Conversion of Jet Engine Combustor From Jet Fuel to Natural Gas

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MY THANKS TO ALL CONTRIBUTORS:

- Dr. Valery Sherbaum, Technion
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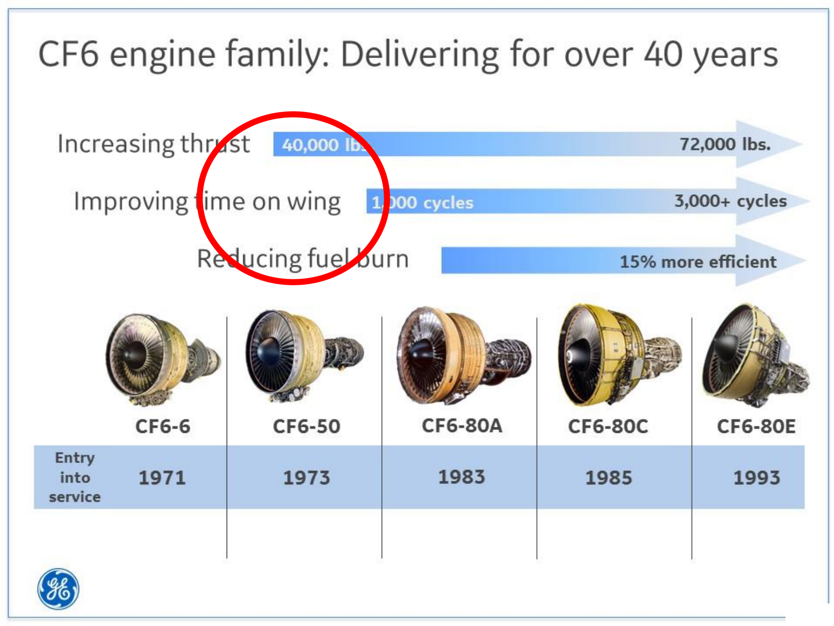
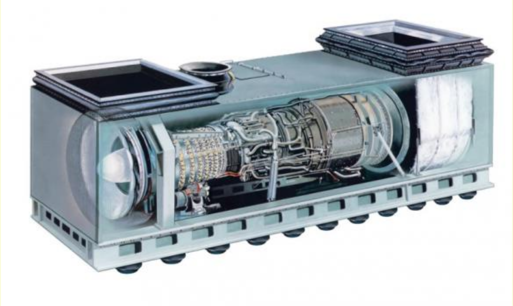
Concept



"Old" models can still function for many more hours

CF6-6



LM2500

Objectives

- The conversion of jet engine combustion chamber from operating on liquid jet fuel (JetA1 / kerosene) to natural gas (Methane / CH4)
- The conversion should be done with minimum modifications of the combustion chamber. Ideally, only the fuel nozzle should be changed
- The amount of the NOx and CO emissions of the modified combustion chamber should be minimal and not greater than of the original design.

Emission requirement (target)

As for GE LM1800 e (18 Mwe):

NOx @15% O2, 25 ppm vd
CO @15% O2, 25 ppm vd

(@ 60% relative humidity, Ta 15 deg C)

Method

1. Evaluate performance (CFD) under normal operating condition using liquid jet fuel (for reference data)
2. Design a NG fuel nozzle and evaluating performance using NG under similar normal (P_{s3} & T_{s3}) operating conditions
3. Validation of simulations under laboratory conditions:
   - Design a reduced model of the combustor, operating at atmospheric pressure,
   - Simulate performance at laboratory conditions (kerosene & NG),
   - Compare and calibrate CFD code
4. Optimize fuel nozzle's design

Operating Condition using Jet Fuel (for reference data)

	Corrected data (standard day ISA Conditions)		
	Fuel Flow rate, kg/hr	Static Pressure, PS3 bar-a	Static Inlet temperature, T3 deg K
Ground idle	350	2	420
Max Continues	4,000	23	770

1. CFD Model (Simulation Condition)

For kerosene and methane:

Chemical Reaction Model: Non-premixed Combustion
Equilibrium chemistry approximation (minimum Gibbs Energy): intermediate species are calculated, while there is no need for detailed kinetic data; 25 chemical species for Jet A and 23 for Methane

Solution method : Pressure velocity coupling; solver - pressure-based, SIMPLE scheme, method of a discretization – second order upwind.
Turbulence Model: Standard k – ε, Enhanced Wall Treatment.

Multi-Phase Treatment (kerosene): Lagrangian Discrete Phase. Pressure swirl atomizer
NOx Model: Thermal, Prompt. Post processing
Number of cells ~ 14,000,000**, Convergence Criteria:** 1.E-6

For methane (only):

Detailed chemistry:, ***Steady Flamelet combustion model*** using the GRI-Mech 3.0, optimized for NG with 325 reactions and 53 species.

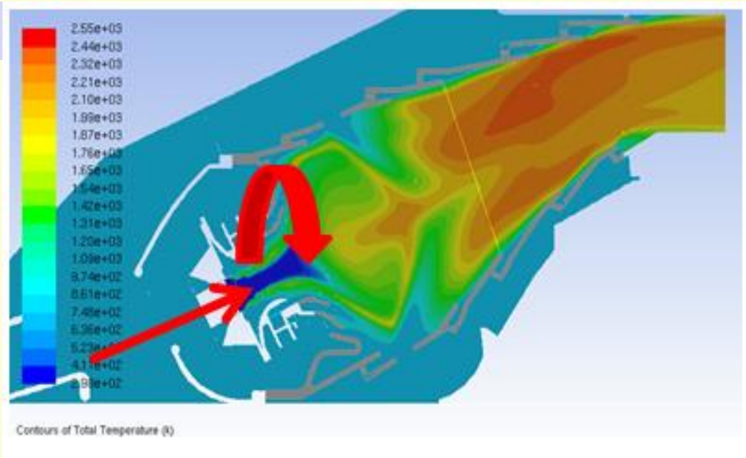
The Flamelet and Equilibrium models gave close results.

Performance at Max. Continues (jet fuel)

Total Temperature [K]

2550 K

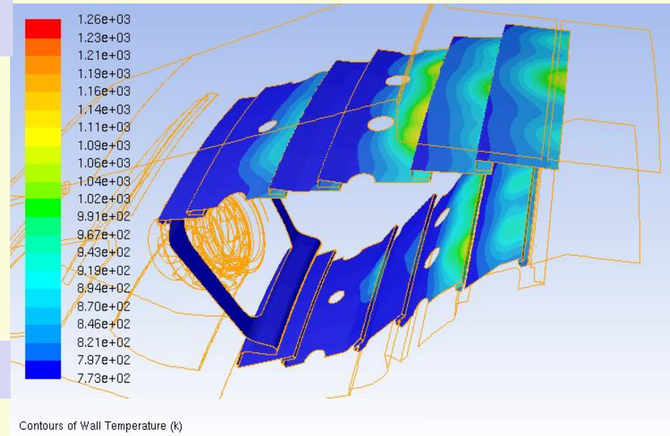
300 K



Liner Wall Temperature [K]

1250 K

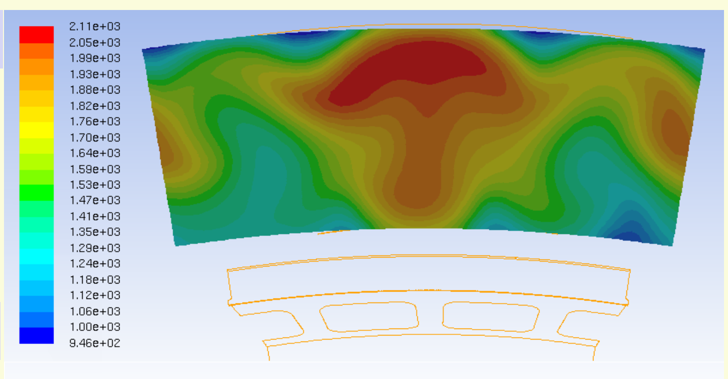
770 K



Exhaust Total Temperature [K]

2100 K

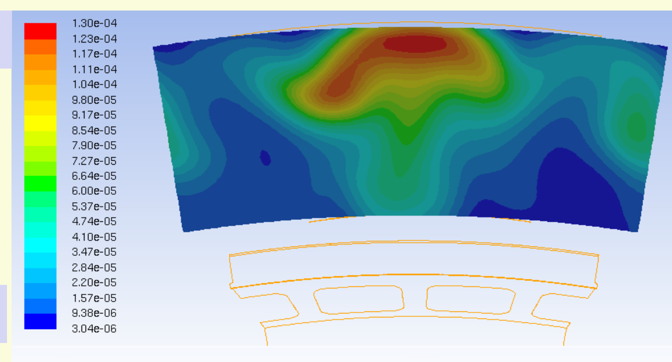
940 K



NOx at exhaust [mole fraction]

130 ppm

3ppm

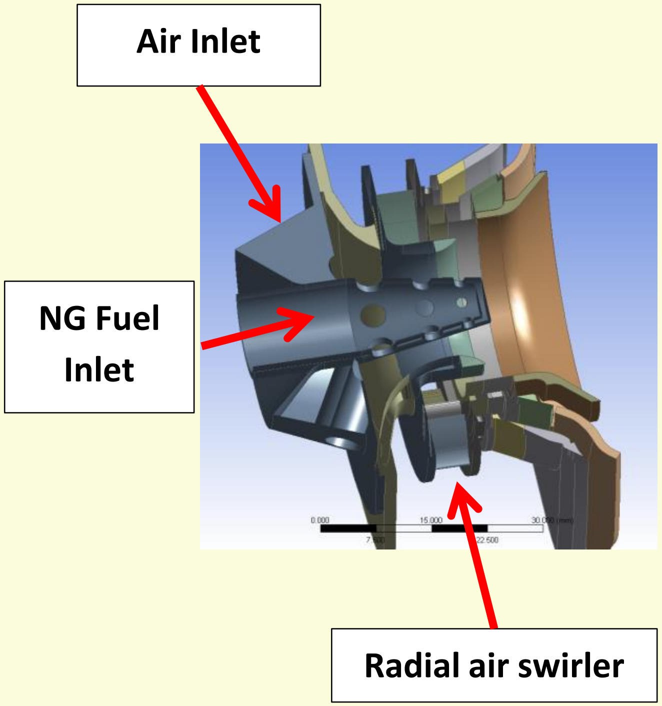


2. Design a NG Fuel Nozzle

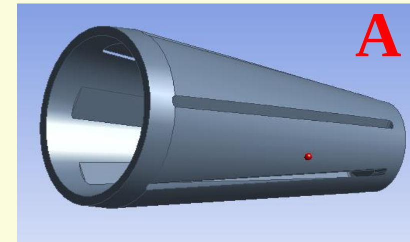
Design a NG fuel nozzle and evaluating performance using NG under similar P_{s3} & T_{s3} operating conditions.

NG Nozzle Optimization

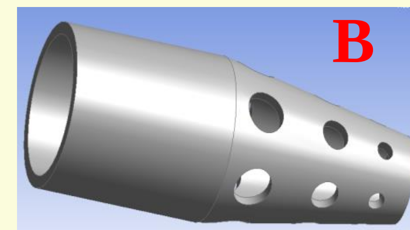
In order to study the effect of gaseous fuel distribution and its velocities, several options of nozzle's designs were investigated:



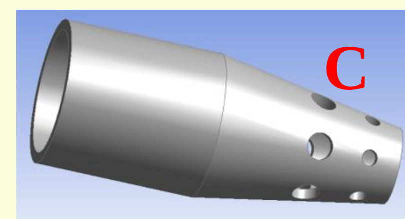
Option A: slots



Option B: 3 rows of circular holes (same area as in A)

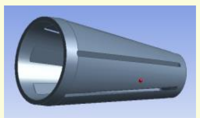
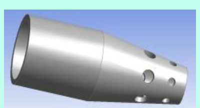


Option C: 2 rows holes (smaller area than in A & B)



Simulation were done using two CFD models: Flamelet and Equilibrium. Both models gave close results.

NG Nozzles – Simulations Results

		MWA	Max Section	Max Wall	Pattern factor	MWA Unburnt CH_4	MWA CO	MWA NOx
		Temperatures [K]				Concentrations [ppm dv] Mole Fraction		
	A	1641	2102	1269	0.53	0.52	426	32
	B	1640	2052	1312	0.48	0.024	188	32
	C	1635	1996	1227	0.42	0.01	42.0	31

Required values: NOx @15% O_2, 25 ppmvd CO and @15% O_2, **25 ppmvd**

MWA – Mass Weighted Average

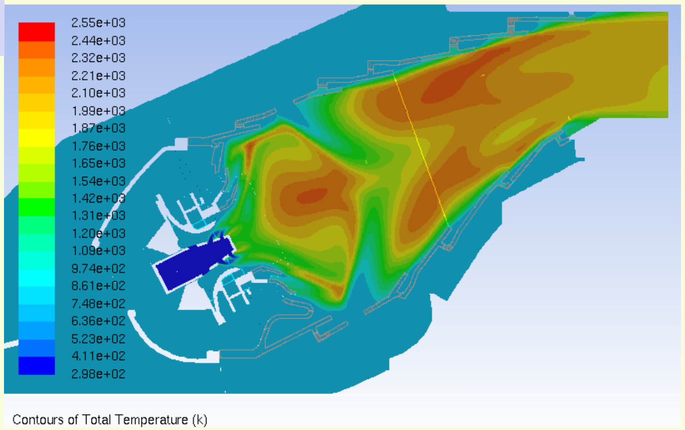
$$Pattern\ Factor = \frac{T_{\max} - T_{avg}}{T_{avg} - T_{inlet}}$$

Option **C** (NG) Nozzle Results

Total Temperature [K]

2550 K

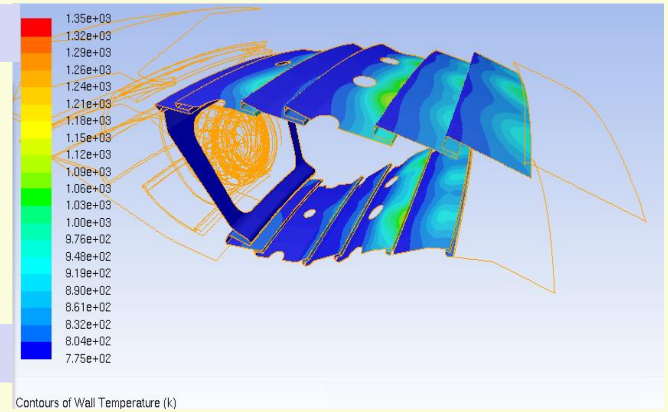
300 K



Liner Wall Temperature [K]

1350 K

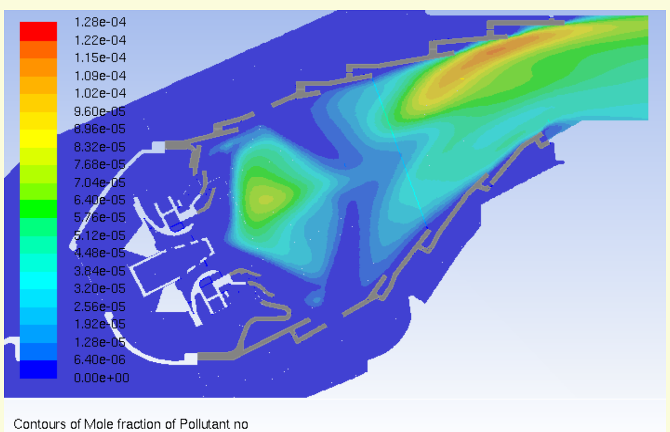
770 K



NOx at exhaust [mole fraction]

130 ppm

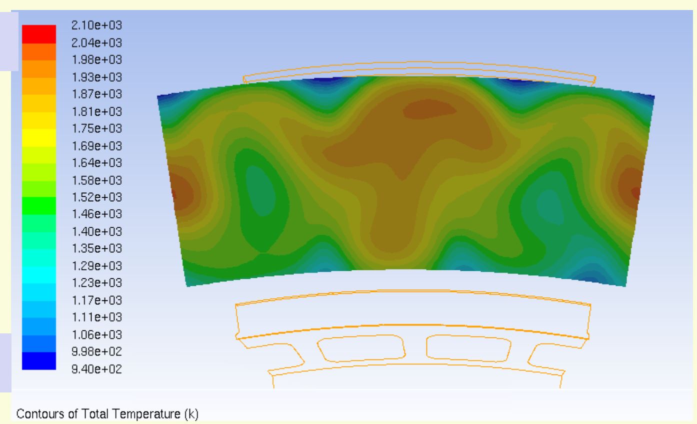
0ppm



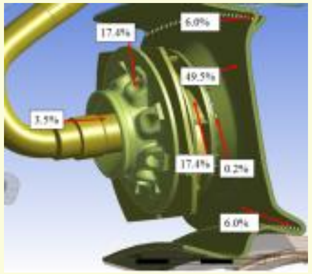
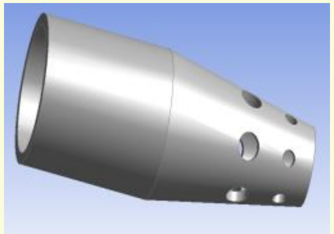
Exhaust Total Temperature [K]

2100 K

940 K



Summary of Simulations (Nominal Operating Conditions)

	Air & Kerosene	Air & Methane (Option C)
Design		
CO, ppm	276	42
NOx, ppm	74	33
Pattern factor	0.46	0.42

All values are at entrance to turbine's rotor blades in ppm (dry mass fraction)

$$Pattern\ \ Factor = \frac{T_{\max} - T_{avg}}{T_{avg} - T_{inlet}}$$

3. Validation of Simulations (laboratory conditions)

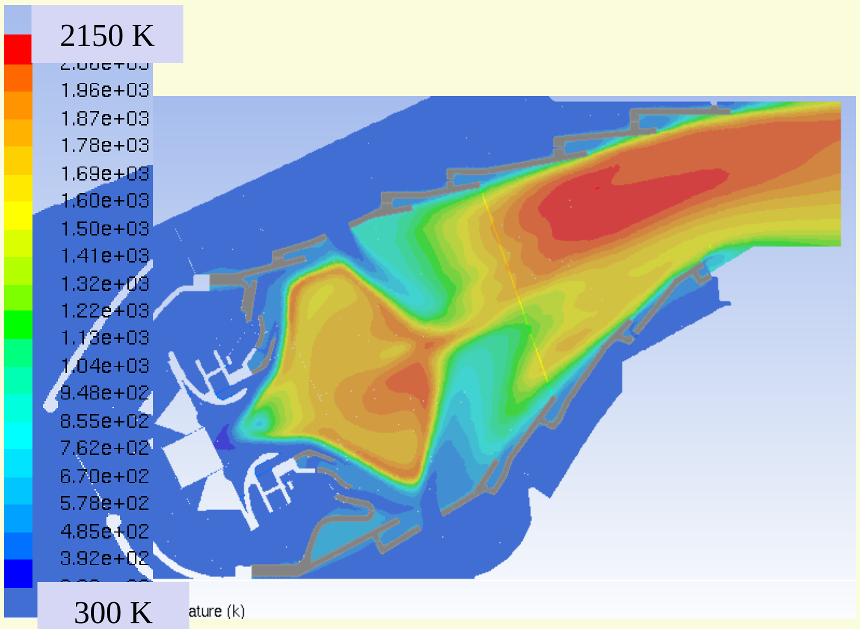
- Design a sector model of the combustor, operating at Pa= 1bar, Ta= 400K
- Simulate performance at laboratory conditions,
- Compare and calibrate CFD code
- Solid cone atomizer
- Conditions for test sector (3 fuel atomizers):

Test date	Air flow [g/s]	Air temp [K]	Kerosene flow rate [g/s]	Methane flow rate [g/s]
CFD	330	400	7.8	6.5
Test	370	420	8.0	6.5

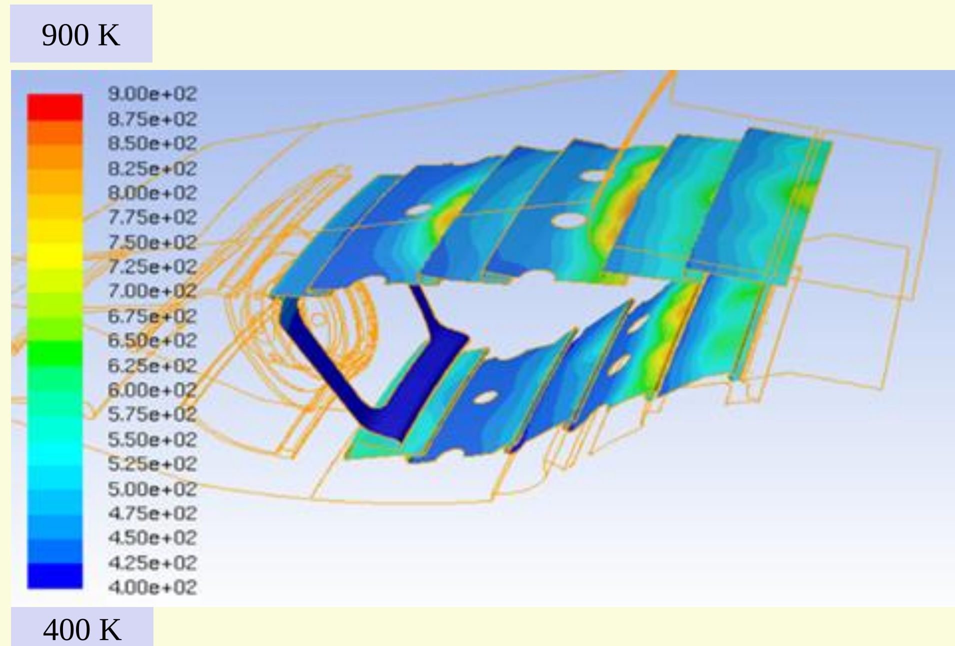
Note: The air mass flow per atomizer at our experiment is higher than the CFD, because some of the inlet air enter through the side walls.

CFD Simulations for Kerosene (Laboratory Test Conditions)

Total Temperature [K]



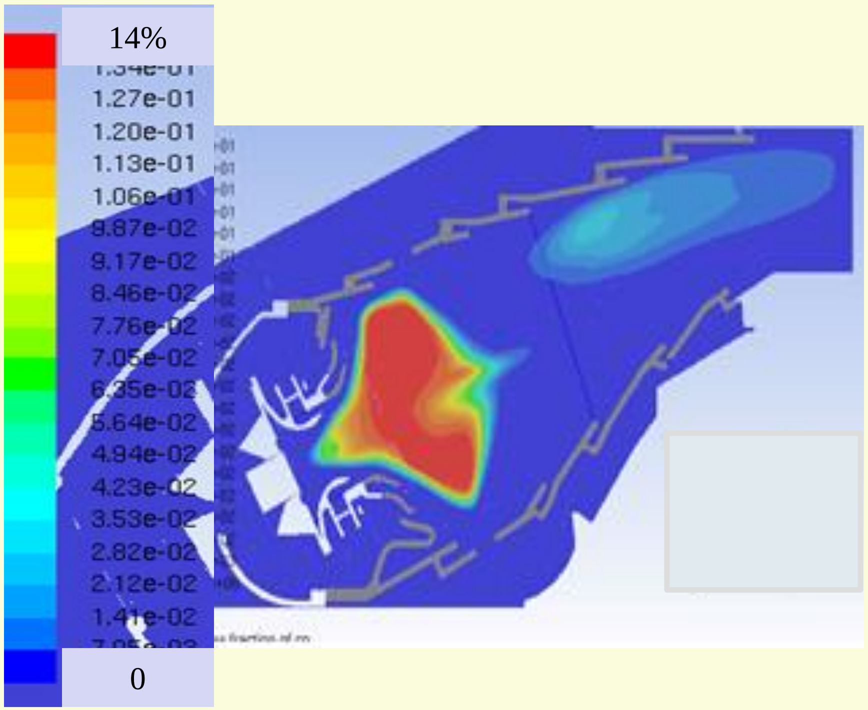
Liner Wall Temperature [K]

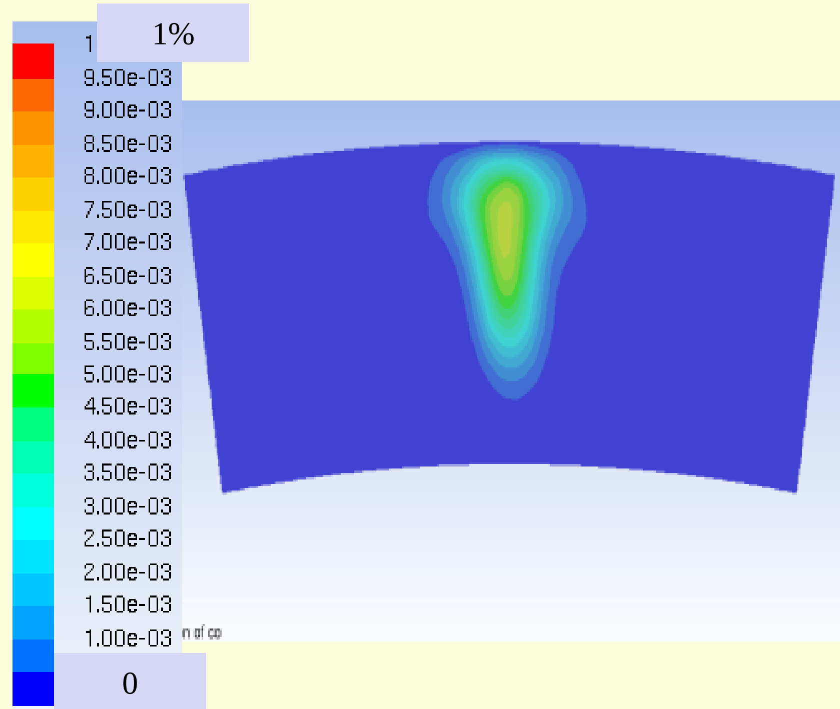


Incomplete reaction process within the combustor !

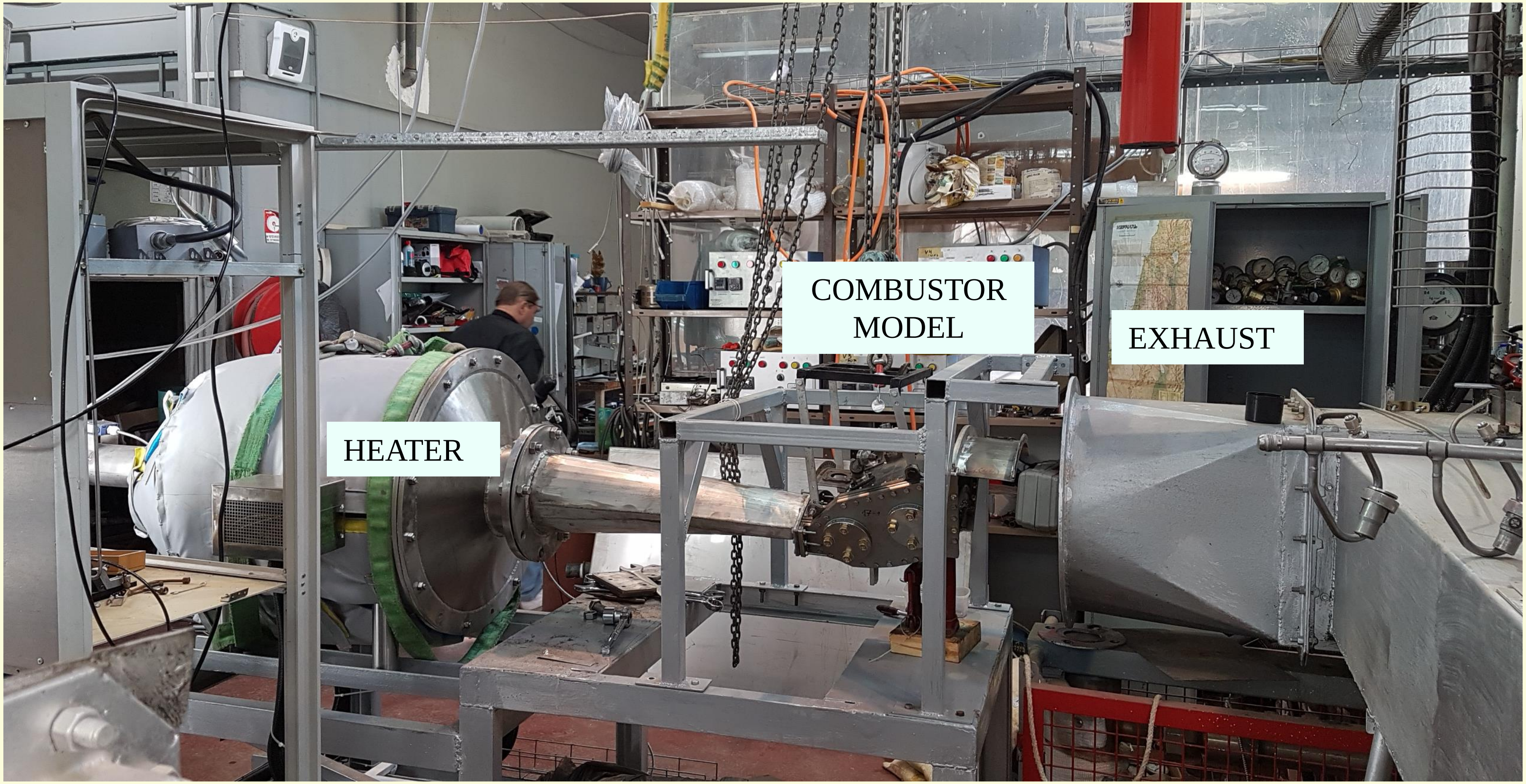
CFD Simulations for Kerosene (Laboratory Test Conditions)

CO Mass Fraction

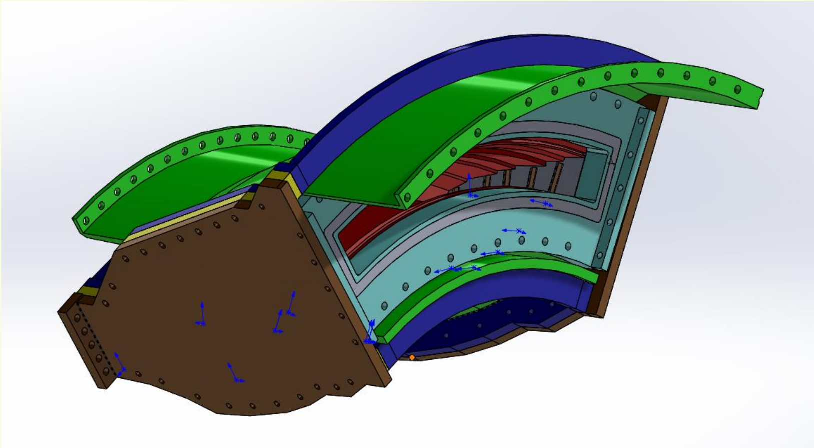




The test rig



Fully assembled combustor sector



Liner

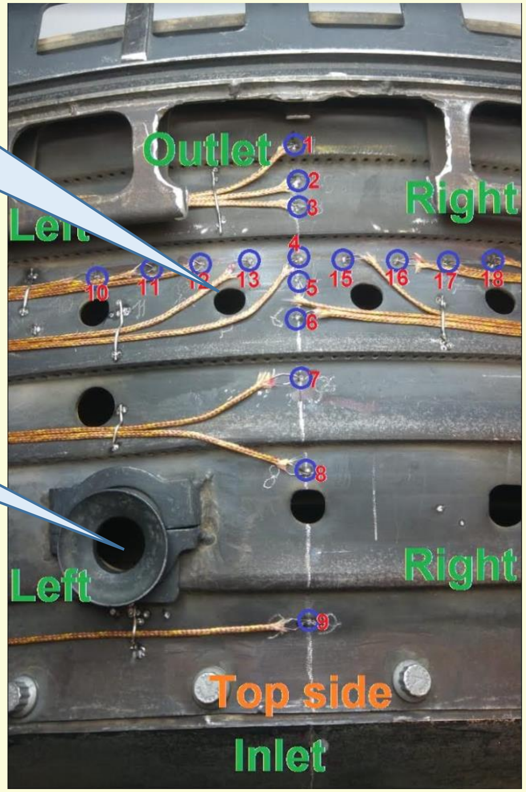
Liner sector with welded walls

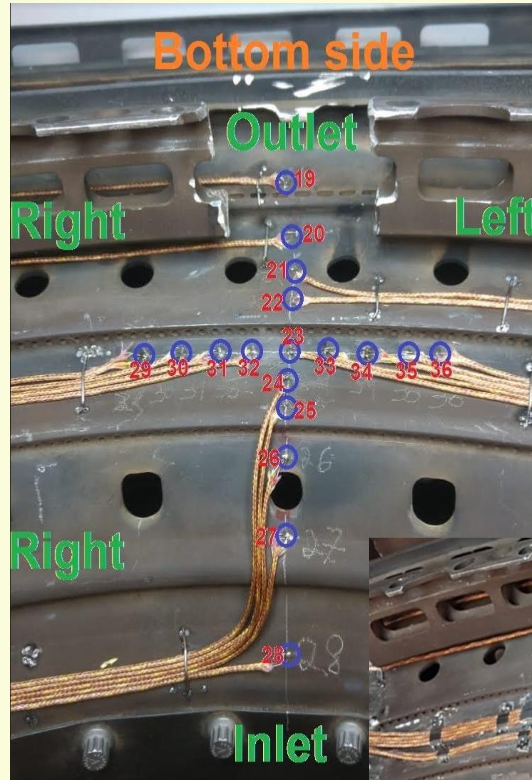
The liner and outer case sector with 3 fuel nozzles installed. (without outer side walls)

Wall Thermocouples

Dilution holes

Ignitor location

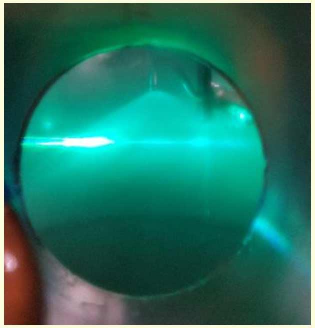


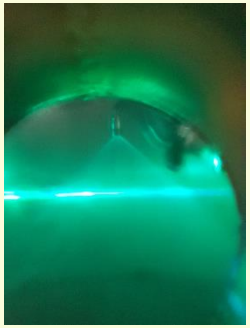


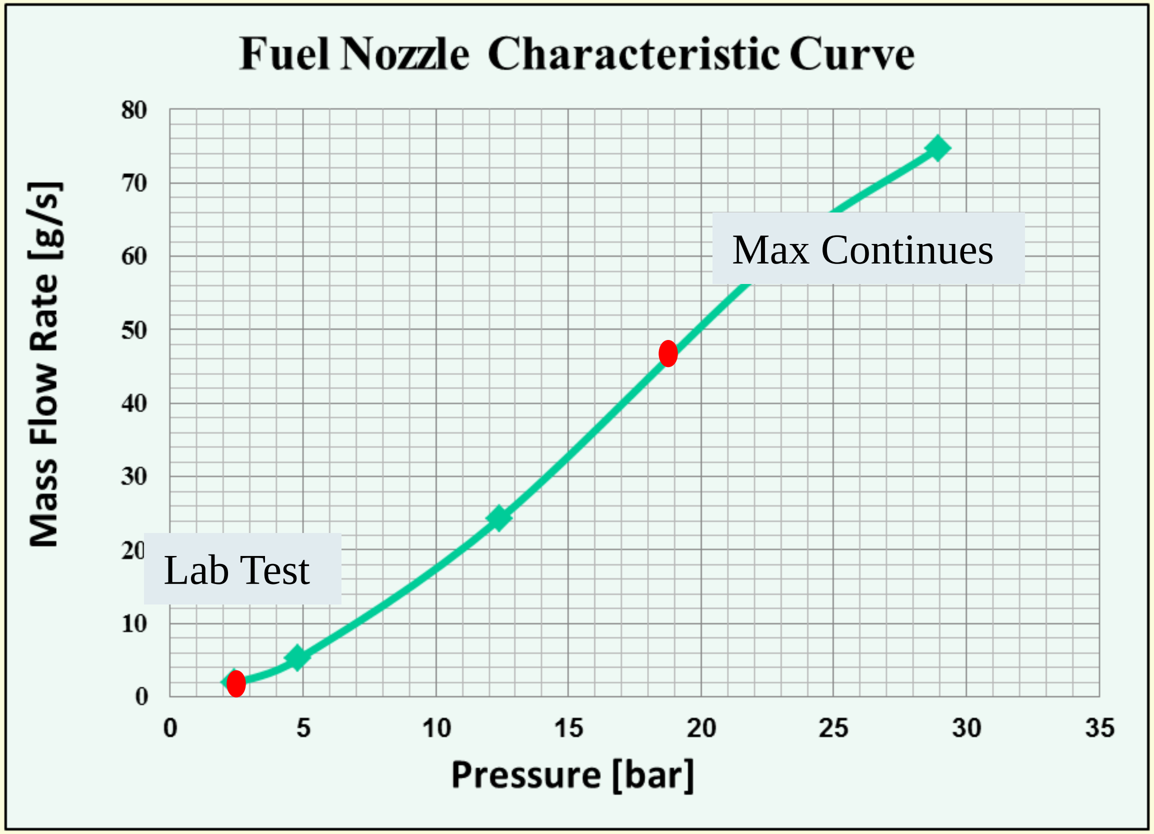
Covered wall thermocouples

Fully assembled combustor sector

Fuel Nozzle Operation

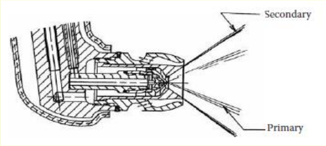




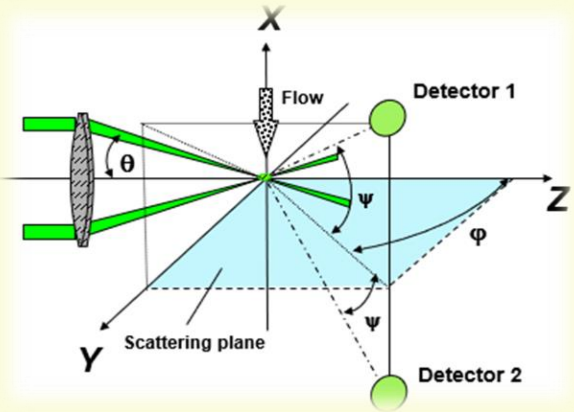


For the amount of the required flow rate, the fuel Spray Pressure is Too Low …

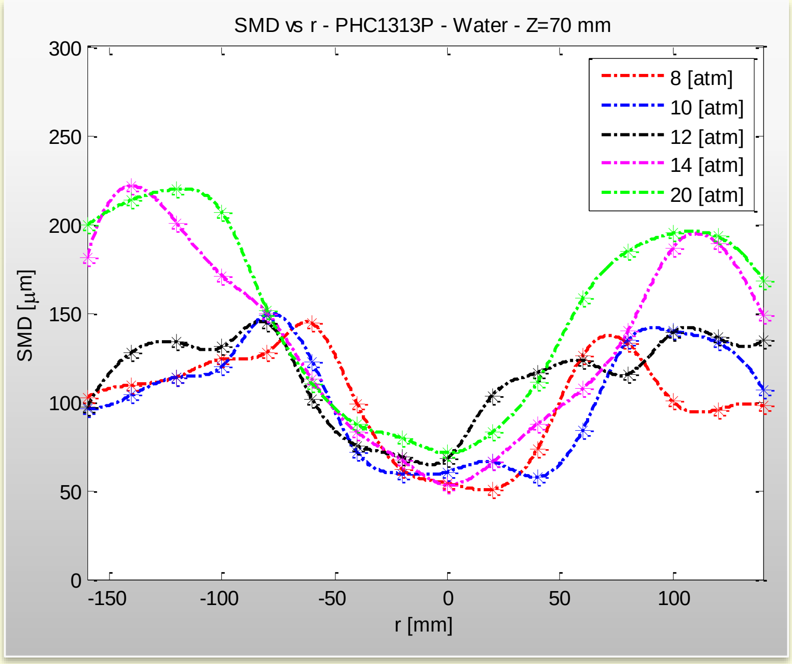
Fuel Spray Measurements



Dual Orifice Atomizer

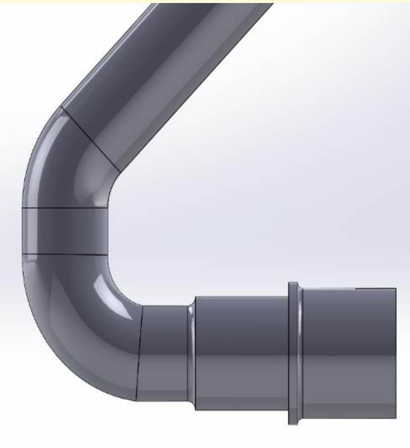


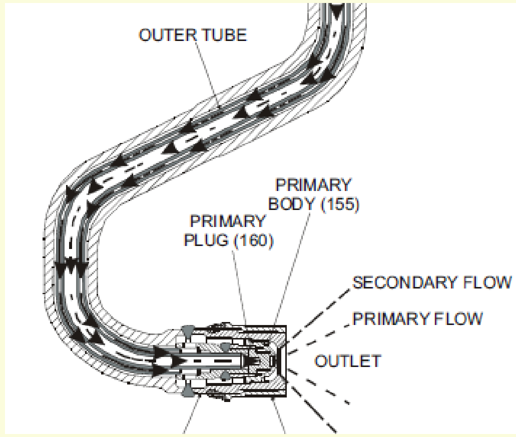
Phase Doppler System



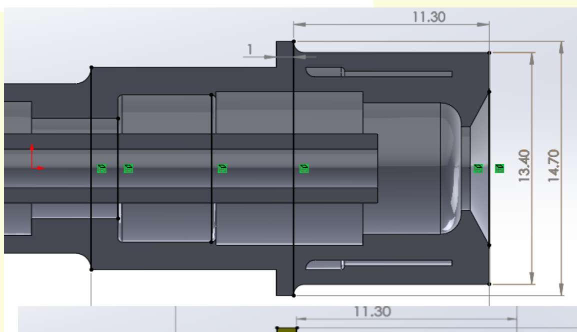
Droplet Size Distribution

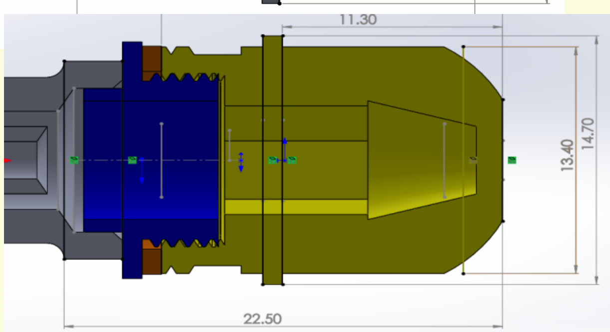
Modification of Fuel Nozzle





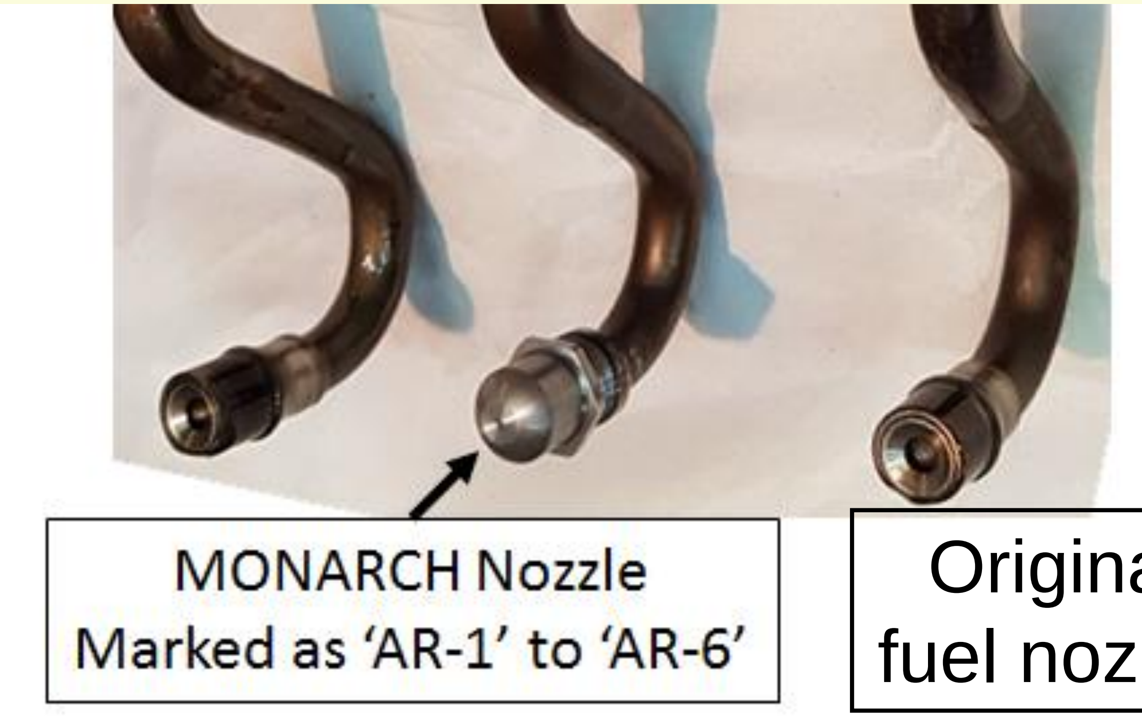
As the fuel flow rate was reduced significantly, the atomizer head had to be replaced and a "transplant" operation was performed. A modified Monarch atomizer was installed instead.

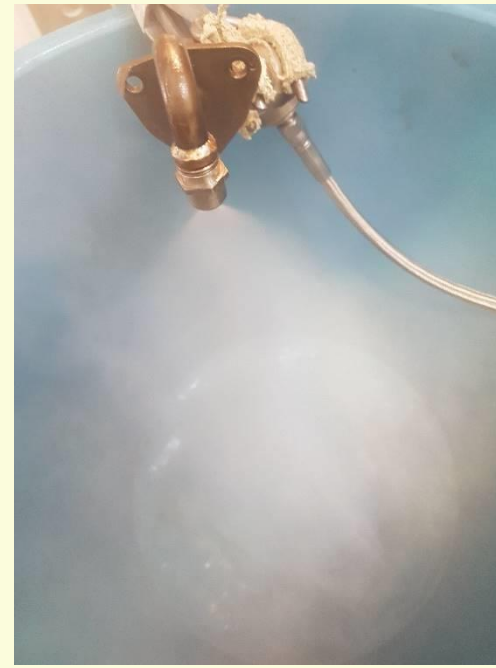




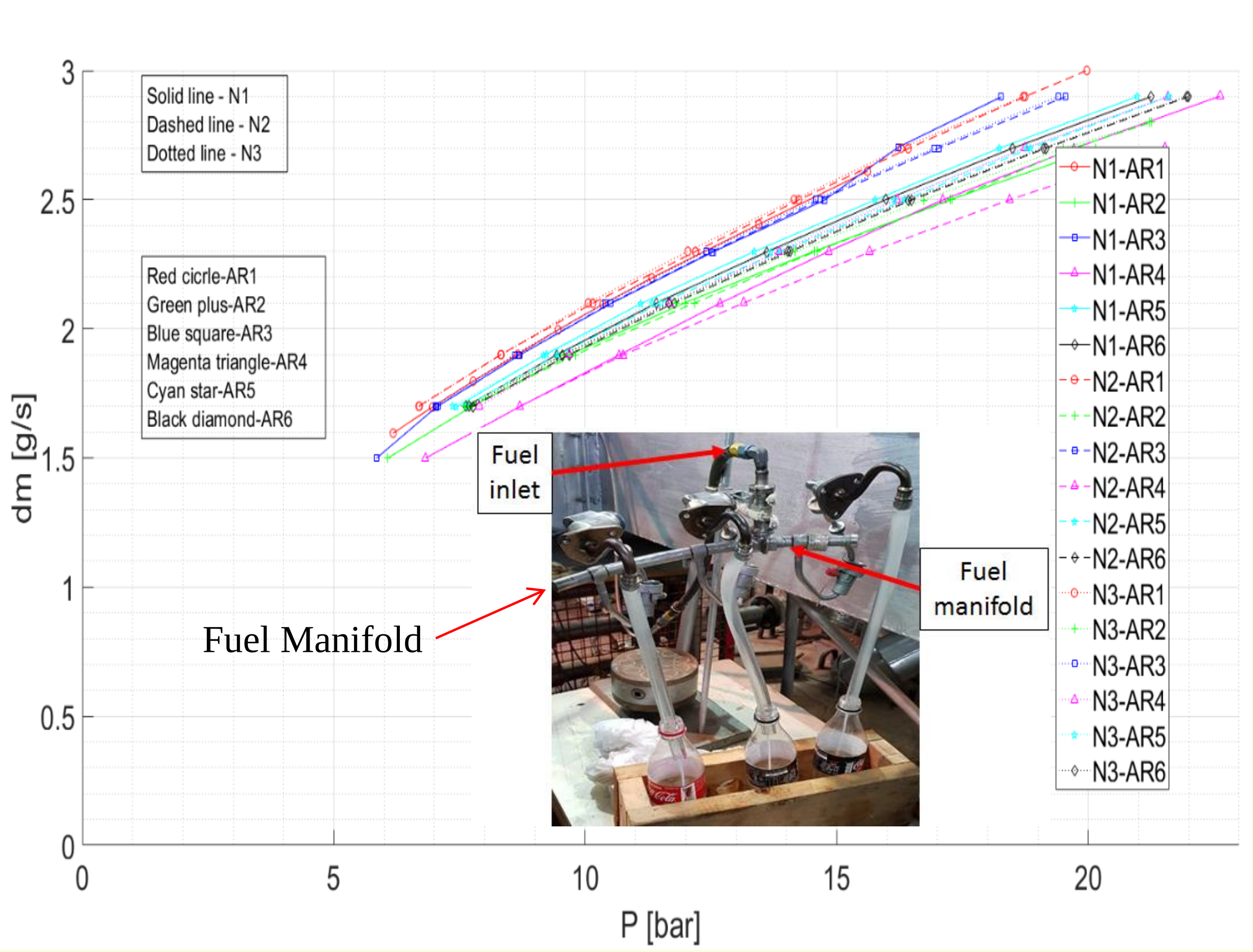
Monarch Oil Burner Nozzles

Modification of Fuel Nozzle





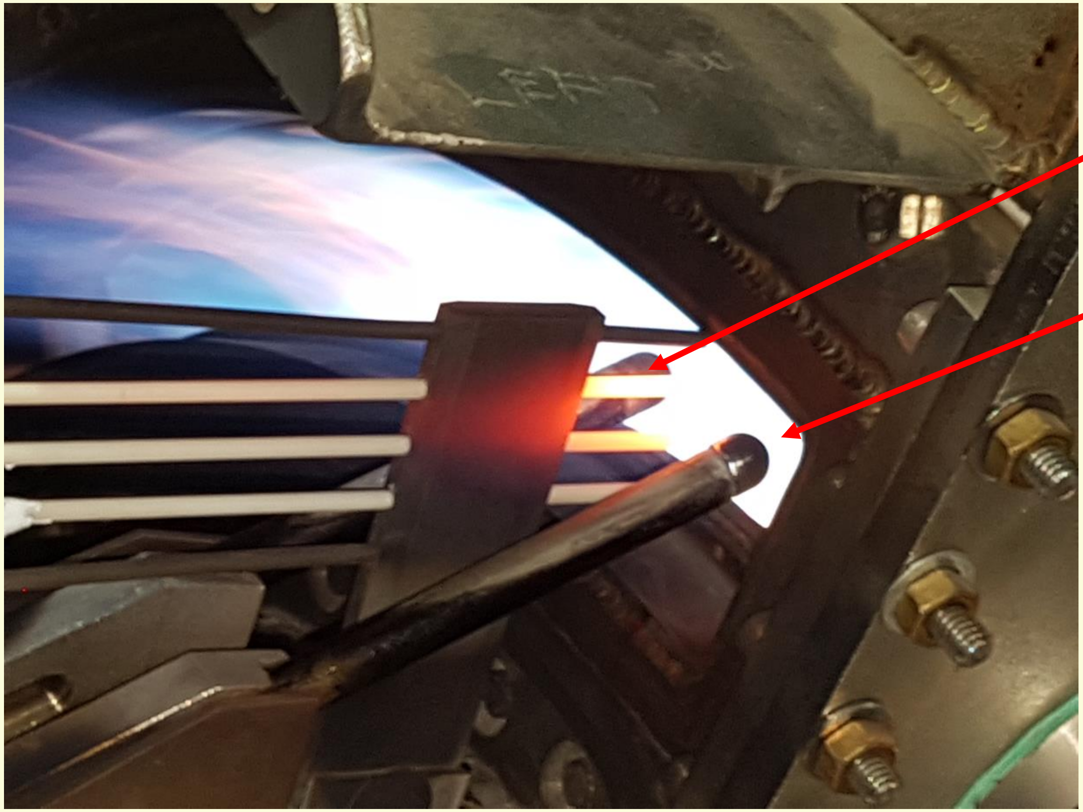
Calibration of Fuel Nozzle



3 HOUSINGS
6 FUEL NOZZLES
18 COMBINATIONS

We found that the combination [N1-AR5, N2-AR2, N3-AR6] gives good uniform performance.

Diagnostics



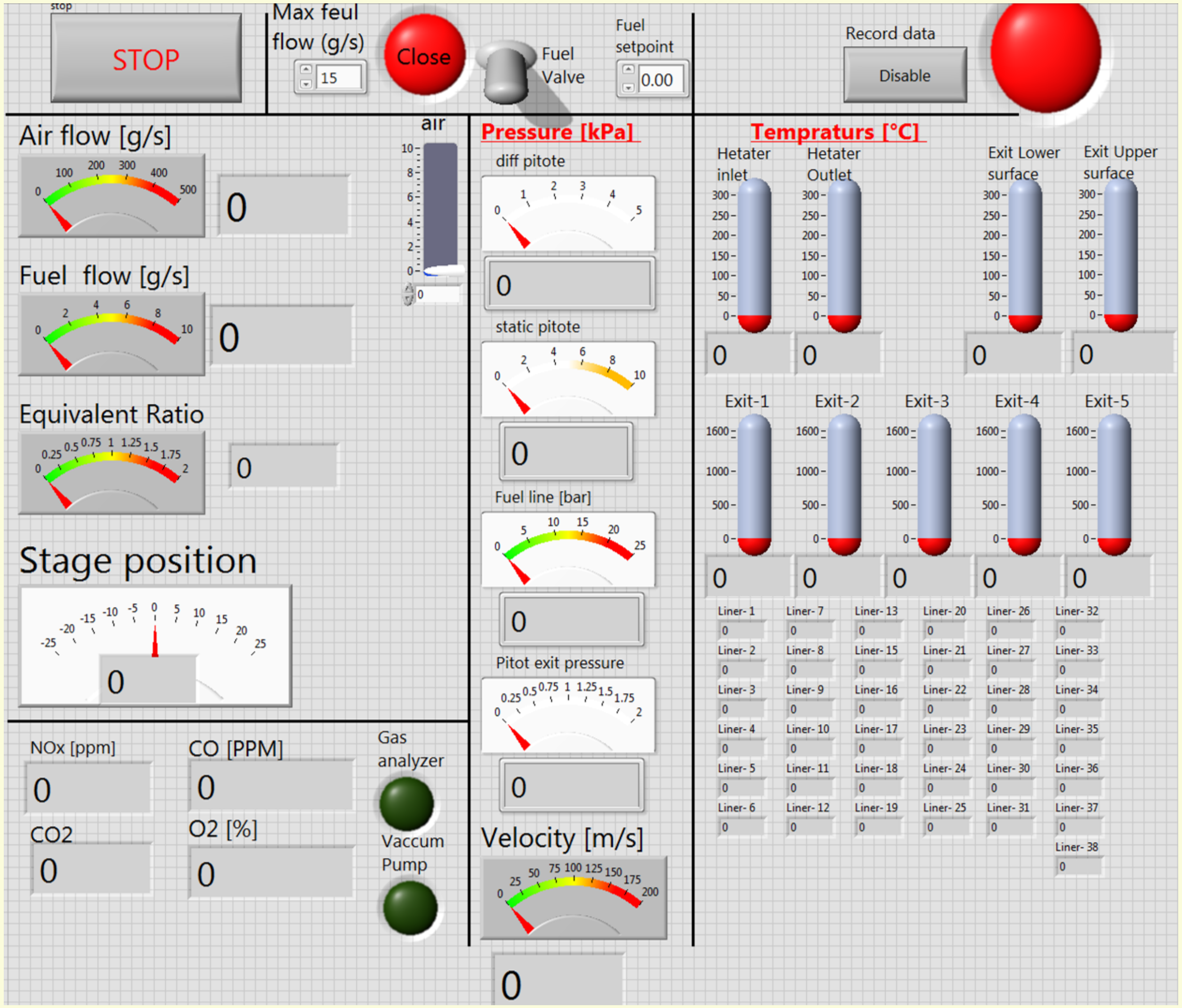
Water cooled Pitot Tube

Water cooled Gas sampling Probe

Rotating rake of K & R type thermocouples

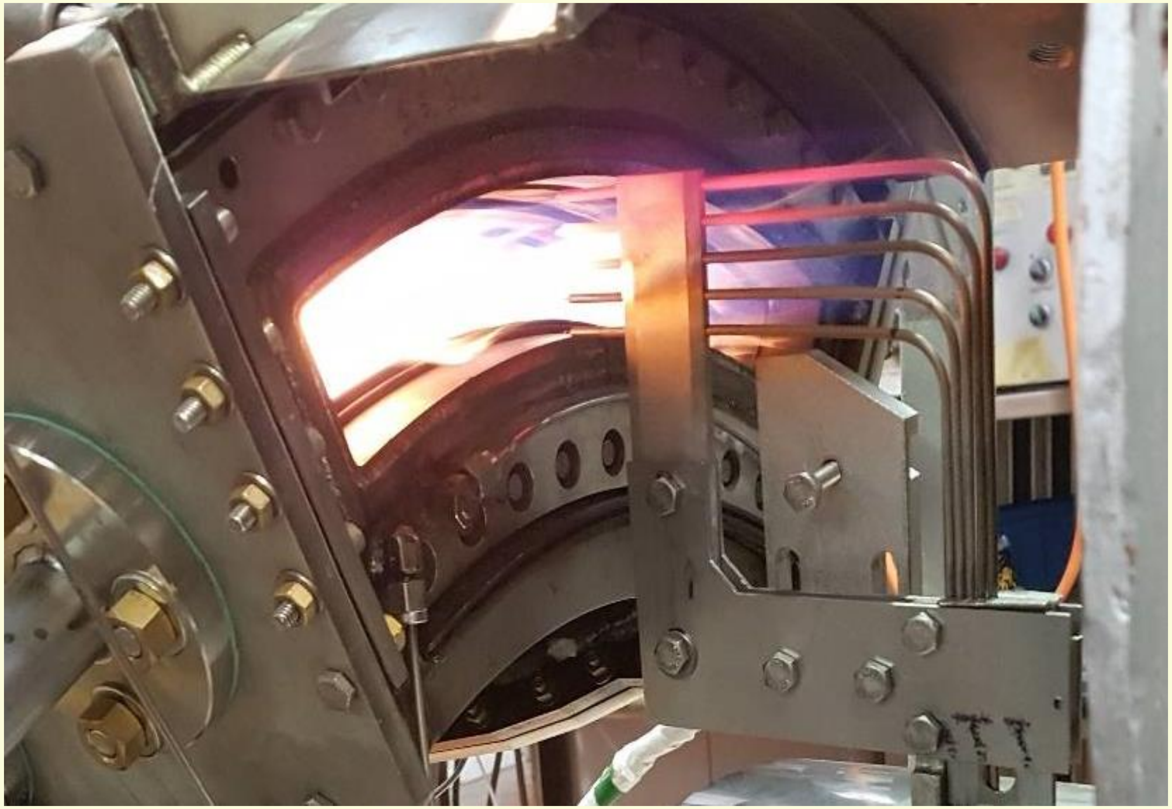
Water-cooled gas probe

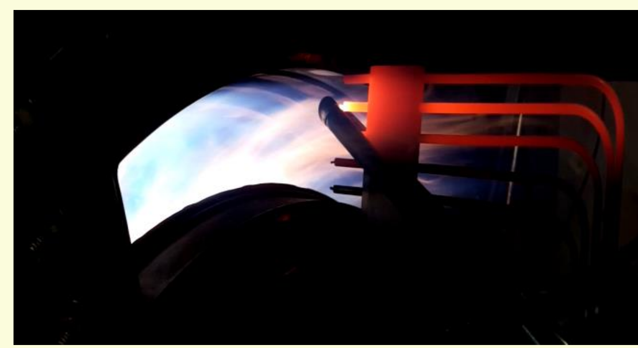
LabView Data Acquisition Main Panel



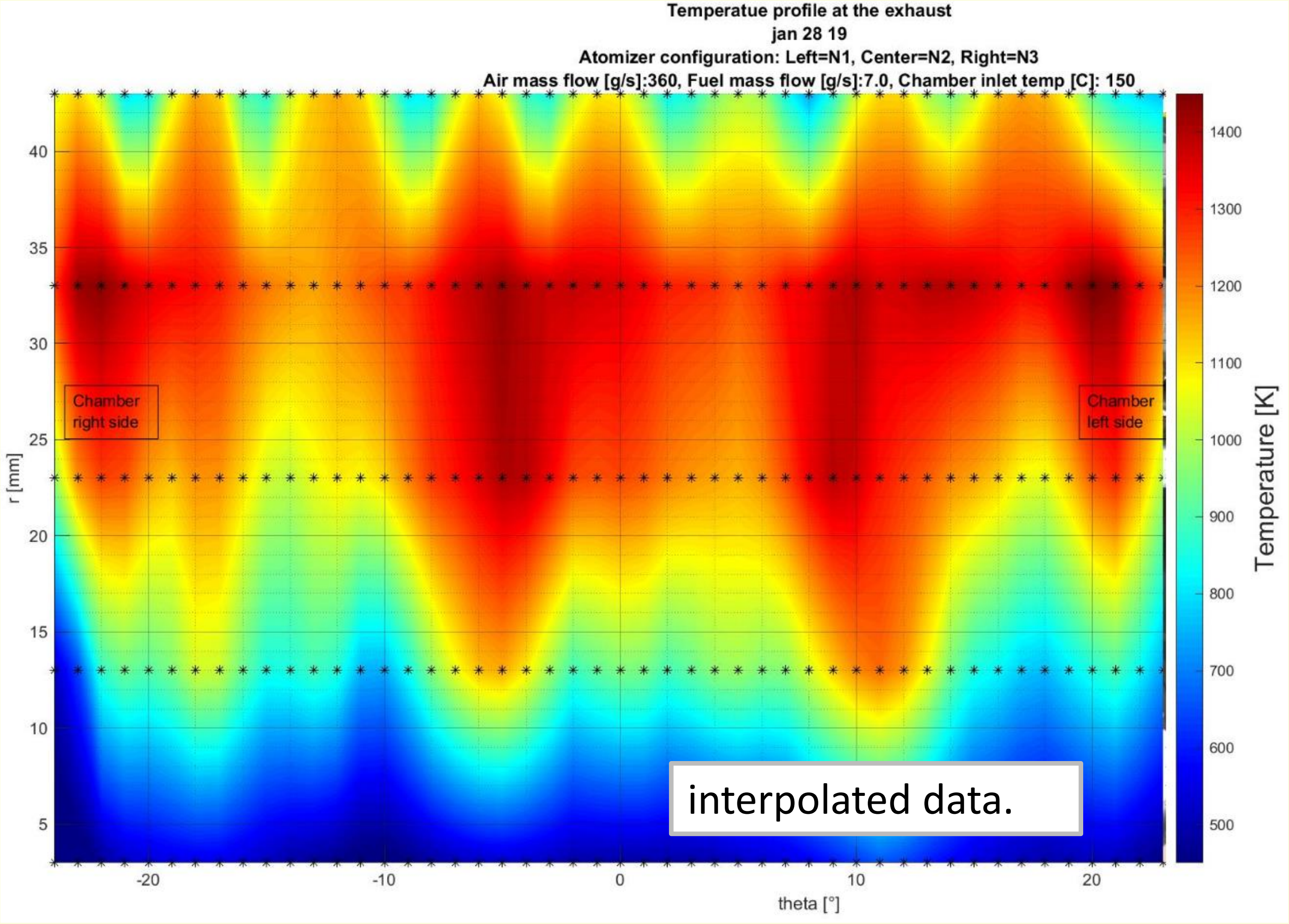
screen view

kerosene Combustion





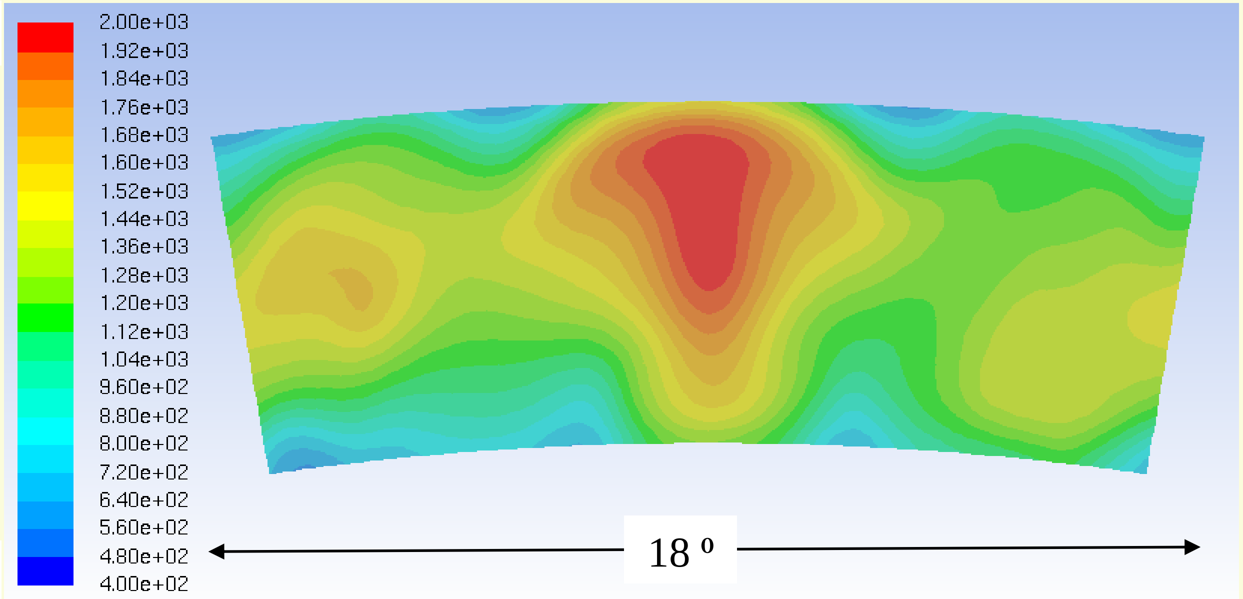
Measured Temperature distribution



Exhausts Temperature Distribution CFD Vs. Measurements

2000 K--

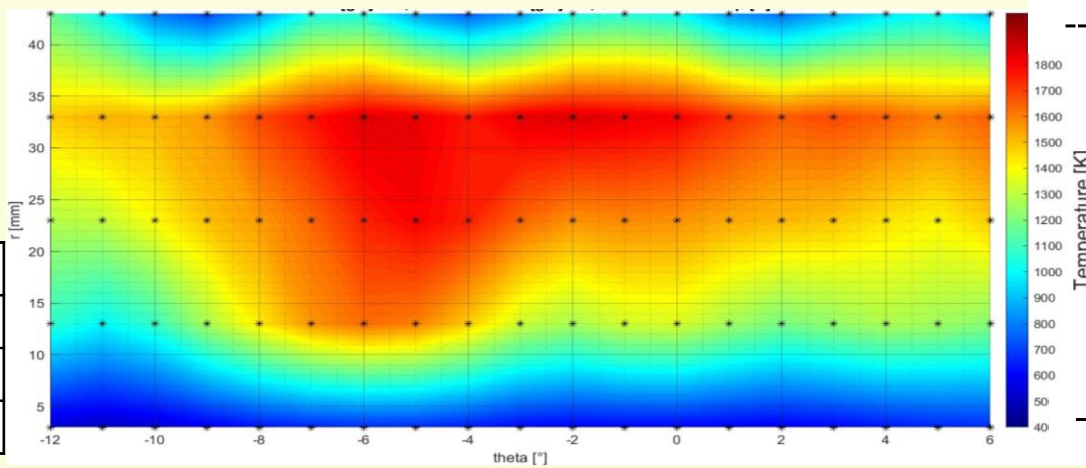
CFD



400 K --

--2000 K

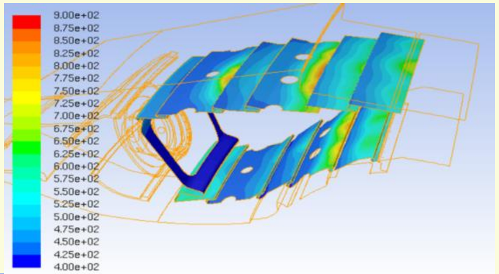
Measurements



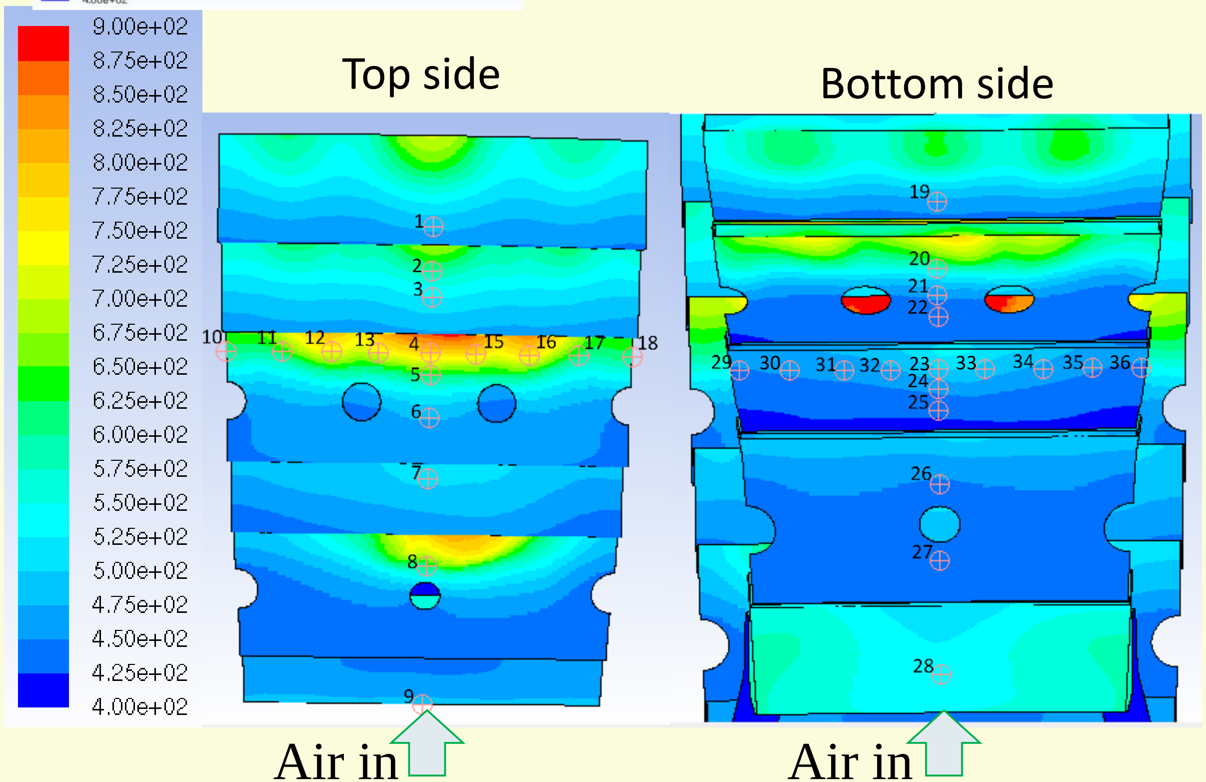
--400 K

	CFD	Meas.
Max Temperature [K]	2020	1857
Min Temperature [K]	637	537
MWA Temperature [K]	**1309**	**1318**

Wall Temperature Distribution

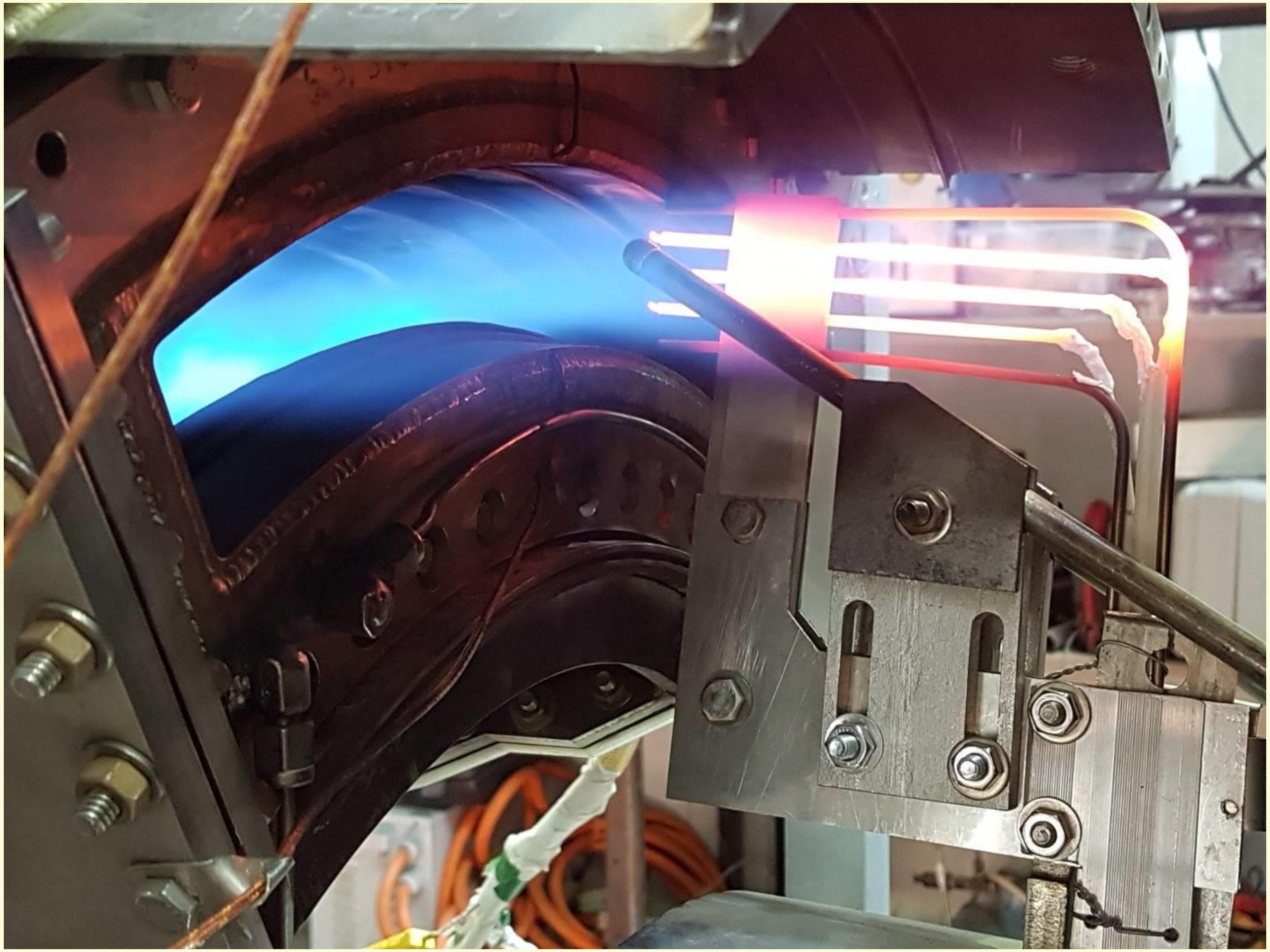


CFD Vs. measurements: Kerosene Fuel



Tc	CFD	Test results	error [k]	relative error [%] (CFD-test)/CFD
1	479	464	14.6	3
2	590	485	105.0	18
3	522	467	55.1	11
4	663	496	167.0	25
6	477	463	14.4	3
7	506	462	43.7	9
8	616	448	167.8	27
9	490	439	51.4	10
10	551	520	30.2	5
11	560	490	70.1	13
12	605	500	105.9	17
13	705	504	201.0	29
15	750	500	250.3	33
16	738	490	248.2	34
17	612	476	135.4	22
18	549	479	70.2	13
19	457	448	8.6	2
20	441	485	-44.2	-10
21	418	452	-33.8	-8
22	434	429	5.1	1
23	478	451	26.7	6
24	414	441	-27.1	-7
25	409	429	-20.2	-5
26	410	442	-31.8	-8
27	440	423	16.9	4
28	503	422	80.4	16
29	441	433	8.3	2
30	428	441	-13.0	-3
31	453	452	1.6	0
32	460	452	8.1	2
33	477	458	18.8	4
34	458	462	-4.4	-1
35	447	461	-14.0	-3
36	441	461	-20.1	-5

Methane Combustion

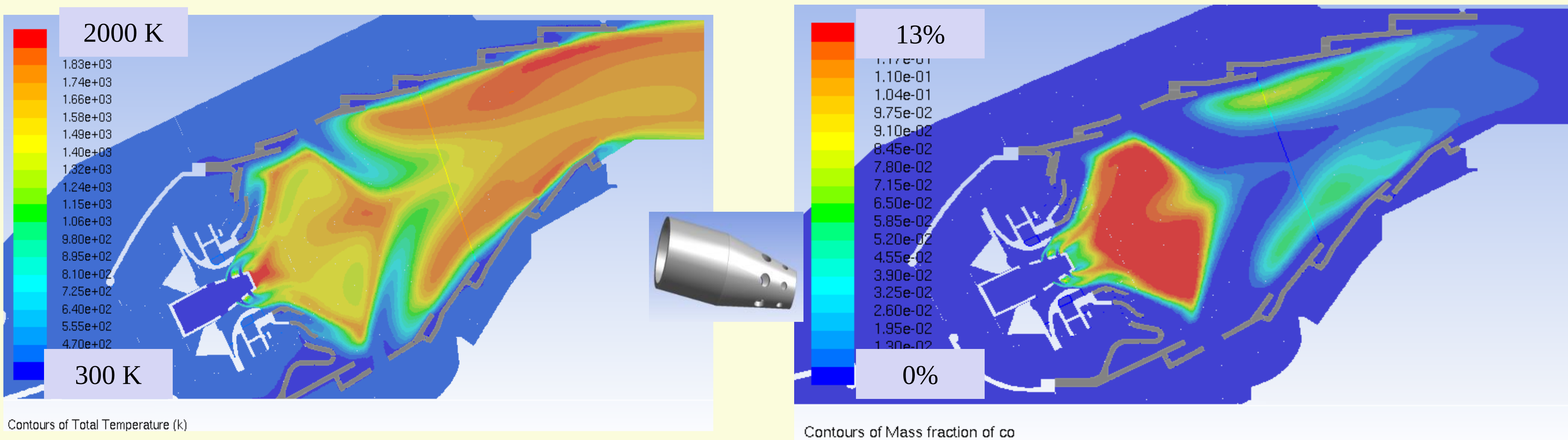


CFD simulations, Methane Combustion

Type C fuel nozzle, Laboratory Test Condition, Pa= 1bar, Ta = 400K

Temperature distribution

CO distribution

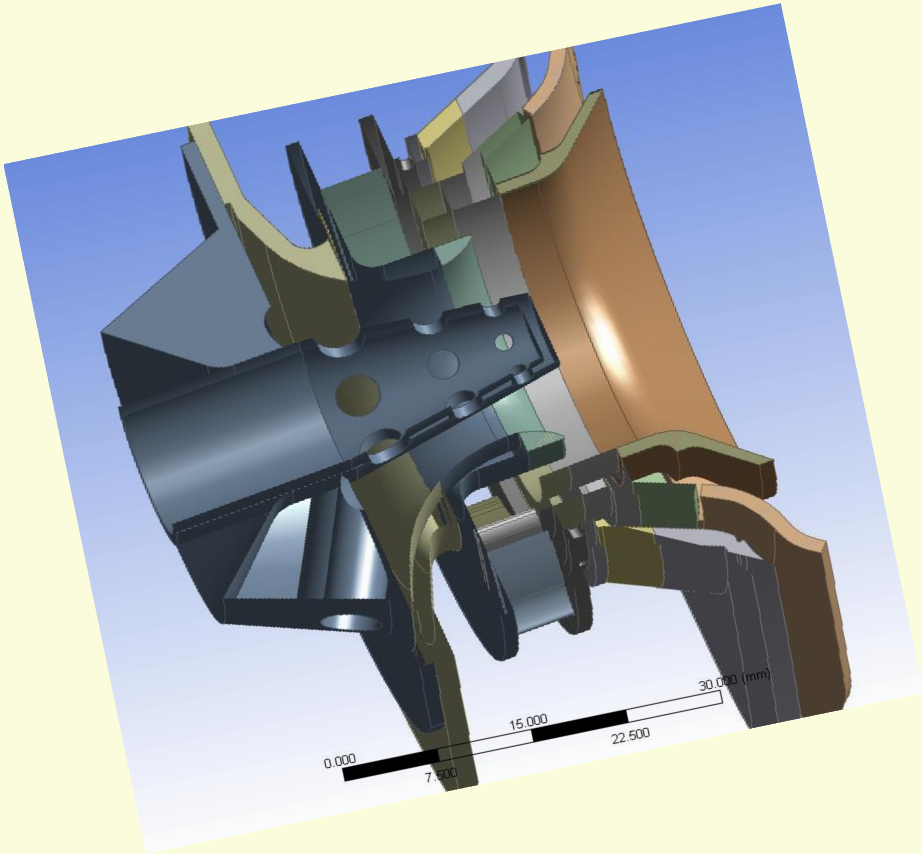


Simulation Parameters (sector 18^o) :

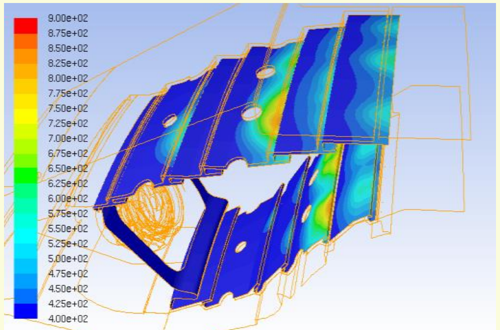
Air flow rates= 109.5 g/s
Fuel flow rate=2.155 g/s
T_a=400K, P_a=1bar,
T_{fuel}=300K

	Temperature, K			Velocity [m/s]	Mass fraction [ppm]		%
Option	MWA exit	Max Liner Wall	Max Center Section	MWA	MWA CO	MWA NOx	Unburned Fuel
P= 1 bar T_{air}=400K	1280	940	2241	80.6	761	0.3	0.8 (8000 ppm)

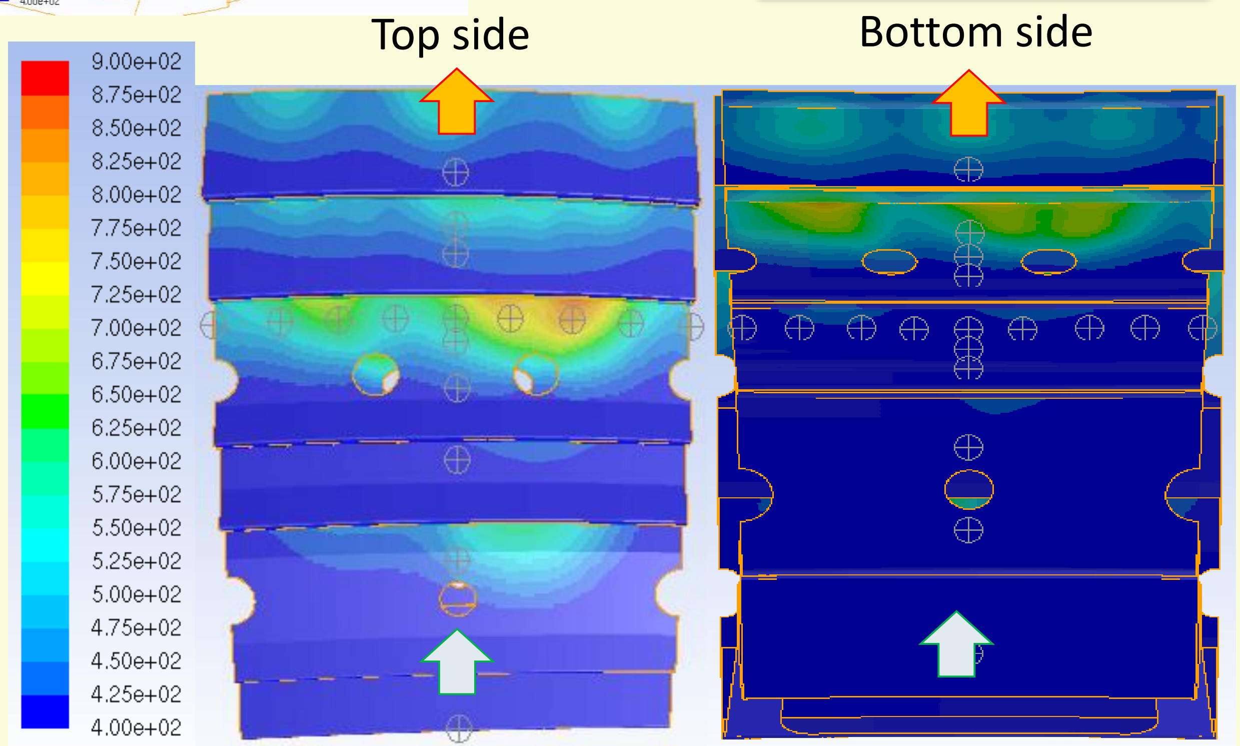
Methane Fuel Nozzle



Wall Temperature Distribution



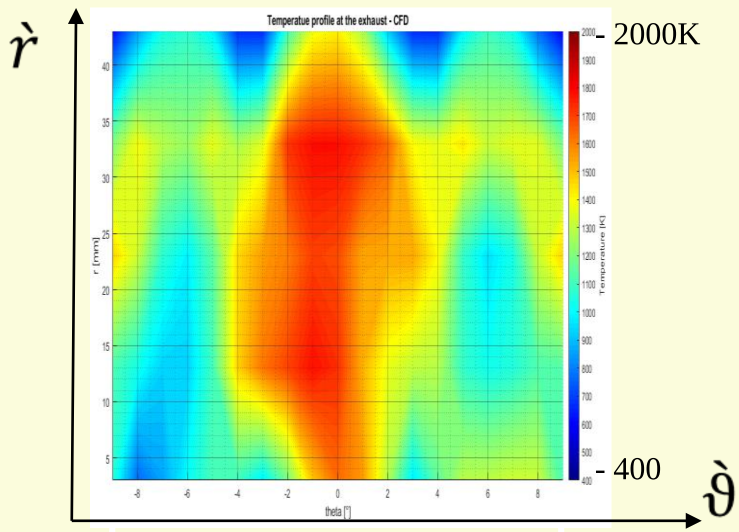
CFD Vs. measurements: Methane Fuel



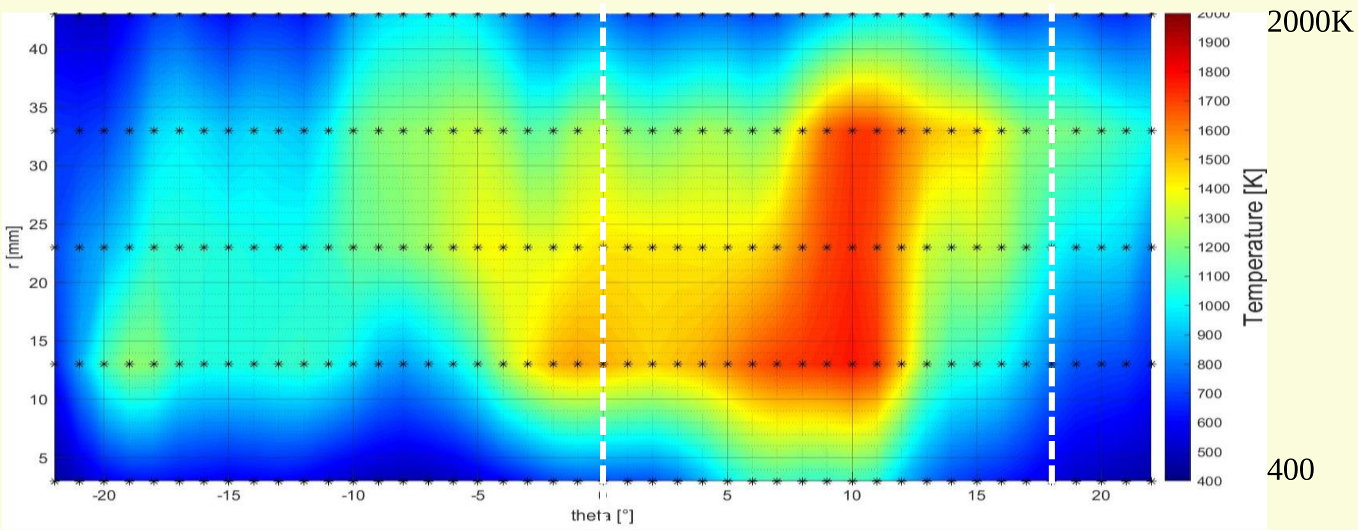
Tc	CFD [K]	CFD error from location [K]	Test [K]	error [k]	relative error [%] (CFD-test)/CFD
1	417.7	25	441.9	-24.2	-5.8
2	493.4	25	456.8	36.6	7.4
3	435.9	25	445.0	-9.1	-2.1
4	611.6	75	469.9	141.7	23.2
6	425.6	50	440.2	-14.6	-3.4
7	413.9	25	443.9	-30.0	-7.2
8	470.3	50	446.3	24.0	5.1
9	369.3	25	425.6	-56.3	-15.3
10	485.5	50	527.9	-42.4	-8.7
11	547.8	50	477.7	70.1	12.8
12	630.3	75	467.1	163.2	25.9
13	551.9	50	466.4	85.5	15.5
15	734.3	75	498.8	235.5	32.1
16	782.5	100	561.4	221.1	28.3
17	592.4	50	563.1	29.3	4.9
18	483.8	50	516.5	-32.7	-6.8
19	423.1	50	440.8	-17.7	-4.2
20	530.9	50	483.1	47.8	9.0
21	427.1	50	442.2	-15.1	-3.5
22	401.7	25	419.0	-17.3	-4.3
23	405.9	25	435.3	-29.4	-7.2
24	398.9	25	427.7	-28.8	-7.2
25	398.8	25	418.6	-19.8	-5.0
26	399.5	25	427.1	-27.6	-6.9
27	391.8	25	413.4	-21.6	-5.5
28	367.4	25	411.0	-43.6	-11.9
29	398.4	25	433.8	-35.4	-8.9
30	406.3	50	432.8	-26.5	-6.5
31	408	50	430.5	-22.5	-5.5
32	401.9	25	431.7	-29.8	-7.4
33	409.3	50	443.3	-34.0	-8.3
34	403.2	25	447.6	-44.4	-11.0
35	397.3	25	447.0	-49.7	-12.5
36	397.4	25	441.1	-43.7	-11.0

Temperature Distribution, CFD Vs. Measurements, Methane Fuel

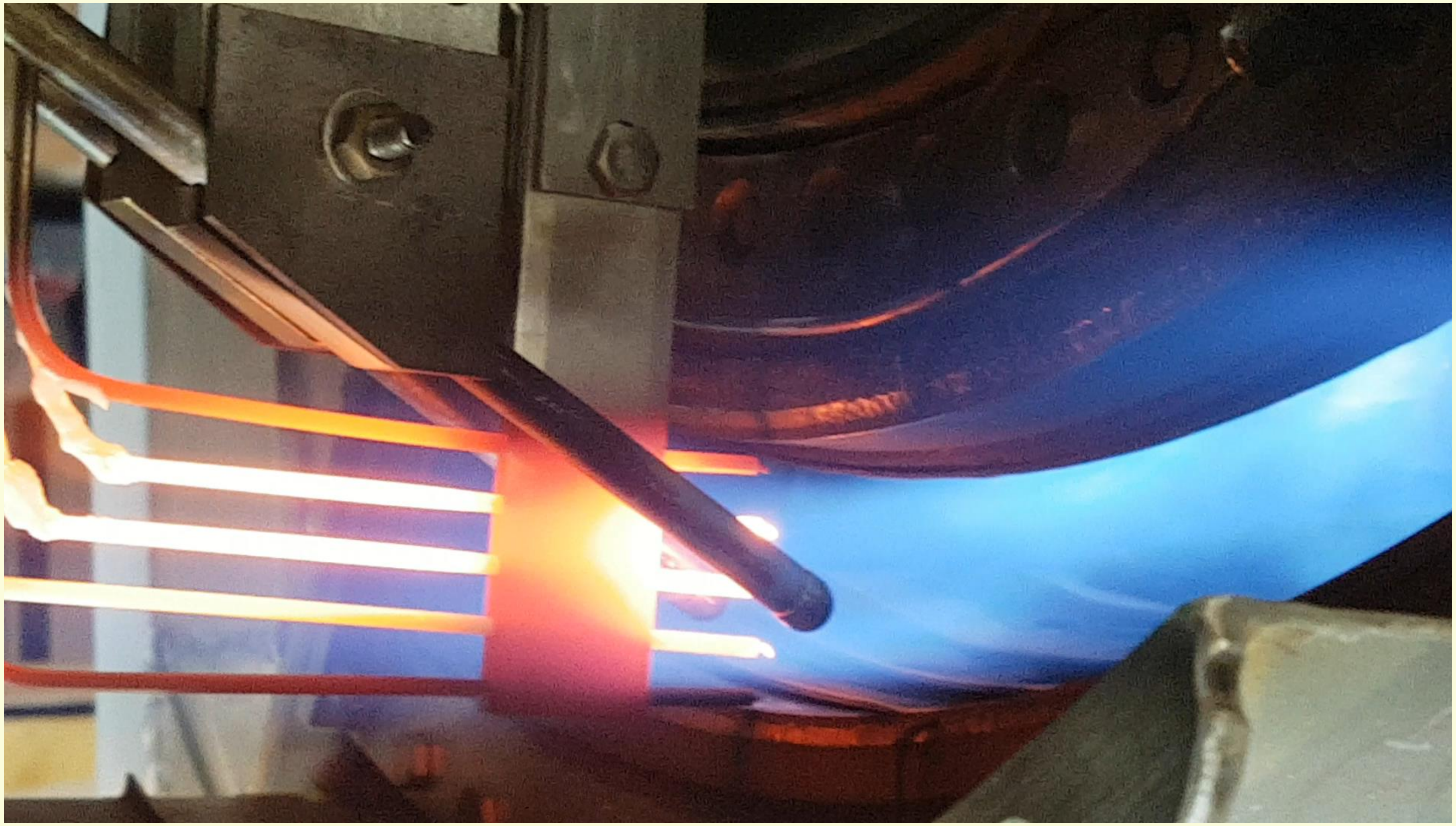
CFD



Measurements



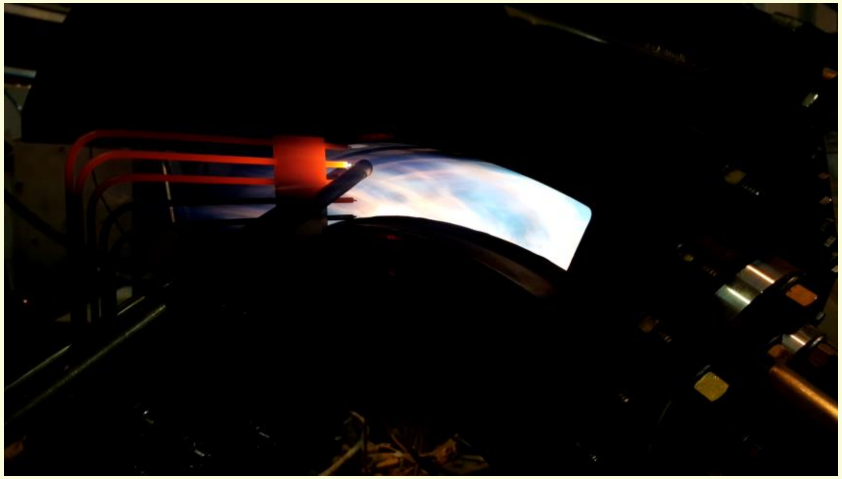
Video of Methane combustion

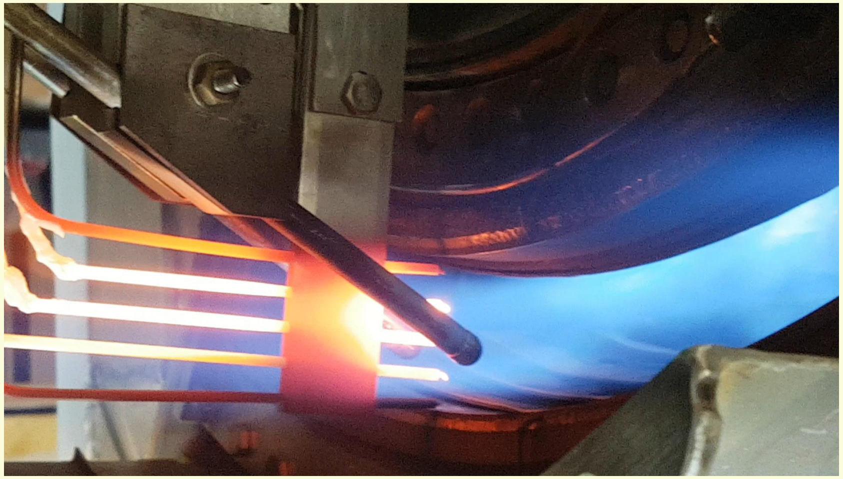


Combustion Video

Kerosene

Methane

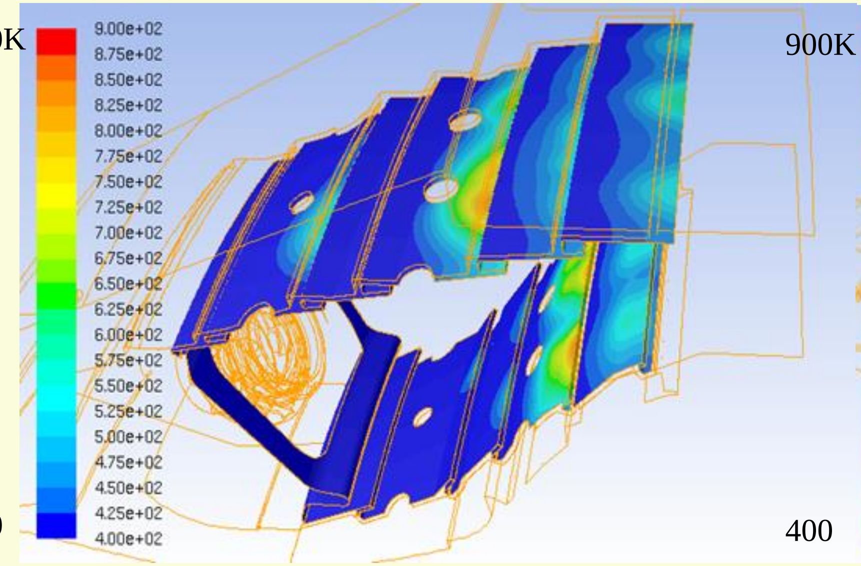




Comparison of wall temperature – Kerosene Vs. Methane

Methane

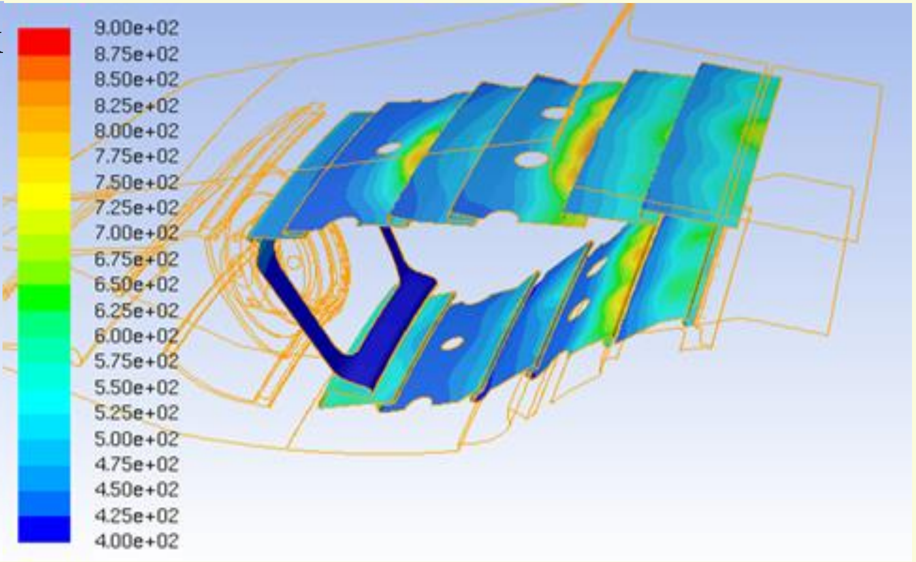
900K



400

Kerosene

900K



400

Comparison of Wall Temperature

METHANE

Tc	CFD [K]	Test [K]	error [k]	relative error [%] (CFD-test)/CFD
1	417.7	441.9	-24.2	-5.8
2	493.4	456.8	36.6	7.4
3	435.9	445.0	-9.1	-2.1
4	611.6	469.9	141.7	23.2
6	425.6	440.2	-14.6	-3.4
7	413.9	443.9	-30.0	-7.2
8	470.3	446.3	24.0	5.1
9	369.3	425.6	-56.3	-15.3
10	485.5	527.9	-42.4	-8.7
11	547.8	477.7	70.1	12.8
12	630.3	467.1	163.2	25.9
13	551.9	466.4	85.5	15.5
15	734.3	498.8	235.5	32.1
16	782.5	561.4	221.1	28.3
17	592.4	563.1	29.3	4.9
18	483.8	516.5	-32.7	-6.8
19	423.1	440.8	-17.7	-4.2
20	530.9	483.1	47.8	9.0
21	427.1	442.2	-15.1	-3.5
22	401.7	419.0	-17.3	-4.3
23	405.9	435.3	-29.4	-7.2
24	398.9	427.7	-28.8	-7.2
25	398.8	418.6	-19.8	-5.0
26	399.5	427.1	-27.6	-6.9

KEROSENE

Tc	CFD	Test results	error [k]	relative error [%] (CFD-test)/CFD
1	479	464	14.6	3
2	590	485	105.0	18
3	522	467	55.1	11
4	663	496	167.0	25
6	477	463	14.4	3
7	506	462	43.7	9
8	616	448	167.8	27
9	490	439	51.4	10
10	551	520	30.2	5
11	560	490	70.1	13
12	605	500	105.9	17
13	705	504	201.0	29
15	750	500	250.3	33
16	738	490	248.2	34
17	612	476	135.4	22
18	549	479	70.2	13
19	457	448	8.6	2
20	441	485	-44.2	-10
21	418	452	-33.8	-8
22	434	429	5.1	1
23	478	451	26.7	6
24	414	441	-27.1	-7
25	409	429	-20.2	-5
26	410	442	-31.8	-8

Wall temperature is lower during methane combustion by ~50 ^oC (CFD) , 10 ^oC (measurements)

Conclusions

- The conversion of fuel from jet fuel to NG is doable.
- The CFD simulations have indicated that the global performance of the combustor operating on NG are at least as good as while operating on kerosene fuel. This includes combustion efficiency, lower emissions and lower wall temperatures.
- The experiments have clearly demonstrated the ability of the combustor to operate with methane using the existing spark plug and the newly designed fuel nozzles. This includes fast ignition and stable combustion operation.
- Additional tests are required to find the global stable operational and emission envelope of the combustor.

The End

Aeroderivative Gas Turbines

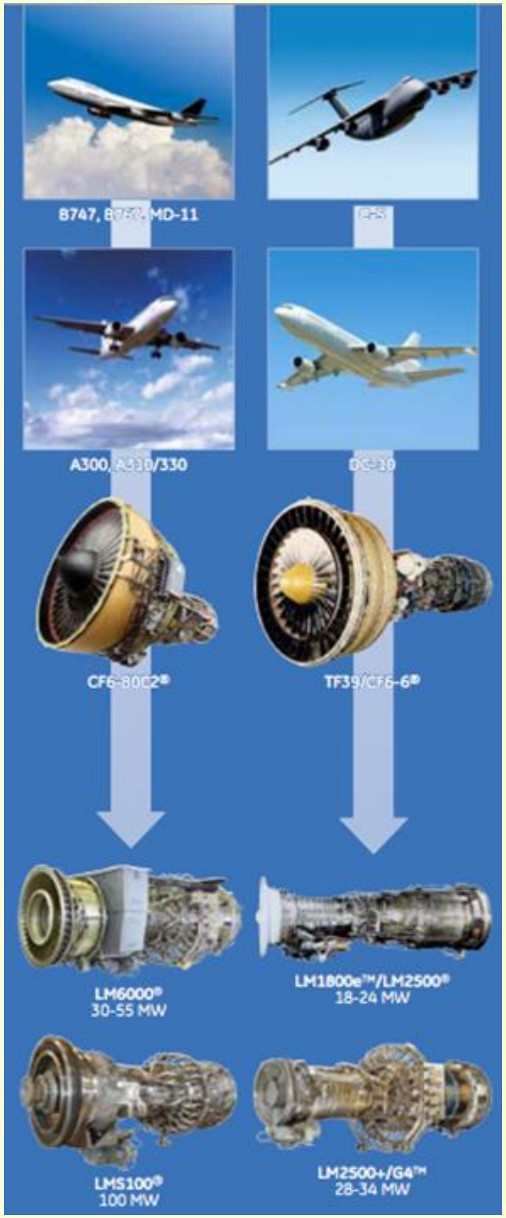
There has been a steady growth in the use of aero-derivative gas turbines, which are stationary variants of aero-engine.

In year 2000

AERO ENGINE		GAS TURBINE	
F404	→	LM1600	150 UNITS
CF6-6	→	LM2500	1130
CF6-80C2	→	LM6000	300

The target:
To convert existing jet engine to stationary electric generator:

1. Reducing fan size and coupling to an electric generator
2. **Converting their fuel from jet fuel to Natural Gas (NG)**



(*) GE Aeroderivative, Gas Turbines – Design and Operating Features
G.H. Badeer, GE IAD, , GE Power SystemsEvendale, OH, GER-3695E

1.) CFD Model (Simulation Condition

Chemical Reaction Model: Non-premixed Combustion (Kerosene & Methane)

For kerosene and methane:

- ***Equilibrium chemistry approximation (minimum Gibs Energy)***; intermediate species are calculated, while there is no need for detailed kinetic data.

Reduced chemistry: calculated 25 chemical species:
JetA: C12H23 (Jet-A), NCO, O3, C2H4, HNO3, CO2H2, HNO2, HOCO, CH2O, H2CO2, CHO, HCO, C2H6, HONO, H2O2, HO2, OH, CH4, C(s), H2, CO2, H2O, CO, O2, N2

Methane (23 species): CH4, CH3OH, C2H4, O3, HNO3, CO2H2, HNO2, HOCO, CHO, CH2O, H2CO2, HONO, H2O2, C2H6, HO2, OH, CO2, C(s), CO, H2, H2O, O2, N2

Detailed chemistry: For methane (only), ***Steady Flamelet combustion model*** using the GRI-Mech 3.0, optimized for NG with 325 reactions and 53 species.

The Flamelet and Equilibrium models gave close results.