M.Sc. Thesis

School of Engineering
Department of Power and Propulsion

Emissions Estimation from Industrial Gas Turbine Combustors

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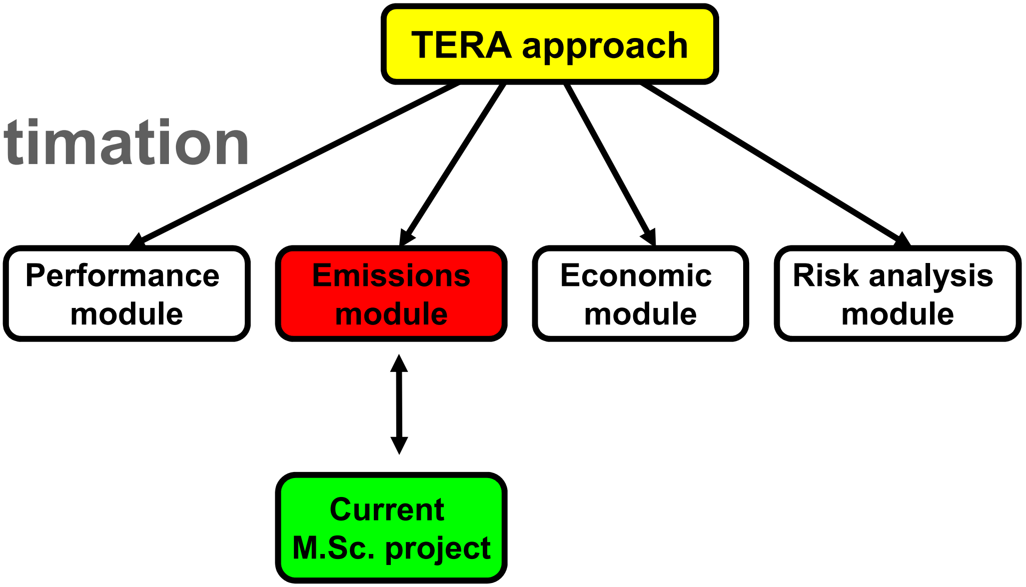
Contents

1. T.E.R.A. approach

T. E. R. A.

Techno - **E**conomical **R**isk **A**nalysis

- Investigation of advanced low carbon power cycles
- Performance analysis
- Environmental impact estimation
- Economic evaluation
- Risk analysis



TERA approach

Performance module

Emissions module

Economic module

Risk analysis module

Current M.Sc. project

2. Project objectives

Development of an algorithm aimed to estimate the pollutant emissions trends from industrial gas turbine combustors

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Application to the T.E.R.A. selected cycles (particular gas turbine)

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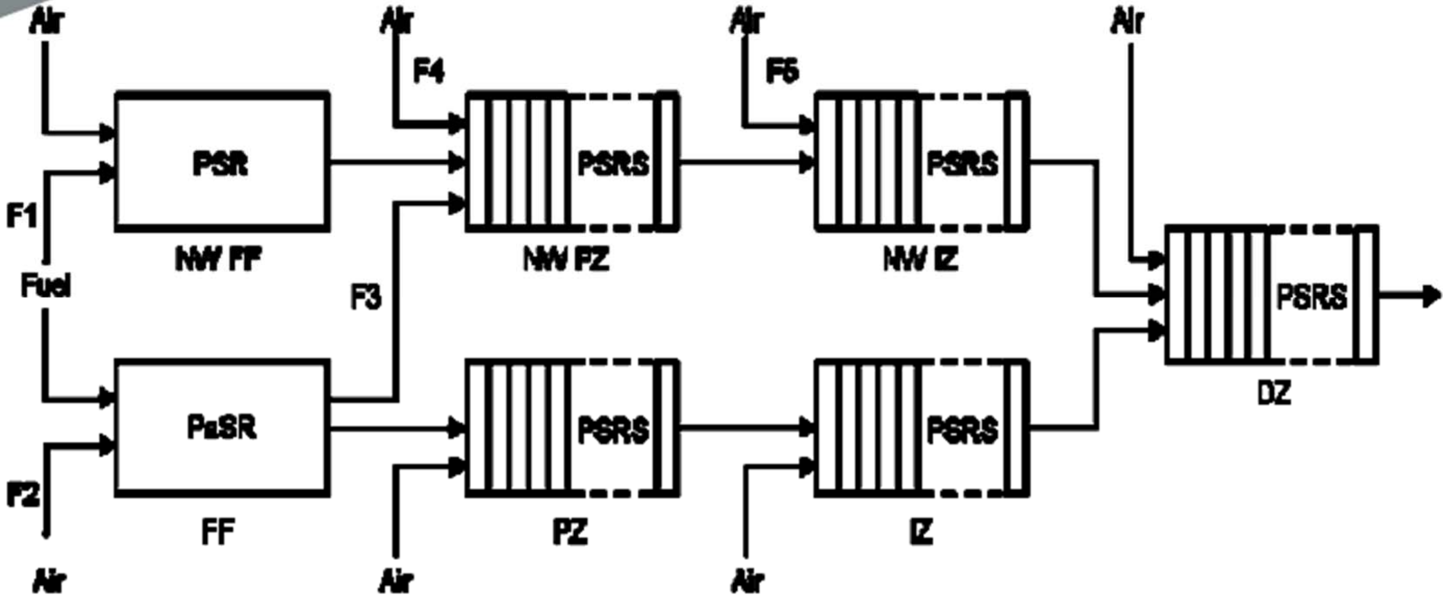
Investigation of the estimative potential of the model (parametric analysis)

Reactors arrangement



Reactors used:

- ✓ Perfectly stirred reactors (PSR)
- ✓ Series of perfectly stirred reactors (PSRS)
- ✓ Partially stirred reactors (PaSR)

F1	0.20
F2	0.65
F3	0.25
F4	0.20
F5	0.20

3. Algorithm development

Empirical correlations

NOx

Thermal NO:

$$\frac{dY_{NO}}{dt}=\frac{2M_{NO}}{\rho}\left(1-\alpha^{2}\right)\left[\frac{R_1}{1+aK_1}+\frac{R_6}{1+K_2}\right]$$

Prompt NO:

$$\frac{dY_{NO}}{dt}=\left(\frac{M_{NO}}{\rho}\right)f_{pr}k_{pr}^{'}\left[O_2\right]_e^a\left[N_2\right]_e\times\left[CH_4\right]\exp\left(\frac{-36499.507}{T}\right)$$

CO

$$\frac{dY_{CO}}{dt}=-k_{7f}\left(\frac{M_{CO}}{\rho}\right)\left[\mathrm{OH}\right]_{\varepsilon}\times\left[1+\frac{\left[CO\right]_e}{\left[CO_2\right]_e}\right]\left(\left[CO\right]-\left[CO\right]_e\right)$$

UHC

$$\frac{dY_{CH_4}}{dt}=-10^{10.2}\left(\frac{M_{CH_4}}{\rho}\right)e^{\left(\frac{-48400}{RT}\right)}\left[Y_{CH_4}\right]^{0.7}\left[Y_{O_2}\right]^{0.8}$$

Soot/ smoke

Formation:

$$S_f=1.4887\times10^{-4}\left(\frac{\phi FAR_s}{\dot{m}_a T}\right)P^{2}\times\left(18-H_{cont}\right)^{1.5}\left(\frac{\dot{m}_{g_t}}{\rho_{soot}}\right)$$

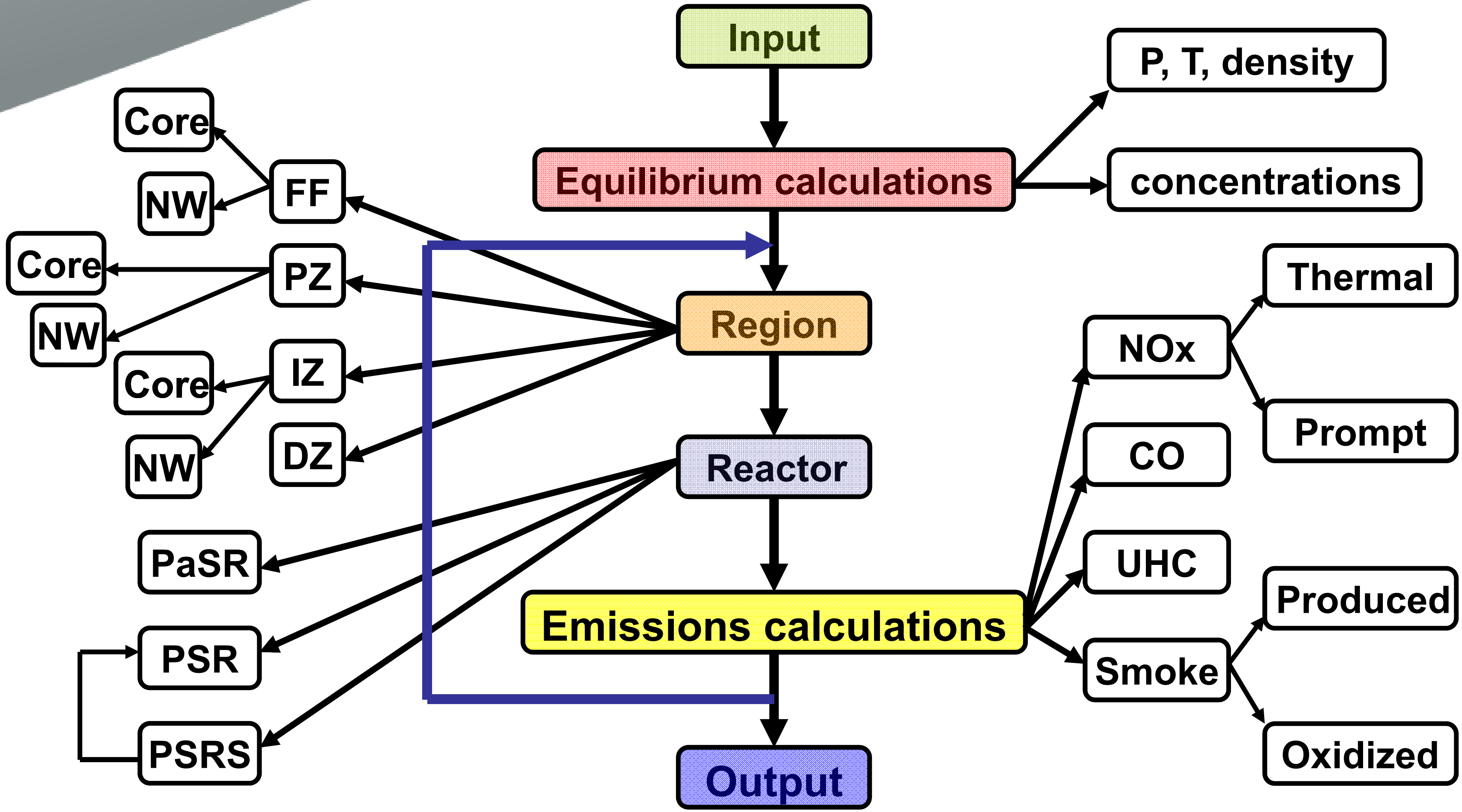
Oxidation:

$$W_{\mathrm{O}_2}=\pi^{1/3}\cdot6^{2/3}\cdot\phi^{2/3}\cdot N^{1/3}\cdot W_{\mathrm{O}_2}'/\rho_{soot}$$

$$W_{\mathrm{OH}}=10.14\cdot\theta\cdot\phi^{2/3}\cdot N^{1/3}\cdot \mathrm{X}_{\mathrm{OH}}\cdot T^{1/2}$$

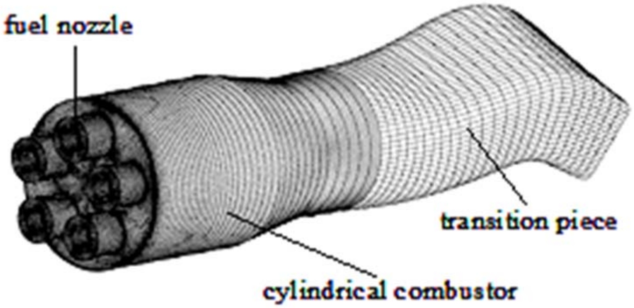
3. Algorithm development

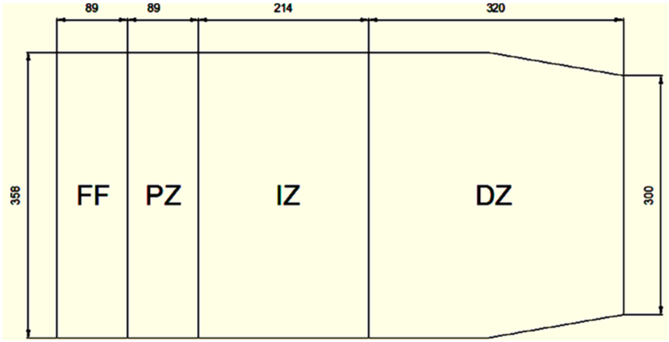
Model flow chart

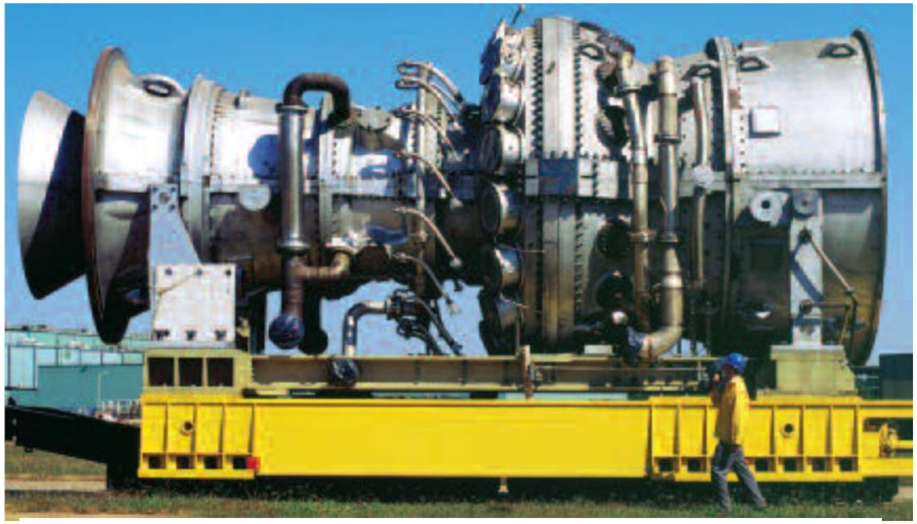


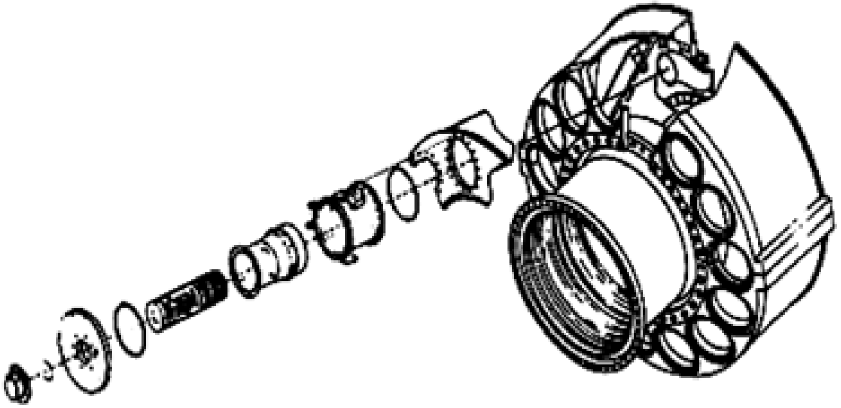
3. Algorithm development

Simulated engine







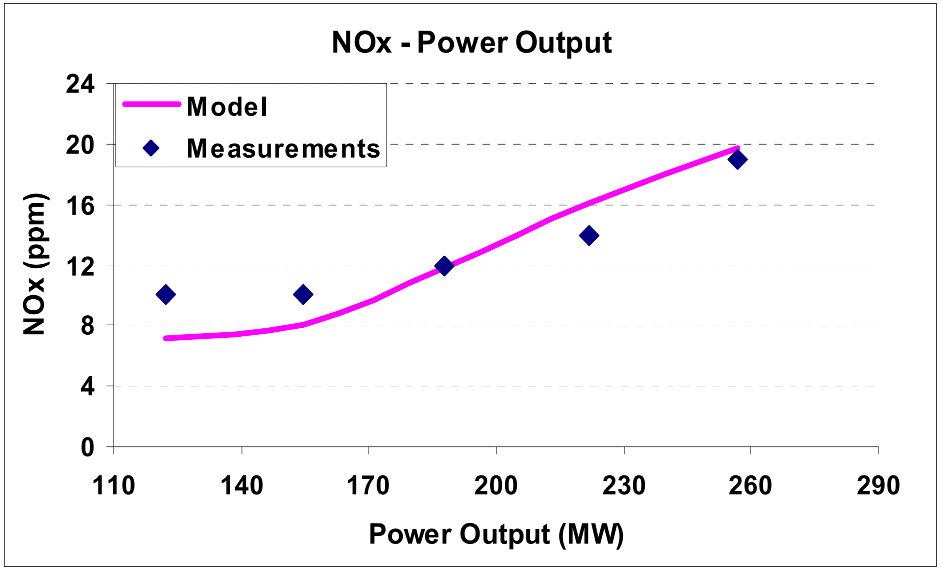


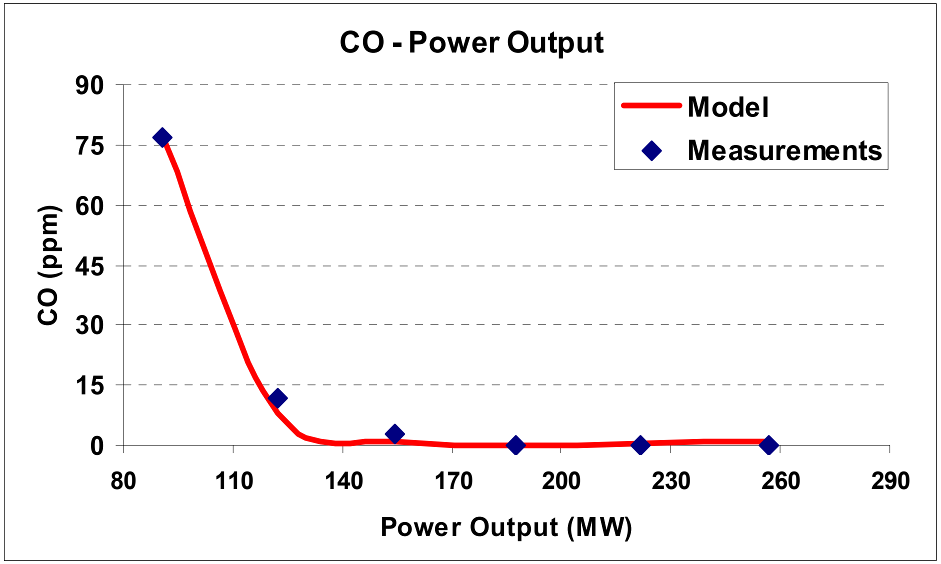
- 18 combustors
- DLN-2+ technology
- 2 operational modes

4. Model results for natural gas

Estimated VS Measured

- Only the second (premixed) stage was simulated
- There is an almost exponential relationship between emissions and power output
- CO emissions were slightly underestimated throughout the covered power range
- Both emissions trends were sufficiently reproduced





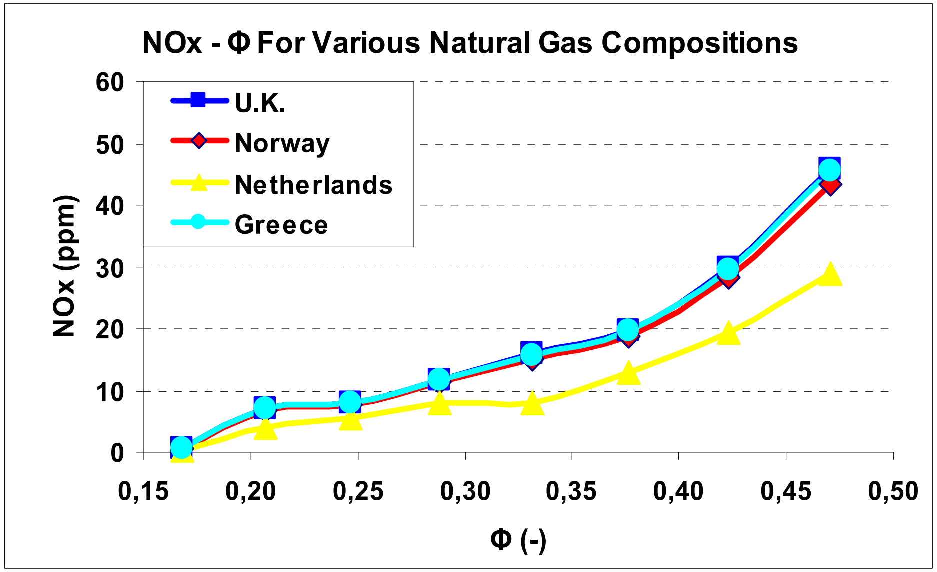
4. Model results for natural gas

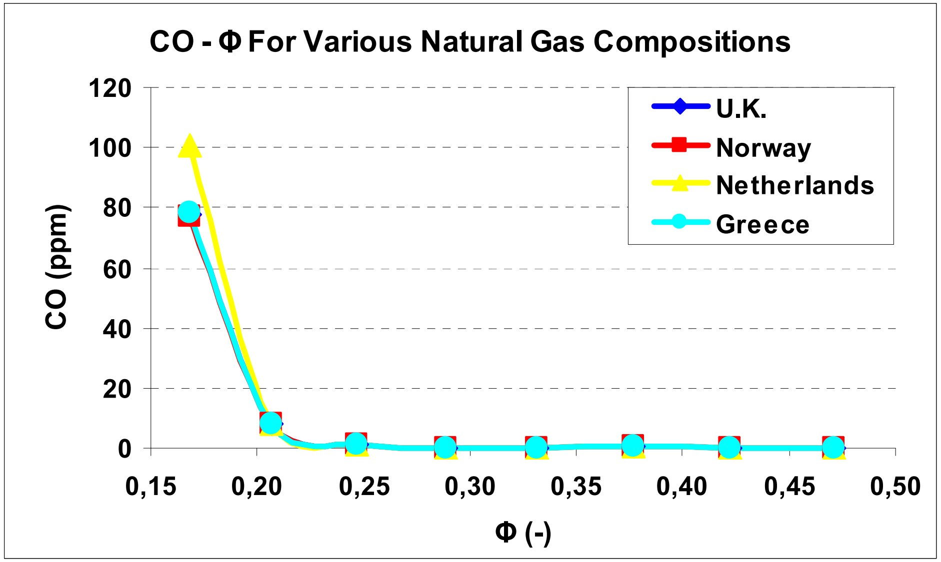
Fuel composition impact

Lowest value

	NG used in U.K.	NG used in Greece	NG used in Norway	NG used In Netherlands
CH_4	0.8620	0.9322	0.7812	0.6998
C_2H_6	0.1080	0.0305	0.0993	0.0463
C_3H_8	-	0.0128	0.0485	0.0090
C_4H_{10}	-	0.0081	0.0160	0.0085
N_2	0.0250	0.0137	0.0308	0.2154
CO_2	0.0050	0.0027	0.0242	0.0210
Total	**1.0000**	**1.0000**	**1.0000**	**1.0000**

NG used in Netherlands is expected to produce lower NOx but higher CO emissions than the rest NGs

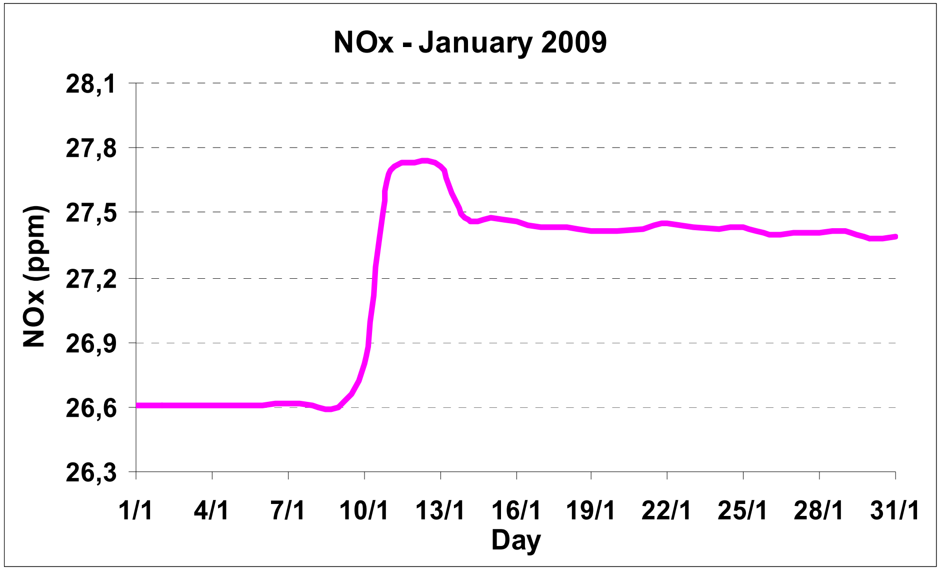


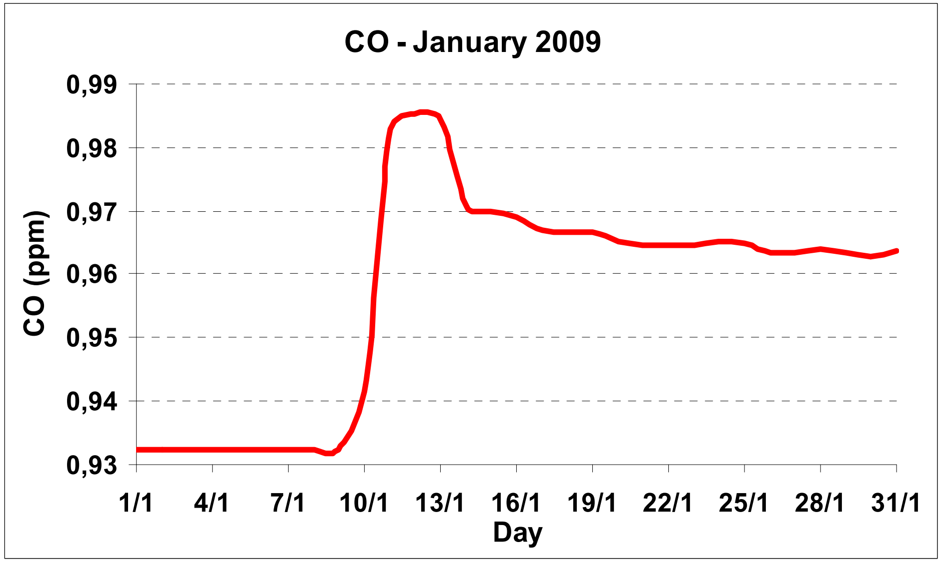


4. Model results for natural gas

Daily emissions results

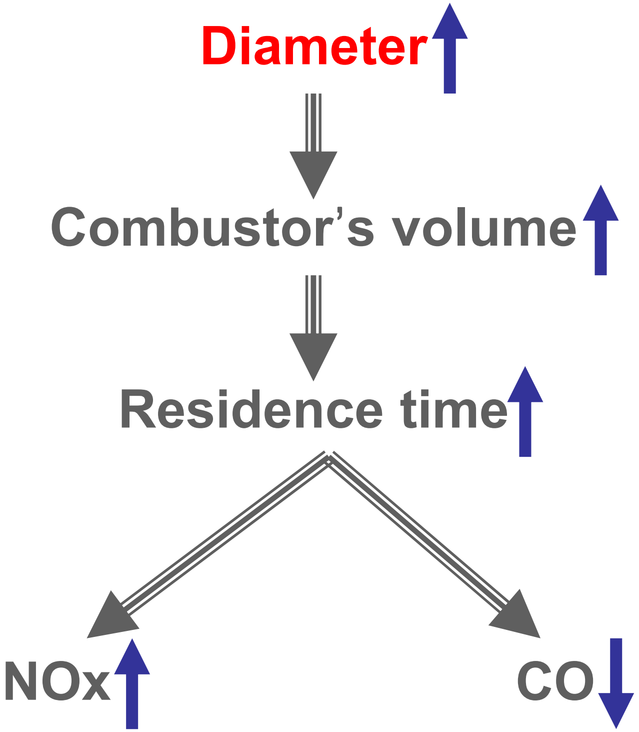
- The composition of natural gas is not steady even within a day
- Both NOx and CO emissions vary daily due to the fuel composition change
- 1.34% rise in fuel hydrocarbon content results in 4.24% and 5.69% increase in NOx and CO emissions respectively





4. Model results for natural gas

Combustor’s size impact



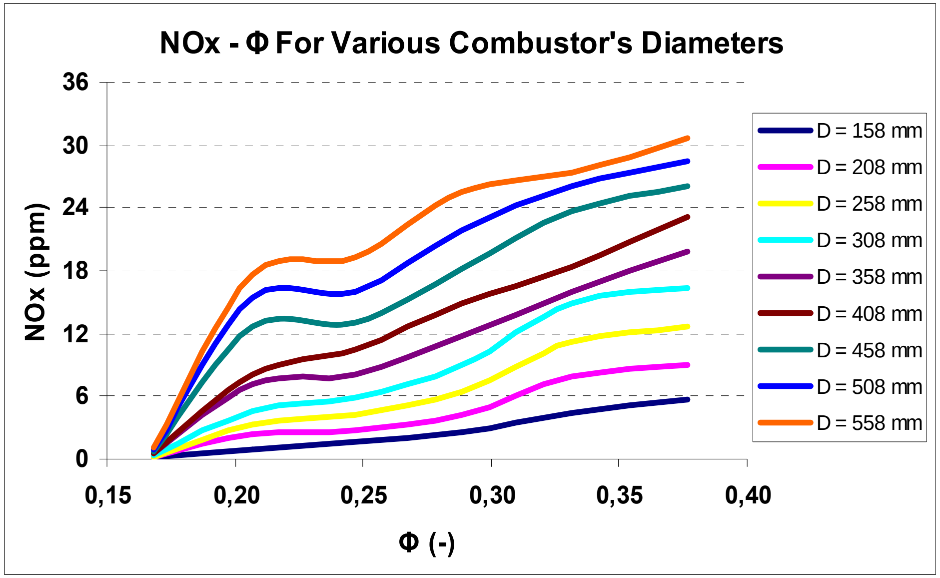
Diameter ↑

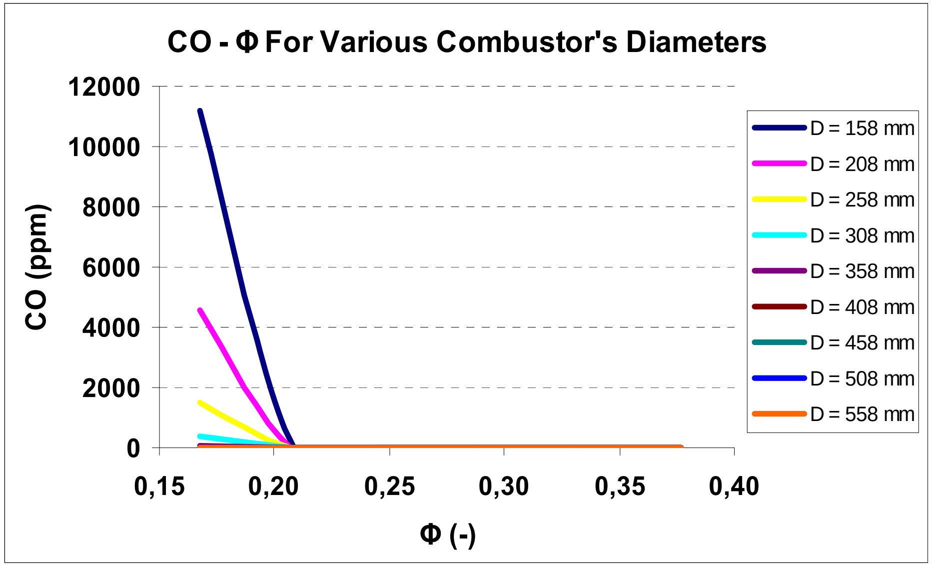
Combustor’s volume ↑

Residence time ↑

NOx ↑

CO ↓





5. Model results for syngas

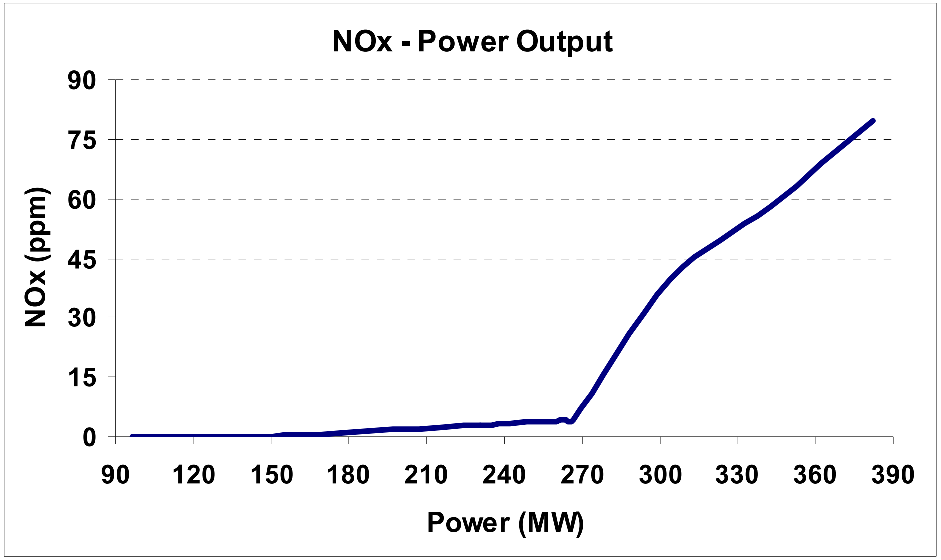
Emissions – Power

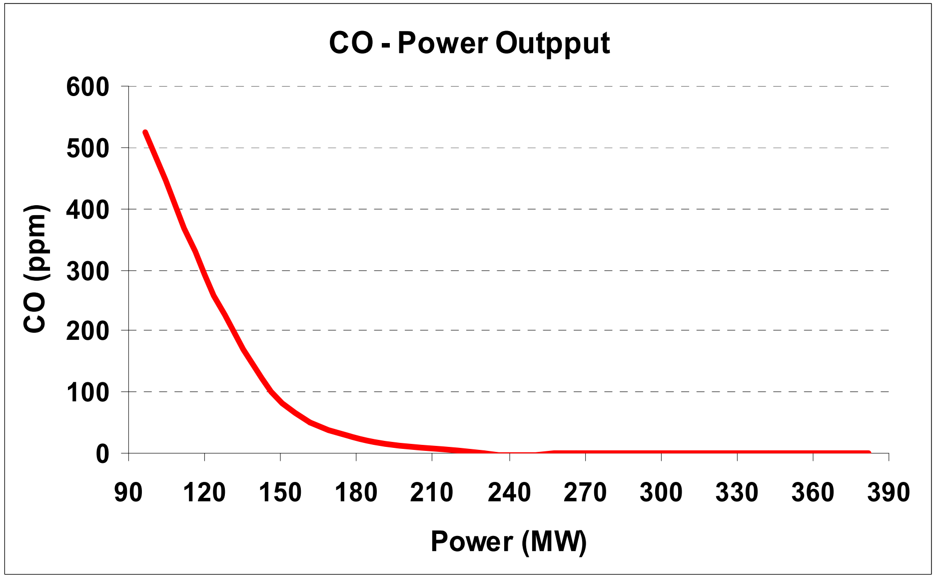
- Again, only the second stage of the engine was simulated

- After design point (266MW) there is a dramatic increase in NOx emissions

- CO emissions are expected to be high during part load operation (load < 180MW)

- The low emissions area is estimated between 240MW and design point

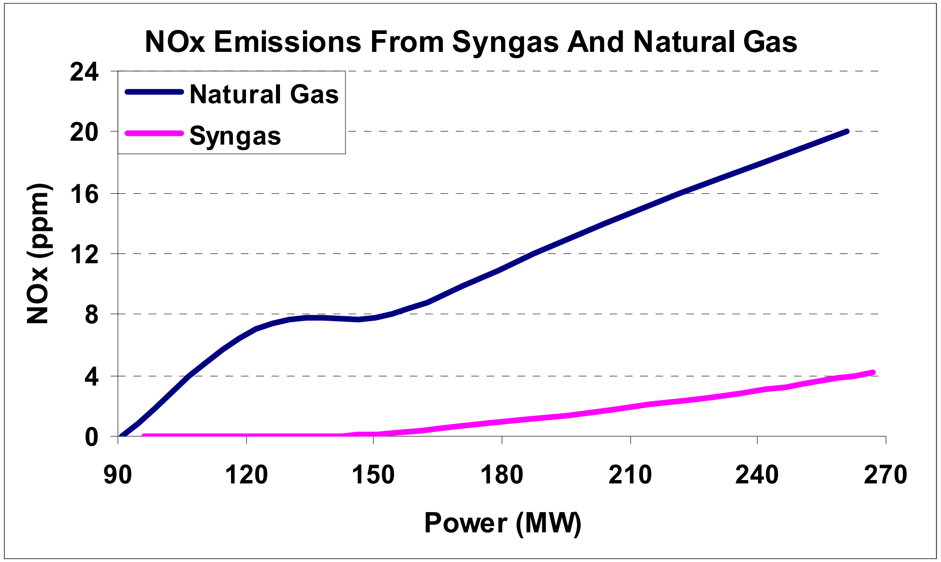


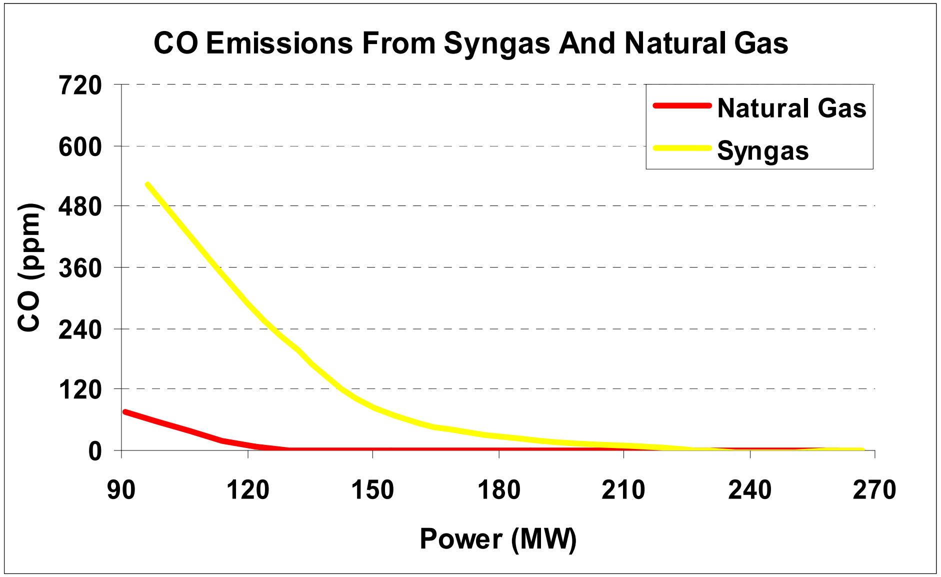


5. Model results for syngas

NG VS Syngas

- ✓ Close to DP, if the engine is fed with syngas, it is expected to produce lower NOx and similar CO emissions with NG
- ✓ During part load operation NG is favored since it will produce lower CO emissions than syngas (for the same engine)
- ✓ Syngas mass flow = almost 5 x NG mass flow (for the same power output), due to the lower LHV of syngas





5. Model results for syngas

Parametric analysis

Highest values

		Natural Gas		Syngas	
	Parameter Range	NO_x	CO	NO_x	CO
Fuel Inlet Temperature	273 – 493 K	9.34%	-12.59%	61.45%	-12.5%
Ambient Temperature	263 – 318 K	5.97%	-44.07%	83.45%	-8.18%
Ambient Relative Humidity	0 – 100%	-9.34%	12.59%	-5.40%	3.42%

- **The change of the parameters is expected to produce similar changes in emissions trends of both fuels (either increasing or decreasing)**
- **The variation of ambient temperature is estimated to cause the highest change in emissions production of both fuels**
- **The ambient relative humidity has the lowest impact in emissions production of both fuels**

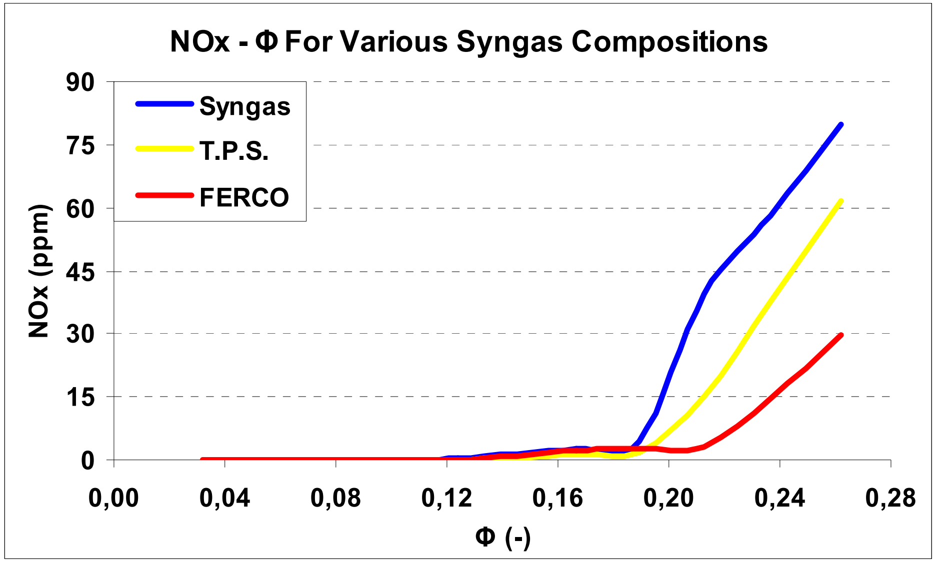
5. Model results for syngas

Fuel composition impact

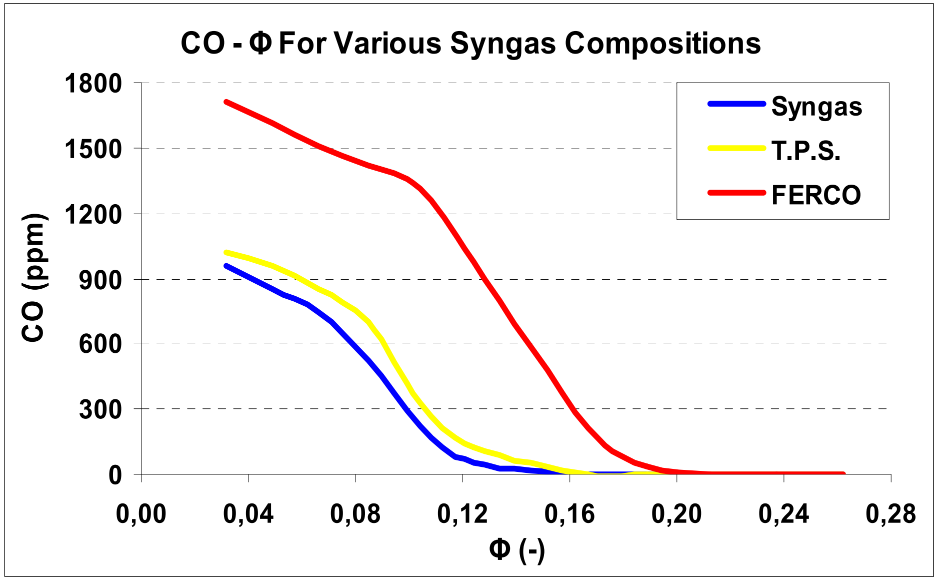
Highest values

	SYNGAS	TPS	FERCO
CH_4	0.0260	0.0186	0.1118
C_2H_6	-	-	0.0094
C_2H_4	-	0.0108	0.0639
N_2	0.8240	0.4977	-
H_2O	0.0140	0.0070	-
H_2	0.0740	0.0117	0.0198
CO	0.0030	0.2163	0.5553
CO_2	0.0590	0.2379	0.2398
Total	**1.0000**	**1.0000**	**1.0000**

FERCO syngas is expected to produce the lowest NOx but the highest CO emissions



NOx - Φ For Various Syngas Compositions



CO - Φ For Various Syngas Compositions

6. Conclusions

- Emissions trends were sufficiently reproduced
- Estimated emissions were in agreement with the measured data for the natural gas case
- The results of parametric analysis were (more or less) in accordance with the established theory
- Air/fuel temperature, ambient conditions, fuel composition and the size of combustor strongly affect the emissions
- From an emissions point of view, syngas could substitute natural gas in the particular engine

7. Recommendations

- Simulation of a different engine – further validation of the model
- Use of more accurate geometry data for the combustor
- By using Variflow results an improved version of the model should be able to estimate the emissions trends for the entire power range of the engine
- Adaptation of a different reactors arrangement
- Use of different semi-empirical equations