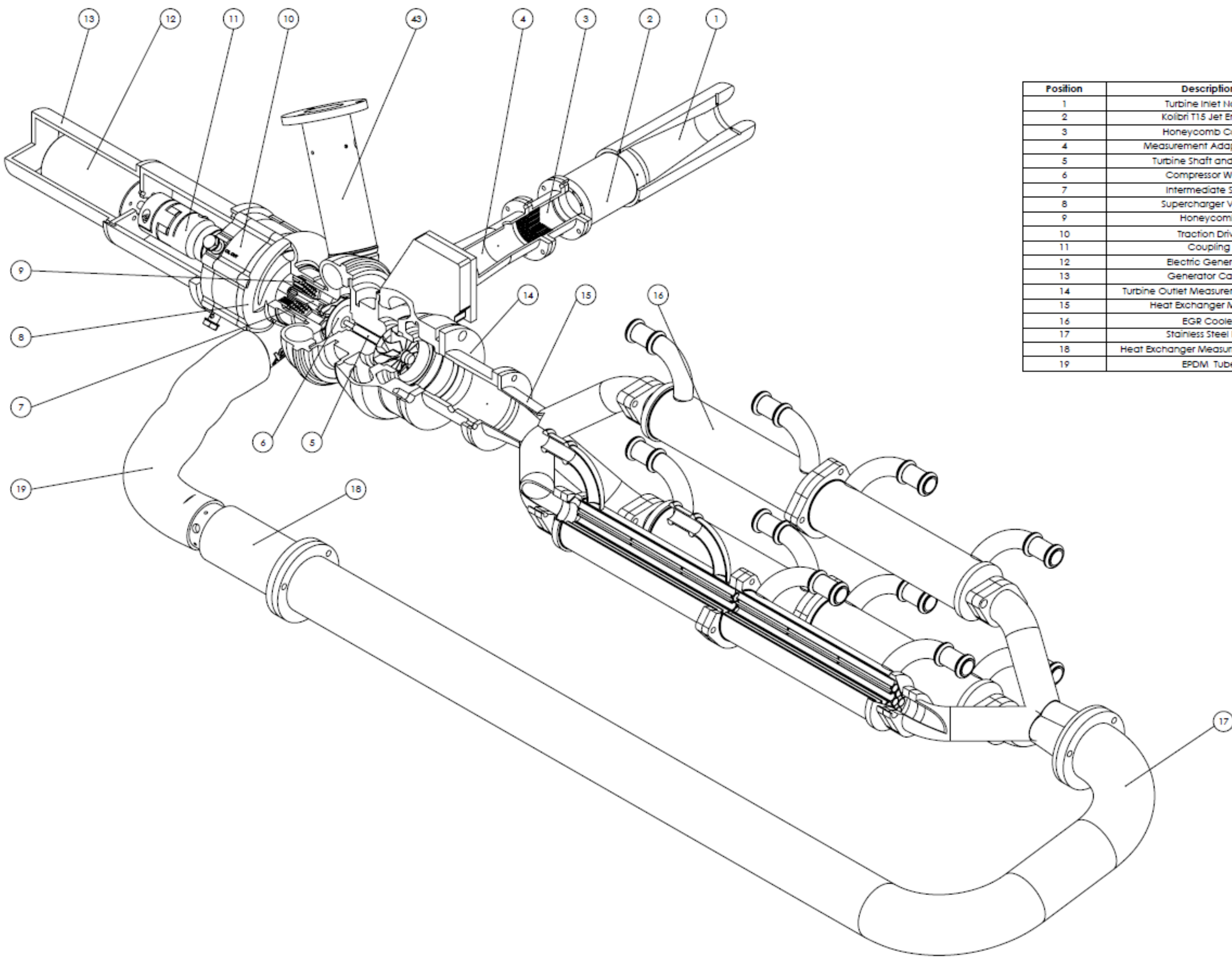


Preliminary assessment for the enhancement of UAV mission with IBC: Hermes 900 UAV mission

- **Mission specifications:**
  - Turbocharged, four-cylinder ROTAX 914 piston engine
  - Fuel consumption at 4500 RPM: $15\,l/hr$
  - Total flow rate through engine: $\approx 0.06\,kg/sec$
  - Power production at 4500 RPM: $60\,kW$
  - Actuator load: $\approx \mathbf{5\,kW}$
  - Mission length: $\mathbf{30-40\,hrs}$

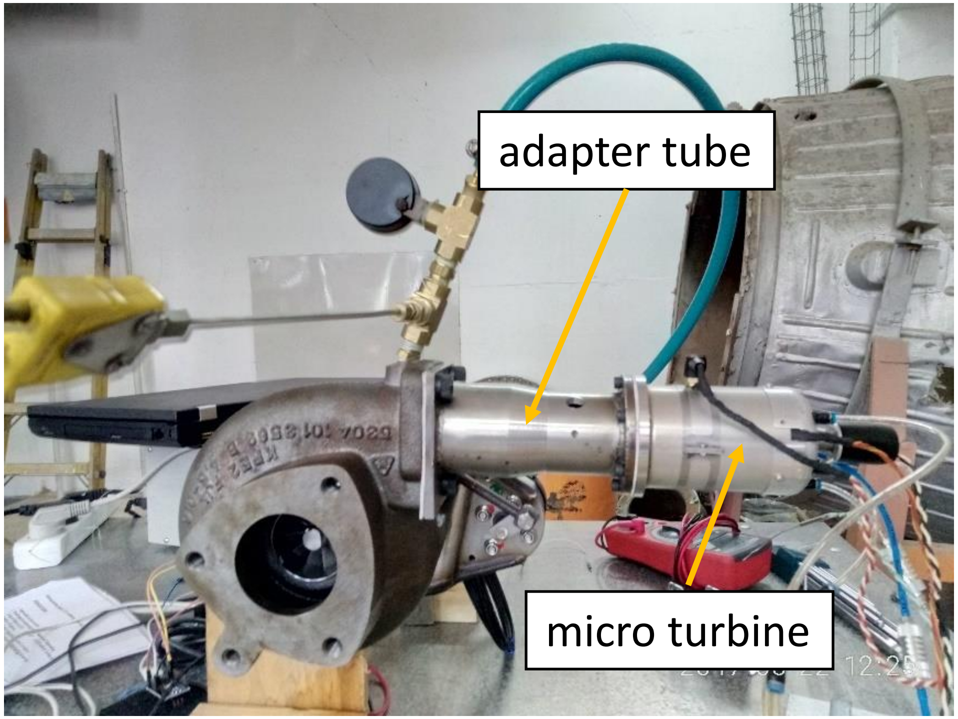
- **IBC performance:**
  - **6 kW** of electric power
  - $\mathbf{1.5\,l/hr}$ savings in fuel
  - **Reduction of** $\approx \mathbf{30kg}$ from the overall UAV mass that can be utilized for extension of mission duration or increased payload

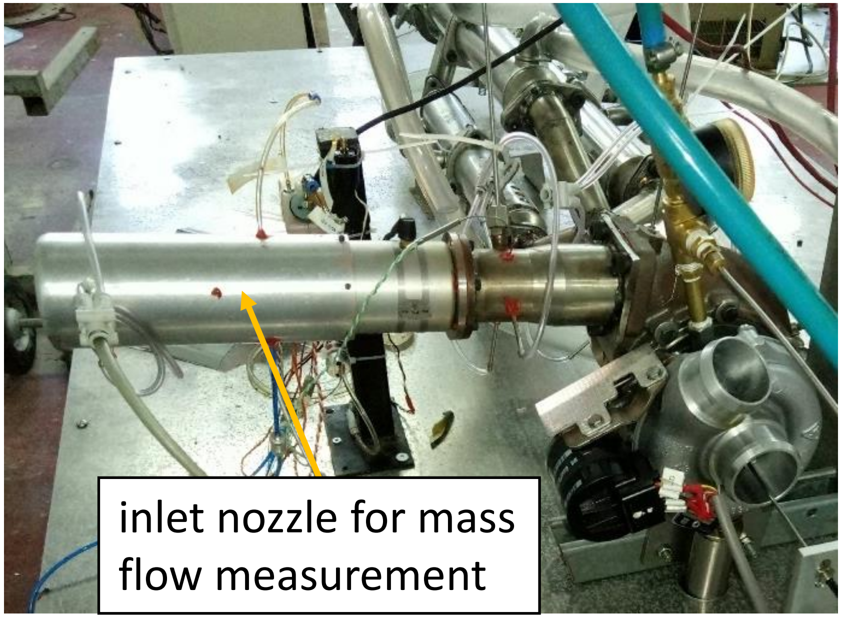
Experimental facility



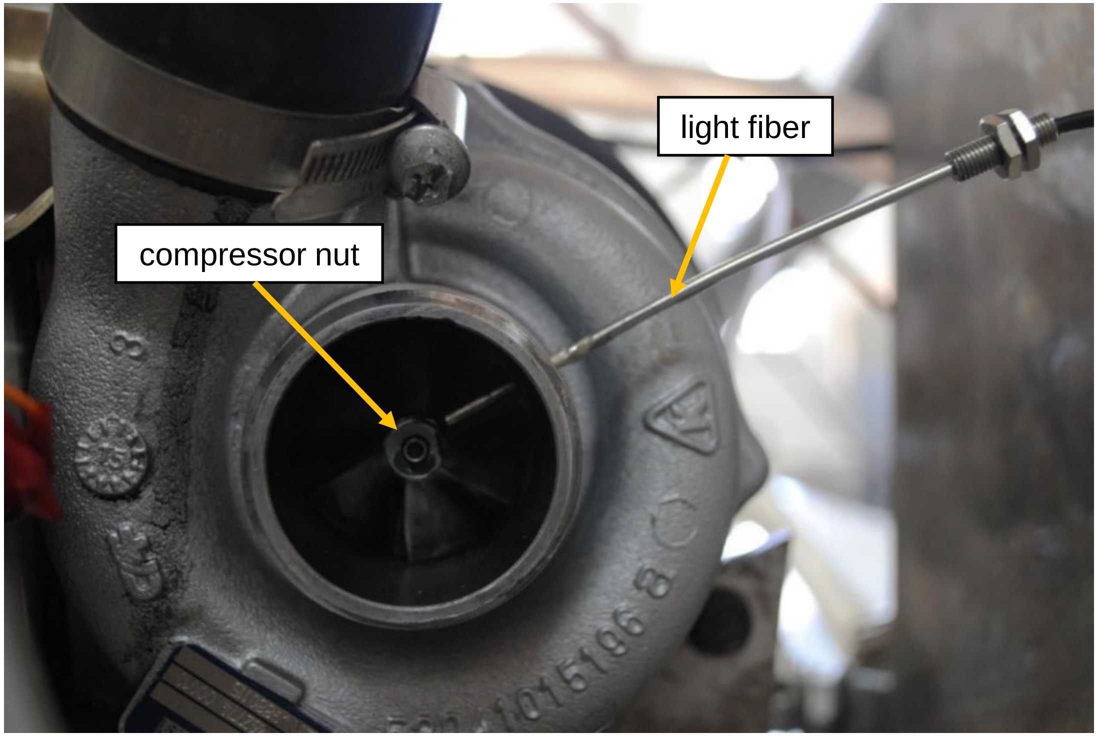
Position	Description
1	Turbine Inlet Nozzle
2	Kolibri T15 Jet Engine
3	Honeycomb Casing
4	Measurement Adapter Tube
5	Turbine Shaft and Wheel
6	Compressor Wheel
7	Intermediate Shaft
8	Supercharger Volute
9	Honeycomb
10	Traction Drive
11	Coupling
12	Electric Generator
13	Generator Casing
14	Turbine Outlet Measurement Adapter
15	Heat Exchanger Manifold
16	EGR Cooler
17	Stainless Steel Pipe
18	Heat Exchanger Measurment Adapter
19	EPDM Tube

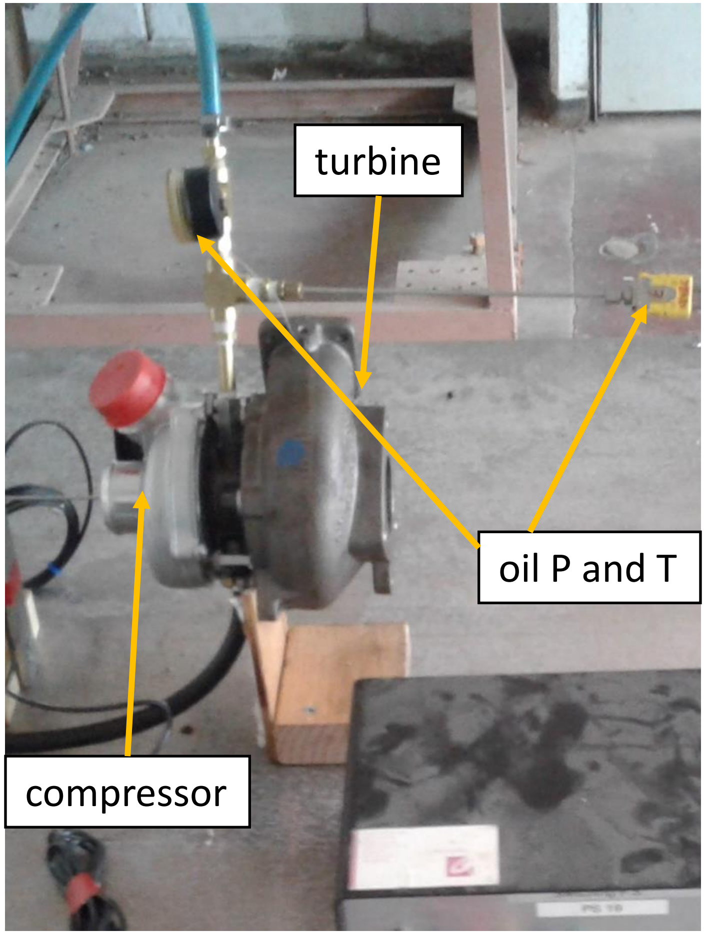
Experimental facility: Micro turbine assembly





Experimental facility: Turbocharger assembly





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Experimental facility: Heat exchanger

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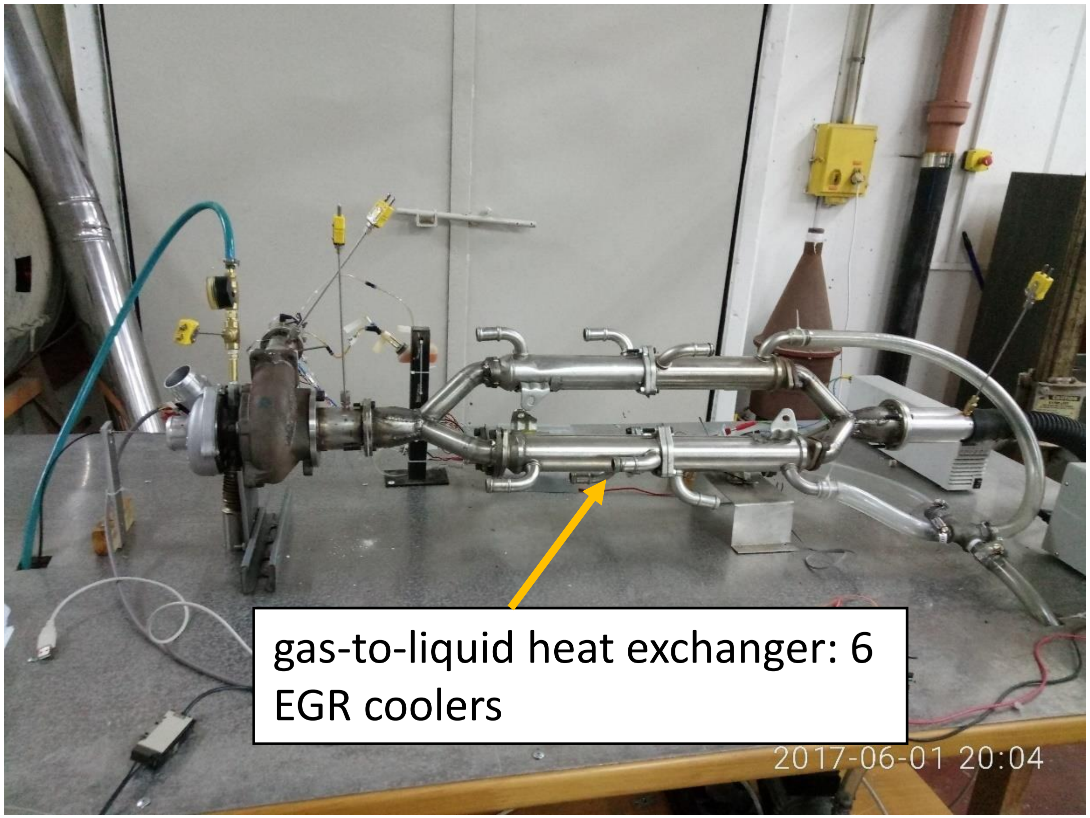


gas-to-liquid heat exchanger: 6 EGR coolers

manifold splits mass flow

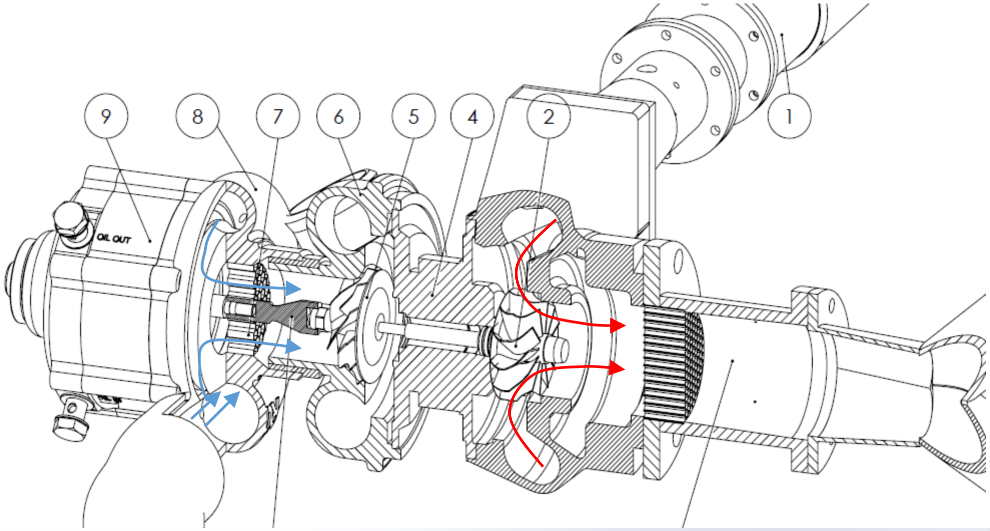
Experimental facility

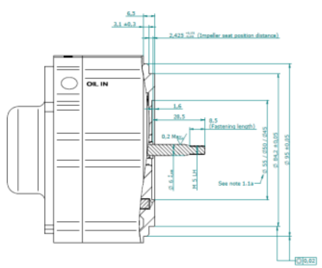
Experimental facility

Experimental facility: Adaption of transmission

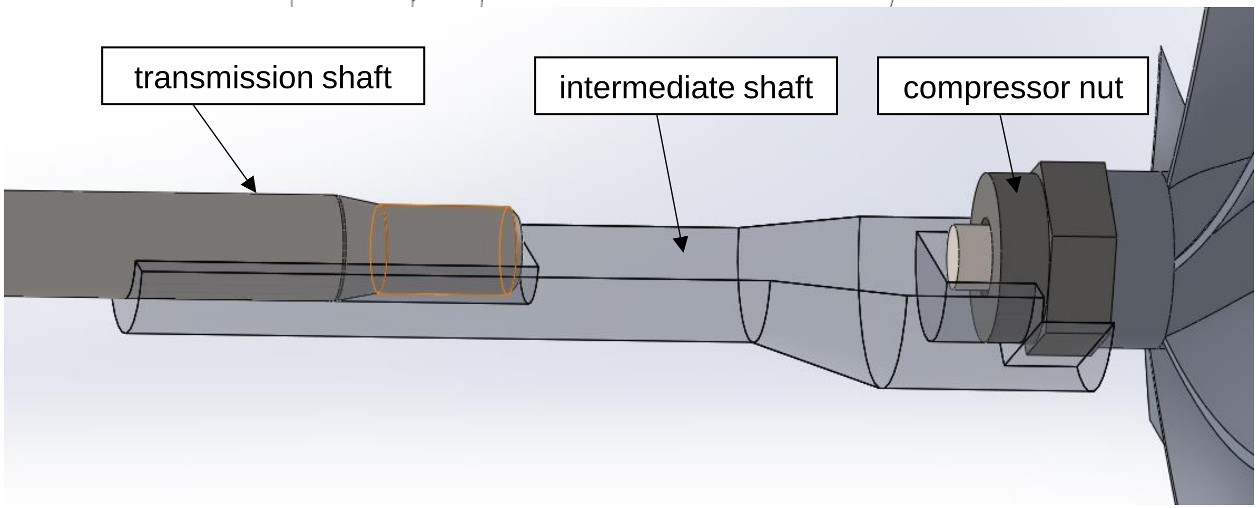
Intermediate shaft

- Connects turbocharger with transmission shaft
- Flow straightener before compressor inlet





Rotrex Traction Drive Transmission



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Conclusion: Relevance of IBC

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Inverted Brayton Cycle

- **Advantages:**
  - Does not interfere with primary engine cycle
  - Operates at low backpressure
  - Allows turbine expansion beyond atmospheric limitations
  - Broad spectrum of applications

- **Challenges:**
  - Effective IBC requires high component efficiencies, particularly of turbomachinery and heat exchanger
  - Optimum expansion ratio requires careful system design
  - Sub-atmospheric pressures in the IBC system requires efficient sealing of cycle components and separation of condensed water

Conclusion: Research efforts thus far

Thermodynamic Simulation

- Development of simulation software
- Calculations for prototype design

Experimental Facility

- CAD design of an experimental test rig
- Selection of measurement techniques
- Assembly of the test rig
- Preliminary operation tests

Conclusion: Further research efforts

Experimental Facility – still to come

- Generator
- Advanced sensor array
- Experimental campaign
- Iterated component optimization

Thank you for your attention!