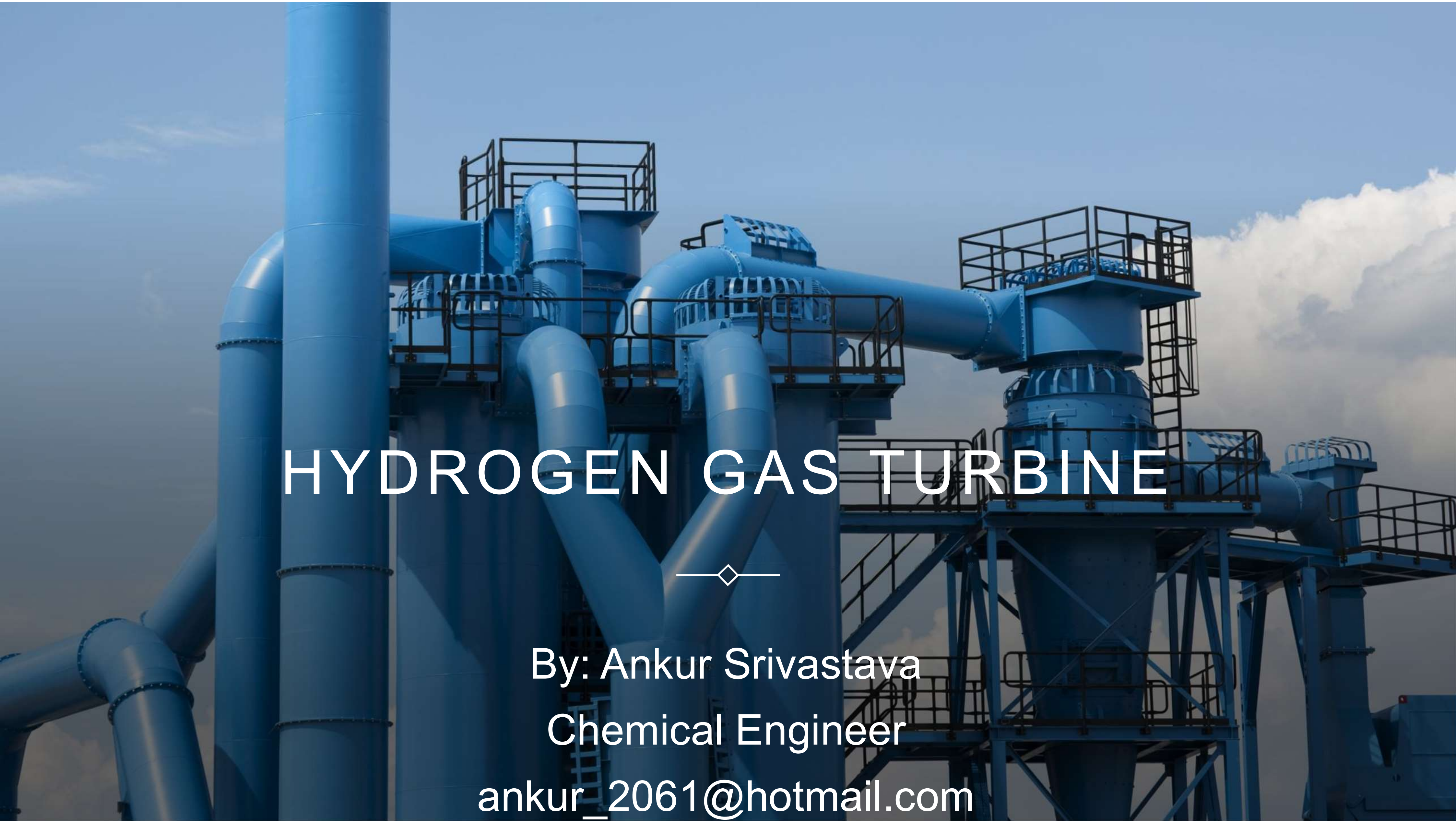

HYDROGEN GAS TURBINE

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Gas Turbine – General Information

Extensively used in all phases of the gas industry as a source of shaft power

Used for driving compressors, electrical generators and other equipment

Advantages of Gas Turbines

- Compact and Light weight
- Minimal Maintenance
- Short Installation Times

Basic Gas Turbine thermodynamic cycle is termed the Brayton Cycle

Industrial Gas Turbine Types

Initially developed as an aircraft powerplant

With technological developments it was adopted for high-power stationary applications

Two basic types for high-power stationary applications

- Industrial or Heavy-Duty Design
- Aircraft Derivative Design

Although industrial turbines categorised as gas turbines are multi-fuel turbines which can use a wide variety of fuels including liquid fuel, this presentation is limited to gas turbines using gaseous fuels such as natural gas, hydrogen & hydrogen-rich gases

Heavy Duty Turbine

Designed exclusively for stationary use

Specified where high power output is required, 26 MW and above

Advantages of Heavy-Duty Turbine

- Less Frequent Maintenance
- Can burn a wide variety of fuels including hydrogen
- Power outputs up to 150 MW available

Aircraft Derivative Turbine

Based on Aircraft Engine design

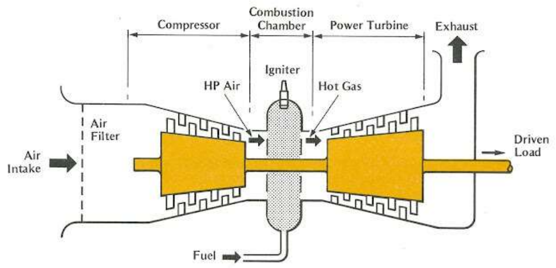
Adapted for industrial use to develop shaft power

Advantages of Aircraft Derivative Turbines

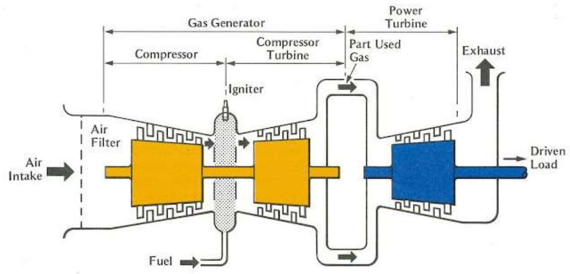
- Higher efficiency than heavy-duty
- Quick overhaul capability
  - Lighter and more compact and hence suitable for applications such as offshore installations

Single and Split Shaft Turbine Design

- Gas Turbines are also differentiated by shaft configuration – Single and Split
- In single shaft design all components of the turbine are mounted on one shaft
- In a split shaft design the air compressor components are mounted on one shaft and the power turbine rotating components on another

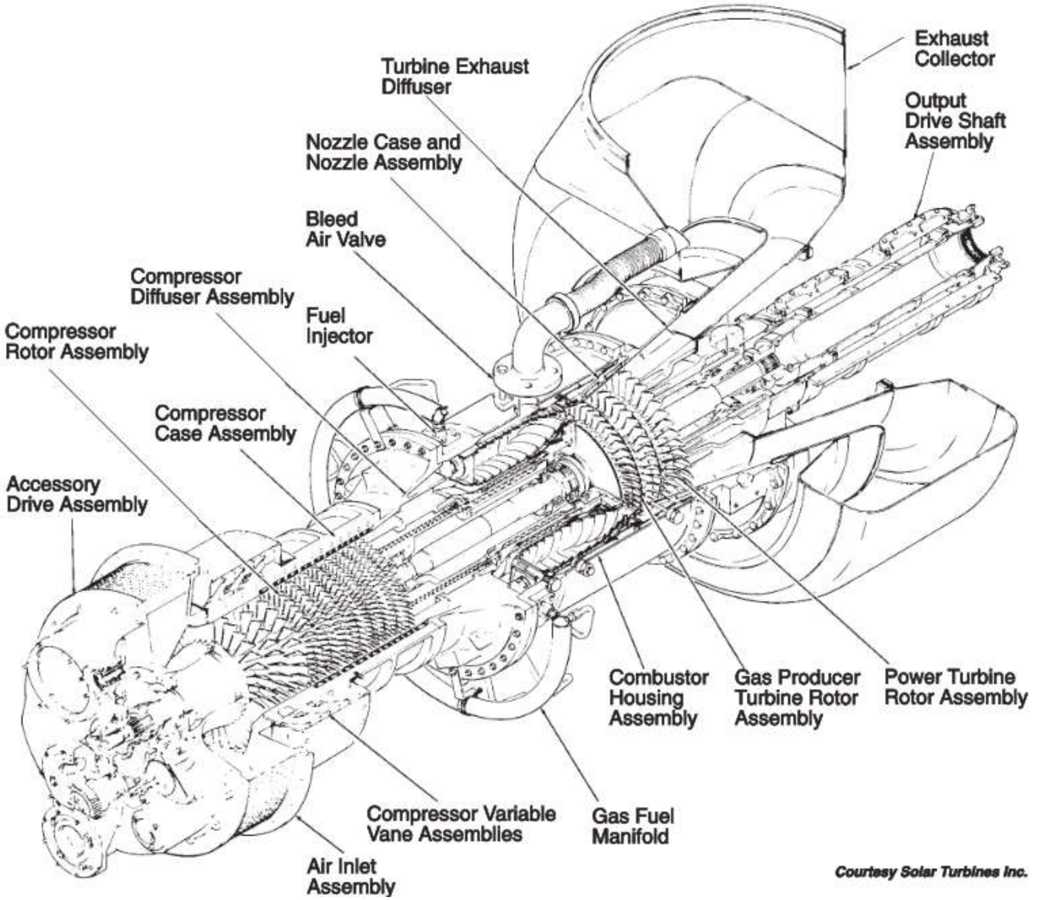


Single Shaft Gas Tuirbine



Two-shaft or Split Shaft Gas Turbine

Gas Turbine Internals – Cutaway View

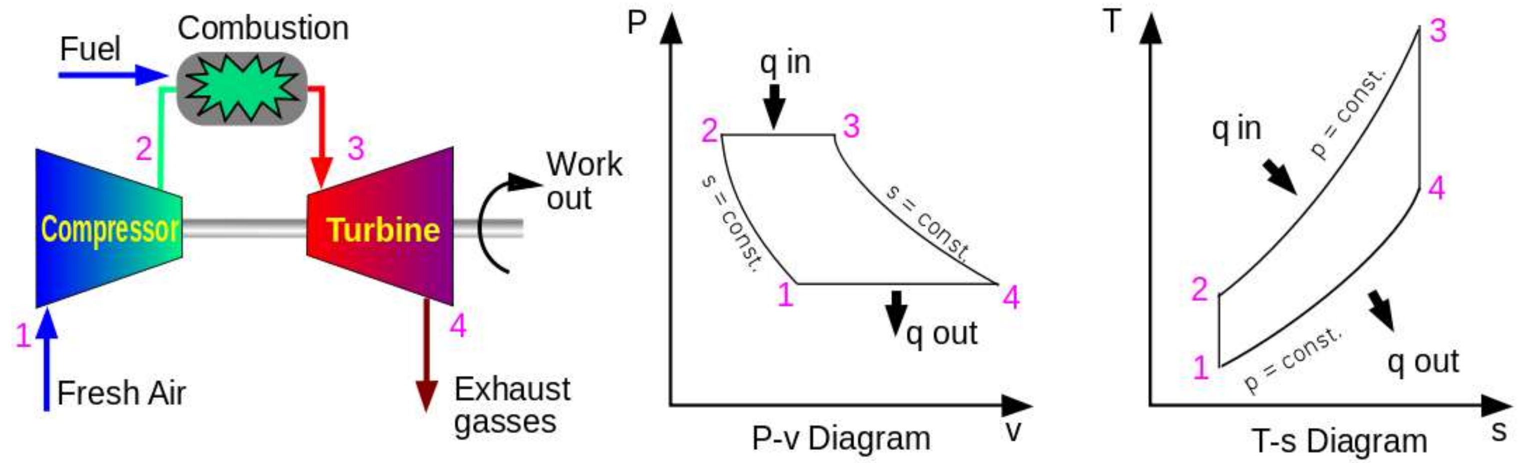


Gas Turbine Thermodynamic Cycle

- Termed as the Brayton Cycle
- Ideal Brayton Cycle is a closed cycle and consisting of the following steps:
  - isentropic compression process
  - constant pressure heating process
  - isentropic expansion process
  - constant pressure cooling process returning the working substance to inlet state of compression process
- Excellent Video for Brayton Cycle

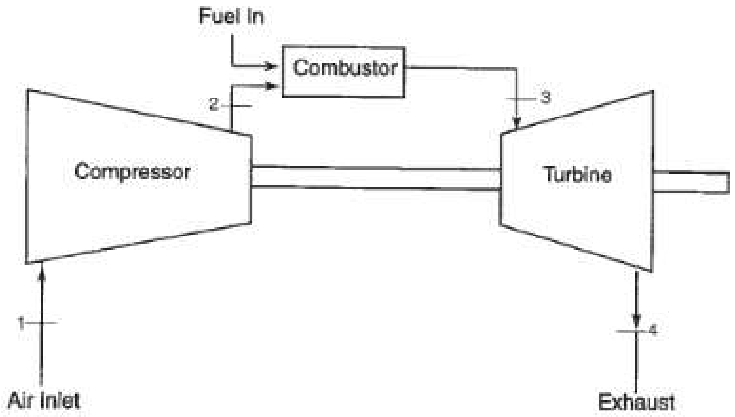
  https://youtu.be/9dDz5hRXB88

Turbine Ideal Brayton Cycle



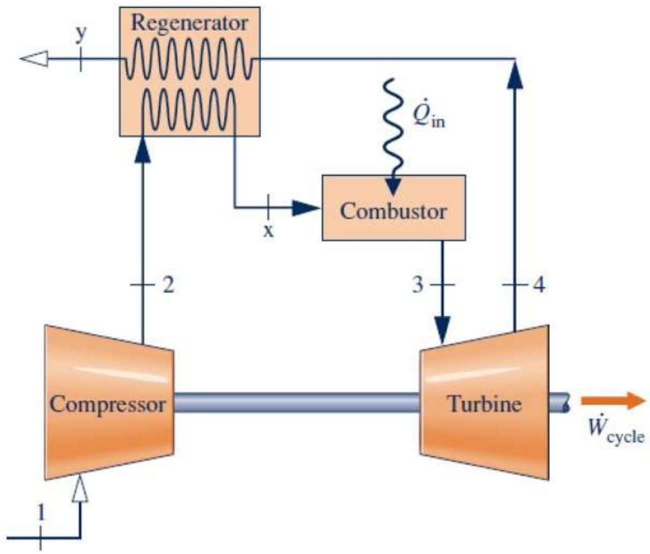
Simple Open Cycle Turbine

- Intake is atmospheric air to compressor as working substance
- Following compression air enters combustor
- Fuel is introduced into combustor and temperature raised by combustion
- Gaseous combustion products then expanded back to atmosphere thru a turbine
- Turbine derives enough power to drive both the compressor and the load



Regenerative Ideal Brayton Cycle Turbine

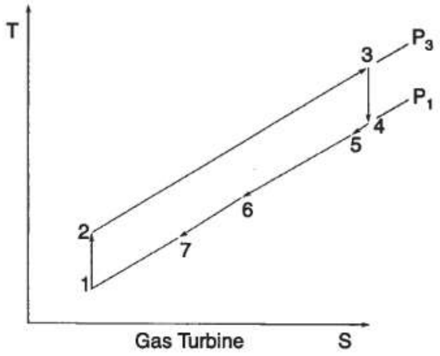
- A regenerator (heat exchanger) is added in the system
- The hot exhaust gases from the turbine heat the compressed air from the compressor
- Advantages of Regenerative Gas Turbine
  - ➢ Results in an increase in thermal efficiency compared to the simple open cycle
  - ➢ Increase in output power
  - ➢ Decrease in exhaust gas temperature

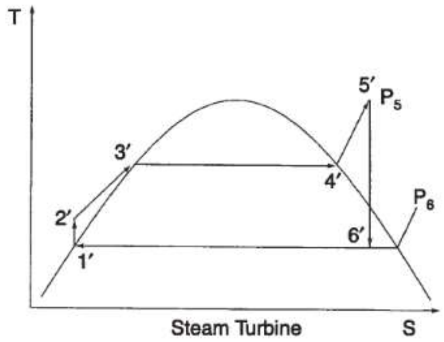


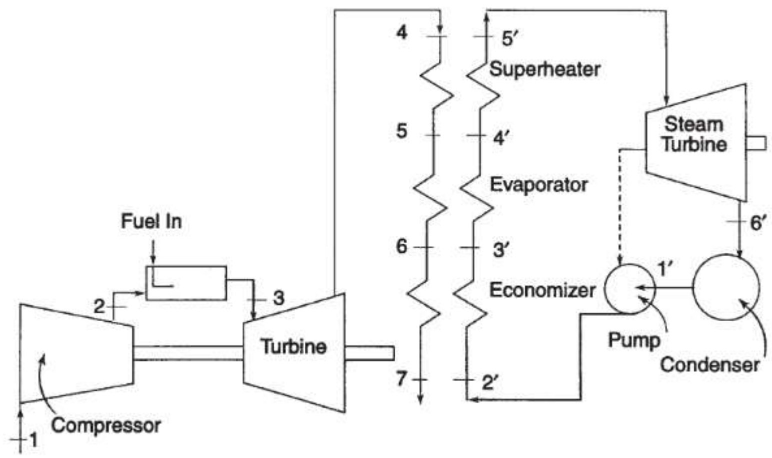
Combined-Cycle Gas Turbine (CCGT)

- Instead of using hot exhaust gases from the turbine for regeneration, the exhaust gases are used to generate steam from a Heat Recovery Steam Generator (HRSG)
- Additional power is generated by hot exhaust gases passing successively through the superheater, evaporator, & economizer of the HRSG before exhausting to the atmosphere in a basic Rankine Cycle.
- Steam from the HRSG is used to drive a steam turbine to produce additional power.
- Refer the next slide for the Combined-Cycle Turbine System schematic including the T-S diagram.

Combined-Cycle Gas Turbine (CCGT) (contd.)







Gas Turbine Performance - 1

- Expressed in terms of power and heat rate
- Power is the net power available at the output shaft of the turbine after subtracting all losses and power take-offs
- Heat Rate is a measure of the thermal efficiency or the amount of heat energy (in the form of fuel) which must be input to the turbine to produce the output power.
- Heat rate is expressed as kJ/(kW.h) based on LHV of the fuel combusted
- Thermal efficiency of the gas turbine can be calculated as follows:

$$\text{Thermal efficiency} = \frac{3600}{\text{Heat Rate}, \frac{\text{kJ (LHV)}}{\text{kW} \cdot \text{h}}}$$

Gas Turbine Performance - 2

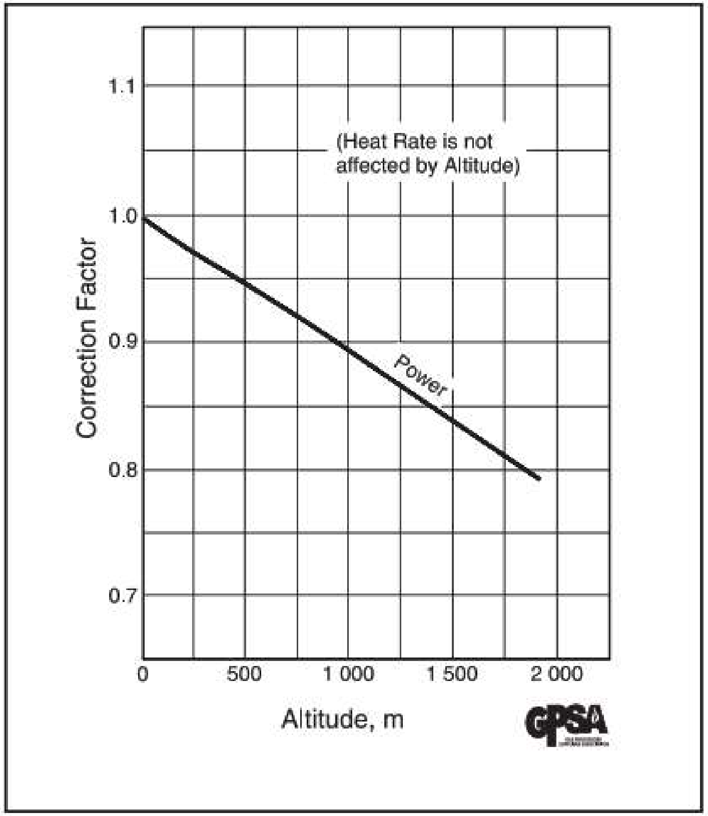
- Power and Heat Rate have dependency on the following parameters:
  - Ambient Air Temperature
  - Altitude (from Mean Sea Level)
  - Barometric Pressure
  - Humidity (expressed as % Relative Humidity)
- Gas Turbine manufacturers provide power and heat rate data for their turbines based on a standard set of conditions known as ISO conditions for technical comparison.
- ISO Conditions for gas turbines
  - Ambient Temperature = 15ºC
  - Altitude = 0 m (sea level)
  - Ambient Pressure = 101.325 kPa (abs)
  - Relative Humidity = 60%

Gas Turbine Performance -3 (Site Rated Power)

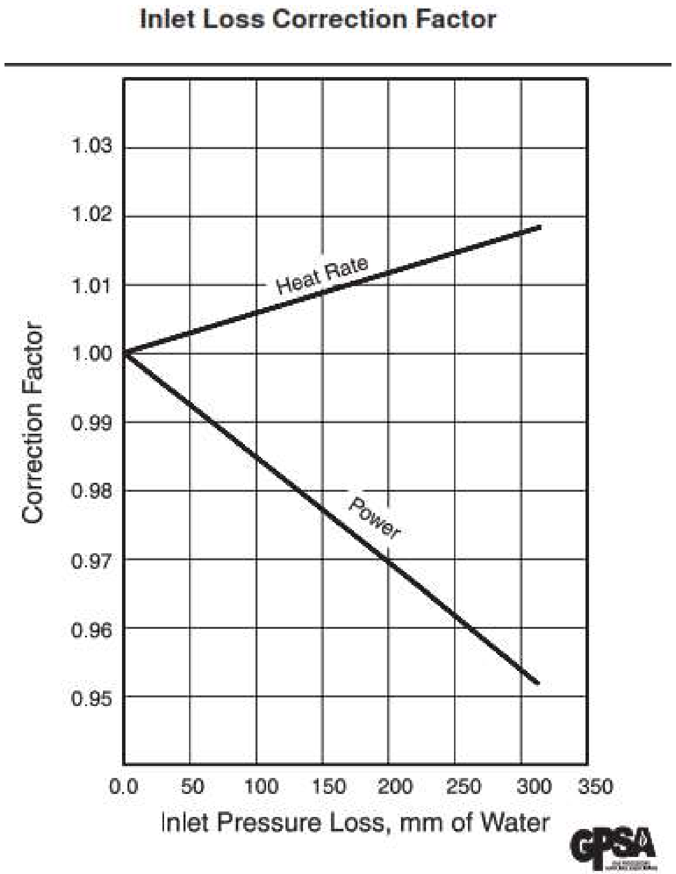
- The site rated power for the given gas turbine can be calculated based on correcting the ISO conditions for altitude, inlet losses, exhaust losses, ambient temperature and relative humidity
- Refer the subsequent slides for correction factor charts of the ISO conditions based on actual site conditions

Gas Turbine Performance - 4 (Altitude Correction)

Altitude Correction Factor

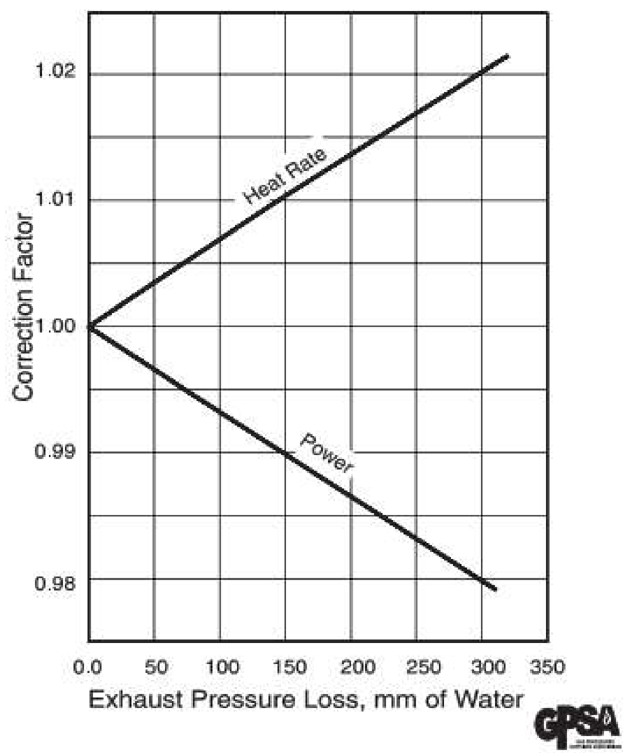


Gas Turbine Performance - 5 (Inlet Losses Correction)



Gas Turbine Performance - 6 (Exhaust Losses Correction)

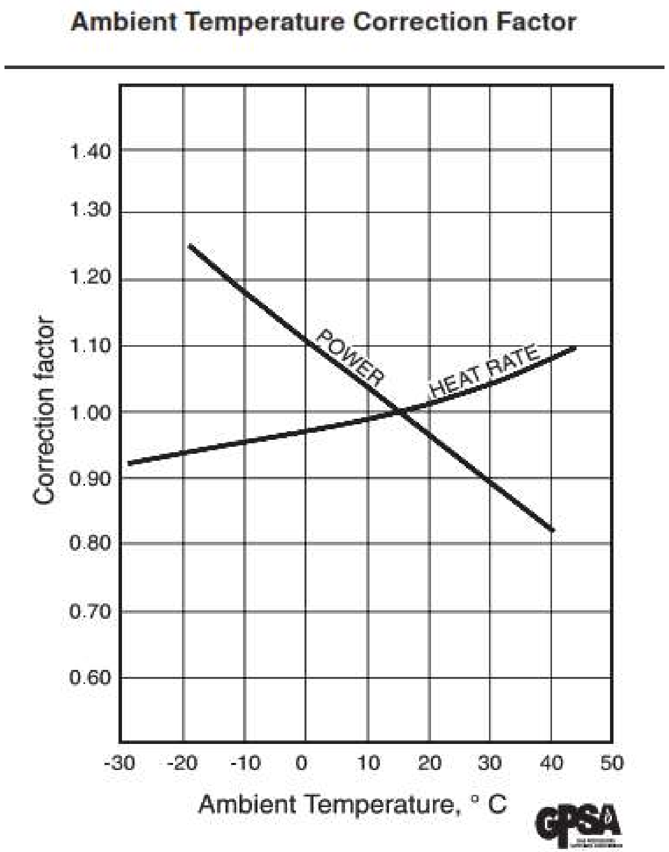
Exhaust Loss Correction Factor



Approximations for Inlet / Exhaust Losses for Gas Turbines

- Inlet losses are approximated as 100 mm of water column
- Exhaust losses are somewhat higher and are approximated as 150 mm of water column without heat recovery
- Exhaust losses with exhaust used for heat recovery in a HRSG <u>without</u> firing maybe approximated as 200 mm of water column
- Exhaust losses with exhaust used for heat recovery in a HRSG <u>with</u> firing maybe approximated as 300 mm of water column

Gas Turbine Performance - 7 (Ambient Temp. Correction)



Gas Turbine Performance - 8 (Humidity Correction)

- Change in Relative Humidity doesn’t change the power output
- Heat Rate change is minimal for change in Relative Humidity

Gas Turbine Performance - 9 (Applying Correction Factors)

- Site Power (SP) calculation

  $SP = (ISO\ Power)*CF_{alt}*CF_{inletloss}*CF_{exhaustloss}*CF_{Tamb}$

  where:

  SP = Site Power, kW

  ISO Power = ISO power for given turbine, kW

  CF_{alt} = Correction factor for altitude

  $CF_{inletloss}$ = Correction factor for inlet loss

  $CF_{exhaustloss}$ = Correction factor for exhaust loss

  CF_{Tamb} = Correction factor for ambient temperature

Gas Turbine Performance -10 (Applying Correction Factors)

- Heat Rate (HR) Calculation

  $HR = (ISO\ HR)*CF_{inletloss}*CF_{exhaustloss}*CF_{Tamb}$

  where:

  HR = Site Heat Rate, kJ/(kW.h)

  ISO HR = ISO Heat Rate for given turbine, kJ/(kW.h)

  $CF_{inletloss}$ = Correction factor for inlet loss

  $CF_{exhaustloss}$ = Correction factor for exhaust loss

  CF_{Tamb} = Correction factor for ambient temperature

Emissions from Gas Turbines

- In general gas turbines have lower emissions relative to other heat engines in similar service
- Emissions are a major criteria in the selection of a gas turbine for a given application.
- CO emissions if any are due to incomplete combustion of the fuel carbon. However, ample excess air ensures that CO emissions are negligible.
- Unburned Hydrocarbons (UHC) are formed by incomplete combustion of the fuel. Combustion efficiency plays a role in determining the CO and UHC content. Modern combustor designs have ensured that CO and UHC emissions are negligible.
- Sulfur Oxides (SO_X) are a direct function of the sulfur content in the fuel
- Most significant are the Nitrogen Oxide (NO_X) emissions from gas turbines. These are the function of the type of fuel, firing temperature, compressor discharge temp., and residence time in the combustion zone.

NO_X Emissions from Gas Turbines

- NO_X emissions are categorized into two types based on mechanism of formation:
  - Thermal NO_X: Formed by oxidation of the Nitrogen in the combustion air. It is a function of the stoichiometric flame temperature and is of the order of ppm (by volume) in the exhaust. Generally thermal NO_X is unavoidable.
  - Organic NO_X: Formed by oxidation of organically bound N_2 in the fuel. N_2 bound with fuel appears as 100% NO_X in the exhaust.
- Higher stoichiometric flame temperatures increase the thermal NO_X. Reducing the flame temperature increases the Organic NO_X if the fuel has organically bound N_2.

Factors Influencing NO_X formation

- Pressure and Temperature: Higher Pressure and Temperature in the primary combustion zone increases the NO_X emissions exponentially
- Fuel / Air Ratio: Where the fuel/air mixture is lean NO_X emissions are higher whereas high Fuel / Air mixture gives lower NO_X emissions
- Fuel and Air Mixing
- Combustor Geometry
- Residence time in the combustor: Higher residence times in the combustor increases the NO_X emissions linearly

NO_X formation Correlations for Gas Turbines - 1

- Lefebvre Correlation

$$NO_X = \frac{9 \times 10^{-8} \times P^{1.25} \times V_c \times \exp(0.01 \times T_{st})}{m_a \times T_{pz}}$$

where:

NO_X = NO_X emissions in g/kg

P = pressure in the gas turbine combustor, kPa

V_c = Volume of gas turbine combustor, m^3

T_{st} = stoichiometric flame temperature, K

m_a = mass flow rate of air in combustor, kg/s

T_{pz} = primary zone temperature, K

NO_X formation Correlations for Gas Turbines - 2

- Rokke et. al. correlation for NOX from natural gas fired turbines (1.5 MW to 35 MW)

$$NO_X = 18.1 \times P^{1.42} \times m_a \times f^{0.72}$$

where:

NO_X = ppmv corrected to 15% O_2 dry (Ref: 40 CFR § 60.332 US EPA)

P = pressure in the gas turbine combustor, atm

m_a = mass flow rate of air in combustor, kg/s

f = fuel-air ratio

NO_X formation Correlations for Gas Turbines - 3

- Rizk and Mongia Correlation

$$NO_X = \frac{0.15 \times 10^{16} \times (\tau - 0.5\tau_e)^{0.5} \times \exp\left(-71000 / T_{st}\right)}{P^{0.05} \times \left(\frac{\Delta P}{P}\right)^{0.5}}$$

where:

τ = residence time in combustion zone, seconds

τ_e = evaporation time, seconds

T_{st} = stoichiometric flame temperature, K

P = pressure in the gas turbine combustor, Pa

ΔP = Pressure Drop in turbine combustor, Pa

NO_X = NO_X emissions in g/kg

NO_X formation Correlations for Gas Turbines - 4

- Bakken and Skogly Correlation for natural gas fired turbines (GE LM-2500)

$$NO_X = 62 \times P^{0.5} \times f^{1.4} \times \exp\left(\frac{-635}{T}\right)$$

where:

NO_X = ppmv corrected to 15% O_2 dry (Ref: 40 CFR § 60.332 US EPA)

P = pressure in the gas turbine combustor, Pa

f = fuel-air ratio

T = combustion mean temperature, ºC

NO_X formation Correlations for Gas Turbines - 5

- Sullivan Correlation

$$NO_X = A_{nox} \times P^{0.5} \times f^{1.4} \times m_a^{-0.22} \times \exp\left(\frac{T}{250}\right)$$

where:

NO_X = ppmv corrected to 15% O_2 dry (Ref: 40 CFR § 60.332 US EPA)

A_{nox} = turbine combustor geometry parameter, constant

P = pressure in the gas turbine combustor, Pa

f = fuel-air ratio

m_a = mass flow rate of air in combustor, kg/s

T = combustion mean temperature, K

NO_X formation Correlations for Gas Turbines - 6

- Odgers and Kretschmer Correlation

$$NO_X = 29 \times \exp(-21670/T) \times P^{0.66} \times \left(1 - \exp(-250 \times \tau)\right)$$

where:

T = combustion mean temperature (flame temperature), K

P = combustor pressure, Pa

τ = residence time in the combustor, s

NO_X formation for Hydrogen / Hydrogen Rich Gas - 1

- Temperature Dependence of NO_X formation for combusting hydrogen

Table 3 NOx formation by hydrogen combustion

Temperature [K]	NOx [ppm] (Daniele et al., 2008)	NOx [ppm] (Lin et al., 2012)
1400	0,3	0,25
1500	0,6	0,7
1600	1	1,1
1700	1,5	1,8
1800	2,5	2,0
1900	4	
2000	9	
2200	40	

- Plotting the data as a chart and developing a trendline for the chart the following equation correlates the NO_X formation with the turbine combustor exit temperature:

$$NO_X = 8 \times 10^{-5} \times e^{(0.0058 \times T)}$$ -------- Eqn 1

NO_X formation for Hydrogen / Hydrogen Rich Gas -2

- Equivalence Ratio Dependence of NO_X formation for combusting pure hydrogen
  - ➢ The equivalence ratio (ER) is defined as the ratio between actual fuel/air ratio to the ideal stoichiometric fuel/air ratio.

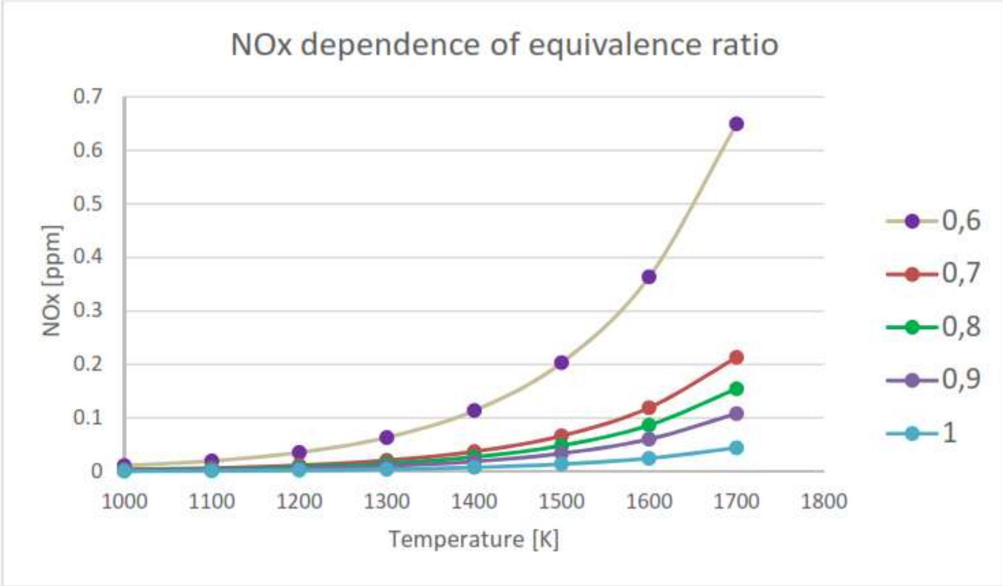


Figure 12 NOx dependence of equivalence ratio (Cam et al., 2017).

The end points in the figure above are the emission at the exit of the combustor. Table 4 shows useful data points collected from Figure 12.

Table 4 NOx values provided by (Cam et al., 2017).

Fuel/air ratio	***NOX [ppm]***
0,6	**0,033**
0,7	**0,083**
0,8	**0,217**
0,9	**0,383**
1	**0,250**

NO_X formation for Hydrogen / Hydrogen Rich Gas - 3

- Improved NO_X emission model by fitting both temperature and equivalence ratio into a single equation
- Coefficient generated by fitting Table 4 data to eqn 1 giving the following expression:

$$C_{new} = \frac{NO_X}{e^{0.0058 \times T}}$$ -------------- Eqn 2

where:

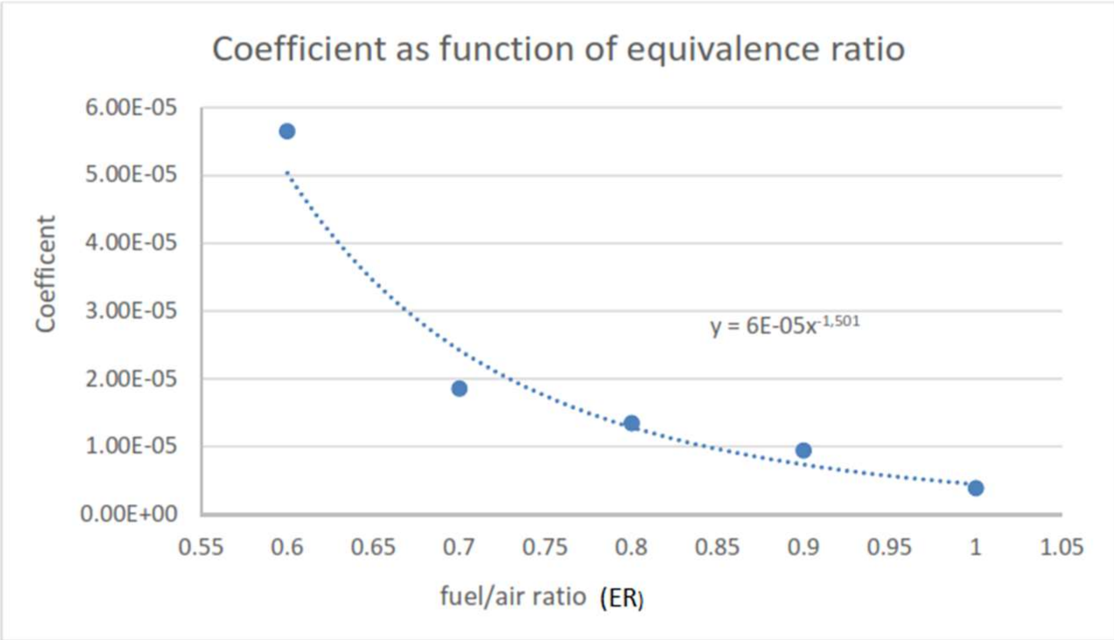
C_{new} = coefficient based on equivalence ratio (ER)

T = Temperature (Range: 1100-1900 K)

Refer the Plot of the equivalence ratio (ER) vs coefficient in the next slide

NO_X formation for Hydrogen / Hydrogen Rich Gas - 4

- Plot of Equivalence Ratio vs Coefficient



- Trendline eqn $C_{new} = 6 \times 10^{-5} \times ER^{-1.501}$ ----- Eqn 3

NO_X formation for Hydrogen / Hydrogen Rich Gas - 5

- Combining eqn 1 and 3 a comprehensive equation for NO_X emissions encompassing both temperature and equivalence ratio (ER) is obtained as follows:

$$NO_X = 6 \times 10^{-5} \times ER^{-1.501} \times e^{0.0058 \times T}$$

where:

NO_X = NO_X emissions in ppmv

ER = equivalence ratio

T = combustor exit temperature, K

Reference: Hydrogen-fired gas turbine for power generation with exhaust gas recirculation, Emission and economic evaluation of pure hydrogen compare to natural gas, by Nemir Gibrael, Hamse Hassan, Academy of Economics, Society and Technology

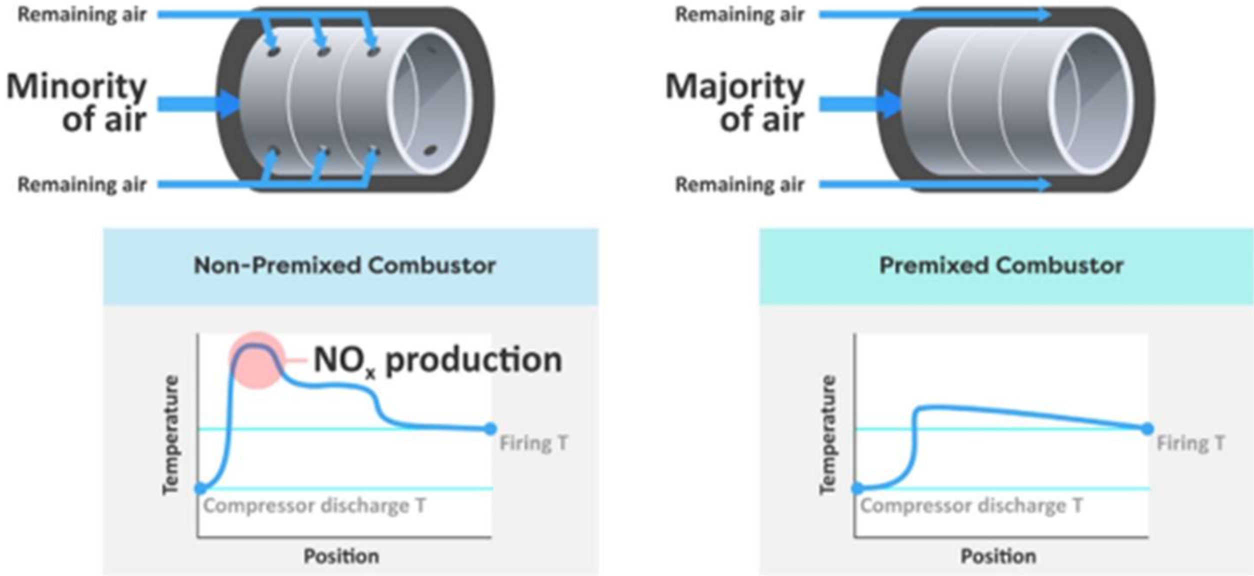
NO_X Reduction Methods for Gas Turbines

- Two approaches for NO_X reduction:
  - ➢ Water or Steam Injection: The effect of steam and water injection is to increase the thermal mass by dilution and thereby reduce peak temperatures in the flame zone. The rate of CO emissions increases with the rate of water injection. Depending on the initial NO_X levels, injection of water or steam may reduce NO_X by 60% or higher.
  - ➢ Dry Low Emission (DLE) Technology: DLE technology was developed to achieve lower emissions without using water or steam injection to reduce combustion temperature. The new burners using DLE technology are called Dry Low NO_X (DLN) burners. NO_X content in exhaust gas as low as 10–25 ppmv can be achieved by this method. However, DLN technology is complex, especially for dual-fuel turbines, and has an impact on the CAPEX of the gas turbine.

Combustor Technologies – Diffusion Flame & Lean Pre-Mixed

- Diffusion Flame Combustors: The DFC technology involves the supply of the fuel and the oxidizer in an unmixed state. The fuel/air mixing and combustion take place simultaneously in the primary combustion zone. This generates regions of near-stoichiometric fuel/air mixtures where the temperatures are very high. The DFC design yielded optimum thermodynamic properties with low pressure losses and a combustion efficiency of practically 100%.
- Lean Pre-Mixed Combustion: Lean premixed stationary combustion turbine means any stationary combustion turbine designed to operate at base load with the air and fuel thoroughly mixed to form a lean mixture before delivery to the combustor. Following are its basic characteristics:
  - ➢ Atmospheric Nitrogen (from combustion air) acts as a diluent
  - ➢ Fuel is mixed with air upstream of the combustor at fuel lean conditions
  - ➢ Fuel to air ratio typically approaches one-half of the ideal stoichiometric level
  - ➢ Excess air is the key to limiting NO_X formation, as very lean conditions cannot produce the high temperatures that create thermal NO_X.

Combustor Technologies – Diffusion Flame & Lean Pre-Mixed (contd.)



Comparison of Diffusion Flame (Non-Premixed) and Lean Premixed Combustors

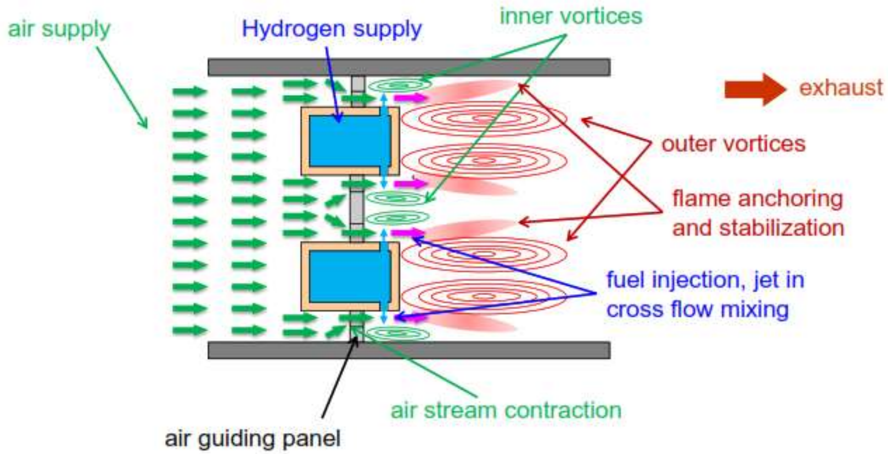
Pure Hydrogen as a Fuel for Gas Turbines

- Primary effort for developing gas turbines operated on pure H_2 is on the combustor front.
- Diffusion Flame Combustor (DFC) gas turbines using 100% H_2 produce three times the NO_X emissions than that for natural gas. Steam or Water injection to DFC alleviates the NO_X problem helping meet environmental regulations. Cost and complexity increases with the Demineralized Water requirements and overall water management systems.
- The current DLN combustor technology which involves the lean premixing of fuel and air to reduce NO_X emissions while being mature for natural gas and other fuels cannot be applied for burning 100% hydrogen. High flame speeds with 100% H_2 are required to prevent flashback in the combustor. Higher flame speeds have their own drawbacks in terms of excessive combustor pressure drops and flame stability.
- Current commercial gas turbine lean pre-mix combustor technology permits a maximum 50% by volume hydrogen mixture with most commercial systems operating well below this limit.

Advances in Burner technology for 100% H_2 Combustion

- Micromix Combustion Technology
  - First developed in Germany for aerospace applications
  - Reduces NO_X emissions at dry conditions (without water or steam injection)
  - Basic principle is to reduce the residence time of N_2 and O_2 in the hot flame zone
  - The air and fuel (hydrogen) are mixed in a cross-flow pattern
  - The flame geometry is entirely different. Instead of a single conventional flame, thousands of small and short diffusion flames provide the necessary heat release.

Micromix Combustion Technology for pure H_2



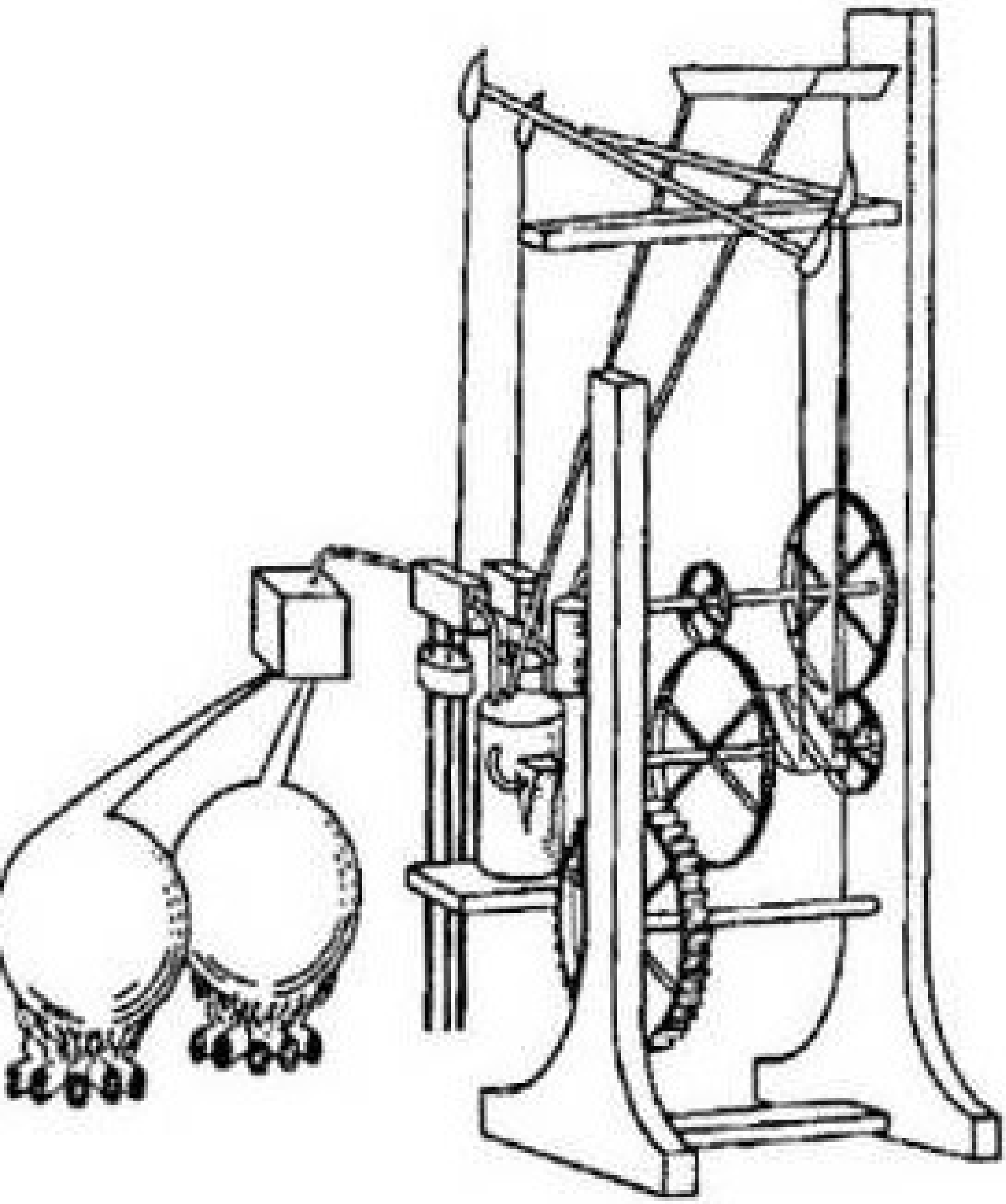
Principle of the Micromix Combustion

Micromix Combustion Technology for pure H_2 (contd.)

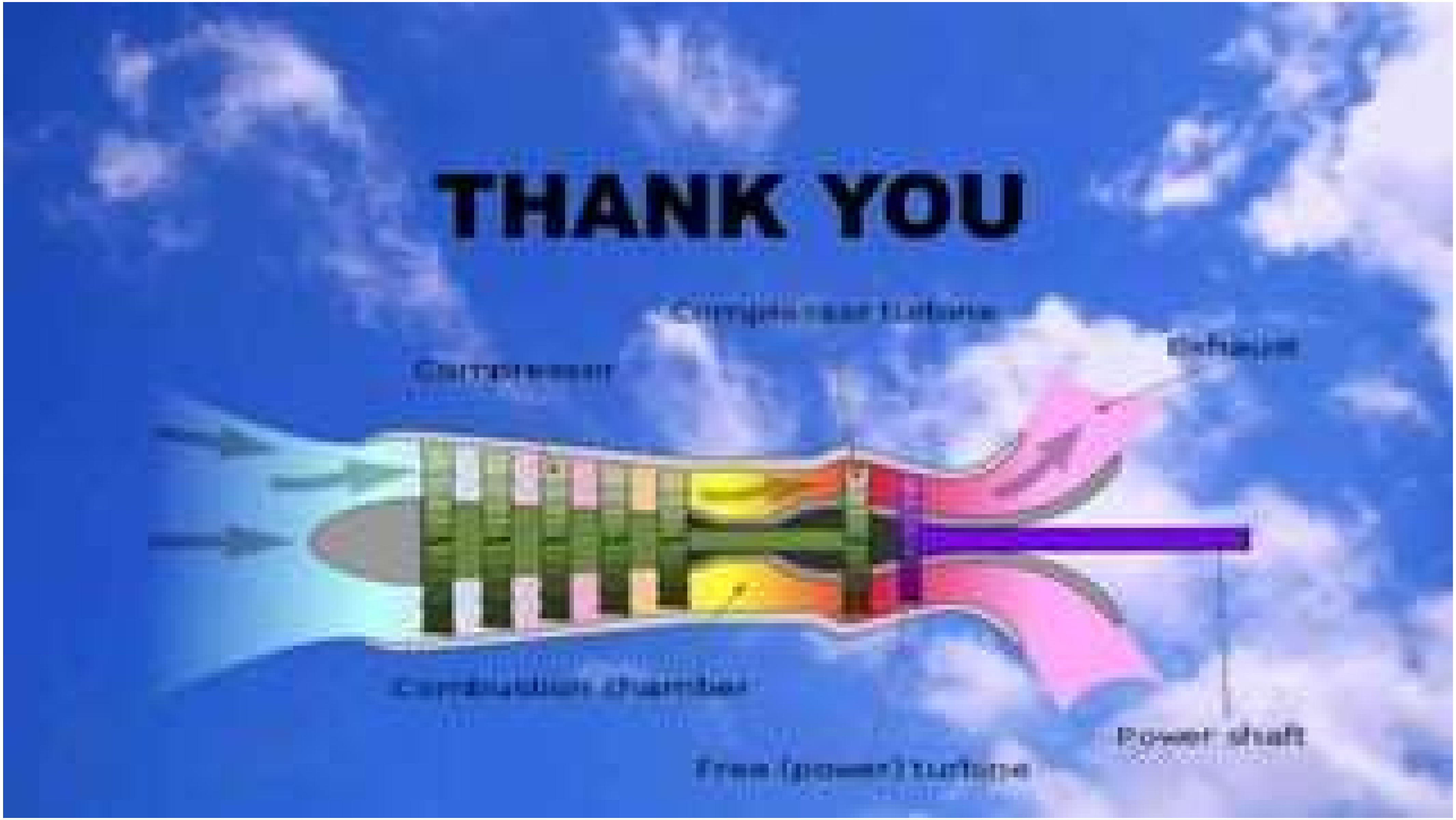
- Hydrogen fuel is supplied using Hydrogen supply ducts located within the air flow.
- Hydrogen supply ducts are connected by air guiding panels, which include small air flow gates, where the air flow is contracted into small air streams.
- The contraction of the air flow leads to the creation of small air vortices in the wake of the air guiding panel.
- The Hydrogen fuel is injected perpendicularly to the small air streams (jet in cross flow) as shown by the blue arrows in the figure.
- The mixture of fuel and air flows into the combustion chamber and larger vortices are created in the wake of the hydrogen injection ducts.
- The system of vortex pairs (green and red colored in the figure) with streams of fuel and air in-between allows stabilization of Micromix flames along the inter-vortex shear layers.
- The major advantages of this combustion principle are the inherent safety against flash-back and the low NO_X emissions due to a very short residence time of reactants in the flame region of the micro-flames.

Why hydrogen fueled gas turbines?

- With advanced burner technologies available using pure hydrogen or hydrogen-rich fuel will reduce NO_X emissions while simultaneously reducing / eliminating UHC and CO_2 emissions.
- Taking a small step towards a net zero carbon world by the year 2050 and mitigate disastrous climate change in accordance with the Paris Climate Accords.



THE FIRST GAS TURBINE BY JOHN BARBER -1791


THANK YOU
Combustion chamber
Free (power) turbine
Power shaft