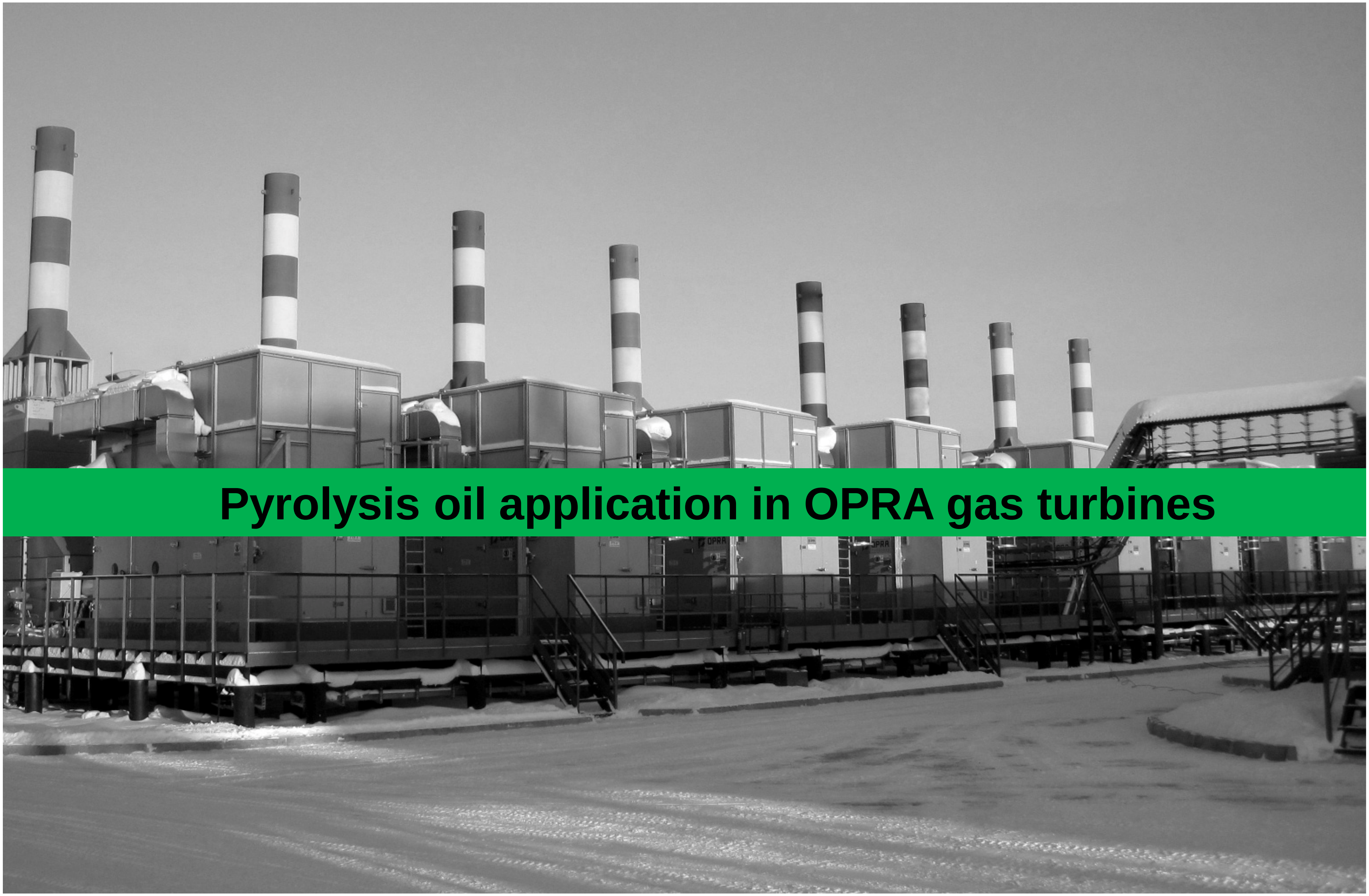
Pyrolysis oil application in OPRA gas turbines



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OPRA TURBINES

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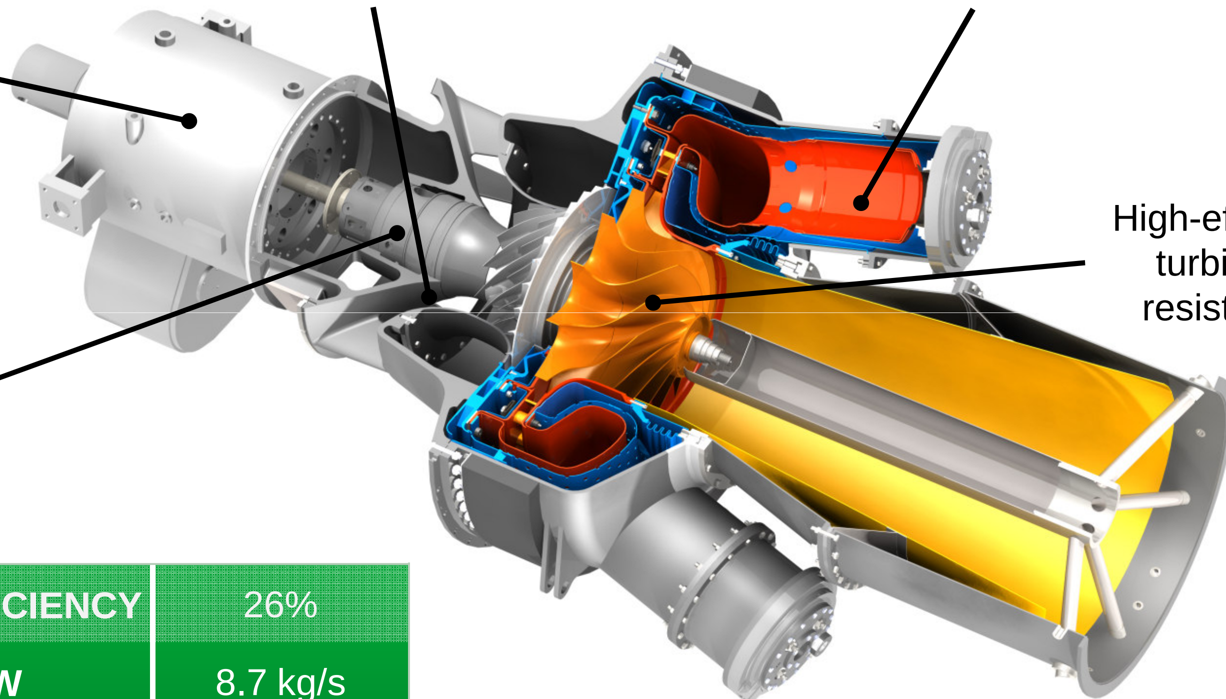
Introduction to OPRA

- OPRA was established in the Netherlands in 1991
- OPRA is an internationally expanding, high growth company with unique, proprietary technology
- The OP16 combines robustness and simplicity with high performance
- OPRA has demonstrated market success for oil & gas as well as industrial and commercial CHP applications
- OPRA has sold more than 65 gas turbines over the last five years
- The OP16 has accumulated more than 700.000 operating hours

The 1.9 MW OP16 gas turbine engine combines the best of simplicity and high performance

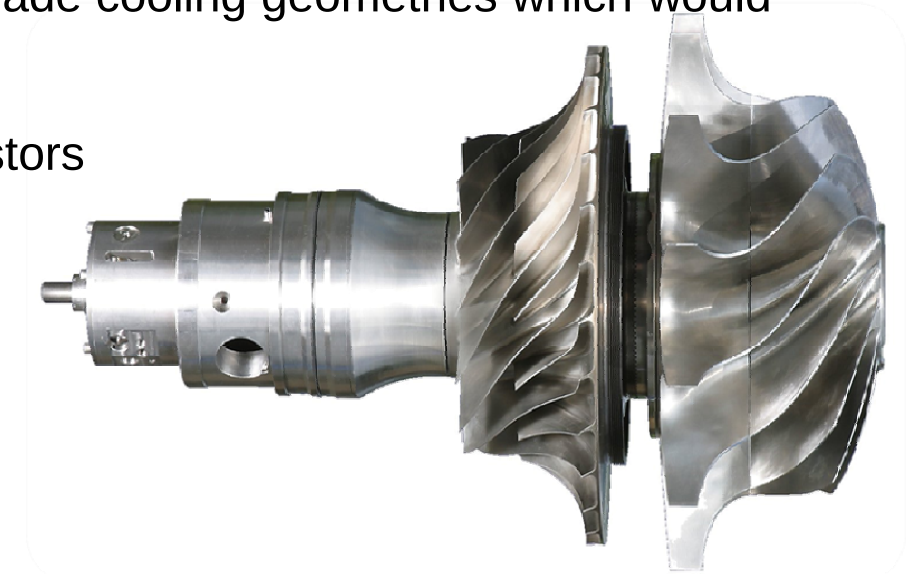


ELECTRIC EFFICIENCY	26%
EXHAUST FLOW	8.7 kg/s
EXHAUST GAS TEMP.	570ºC
ROTOR SPEED	26,000 rpm

*Foreign Object Damage

Application of pyrolysis oil in the OP16 gas turbine

- The OP16 all radial design is robust
- A radial turbine less sensitive to contaminants in the fuels
- Performance of a radial turbine impeller is less sensitive to blades surface distortions compared to axial turbines
- OP16 does not require intricate turbine blade cooling geometries which would be subject to plugging
- OP16 engine utilizes four tubular combustors
  - Easy maintenance
  - The size of combustor is not limited



The development of the low calorific fuel combustor

- The low caloric fuel combustor development was done as a part of joint project with BTG Bioliquids BV
- The Pyrolysis oil is one of the good alternatives to fossil fuels as a source of "Green energy".

Development programme

1. Initial test campaign using pyrolysis on the existing OP16 conventional burner
2. Development and testing of a low calorific fuel combustor
3. Full-scale engine testing

Test set-up:

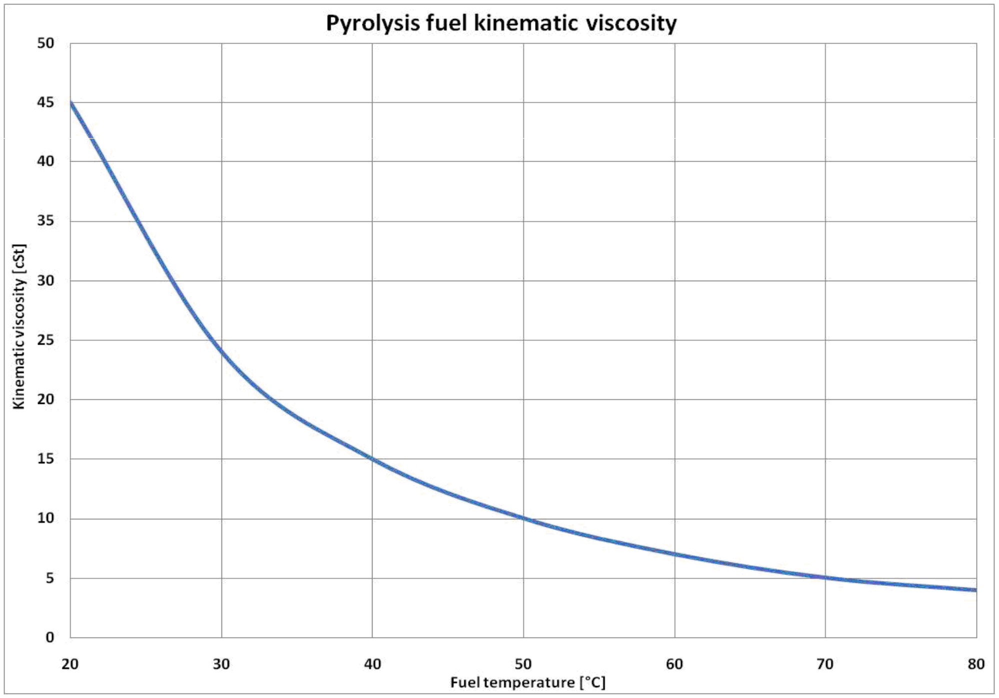
- **Atmospheric combustor test rig at OPRA**
  - Atmospheric combustion rig: Air mass flow rate up to 0.3 kg/s@300°C
  - Flexibility to test wide spectra of liquid and gaseous fuel

- **Combustor hardware**
  - Combustion chamber – convection flame tube working in diffusion combustion mode
  - Fuel injector – Pintle airblast nozzle
  - Fuel system – dual fuel (Pyrolysis oil/Ethanol) with fuel pre-heating
  - Emission indicators

Test campaigns

- Three test campaigns with different flame tube variants were performed
- Determination of optimal burning condition
- Determination of optimal fuel handling condition
- Determination of the emissions

Density [kg/m3]	1150
Low Heating Value [MJ/kg]	18.7
Viscosity at 38 °C [cSt]	17
Polymerization temperature [°C]	140
pH	2.5



Flame tube No 1

- Original OP16 flame tube
- Unburned fuel sediments were found on the flame tube inner walls after the test
- Large amount of unburned fuel as a "sparks" in the combustor exit was observed

Flame tube after first test

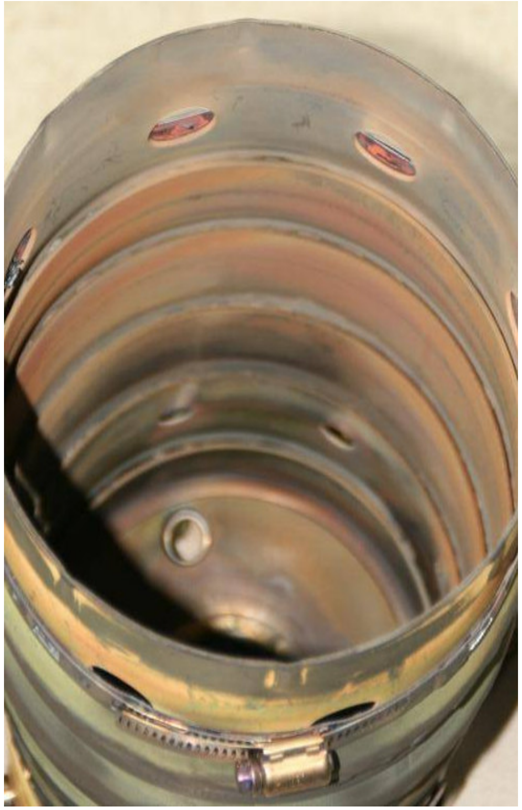
Flame tube No. 2

- Complete wall film cooling was removed
- Amount of sediments on the flame tube inner wall was significantly decreased
- Large amount of sediments found behind the dilution zone
- Not possible to reach full load condition due to overloading of the combustor

Flame tube after second test

Flame tube No. 3

- Air split was changed to reach stoichiometric condition in the primary zone
- Combustor effective area and air flow were decreased to keep same pressure loss – larger combustor volume
- Pure pyrolysis oil was possible to burn between 70-100% load
- During start up and run at combustor loads below 70% a mixture of Pyrolysis oil/Ethanol was required
- Amount and size of unburned fuel were significantly decreased
- No sediment on inner flame tube wall was found also behind the dilution zone



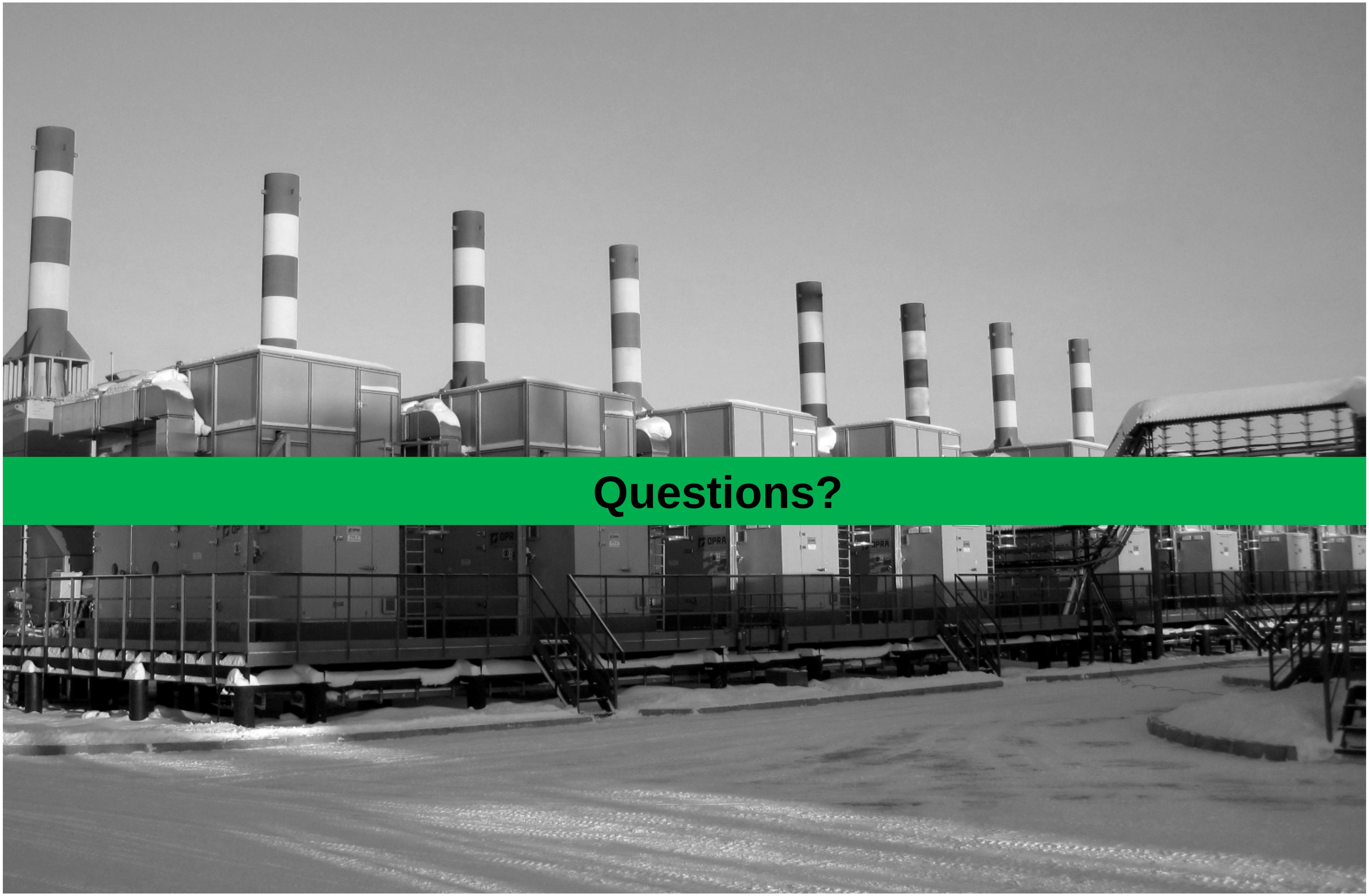
Flame tube after third test

Summary of the test results

- Three test campaigns with different flame tube variants were performed
- The optimal configuration was found for running with pure pyrolysis oil between 70 to 100% load
- The low calorific value and longer residence time needed for proper burning require larger combustor volume
- The air split was changed to keep stoichiometric air – fuel ratio in the primary zone → high flame temperature → increasing of reaction rate

Future work

- Phase 2 of the development program started
- Design of real scaled combustor is undergoing
- Test campaign focusing on combustor performance
- Determination of optimum mixture of pyrolysis oil/ethanol for part-load operation
- Some additional analysis e.g. CFD analyses of new combustor internal flow and fuel flow in the injector is undergoing



Questions?

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