Investigation of Biogas Moderate or Intense Low Oxygen Dilution (MILD) Combustion on Open Furnace Bluff-body Burner

USQ Combustion Meeting

29 Aug 2012

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Outline

1. **Introduction**
2. Research Focus
3. Methodology
4. Current Status
5. Conclusions

Introduction - Background

❑ Energy demand increase - growth of the world's population and substantial economic development (e.g. China and India).

❑ Challenges - efficient energy and limit greenhouse-gas (GHG).

❑ Combustion of fossil fuel - fulfil about 80% (IEA, 2009).

Low Pollutants Emissions (Kyoto Protocol, 1997)

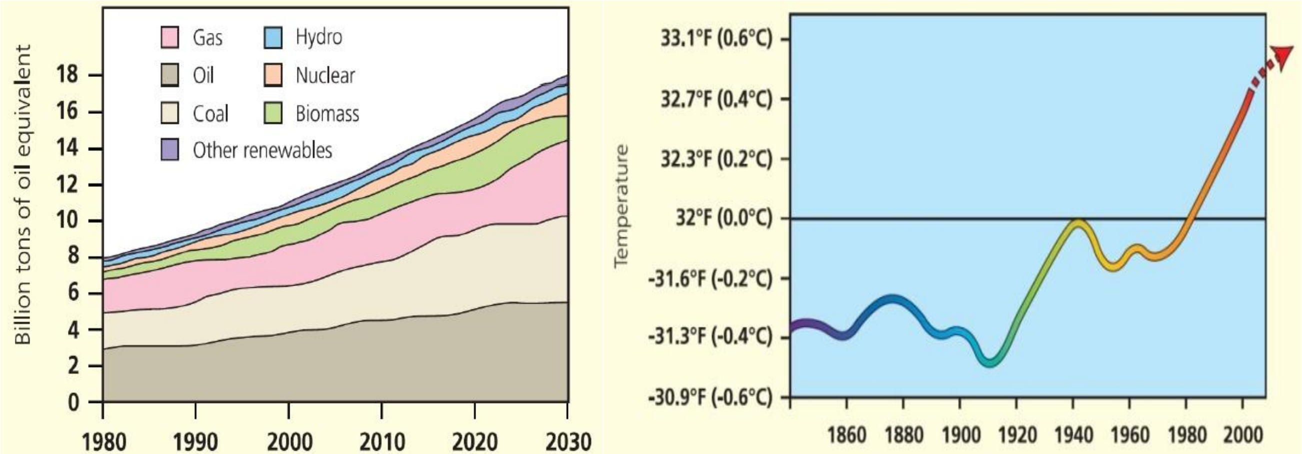


Figure 1 History and prediction of (a) world energy (b) unwanted increase of earth temperature (IEA, 2009 and Maczulak, 2010).

➢ New combustion technology - Moderate or Intense Low Oxygen Dilution (MILD) combustion produces high combustion efficiencies with very low emissions. (Tsuji et al., 2003).

➢ One of the most promising combustion technology (Tsuji et al., 2003 and Cavaliere and de Joannon, 2004, Dally et al., 2004).

Introduction - History

In 1989, Wünning (1991) observed a surprising phenomenon during experiments with a self-recuperative burner.

Furnace: 1000°C and 650°C air preheat temperature, - No flame could be seen, Fuel was completely burnt, CO was below 1ppm in the exhaust

Called that condition
“flameless oxidation” or FLOX

This new combustion technology was also named:

Moderate or Intense Low-oxygen Dilution (MILD) combustion (Dally et al., 2002, Cavaliere and de Joannon, 2004).

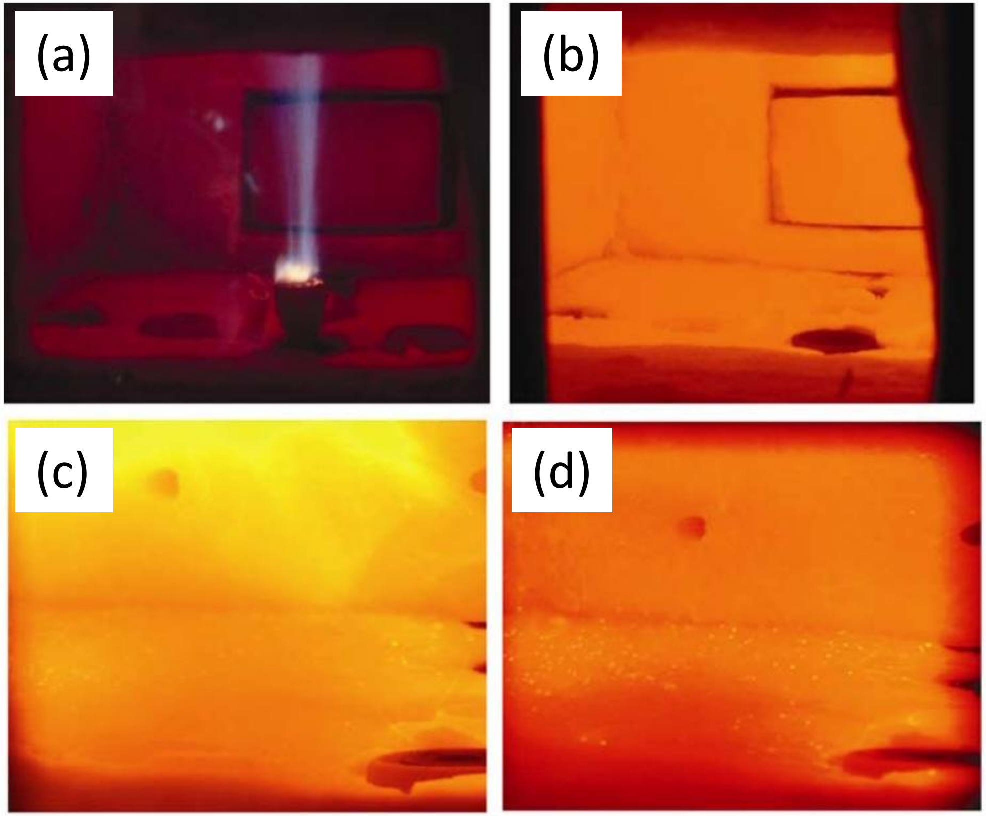
High Temperature Air Combustion (HiTAC) (Katsuki and Hasegawa, 1998 and Tsuji et al., 2003).

Introduction - MILD Summary

MILD combustion summary (Li et al., 2011b) :

- High temperature pre-heat of combustion air and high-speed injections of air and fuel. (Key requirement)
- Strong entrainments of high-temperature exhaust gases, dilute fuel and air jets. (Key tech. to maintain MILD)
- Oxygen dilution: 3%–13%.
- Reactant temperature is greater than fuel self-ignition. (N_2 and CO_2-rich exhaust gas)
- Regenerator - thermal efficiency can increase by 30%, reduce NO_x by 50% (Tsuji et al., 2003).

Comparison MILD and Conventional

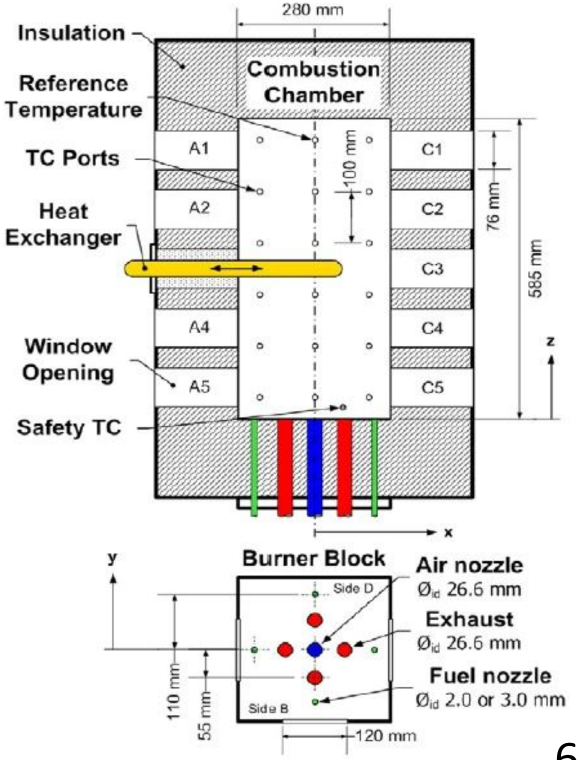


(a) Conventional flame (natural gas)
(b) MILD combustion (natural gas)

(c) Conventional combustion of sawdust
(d) MILD combustion of sawdust

Figure 2 MILD and Conventional combustions on natural gas and sawdust (Dally et al., 2010).

Figure 3 MILD furnace and parallel jet burner (Szegö et al., 2008).



MILD Combustion

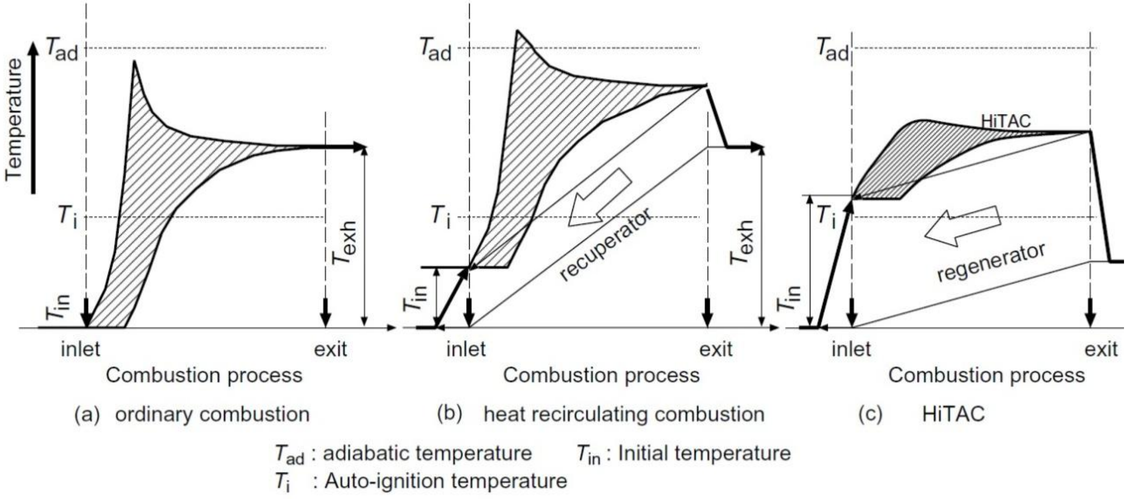
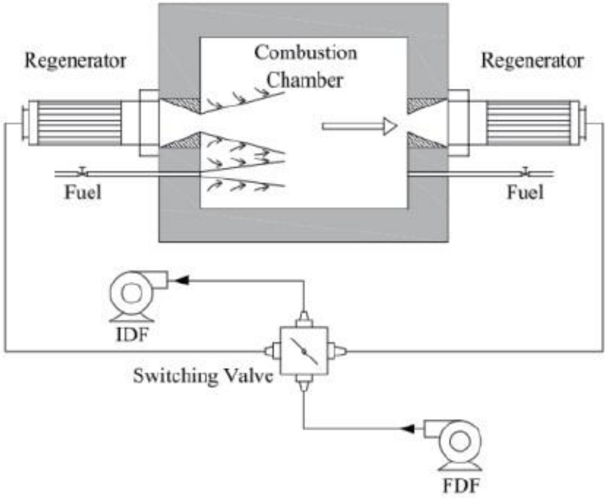
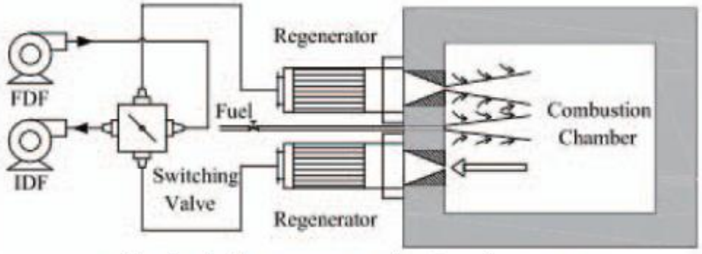


Figure (New) The comparison between Recuperator and Regenerator (Tsuji et al., 2003)



(a) Two-flame regenerative burning system



(b) Single-flame regenerative burning system

Figure (New) Schematic of two-flame and one-flame type regenerative burning systems. (Zhenjun et al., 2010)

21% 8% 2%

Figure (New) Combustion air temperature of 1100 °C and O_2 concentration (Gupta et al., 1999)

Exhaust Gas Recirculation

- EGR works by recirculating a portion of the exhaust gas back to the combustion chamber.

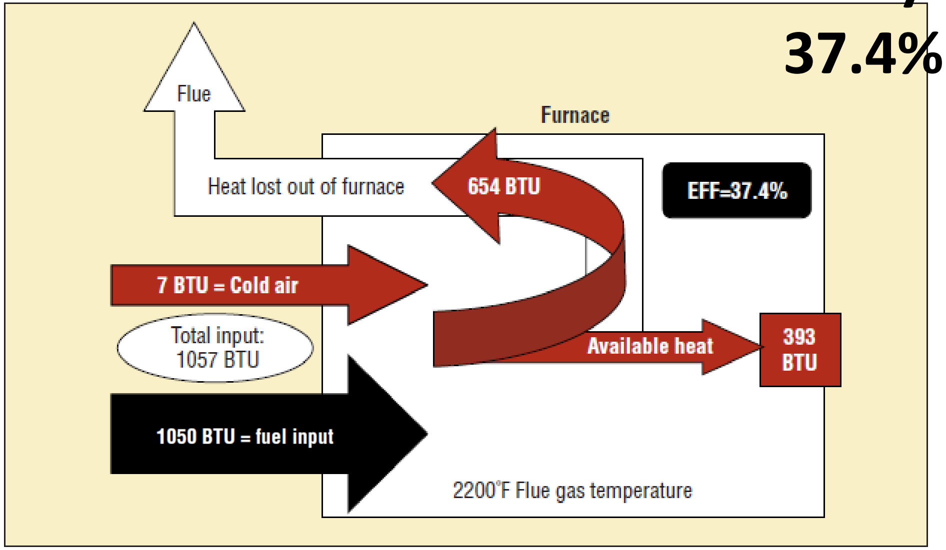
- The main purpose is to dilute oxygen and heat the mixture.

Dilution ratio, $$K_V = \frac{M_E}{(M_F + M_A)} = \frac{(M_T - M_F - M_A)}{(M_F + M_A)}$$

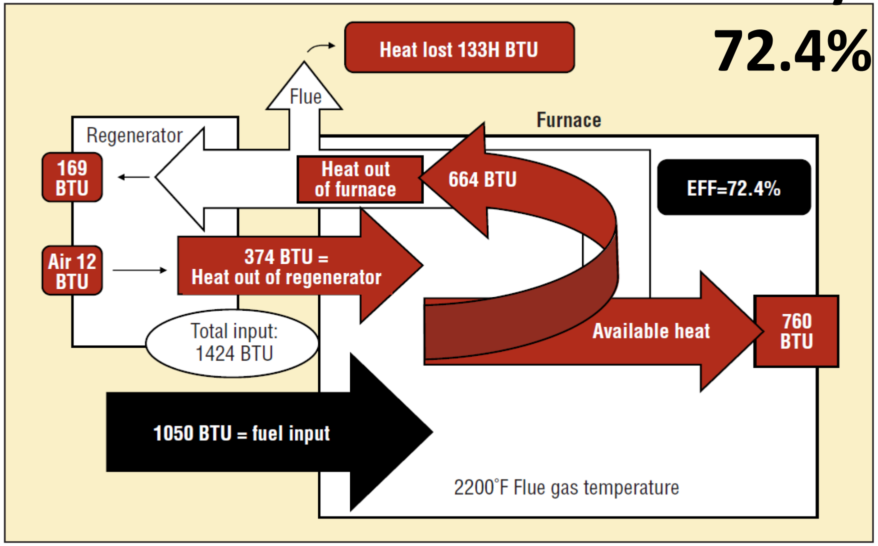
(Wünning and Wünning, 1997, Cavigiolo et al., , 2003 and Galletti et al., 2009)

M_T = Total mass flow rate
M_E = EGR mass flow rate
M_F = Fuel mass flow rate
M_A = Air mass flow rate

Conventional System **Efficiency: 37.4%**



EGR System **Efficiency: 72.4%**



Kraus and Barraclough, 2012

Flame and Temperature Comparison

The maximum temperature increase due to the combustion ($\Delta T = T_{max} - T_{in}$) is lower than the mixture self-ignition temperature (T_{si}) (Cavaliere and de Joannon, 2004).

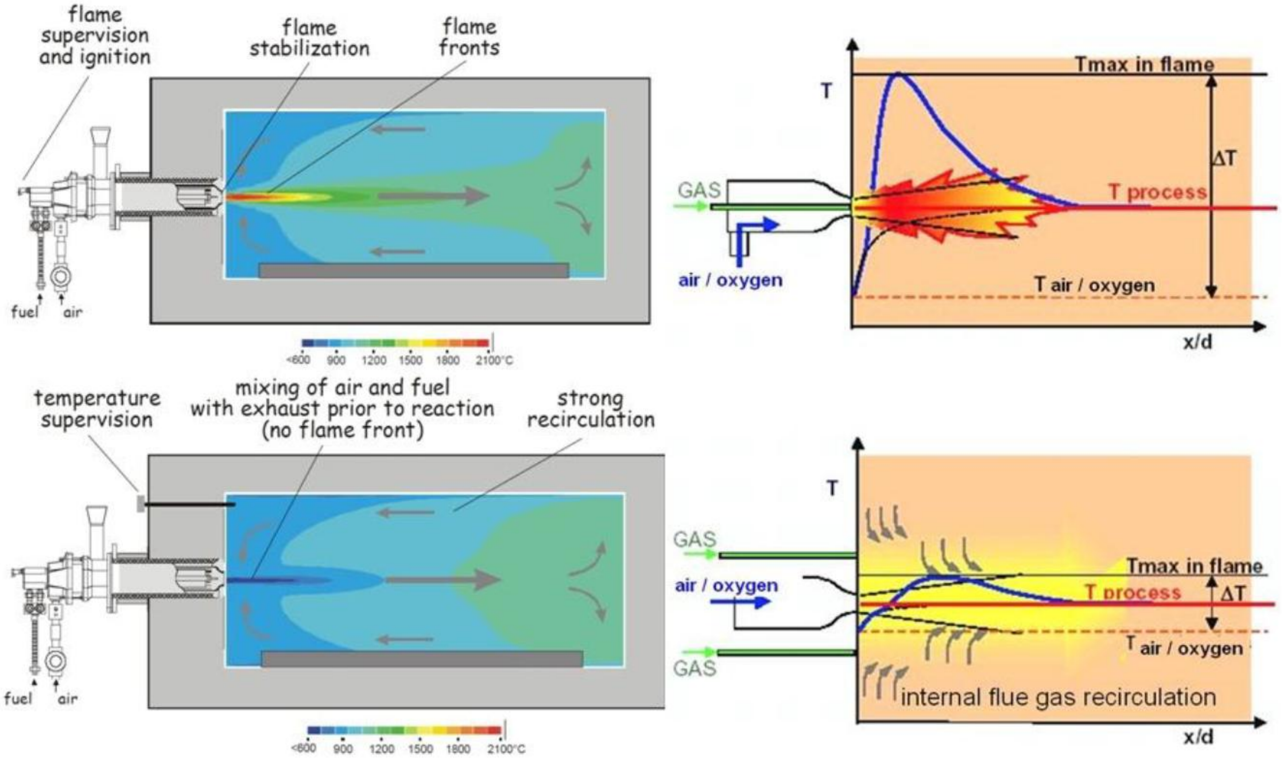


Figure 1: Principles of standard combustion (top) and flameless oxidation (bottom). On the right hand side, the temperature evolution is shown [2].

(Wunning, 2003).

MILD Region and Reacting Zone

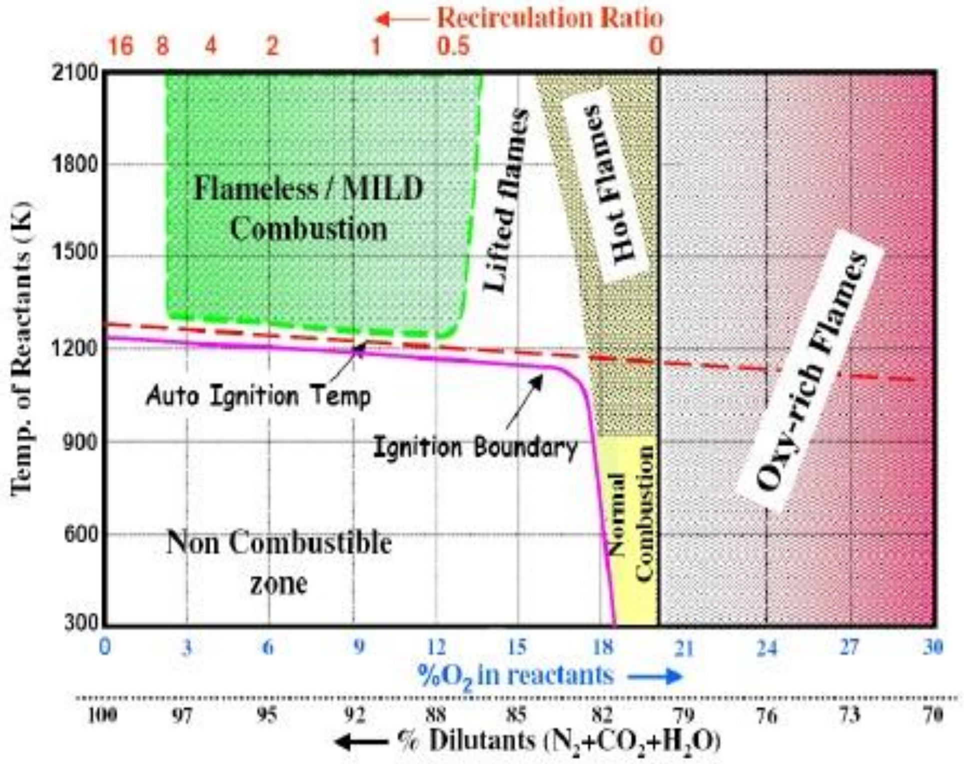
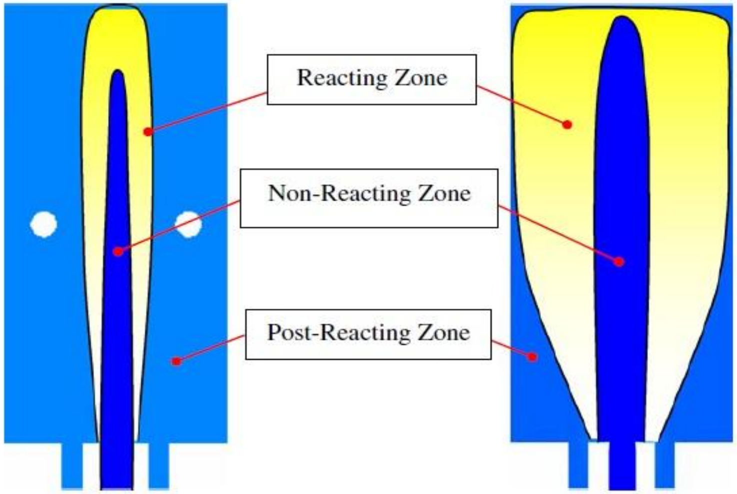


Figure 7 Schematic regime for methane-air jet in hot coflow flames (Rao, 2010).

Oxygen dilution is about 3-13% and the reactant temperature is above the self ignition temperature.

Significantly, both the reacting and non-reacting zones for the MILD case are bigger compared to the conventional case.



(a) Conventional (b) MILD combustion

Figure 8 Closed furnace reacting zone (Li and Mi, 2011).

NOx & Pollutant from Fossil Fuel & Biogas

Table 1: Pollutant from fossil fuel (EIA, 1999)

No.	Pollutant	Gas	Oil	Coal
		(kg of pollutant per 109 kJ of energy input)		
1.	Carbon dioxide	273,780	383,760	486,720
2.	Carbon monoxide	94	77	487
3.	Nitrogen oxide	215	1,048	1,069
4.	Sulphur dioxide	2.34	2,625	6,063
5.	Particulate	16.4	197	6,420
6.	Mercury	0.00	0.016	0.037

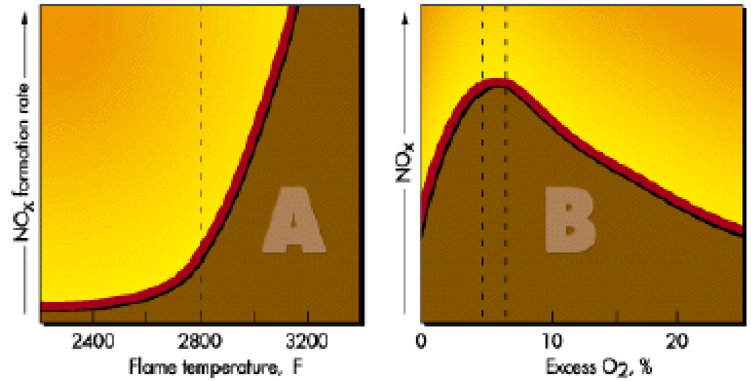
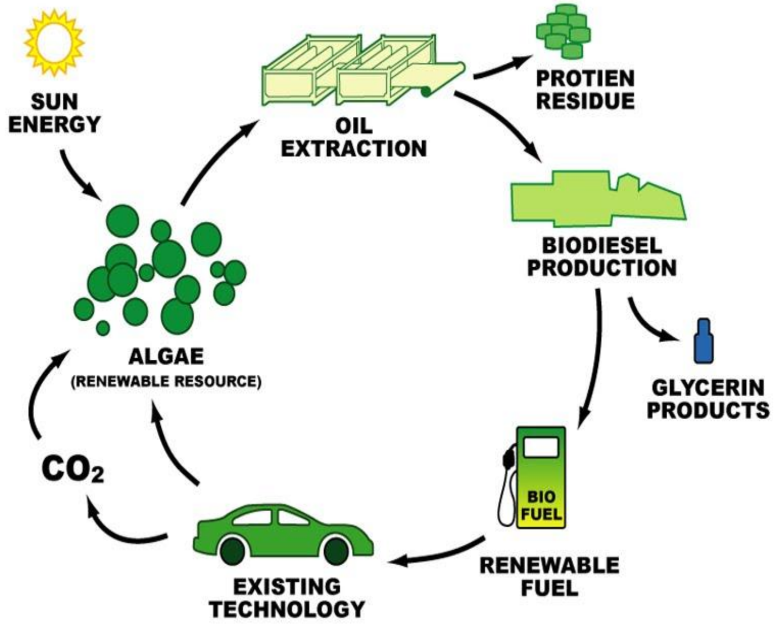


Figure 1: The rate of NO_x formation, (a) flame temperature in Fahrenheit (2800 F is equal to 1810 K) (b) percentage of oxygen level in the oxidiser (AET, 2012).

Biogas cycle



SUN ENERGY

OIL EXTRACTION

PROTIEN RESIDUE

BIODIESEL PRODUCTION

GLYCERIN PRODUCTS

RENEWABLE FUEL

EXISTING TECHNOLOGY

CO_2

ALGAE (RENEWABLE RESOURCE)

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Research Focus

MILD is still not fully commercialized and well adopted in furnace industry, need substantial fundamental and applied research (Cavaliere et al., 2008, Li et al., 2011b, Parente et al., 2011 and Danon, 2011).

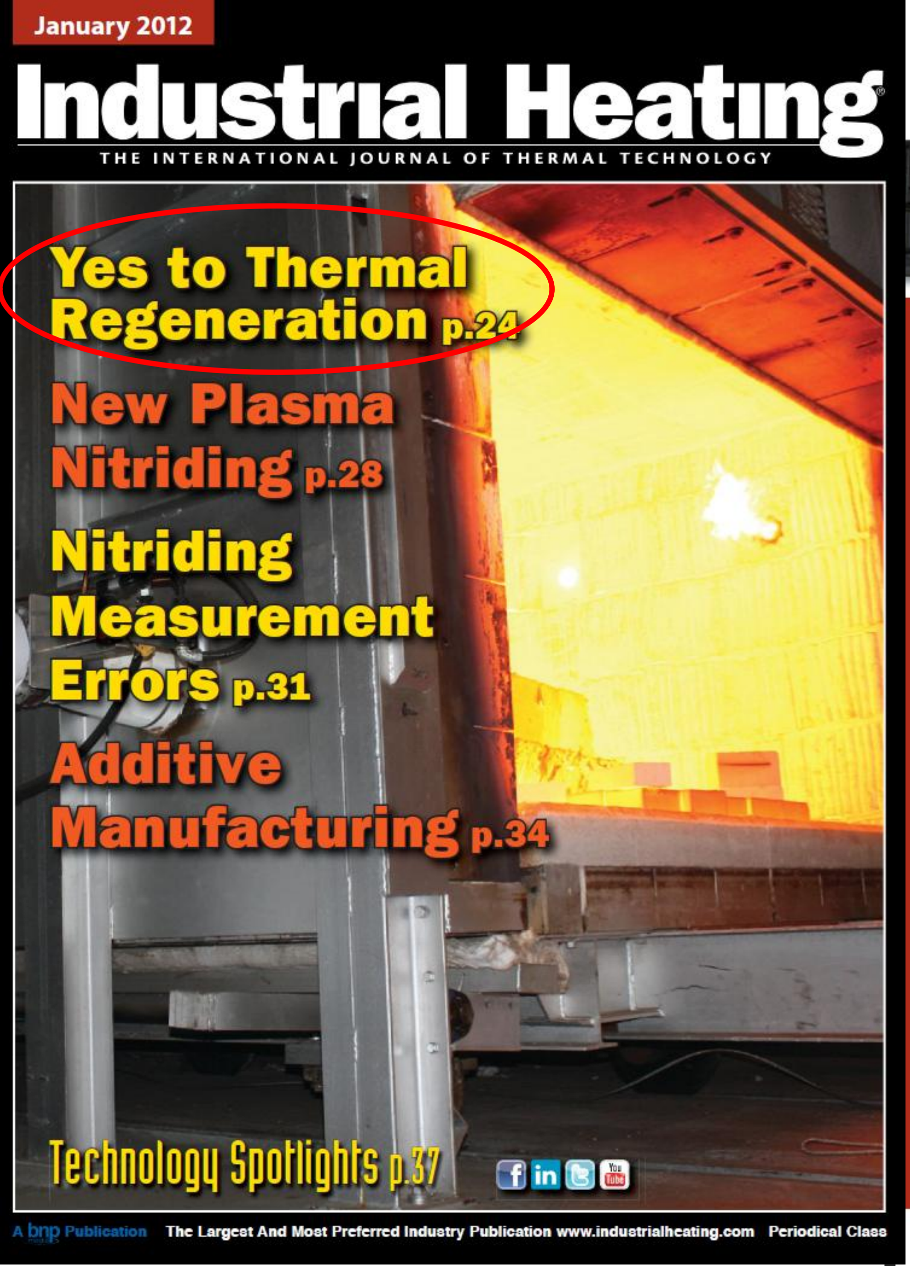
The characteristic of MILD combustion is strong coupling between turbulence and chemistry (Parente et al., 2008).

Mixing field homogeneity (de Joannon et al., 2010) and slower reaction rates - accurate modeling is challenging (Aminian et al., 2011),

Fundamental study on the mixing quality is required.

Furnace efficiency - lean and clean operation and fuel cost is nearly 67% plant's energy budget (Thomas, 2011).

More understanding on flame structure is necessary to widen the application range of the MILD combustion (Medwell, 2007) especially on open furnace.



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On the Cover:
Olson Industries' new regenerative heat system is installed on an in-house test furnace. The new system separates the burners from the regenerators and promises energy efficiency with lower up-front costs.

FEATURE ARTICLES

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Heat Treating

New Configuration May Make it Harder to Say No to Thermal Regeneration

Bryan J. Kraus and Sean Barraclough – Olson Industries; Burgettstown, Pa.

This new furnace regenerative system eliminates the need to cycle from one burner to another because the preheated combustion air is joined into a single stream that feeds all of the burners, allowing them to fire simultaneously. The system also eliminates specialized regenerative burners directly attached to the regenerator boxes, resulting in a less-expensive installation.

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Vacuum/Surface Treating

Active Screen Plasma Nitriding – An Efficient, New Plasma Nitriding Technology

Jean Georges – Plasma Metal Luxembourg; Pierre Collignon – PD2i Europe ; Christian Kunz – PD2i North America

Active screen plasma nitriding technology (ASPN) is a new industrial solution that enjoys all the advantages of traditional plasma nitriding but does not have its inconveniences. Different-size parts can be treated in the same batch. ASPN is also called "easy nitriding" because it does not require highly skilled operators.

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Process Control & Instrumentation

Impact of Measurement Errors on the Results of Nitriding and Nitrocarburizing Treatments

Karl-Michael Winter – PROCESS-ELECTRONIC GmbH; Heiningen, GERMANY

We have a pretty good idea of what will happen to steel parts if exposed to a defined atmosphere at a given temperature. In order to determine the process parameters, we can use the well-known Lehrer Diagram for a nitriding process, or we might use one of the various FeNC phase diagrams for a nitrocarburizing process.

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Materials Characterization & Testing

Additive Manufacturing Enables Innovative Shock-Wave Control in Supersonic Turbine Blades

Rob Snoeijs – LayerWise N.V.; Leuven, BELGIUM

Scientists at von Karman Institute in Belgium contracted LayerWise to produce a scaled turbine inlet guide vane model for a turbine research project. LayerWise, an additive-manufacturing specialist, built the metal vane specimen as a single part, complete with internal cooling cavity and fine instrumentation channels.

Research Objectives

Investigate the possibility of using a new open furnace which can operate on MILD combustion.

Research work will consist of numerical and experimental.

The main objectives of this research are:

i. Evaluate the efficiency and exhaust gas emissions of the open furnace MILD combustion system using biogas fuel.
ii. Design and construct an open furnace with a bluff-body burner head (experimental technique).
iii. Optimise the burner head design using CFD modelling; validated against the experimental results.
iv. Investigate the impact of hydrogen additive on the operating conditions.

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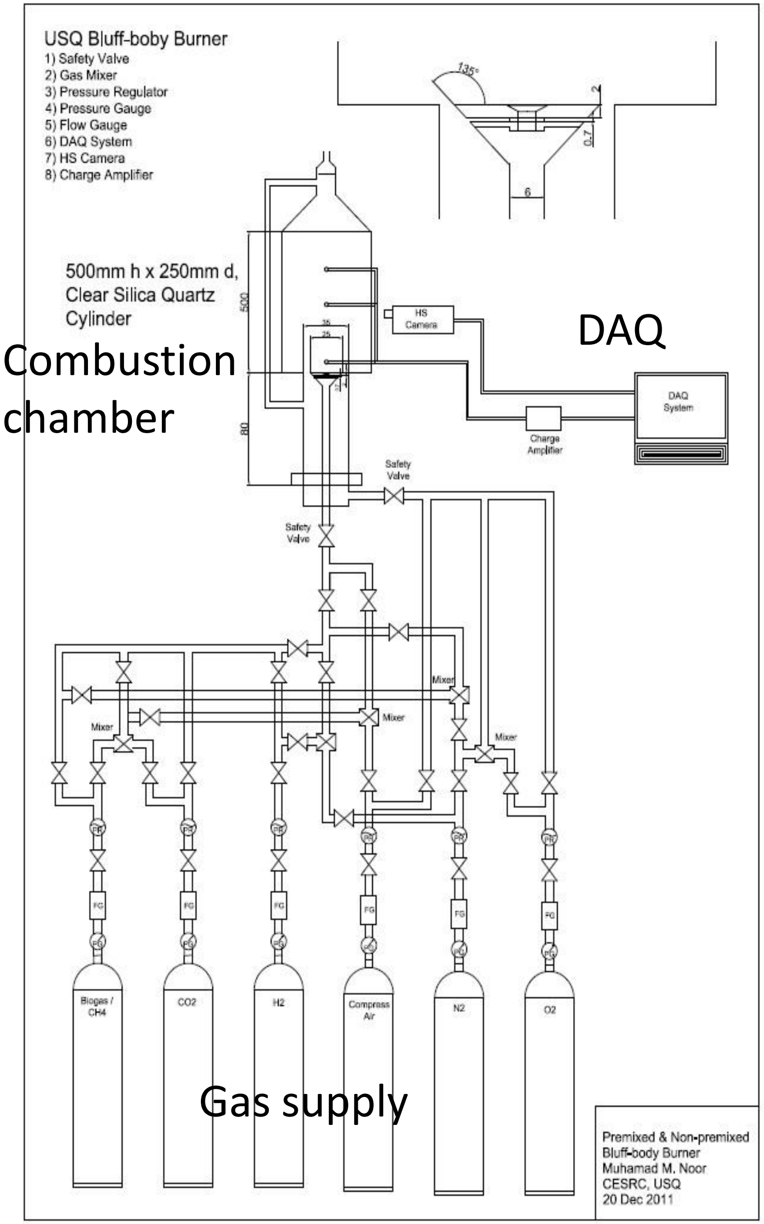
Methodology: Proposed experimental setup



DAQ

Combustion chamber

Gas supply

The parameter for the study will be:

i. EGR - dilute oxygen and preheat the reactant
ii. Supply air and fuel - velocity
iii. Nozzle and bluff body - design
iv. Hydrogen additive – reduce self ignition temperature

Three main parts:

i. Gas supply
ii. Combustion chamber
iii. Data acquisition system

The correct ratio of methane, carbon dioxide and nitrogen mixtures will produce natural gas, low calorific value gases like biogas and coal seam gas.

Figure 14 Proposed experimental setup

Methodology: Image of Experimental setup

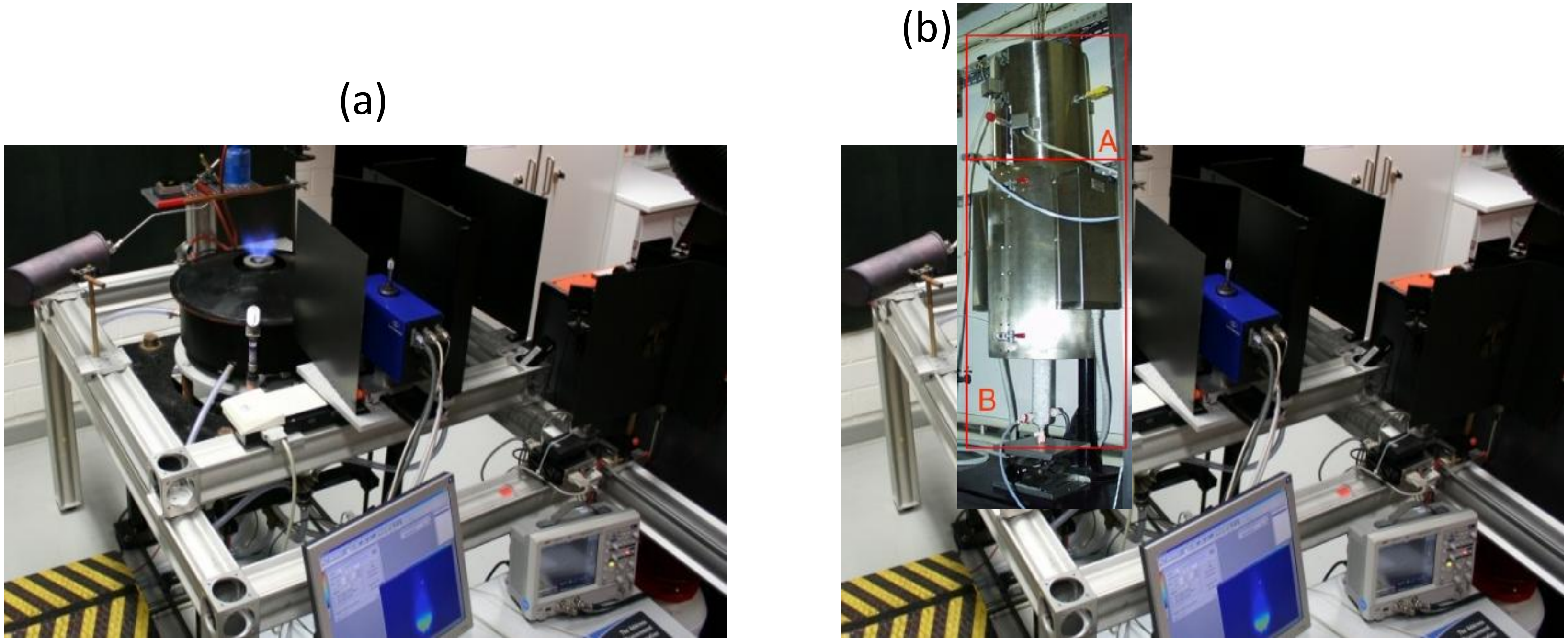


Figure 15 The image of (a) experiment setup with high speed camera and data acquisition computer (http://www.uni-due.de), (b) the burner head with 1mm fuel jet (Derudi et al., 2007b)

Burner head design will be selected by using CFD modelling, before experimental work.

Supply air will be preheated using regenerator or electrical heater (if $T_{mix} < T_{si}$)

CFD Modelling

Sensitivity to turbulence model (e.g. standard *k-ε* model (Launder and Sharma, 1974)) will be investigated.

The parameters for the modelling works after the experiment:

i. Temperature, velocity and the angle of the supply air
ii. Temperature, velocity and the angle of the fuel
iii. Percentage of EGR
iv. Location of the EGR input to supply air
v. Burner head design and fuel properties

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Early Furnace Design

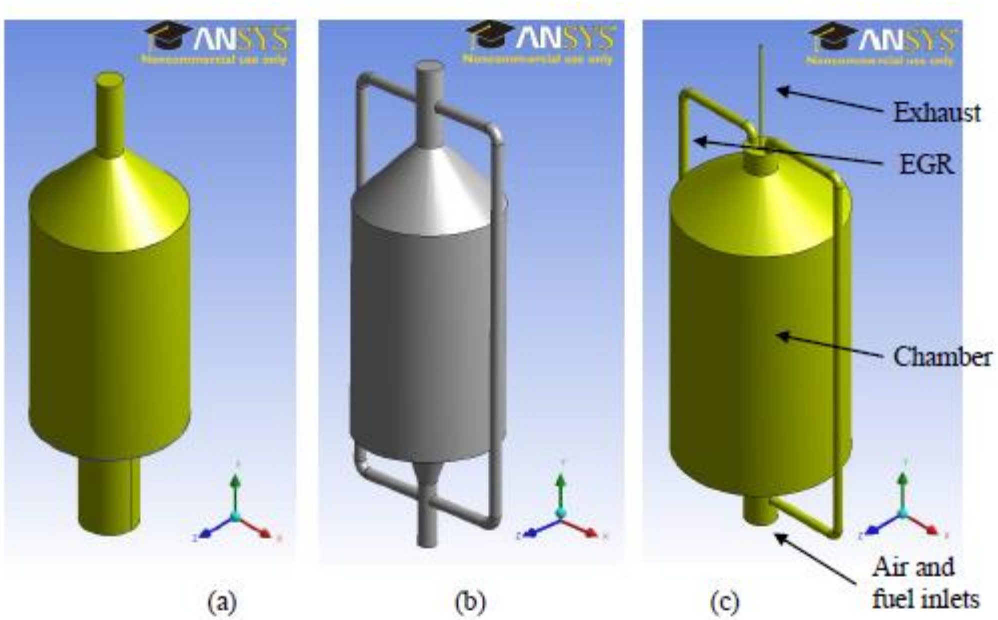
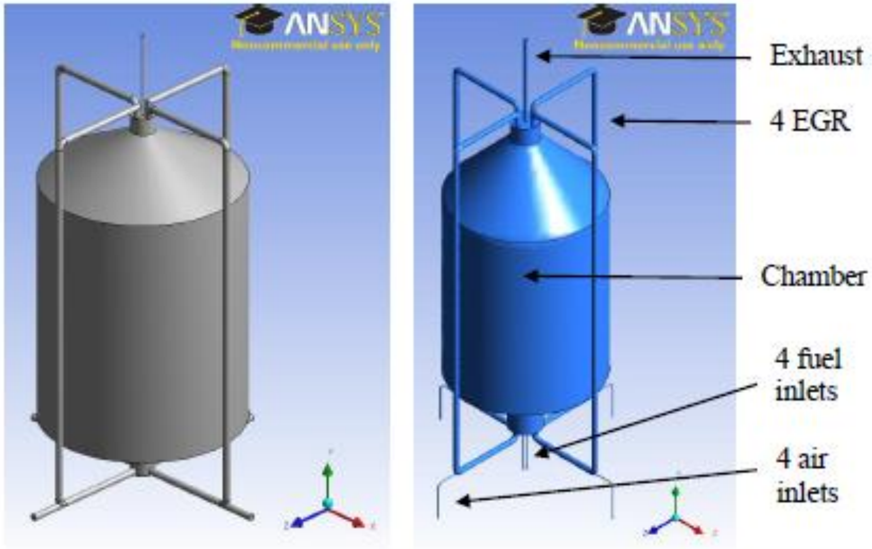


Figure 3: First combustion chamber model (a) No EGR (b) with 2 EGR pipe (c) with 2 EGR pipe and EGR inlet modified

Table 2: Typical data for furnace and burner in figure 3(c) above

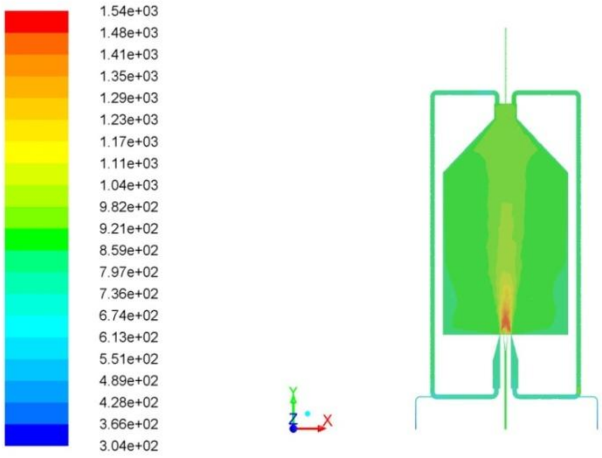
Item	Data
Fuel	$0.5CH_4 + 0.2H_2 + 0.3CO_2$
Oxidiser	Atmospheric air, heated to 800 K
Fuel inlet	Round 1,256 mm^2, 40~50 m/s each
Air inlet	Annulus 5,140 mm^2, 80~100 m/s each
Chamber size	Diameter 375mm, Height 650mm
EGR	2 EGR with 386.9 mm^2 each inlet
Mesh method	Tetrahedrons (Patch conforming method) with 92,034 nodes and 421,172 elements
Radiation model	Discrete Ordinate (DO) model. Absorption coefficient: Weighted Sum of Gray Gas (WSGGM) model.

Furnace Design (Jun 2012)



(a) (b)

Figure 4: Final model with 4 EGR, (a) Air inlet internal diameter is 22 mm, (b) Air inlet internal diameter is 5 mm



Combustion temperature in the chamber for figure 4(b)

Table 3: Typical data for furnace and burner in figure 4(b)

Item	Data
Fuel	$0.5CH_4 + 0.2H_2 + 0.3CO_2$
Oxidiser	Atmospheric air, heated to 800 K
Fuel Inlet	4 x 19.6 mm^2, 20 m/s each
Air Inlet	4 x 19.6 mm^2, 80 m/s each
Chamber size	Diameter 600mm, Height 860mm
EGR	4 EGR with 386.9 mm^2 each inlet
Mesh method	Tetrahedrons (Patch conforming method) with 111,975 nodes and 501,831elements
Radiation model	Discrete Ordinate (DO) model. Absorption coefficient: Weighted Sum of Gray Gas (WSGGM) model.

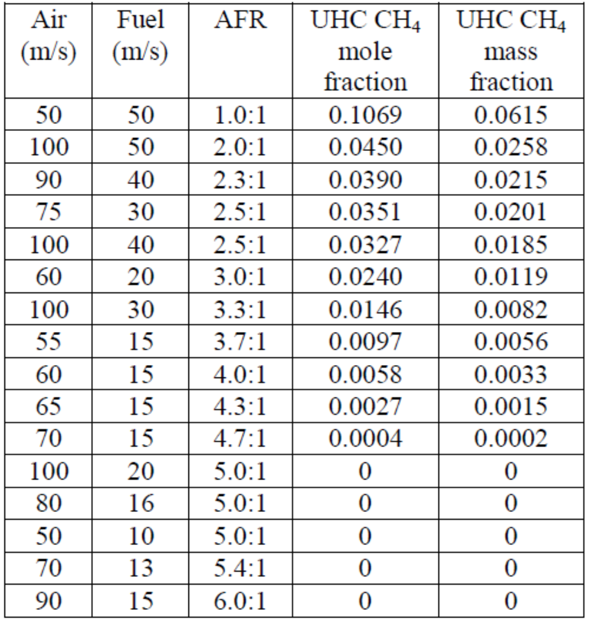
AFR Study 1 – MPC2012

The fuel mole fraction to produce Lower Calorific Value (LCV) is 53.44% CH_4, 13.36% H_2, 30.00% CO_2, 1.30% N_2, 1.70% C_2H_6, 0.01% C_3H_8 and 0.01% C_4H_{10}.

The air mole fraction is 21.008% O_2 and 78.992% N_2.

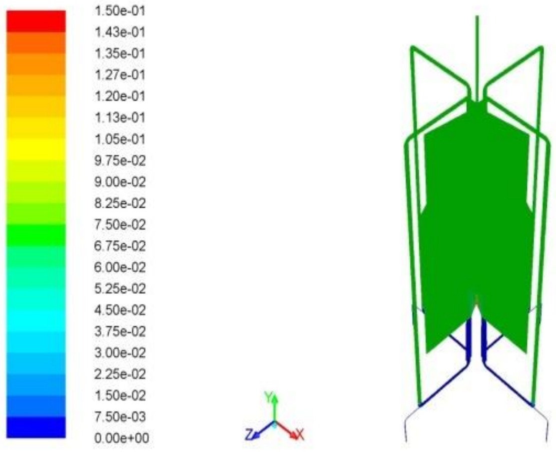
When AFR reach 5:1, CH4 mole fraction in EGR pipe is Zero

Table 1: Air and fuel velocity compositions and mole fraction for unburned CH_4

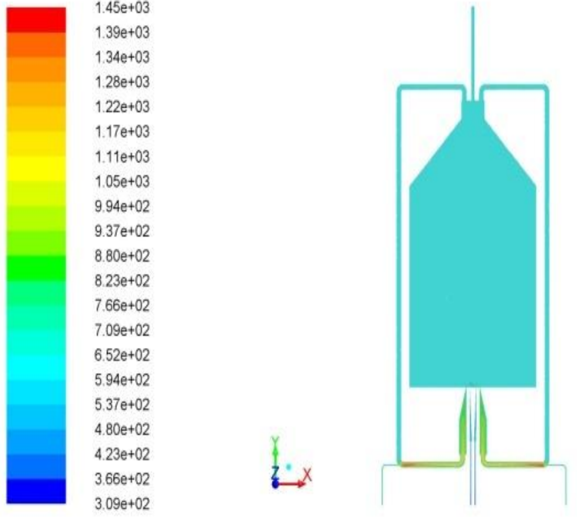


Air (m/s)	Fuel (m/s)	AFR	UHC CH_4 mole fraction	UHC CH_4 mass fraction
50	50	1.0:1	0.1069	0.0615
100	50	2.0:1	0.0450	0.0258
90	40	2.3:1	0.0390	0.0215
75	30	2.5:1	0.0351	0.0201
100	40	2.5:1	0.0327	0.0185
60	20	3.0:1	0.0240	0.0119
100	30	3.3:1	0.0146	0.0082
55	15	3.7:1	0.0097	0.0056
60	15	4.0:1	0.0058	0.0033
65	15	4.3:1	0.0027	0.0015
70	15	4.7:1	0.0004	0.0002
100	20	5.0:1	0	0
80	16	5.0:1	0	0
50	10	5.0:1	0	0
70	13	5.4:1	0	0
90	15	6.0:1	0	0

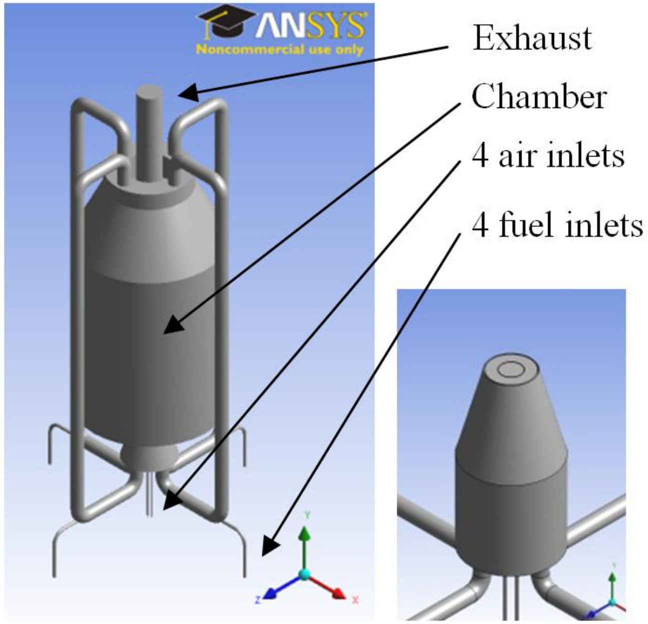
The CH_4 mole fraction between 0 to 0.15 with UHC in the EGR pipe



Comb. temperature with unwanted burning in EGR pipe due to unburned CH_4 in EGR

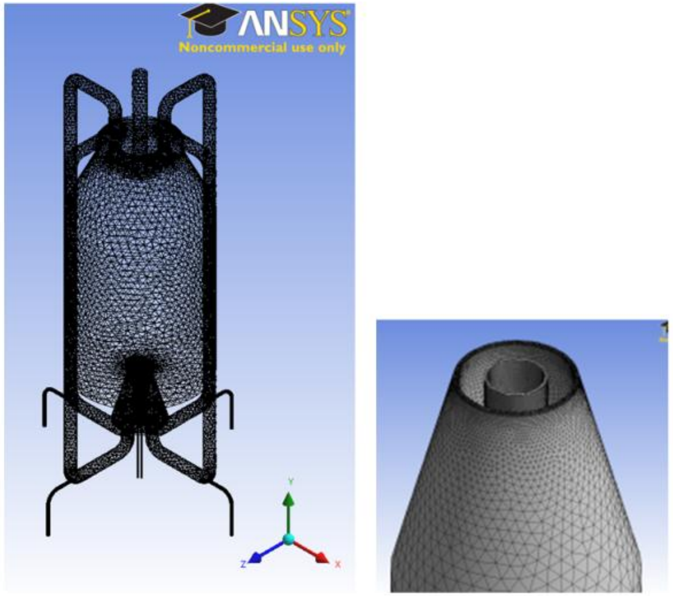


AFR Study 2 – SREC2012



(a) (b)

Figure 1: Open furnace with 4 EGR (a) total geometry (b) air (outer) and fuel (inner) bluff body nozzle



(a) (b)

Figure 2: Meshing for open furnace with 4 EGR (a) 911,669 mesh element and 189,372 mesh nodes (b) mesh element refinement air and fuel nozzle

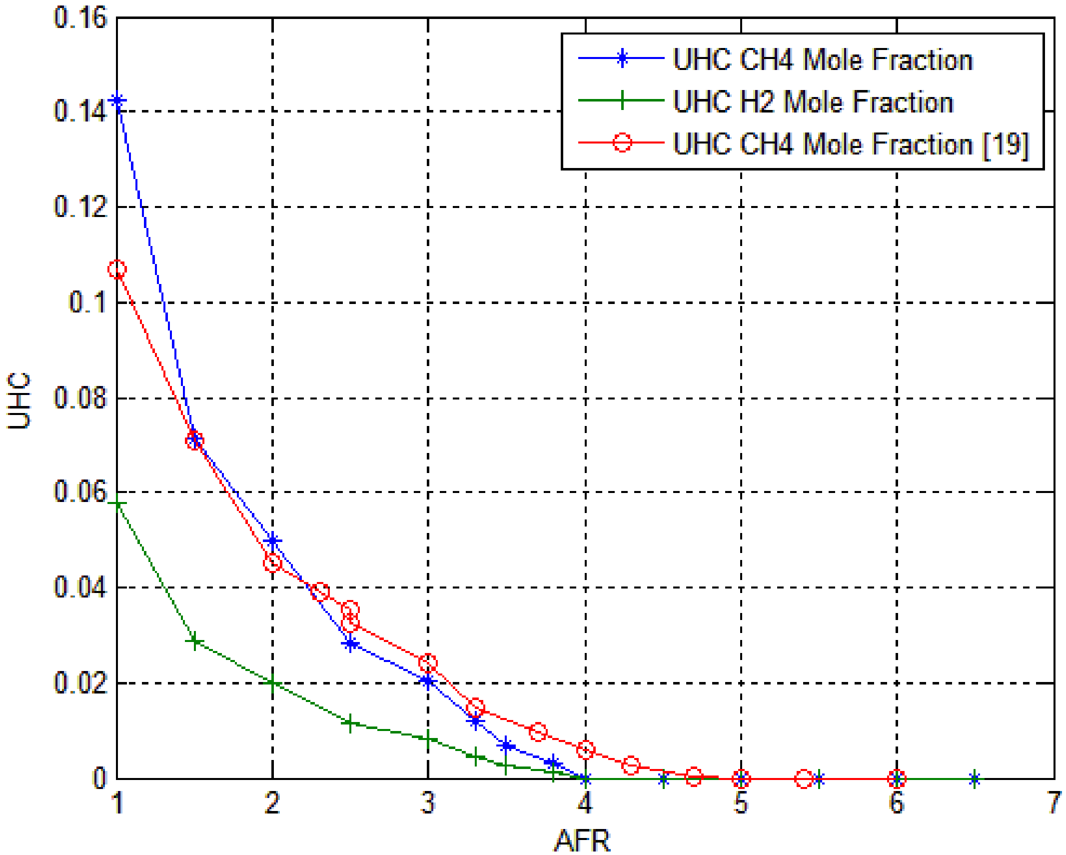
AFR Study 2 – SREC2012

LCV is 50% CH_4, 20% H_2, 30% CO_2

The air mole fraction is 21.008% O_2 and 78.992% N_2.

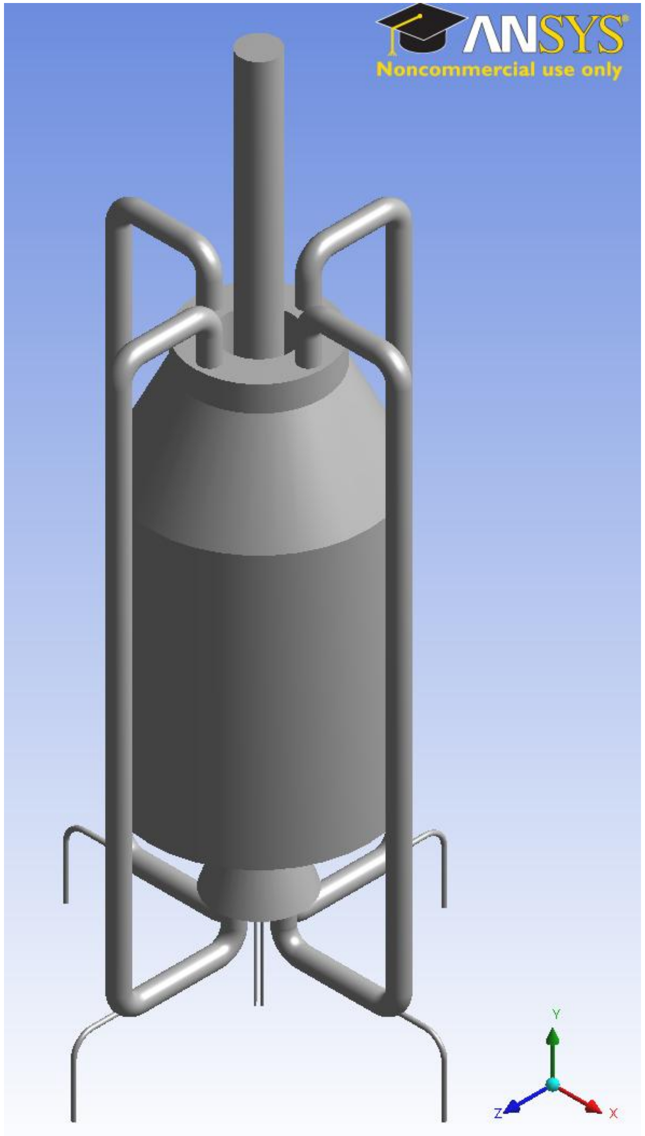
When AFR reach 4:1, CH_4 mole fraction in EGR pipe is become Zero

Air Velocity (m/s)	Fuel Velocity (m/s)	Air Volume (m^3/s)	Fuel Volume (m^3/s)	Total Volume (m^3/s)	AFR
20	100	0.0028	0.0028	0.0057	1.0
30	100	0.0043	0.0028	0.0071	1.5
40	100	0.0057	0.0028	0.0085	2.0
50	100	0.0071	0.0028	0.0099	2.5
60	100	0.0085	0.0028	0.0114	3.0
65	100	0.0092	0.0028	0.0121	3.3
70	100	0.0099	0.0028	0.0128	3.5
75	100	0.0107	0.0028	0.0135	3.8
80	100	0.0114	0.0028	0.0142	4.0
100	125	0.0142	0.0035	0.0177	4.0
100	120	0.0142	0.0034	0.0176	4.2
90	100	0.0128	0.0028	0.0156	4.5
100	100	0.0142	0.0028	0.0170	5.0
90	82	0.0128	0.0023	0.0151	5.5
120	100	0.0170	0.0028	0.0199	6.0
100	77	0.0142	0.0022	0.0164	6.5

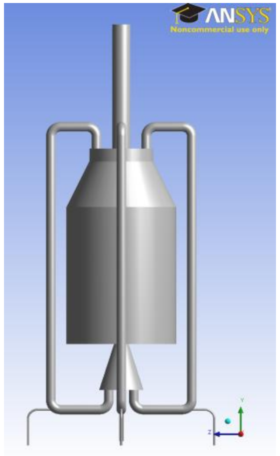


Furnace Design (Aug 2012)

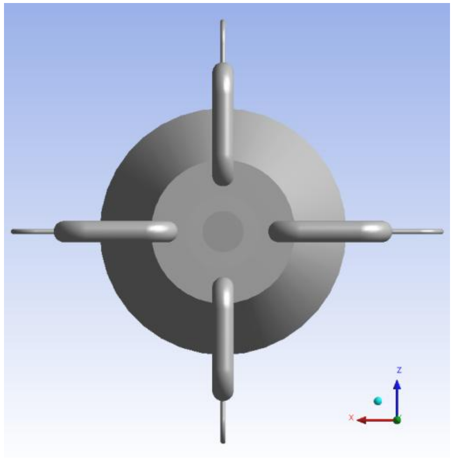
3D View



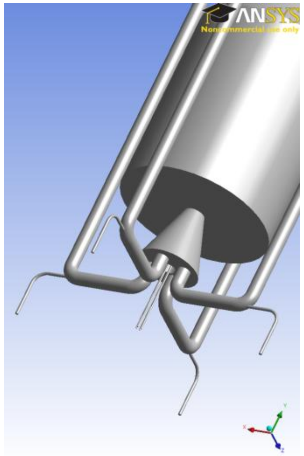
2D View



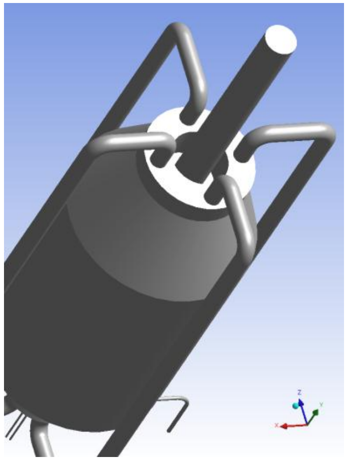
Plan View



Bottom View



Top View

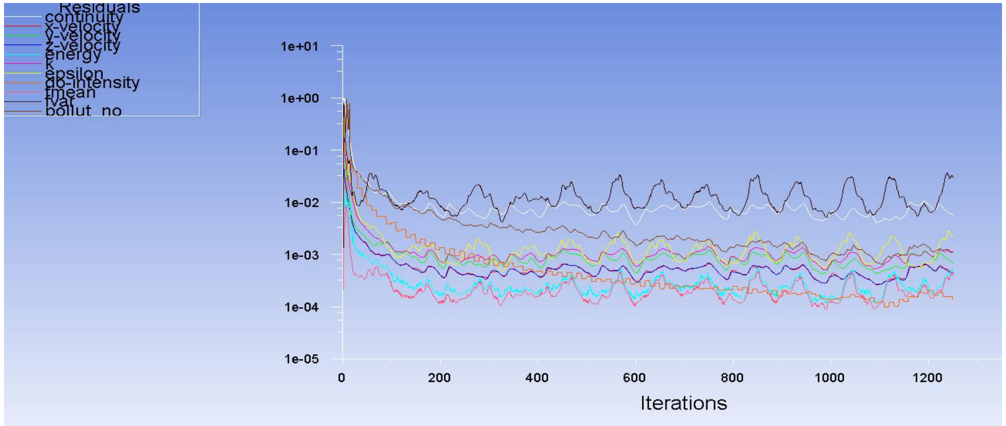


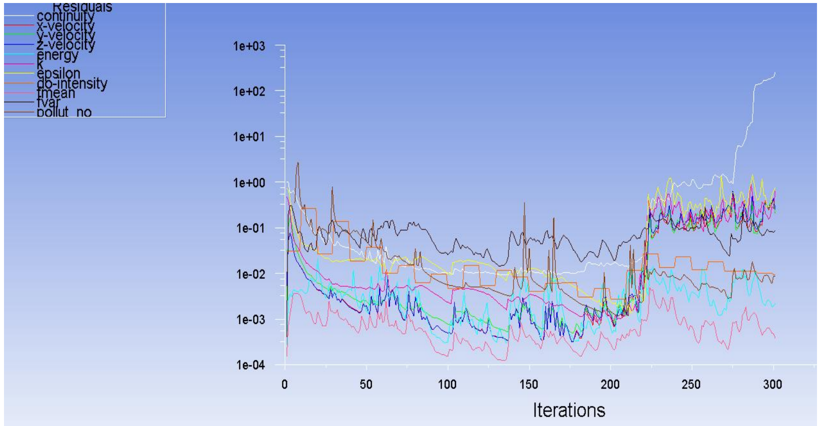
Calculation & Residuals

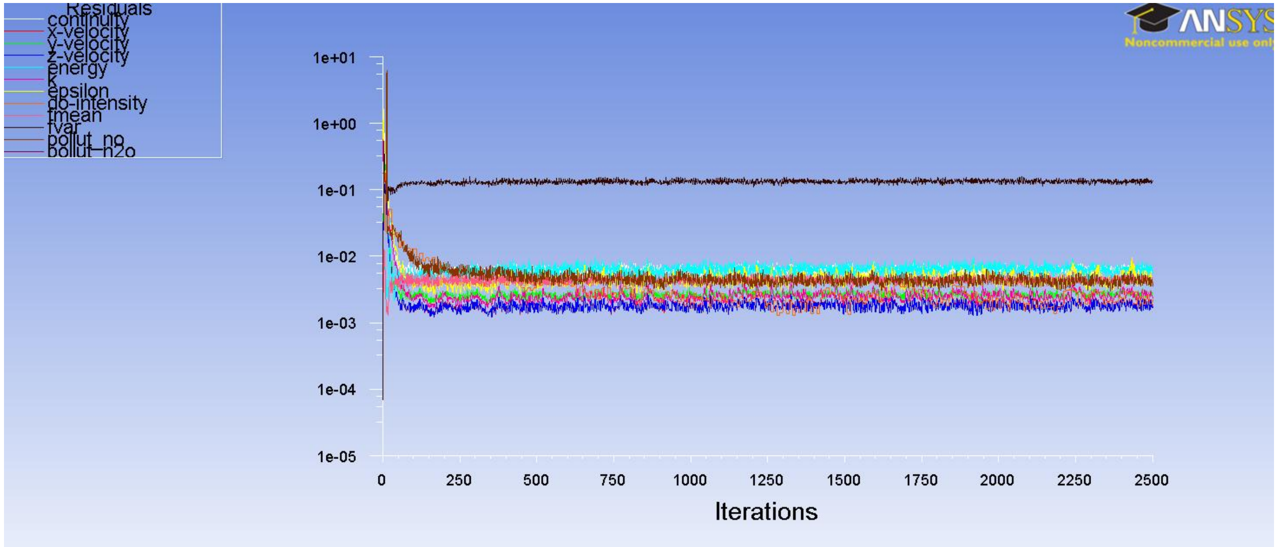
Time taken for:

Coarse mesh : 20 – 40 second per step
Medium mesh : 45 – 100 second per step
Fine mesh : 120 – 300 second per step

Problem – floating point, computer hang, divergence



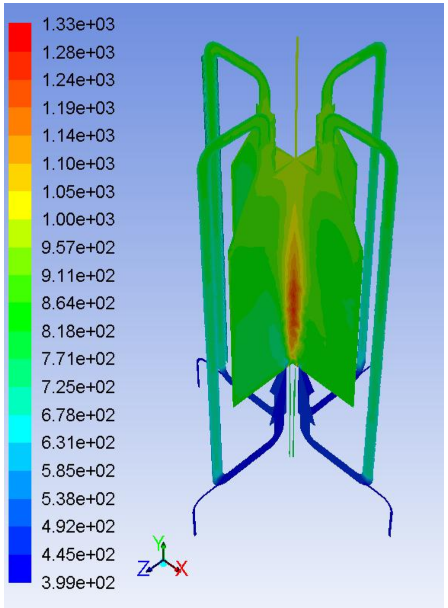




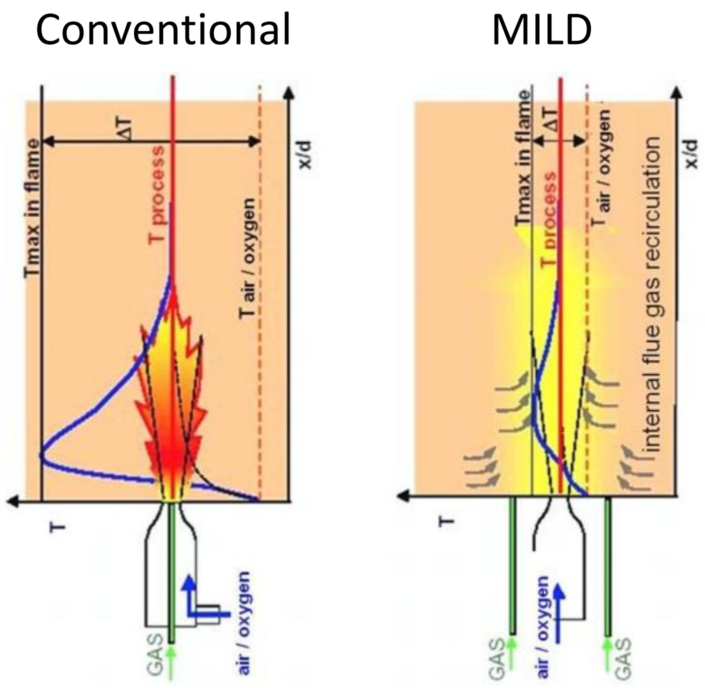
Latest Result

LCV is 50% CH_4, 20% H_2, 30% CO_2

Normal Air 21.008% O_2 and 78.992% N_2.



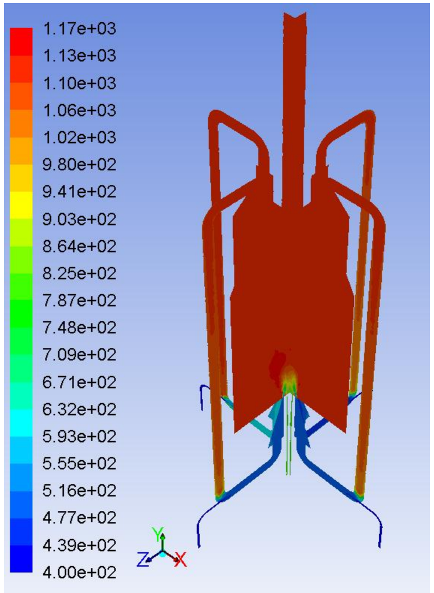
Air 200 m/s 400K and Fuel 120 m/s 800K



(Wunning, 2003)

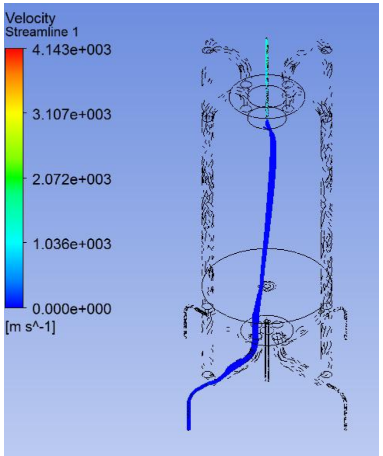
LCV is 50% CH_4, 20% H_2, 30% CO_2

Low Oxygen Air: 7.0% O_2 and 93.0% N_2.

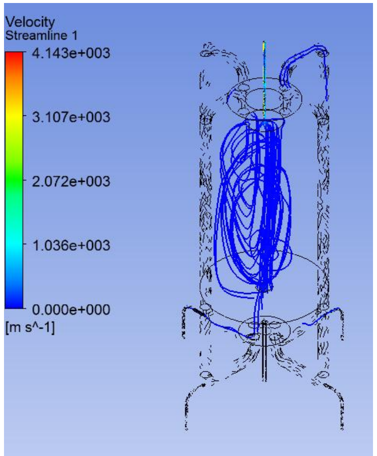


Air 200 m/s 400K and Fuel 170 m/s 800K

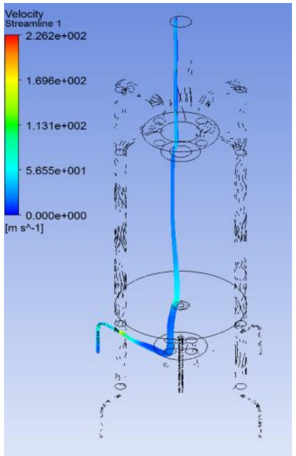
Velocity, Mole fraction, Streamline



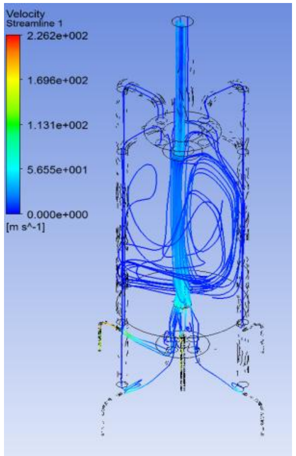
Streamline from Air Inlet(10mm exhaust)



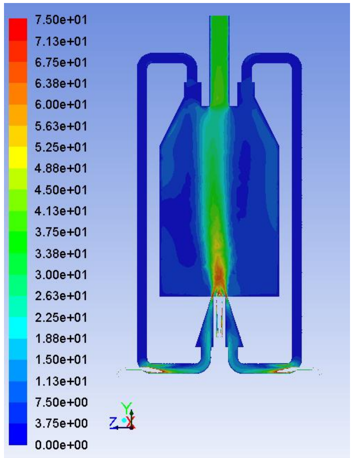
Streamline from Chamber (10mm exhaust)



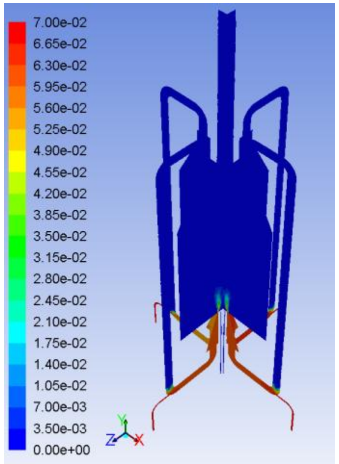
Streamline from Air Inlet(100mm exhaust)



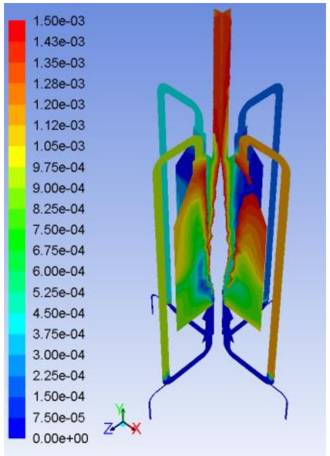
Streamline from Chamber (100mm exhaust)



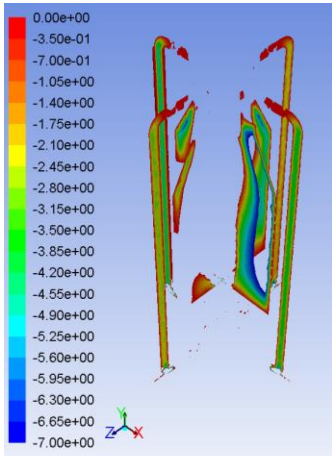
Velocity Magnitude



Oxygen mole fraction



CH4 mole fraction (Not zero in EGR and exhaust)



EGR flow down still not strong enough to dilute oxygen in fresh air

Outline

1. Introduction
2. Research Focus
3. Methodology
4. Current Status
5. **Conclusions**

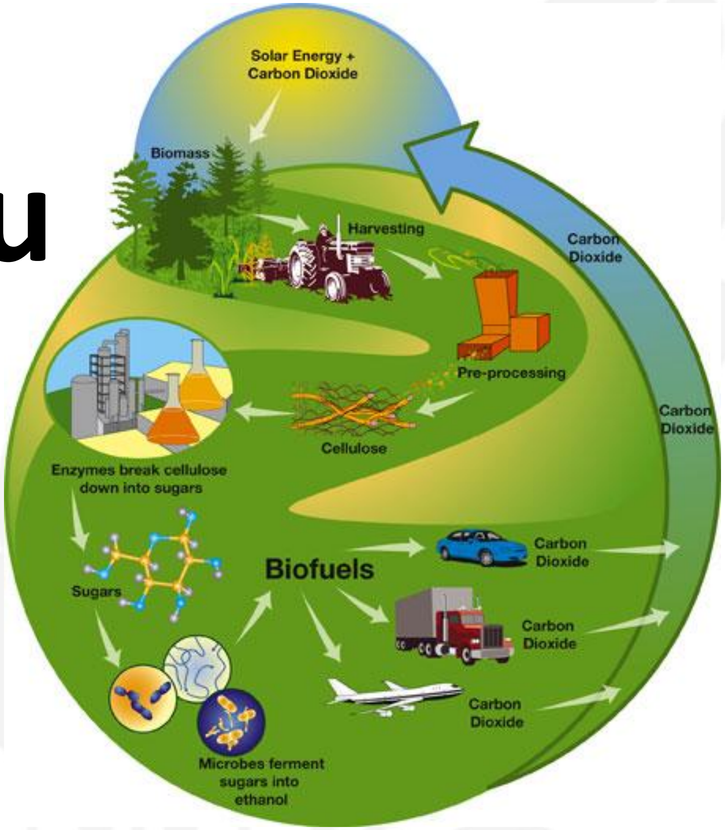
Conclusion

1) CFD Progress to design and develop the parameter for open furnace

2) The experimental setup is in progress


CO2
Biofuels
Recycle Carbon
Dioxide
BIOFUELS

Thankyou


Solar Energy +
Carbon Dioxide
Biomass
Harvesting
Carbon
Dioxide
Pre-processing
Carbon
Dioxide
Cellulose
Enzymes break cellulose
down into sugars
Sugars
Biofuels
Carbon
Dioxide
Carbon
Dioxide
Carbon
Dioxide
Microbes ferment
sugars into
ethanol


CARBON DIOXIDE
ARGON
COMPRESSED AIR
OXYGEN
ACETYLENE
LPG
FRESH WATER