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#### What is a Burner?



# Device which enables a chemical reaction of fuel and oxidizer (usually Oxygen from air) to produce heat in a controlled way.

wall hung boilers storage water heater cookers

decorative fireplaces hot air generator washer

Heater or dryer for industrial application (steel, glass, food)



# Theoretical Stoichiometric Combustion

complete oxidation of a fuel with no excess air (lambda = ratio air/gas =1):

(e.g. global reaction Methane & Propane)

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 -889kJ$$

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.7N_2 - 2220 \text{ kJ}$$

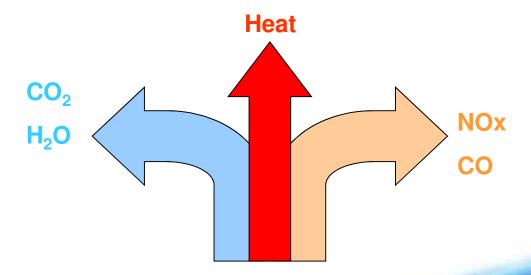
Standard conditions 1 atm. and 25 C



# In reality:

Complete real mechanism is composed of thousands of reactions

Not all reaction come to full completion, giving as a result pollutant emissions



5 $H + H + M \rightarrow H_2 + M$ 6 $H + H + H_2O \rightarrow H_2 + H_2$ 7 $H + O + M \rightarrow OH + M$ 8 $H + OH + M \rightarrow H_2O + M$ 9 $H + O_2 + M \rightarrow HO_2 + M$ 10 $H + O_2 + M_2 \rightarrow HO_2 + M$ 11 $H + HO_2 \rightarrow CH_2 \rightarrow HO_2 + M$ 12 $H + HO_2 \rightarrow CO_2 + OH$ 13 $O + HO_2 \rightarrow O_2 + OH$ 14 $CO + OH \rightarrow CO_2 + M$ 15 $CO + OH \rightarrow CO_2 + M$ 16 $HO_2 + CO \rightarrow CO_2 + OH$ 17 $CH_2O + OH \rightarrow HCO + H$ 18 $HCO + M \rightarrow H + CO + M$ 19 $HCO + OH \rightarrow H_2O + CO$ 20 $CH_3 + H + M \rightarrow CH_3 + H_2$ 21 $CH_4 + O \rightarrow CH_3 + OH$ 22 $CH_4 + O \rightarrow CH_3 + OH$ 23 $CH_4 + O \rightarrow CH_3 + OH$ 24 $CH_4 + OH \rightarrow CH_3 + H_2O$ 25 $CH_4 + OH \rightarrow CH_3 + H_2O$ 26 $CH_3 + O \rightarrow CH_2O + H$	$O + H_2 \longrightarrow OH + H$ $OH + H_2 \longrightarrow H_2O + H$ $2OH \longrightarrow O + H_2O$ $H + H + M \longrightarrow H_2 + M$ $H + H + H_2O \longrightarrow H_2 + H_2O$ $H + O + M \longrightarrow OH + M$ $H + OH + M \longrightarrow H_2O + M$ $H + O_2 + M \longrightarrow HO_2 + M$ $H + O_2 - M_2 \longrightarrow O_2 + OH$ $O + HO_2 \longrightarrow O_2 + OH$ $O + OH \longrightarrow OO_2 + M$ $O + OH \longrightarrow OO_2 + M$ $O + OH \longrightarrow OO_2 + OH$ $O + OH \longrightarrow HOO + H_2O$ $O + OH \longrightarrow HOO + M$ $O + OH \longrightarrow HOO + OH$ $O + OH \longrightarrow HOO$ $O + OH \longrightarrow HOO$ O +		reaction
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16 $HO_2 + CO \rightarrow CO_2 + OH$ 17 $CH_2O + OH \rightarrow HCO + H$ 18 $HCO + M \rightarrow H + CO + N$ 19 $HCO + OH \rightarrow H_2O + CO$ 20 $HCO + O_2 \rightarrow HO_2 + CO$ 21 $CH_3 + H (+ M) \rightarrow CH_4 (-1)$ 22 $CH_4 + CH_3 + CH_4 (-1)$ 23 $CH_4 + CH_3 + CH_4 (-1)$ 24 $CH_4 + CH_3 + CH_3 + CH_4 (-1)$ 25 $CH_4 + CH_2 \rightarrow CH_3 + CH_4 (-1)$ 26 $CH_3 + CH_4 (-1) \rightarrow CH_4 (-1)$	$HO_2 + CO - CO_2 + OH$ $CH_2O + OH - HCO + H_2O$ $HCO + M - H + CO + M$ $HCO + OH - H_2O + CO$ $HCO + O_2 - HO_2 + CO$ $CH_3 + H (+ M) - CH_4 (+ M)$ $CH_4 + H - CH_3 + H_2$ $CH_4 + OH - CH_3 + OH$ $CH_4 + OH - CH_3 + H_2O$ $CH_4 + OH - CH_3 + HO_2$ $CH_4 + OH - CH_3 + HO_2$ $CH_3 + O - CH_2O + OH$	14	$CO + O + M \rightarrow CO_2 + M$
17	$CH_2O + OH \rightarrow HCO + H_2O$ $HCO + M \rightarrow H + CO + M$ $HCO + OH \rightarrow H_2O + CO$ $HCO + O_2 \rightarrow HO_2 + CO$ $CH_3 + H (+ M) \rightarrow CH_4 (+ M)$ $CH_4 + H \rightarrow CH_3 + H_2$ $CH_4 + OH \rightarrow CH_3 + H_2O$ $CH_4 + OH \rightarrow CH_3 + H_2O$ $CH_4 + OH \rightarrow CH_3 + HO_2$ $CH_3 + O \rightarrow CH_2O + H$	15	
18 $HCO + M - H + CO + M$ 19 $HCO + OH - H_2O + CO$ 20 $HCO + O_2 - HO_2 + CO$ 21 $CH_3 + H + M - CH_3 + H_2$ 22 $CH_4 + O - CH_3 + OH$ 24 $CH_4 + OH - CH_3 + H_2O$ 25 $CH_4 + O_2 - CH_3 + OH$ 26 $CH_3 + O - CH_2O + H$	$HCO + M  ightharpoonup H + CO + M$ $HCO + OH  ightharpoonup H_2O + CO$ $HCO + O_2  ightharpoonup HO_2 + CO$ $CH_3 + H (+ M)  ightharpoonup CH_4 (+ M)$ $CH_4 + H  ightharpoonup CH_3 + H_2$ $CH_4 + OH  ightharpoonup CH_3 + H_2O$ $CH_4 + O_2  ightharpoonup CH_3 + HO_2$ $CH_3 + O  ightharpoonup CH_2O + H$	16	
19 HCO + OH - H <sub>2</sub> O + CO 20 HCO + O <sub>2</sub> - HO <sub>2</sub> + CO 21 CH <sub>3</sub> + H (+ M) - CH <sub>4</sub> (- 22 CH <sub>4</sub> + H - CH <sub>3</sub> + H <sub>2</sub> 23 CH <sub>4</sub> + O - CH <sub>3</sub> + OH 24 CH <sub>4</sub> + OH - CH <sub>3</sub> + H <sub>2</sub> O 25 CH <sub>4</sub> + O <sub>2</sub> - CH <sub>3</sub> + HO <sub>2</sub> 26 CH <sub>3</sub> + O - CH <sub>2</sub> O + H	$HCO + OH \rightarrow H_2O + CO$ $HCO + O_2 \rightarrow HO_2 + CO$ $CH_3 + H (+ M) \rightarrow CH_4 (+ M)$ $CH_4 + H \rightarrow CH_3 + H_2$ $CH_4 + OH \rightarrow CH_3 + OH$ $CH_4 + OH \rightarrow CH_3 + H_2O$ $CH_4 + O_2 \rightarrow CH_3 + HO_2$ $CH_3 + O \rightarrow CH_2O + H$	17	
20 HCO + O <sub>2</sub> - HO <sub>2</sub> + CO 21 CH <sub>3</sub> + H (+ M) - CH <sub>4</sub> (-  22 CH <sub>4</sub> + H - CH <sub>3</sub> + H <sub>2</sub> 23 CH <sub>4</sub> + O - CH <sub>3</sub> + OH 24 CH <sub>4</sub> + OH - CH <sub>3</sub> + H <sub>2</sub> O 25 CH <sub>4</sub> + O <sub>2</sub> - CH <sub>3</sub> + HO <sub>2</sub> 26 CH <sub>3</sub> + O - CH <sub>2</sub> O + H	$HCO + O_2 - HO_2 + CO$ $CH_3 + H (+ M) - CH_4 (+ M)$ $CH_4 + H - CH_3 + H_2$ $CH_4 + O - CH_3 + OH$ $CH_4 + OH - CH_3 + H_2O$ $CH_4 + O_2 - CH_3 + HO_2$ $CH_3 + O - CH_2O + H$	18	$HCO + M \rightarrow H + CO + M$
22	$CH_3 + H \stackrel{\leftarrow}{(+ M)} - CH_4 (+ M)$ $CH_4 + H \stackrel{\leftarrow}{-} CH_3 + H_2$ $CH_4 + O \stackrel{\leftarrow}{-} CH_3 + OH$ $CH_4 + OH \stackrel{\leftarrow}{-} CH_3 + H_2O$ $CH_4 + O_2 \stackrel{\leftarrow}{-} CH_3 + HO_2$ $CH_3 + O \stackrel{\leftarrow}{-} CH_2O + H$	19	HCO + OH → H <sub>2</sub> O + CO
22 $CH_4 + H \rightarrow CH_3 + H_2$ 23 $CH_4 + O \rightarrow CH_3 + OH$ 24 $CH_4 + OH \rightarrow CH_3 + H_2O$ 25 $CH_4 + O_2 \rightarrow CH_3 + HO_2$ 26 $CH_3 + O \rightarrow CH_2O + H$	$CH_4 + H \rightarrow CH_3 + H_2$ $CH_4 + O \rightarrow CH_3 + OH$ $CH_4 + OH \rightarrow CH_3 + H_2O$ $CH_4 + O_2 \rightarrow CH_3 + HO_2$ $CH_3 + O \rightarrow CH_2O + H$	20	$HCO + O_2 - HO_2 + CO$
23 CH <sub>4</sub> + O - CH <sub>3</sub> + OH 24 CH <sub>4</sub> + OH - CH <sub>3</sub> + H <sub>2</sub> O 25 CH <sub>4</sub> + O <sub>2</sub> - CH <sub>3</sub> + HO <sub>2</sub> 26 CH <sub>3</sub> + O - CH <sub>2</sub> O + H	$CH_4 + O \rightarrow CH_3 + OH$ $CH_4 + OH \rightarrow CH_3 + H_2O$ $CH_4 + O_2 \rightarrow CH_3 + HO_2$ $CH_3 + O \rightarrow CH_2O + H$	21	$CH_3 + H (+ M) \leftarrow CH_4 (+ M)$
23 CH <sub>4</sub> + O - CH <sub>3</sub> + OH 24 CH <sub>4</sub> + OH - CH <sub>3</sub> + H <sub>2</sub> O 25 CH <sub>4</sub> + O <sub>2</sub> - CH <sub>3</sub> + HO <sub>2</sub> 26 CH <sub>3</sub> + O - CH <sub>2</sub> O + H	$CH_4 + O \rightarrow CH_3 + OH$ $CH_4 + OH \rightarrow CH_3 + H_2O$ $CH_4 + O_2 \rightarrow CH_3 + HO_2$ $CH_3 + O \rightarrow CH_2O + H$		
24 CH <sub>4</sub> + OH ~ CH <sub>3</sub> + H <sub>2</sub> O 25 CH <sub>4</sub> + O <sub>2</sub> ~ CH <sub>3</sub> + HO <sub>2</sub> 26 CH <sub>3</sub> + O ~ CH <sub>2</sub> O + H	$CH_4 + OH - CH_3 + H_2O$ $CH_4 + O_2 - CH_3 + HO_2$ $CH_3 + O - CH_2O + H$		
25 $CH_4 + O_2 \rightarrow CH_3 + HO_2$ 26 $CH_3 + O \rightarrow CH_2O + H$	$CH_4 + O_2 \rightarrow CH_3 + HO_2$ $CH_3 + O \rightarrow CH_2O + H$		
26 $CH_3 + O \leftarrow CH_2O + H$	$CH_3 + O - CH_2O + H$		
	$CH_3 + OH \rightarrow CH_2 + H_2O$		
$CH_3 + OH - CH_2 + H_2O$		27	$CH_3 + OH - CH_2 + H_2O$

M



# Higher (HHV) and Lower (LHV) Heating values

 $HHV = LHV + hv \times (nH2O,out/nfuel,in)$ 

h*v*: heat of vaporization of water,

nH2O,out : moles of water vaporized

nfuel,in: moles of fuel combusted

Fuel_	HHV MJ/kg	HHV <u>BTU</u> / <u>lb</u>	HHV <u>kJ/mol</u>	LHV MJ/kg
<u>Hydrogen</u>	141.80	61,000	286	121.00
<u>Methane</u>	55.50	23,900	889	50.00
<b>Ethane</b>	51.90	22,400	1,560	47.80
<b>Propane</b>	50.35	21,700	2,220	46.35
<u>Butane</u>	49.50	20,900	2,877	45.75



- $CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 + enthalpy$ 
  - CO2 max %= 1/(1+7,52) x 100 = 11,46 % (dry condition) you need to get the water out of the exhaust gas for the analysis damage of instrument
  - O2 % = 21% for no combustion, = 0% for complete combustion
  - O2 % =  $21\% 21/11,46 \times CO2$  meas. %

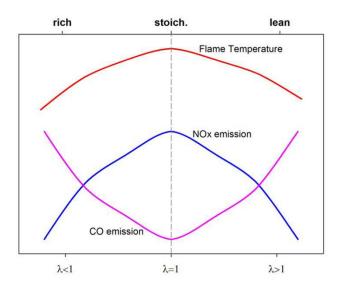


# Stoichiometrical reactions in most cases are not advantageous therefore

# we predominately work in excess air conditions

(e.g.20% Excess Air  $\lambda = 1.2$ )

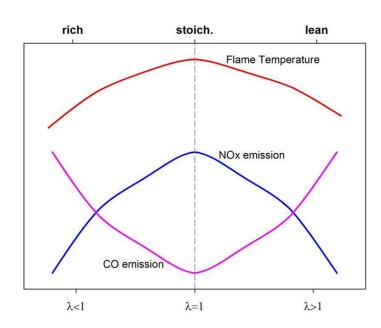
$$CH_4 + 2.4O_2 + 8.3N_2 \rightarrow CO_2 + 2H_2O + 0.4O_2 + 8.3N_2$$





#### **NOX** formation

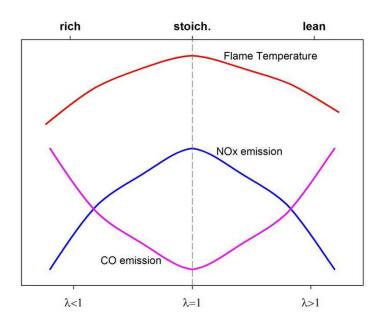
- Fuel NOX Nitrogen contained within the fuel, particularly gases containing ammonia.
   Since Natural Gas contains no Nitrogen this mechanism does not apply for methane.
- Thermal NOX (Zeldovich) occurs at high temps (>1800K) and is predominately NO.
- Prompt NO occurs at low temps in fuel rich flame regions and can be significant in Natural gas flames.





#### **CO** formation

- (a) Poor combustion control (flame stability, mixing etc).
- (b) Flame impact/quenching against cold surfaces (loses heat quickly)
- (c) Equilibrium dissociation of  $CO_2 \Leftrightarrow CO$





A burner design can not be developed without insight on:

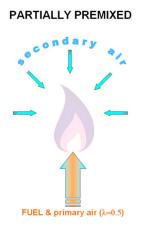
- Air / fuel ratio atmospheric vs premix
- Modulation range
- Reaction chemistry influence
- Temperature effect (quenching of flame, external cooling or heating elements)



Air / Fuel ratio Atmospheric vs. fan assisted Aerated vs. premix

Aside from fixing I, it must also be investigated the effect of SECONDARY AERATION to the flame and how this secondary air reach the combustion area



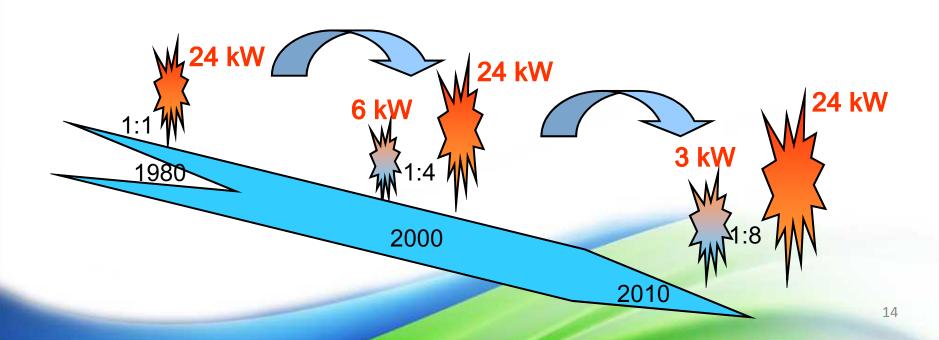






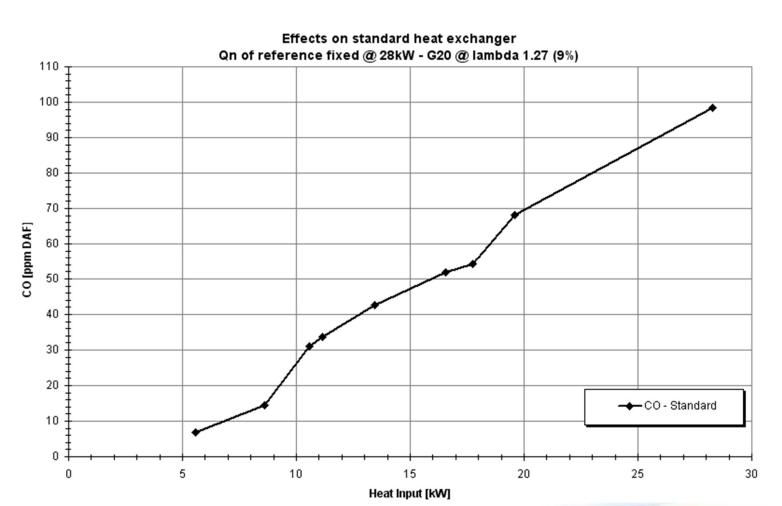
#### **Turn down ratio**

Turn down ratio decreased as the heating units evolved to condensing. This maximises efficiency (decreases stand-by losses and number of burner start) decreases NOx and CO emissions and decreases power consumption,



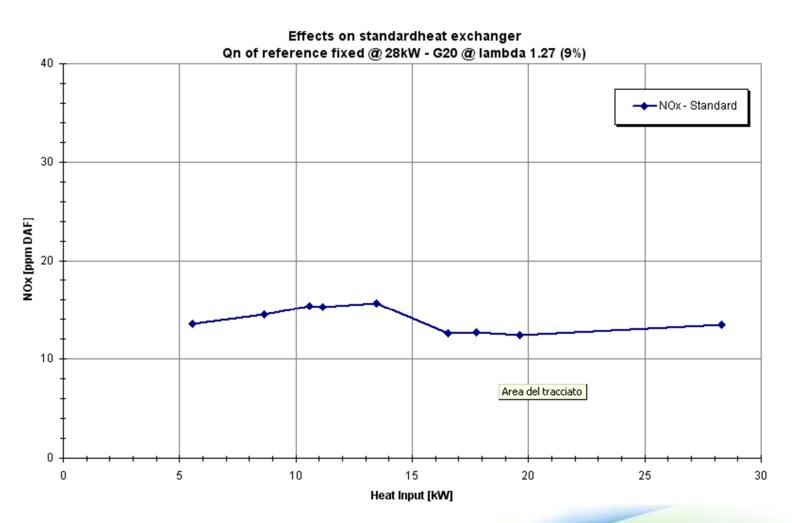
# **Emission VS Modulation Range**





# **Emission VS Modulation Range**

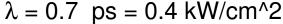


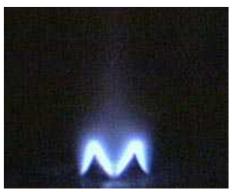


# **Flame VS Modulation Range**





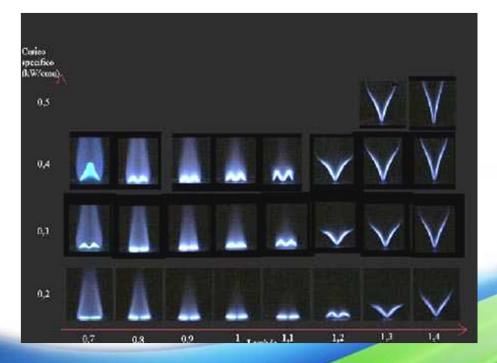




 $\lambda = 0.7 \ ps = 0.4 \ kW/cm^2 \qquad \lambda = 1.1 \ ps = 0.4 \ kW/cm^2 \qquad \lambda = 1.3 \ ps = 0.4 \ kW/cm^2$ 



$$\lambda = 1.3 \text{ ps} = 0.4 \text{ kW/cm}^2$$



Flame behavior for different lambda and specific load



# **Reaction chemistry influence**

It is possible to affect chemistry directly introducing catalytic elements .

It is possible to accelerate or delaying the completeness of the reactions affecting the residential time inside a combustion chamber / HE

Switching from laminar to turbulent fluid dynamics



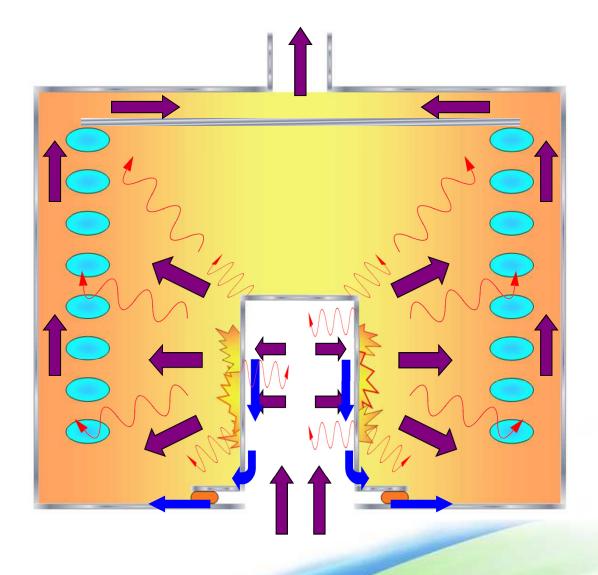
# **Temperature effect**

It is possible to accelerate or delaying the completeness of the reactions introducing or removing heat to the reacting flow (e.g steel or ceramic rod into the flame)

The combustion chamber wall and/or the HE too close to the flame front, or any element that move/transfer heat from the combustion area to the surrounding HAS a deep impact on the emissions.

# **Heat Transfer Effects**





# **Heat Transfer Effects**



The weight of conduction, convection and radiation changes according to the mode of working of the burner.

A burner may operate from blue flame mode

to

radiation mode







#### **Example Nox Reduction Techniques**



The majority of  $NO_X$  produced is temperature dependent therefore ways of lowering combustion temperatures is attempted;

- (a) Lean Burn results in cooler flames, systems are run at ≥20% excess air.
- (b) Low Residence time
- (c) Well mixed systems
- (d) Insert of radiating rod to cool the flame
- (e) Inserts downstream of peak flame area

# **Burner Types**





#### **Burner Types**



# **Premix**

- (a) Fan powered so that the fuel/air ratio can be carefully controlled.
- (b) Run lean (≥20%) with NO<sub>x</sub> emissions < 45 mg/kWh
- (c) Typically produce short intense blue flames
- (d) Short reaction zones and the highest burning velocities hence the smallest residence times & high efficiencies
- (e) The heat exchanger can (and should) be located very close to cool the exhaust as quickly as possible to avoid  $NO_X$  formation.

#### **Burner Types**



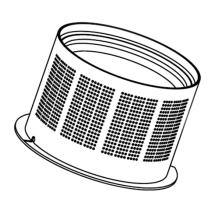
# **Atmospheric**

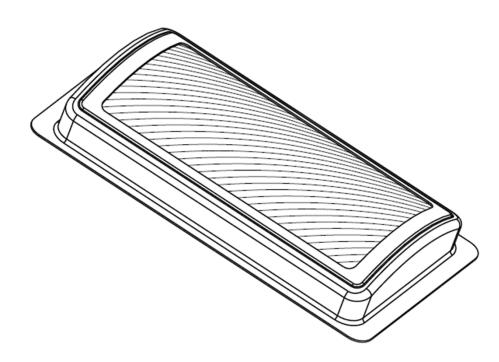
- (a) Most common type of domestic burner (tube arrays, blade assemblies), low cost manufacture with little maintenance.
- (b) Partially premixing (air entrained into gas stream before burner) to lower flame temperature.
- (c) Run on a rich/air mix to form inner combustion zone, preventing thermal NOx with low O concentration.
- (d) Tend to give relatively large flame volumes giving longer residence times for  $NO_x$  production to occur.



# **Design for Application**



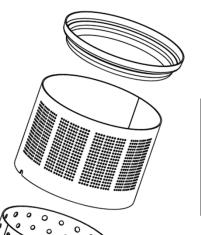




Design for most common premix burners

# **Design for Application**





The front flange , or frame , of a burner defines the interaction between burner and mixture inlet duct. It is, and must be, a component hight customizable

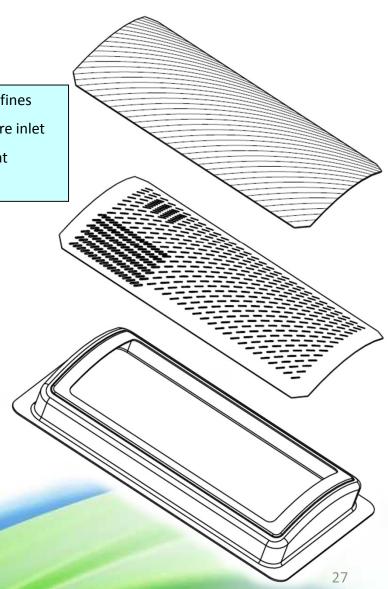
The distributor, one or more, is necessary to properly arrange the mixture flow on the Burning body. It is a key element that affects: Emissions

Noise behaviour

The burner body , or flame diffuser, is the most important component – in contact with the flame region. It is a key element that affects :

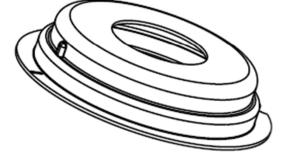
Modulation and emission

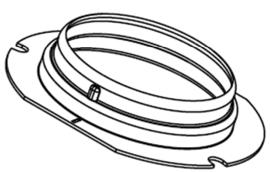
Noise behaviour

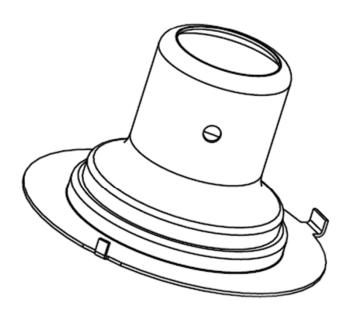


# **Design of Application**









Example of customization of the front flange.

# **Design for Application**



# Cylindrical premix : full metal vs fiber fabric





#### Flat ceramic burner



#### Flat metal



# **Design for Application**



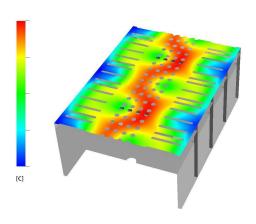


# **Design for Application - CFD**

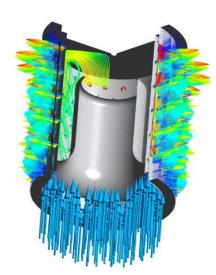


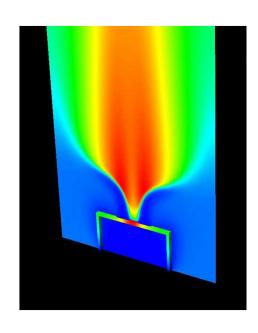
# Flame shape analysis

# Temperature field on fluids and solid materials



Gas mixture





Pressure drops

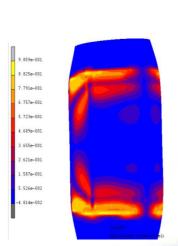
# **Design for Application - FEM**

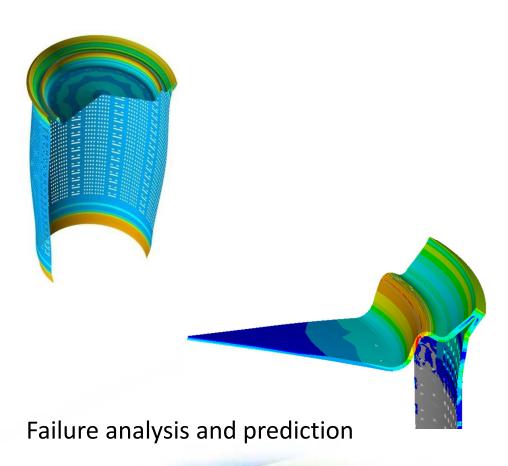


Strain and stress analysis

Welding analysis & design

Non-linear buckling analysis



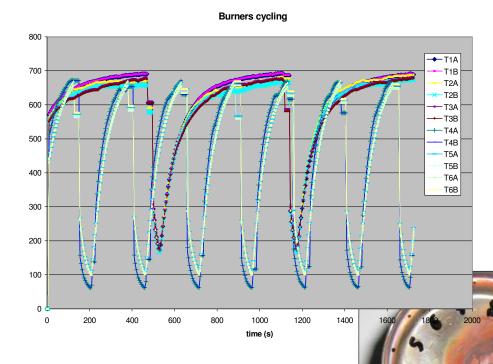


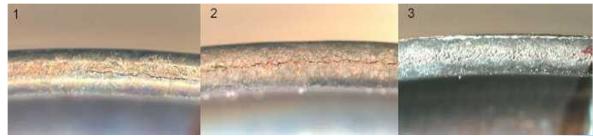
# **Design for Application – Life Tests**





Thermal cycling for accelerated life tests

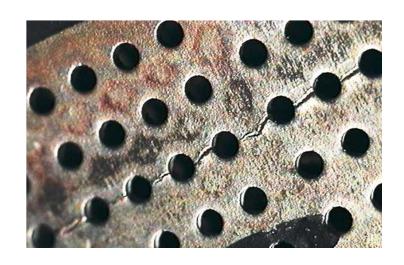




# <u>Design for Application – Structural Failure</u>



Crack on a metal surface of the diffuser due to thermal cycling



# **Test Gas & Interchangeability of Gases**



#### Test gas for second family, T=15°C, p1013,25mbar

	pt brilly lights	/s	esignation Composition	100 Miles	Aller St. H. B.	Allright Wes	MJIPP3	MJINS
	Reference Gas	G20	CH4=100	45,67	34,02	50,72	37,78	0,56
Group	Incomplete combustion gas and sooting limit gas	G21	CH4=87 C3H8=13	49,6	41,01	54,76	45,28	0,68
Н	Light-back limit gas	G222	CH4=77 H2=23	42,87	28,53	47,87	31,86	0,44
ΙI	Flame lift limit gas	G23	CH4=92.5 N2=7.5	41,11	31,46	45,66	34,95	0,59
Group L	Reference gas and light-back limit gas	G25	CH4=86 N2=14	37,38	29,25	41,52	32,49	0,61
	Incomplete combustion gas and sooting limit gas	G26	CH4=80 C3H8=7 N2=13	40,52	33,36	44,83	36,91	0,68
	Flame lift limit gas	G27	CH4=82 N2=18	35,17	27,89	39,06	30,98	0,63
	Reference Gas	G20	CH4=100	45,67	34,02	50,72	37,78	0,56
Group E	Incomplete combustion gas and sooting limit gas	G21	CH4=87 C3H8=13	49,6	41,01	54,76	45,28	0,68
	Light-back limit gas	G222	CH4=77 H2=23	42,87	28,53	47,87	31,86	0,44
	Flame lift limit gas	G231	CH4=85 N2=15	6,82	28,91	40,9	32,11	0,62

A burner has to cover a wide range of gas qualities regarding emissions, stability, ignition, input rate, modulation

- ■The "reference gas" is close to the local line gas quality.
- ■The limit gases test for
  - \* flame lift: light gas with N2
  - \* flash back: high burning velocity through H2
  - \* Incomplete combustion or sooting: with higher calorfic gases
- Group H: Italy, Group E: Germany, Group L: Netherlands

# Test Gas & Interchangeability of Gases



# Test program: defined by standards + appliance manufacturer

Boiler type B, atmospheric burner < 70kW, according EN297  Pressure indicated refer to the inlet pressure							
Test		Test gas groups			Pressure/Heat Input		
	1631	E	H	L	Without governor	With governor	
Ini	tial adjustment with reference gas	G20	G20	G25	Pn	Qn	
Ignition,	Ignition, cross-lightning with reference gas		G20	G25	0.7 pn	0.925 Qn-min	
Light-back with limit gas		G222	G222	G25	Pmin	0.925 Qn-min	
Flower life with limit was		G231	G23	G27	Pmin	0.925 Qn-min	
	Flame lift with limit gas			G21	Pmax	1.05 Qn	
	Updraft	G20	G20	G25	Pmax	1.05 Qn	
Combustion		G21	G21	G26	1.075 Qn	1.05 Qn	
Combustion	Block	C20	620	G25	De	05	
	Downdraft	G20	G20		Pn	Qn	

Boiler type C < 70kW, according EN483  Pressure indicated refer to the inlet pressure							
Test		Test gas groups			Pressure/Heat Input		
		Е	Н	L	Without governor or gas/air ratio control	With governor	
Init	Initial adjustment with reference gas		G20	G25	Pn	Qn	
Ignition,	Ignition, cross-lightning with reference gas		G20	G25	0.7 pn	0.7 pn	
	Light-back with limit gas		G222	G25	Pmin	Pmin	
	Flame lift with limit gas		G23	G27	Pmin-max	Pmin-max	
	Nominal voltage	G20	G20	G25	Pmax	1.05 Qn	
[	Nominal voltage	G21	G21	G26	1.075 Qn	1.05 Qn	
Combustion	Nominal voltage	G231	G23	G27	Pmin	0.95 Qn	
Combustion	85% of the nominal voltage	G20	G20	G25	Pn	Qn	
	110% of the nominal voltage	G20	G20	G25	Pn	Qn	
	Wind conditions	G20	G20	G25	Pn	Qn	

# **Test Gas & Interchangeability of Gases**



DVGW-G260/I (T=273K, p=1,01325mbar)							
Parameter		Unit	L	Н			
	Range	MJ/m <sup>3</sup>	37,8 46,8	46,1 56,5			
Wo,n	Nominal	MJ/m <sup>3</sup>	44,6	54			
	Local change	MJ/m <sup>3</sup>	+2,16 / -4,32	+2,52 / -5,04			
	Range	MJ/m <sup>3</sup>	30,2 47,2				
Ho,n	Nominal	MJ/m <sup>3</sup>	Not defined				
	Local change	MJ/m <sup>3</sup>	Not defined				
D	Realitive density	-	0,55 0,70				
Pappliance	Range	Mbar	18 24				
	Nominal	Mbar	20				

- What happens to burner to different gas qualities?
- One way: Wobbe Index: HV/sqrt (rel. density )
  - Many work done by AGA, AHRI on interchangeability – LNG

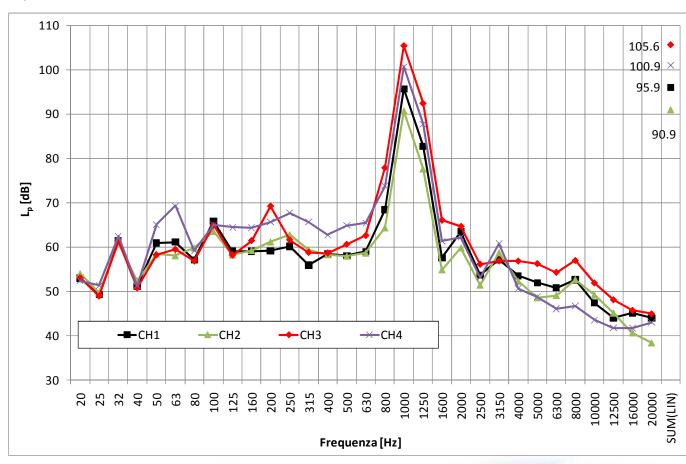
#### Example for input rate change

- Pressure: (no regulator)
- 20 mbar->24 mbar => +10%
- Wobbe:
- 54 MJ/m^3 ->56,5 MJ/m^3 => +5%

# **Design for Application – Noise**



# FFT analysis



#### <u>Design for Application – Noise</u>

# WORGAS®

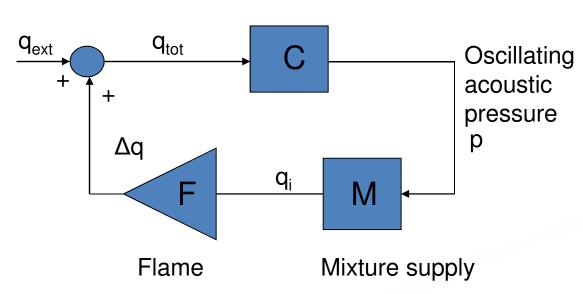
# ASHRAE TC 6.10 (Fuels and Combustion):

Validation of low-order acoustic model of boilers and its application for diagnosing combustion driven oscillations, Prof. David Herrin – University of Kentucky

Pressure – heat release oscillation

heat release proportional to acoustic velocity

#### Combustion chamber



q<sub>i</sub>: volume velocity of the mixture flow

Δq: volume flow oscillation

q<sub>ext</sub>:external perturbation to volume acoustic velocity

 $q_{tot}$ :  $\Delta q + q_{ext}$ 

Feedback loop stability model: Baade, P. K., "Design Criteria and Models for Preventing Combustion Oscillations," ASHRAE Transactions, Vol. 84, Part 1, pp. 449-465 (1978).

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