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CLEAN ENERGY TECHNOLOGIES

TIPS Process Overview

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TIPS in a Nutshell – Part 1

- TIPS (ThermoEnergy Integrated Power System)
- The Key Points
  - Runs at higher pressure meaning temperature of FG condensate is elevated so that it can be used within the cycle (300 – 400 deg F)
  - If you use the heat from the FG condensate the thermal efficiency of the unit increases by ~10%
  - The condensate heat was used to partially replace extractions commonly run from various places in the turbine cycle (there are commonly 5 or 6 points of extraction taken from the steam turbines)
  - Less extraction allows the flow of steam to increase through various sections of the turbine (because less was extracted) producing about 8% more power
  - The power to run the PRT (multi-stage compression/refrigeration) is minimal because CO_2 is delivered at pressure resulting in about 50MW out of 500 MW savings
  - Due to the elevated pressures all components (furnace, heat exchangers, APC) are drastically reduced in size compared with ambient pressure units

TIPS in a Nutshell – Part 2

- Power system efficiency (all sub-critical)
  - TIPS (30% subcritical, 34% supercritical)
  - Air Fired No Carbon Capture(34% subcritical, 38% supercritical)
  - Ambient pressure oxy-fired (23% subcritical, 26% supercritical)
- New Technology
  - Most unit operations are not new and have been used in other configurations in the past
  - Traditional PFBC arrangements are slightly lower pressure than TIPS
  - Condensing FW Heaters are new

History with ThermoEnergy

- **Rationale – Ambient pressure oxy-combustion constraints**
  - Hard to increase the thermal efficiency because it was difficult to find a use for the FG condensate
    - Large amount of low temperature heat was captured within cycle
    - No logical receptors (temperature or quantity) so we discarded the source
    - Meant thermal efficiencies were similar to air-fired systems
  - The auxiliary power consumptions were large (ASU, PRT, FGR)
    - Integration of ASU
    - Configurations of PRT
    - Removal of FGR and look at other moderators
  - Size reduction
    - Size and furnace temperature were interrelated with FGR moderation
    - Ash amount constraints
    - FGR moderation made volume flows similar to air-fired systems

History with ThermoEnergy

- **Rationale – Ambient pressure oxy-combustion constraints**
  - Some impracticality to increasing the furnace temperatures
    - Supercritical circulation
    - Higher steam temperature trends
    - Material constraints
    - If material constraints were overcome there would be a strong motivation for increasing steam side temperatures as opposed to flue side temperatures
    - Ash stickiness and cleanability problems
  - Pros and cons associated with ambient FBCs
    - Could use the bed to moderate furnace temperature
    - Will result in fewer ash problems
    - Need fluidization flow amounts
    - Lower temperatures tend to increase surface requirements
  - Current configuration of oxy-fired systems
    - We had developed one configuration that worked because it matched the air fired performance
    - Difficult to make a practical, simple step change to overcome these constraints although we tried in a number of exercises

History with ThermoEnergy

- **2001**
  - Started discussions with ThermoEnergy who had a patent on the use of pressure (mostly to increase boiler thermal efficiency)
  - Pressure tended to overcome some of the constraints
  - Did a small project performing heat and mass balances on several different configurations (some with gas turbines) using this waste heat in various ways
  - Performance results looked quite favourable, however, equipment and actual operating / capital costs were undefined
- **2006**
  - ThermoEnergy received a contract from NETL to further develop the best configuration
  - We focused on one specific, very simple configuration with a few variations such as furnace type, extraction differences, 2 coals
  - Tried to take advantage of the gasification and PFBC design concepts already developed in industry
  - Focused on using the waste heat within the FW heating system of Rankine cycle to increase boiler efficiency and use within steam cycle to get extra MW output thus offsetting parasitic power consumption

Comparison of Subcritical & Supercritical Cycles

	Subcritical Reheat Regenerative	Supercritical Reheat Regenerative
Main Steam Pressure (psig)	2520	3675
Main Steam Temperature (°F)	1000	1000
Reheat Steam Pressure (psig)	653	715
Reheat Steam Outlet Temperature (°F)	1000	1000
Condenser Outlet Pressure (in. WC)	2	2.5
Condenser Outlet Temperature (°F)	101	101
Economizer Inlet Temperature (°F)	490	502

Waste Heat Utilization Potential for Different Scenarios

Air-fired at 14.7 psia

	Inlet Temperature (°F)	Outlet Temperature (°F)	Btu/lb of Coal
Air	77	626/525	935
FW Water Make Up	77	446	56
Condensate Return	90	446	2231
Economizer Water	446	564	966

Oxy-fired at 14.7 psia

	Inlet Temperature (°F)	Outlet Temperature (°F)	Btu/lb of Coal
Oxygen	77	500	172
FG Recycle	77	572/440	747
FW Water Make Up	77	446	57
Condensate Return	90	446	2259
Economizer Water	446	564	978

Waste Heat Utilization Potential for Different Scenarios

TIPS Case 1 at 1160 psia

	Inlet Temperature (°F)	Outlet Temperature (°F)	Btu/lb of Coal
Oxygen	77	500	182
FW Water Make Up	77	446	70
Condensate Return	90	446	2249
Economizer Water	446	564	946

TIPS Case 2 at 1160 psia

	Inlet Temperature (°F)	Outlet Temperature (°F)	Btu/lb of Coal
Oxygen	77	500	182
FW Water Make Up	77	446	70
Condensate Return	90	446	2333
Economizer Water	446	564	862

Pressure Effects on Sizing Radiant and Convective Surfacing

- Luminous Radiation to SH/RH
  - Increases with emissivity
  - Decreases with reduced furnace size
  - Decreases with FBC due to lower temperatures
- Non-Luminous Radiation
  - Increases with emissivity
  - Decreases with tighter spacings
  - Decreases with flue gas temperature to 4th power
- Convection $Nu = A \times (Re)^m \times (Pr)^n$
  - Large increase as density increases because $m = 0.6$
  - Density ratio is ~130 (FBC) ~ 80 (PC)
  - This means an order of magnitude (x10) convective heat transfer increase compared to that of ambient systems

Pressure Effects on Convective Pass Heat Transfer

Convective Superheater Heat Transfer Coefficients (W/m^2-°C)

Coal Technology	Inside	Wall	Outside	Fouling	Overall
Air-fired at 14.7 psia	2576	9428	61	5678	59
Oxy-fired at 14.7 psia	2576	9459	68	5678	65
TIPS at 380 psia	2436	9459	488	5678	354
TIPS at 1160 psia	2641	9437	1113	5678	618

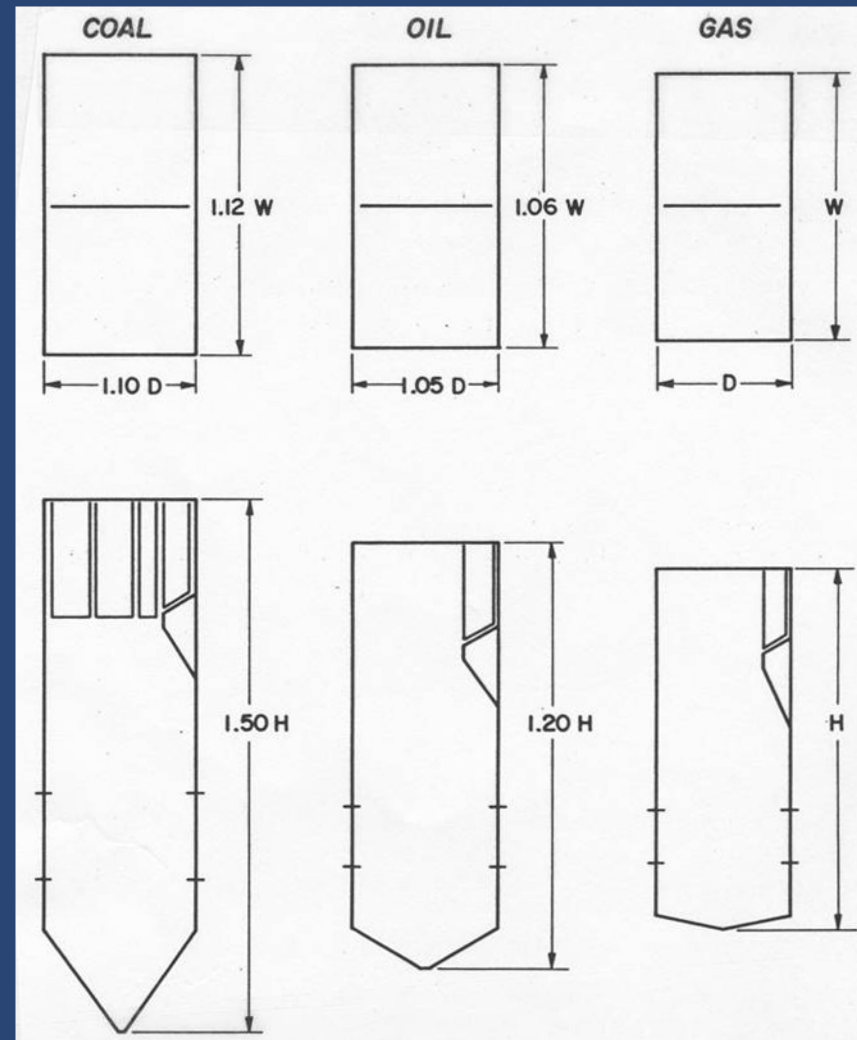
Nonluminous Radiation and Convection Heat Transfer Contributions to Outside Heat Transfer Coefficient (%)

Coal Technology	Nonluminous Radiation	Convection
Air-fired at 14.7 psia	23.4	76.6
Oxy-fired at 14.7 psia	15.4	84.6
TIPS at 380 psia	1.4	98.6
TIPS at 1160 psia	0.8	99.2

Sizing Furnaces (Various Fuels)

- Coal furnaces are typically sized for:
  - Ash amount
  - Ash characteristics
  - Residence time
  - Heat to the walls (steam generation duty)

- Oil and gas furnaces are sized for maximum wall heat input



Furnace Size for Coal

Comparative Proximate Analyses (As Fired)

	Units	Sask Ligite A	Eastern HVBit	Alberta Sub C	Rocky Mountain MVBit
Moisture	Wt %	35.7	8.3	25.1	9.0
Ash	Wt %	9.9	6.4	11.6	12.0
Volatile Matter	Wt %	24.5	31.6	26.6	23.0
Fixed Carbon	Wt %	29.9	53.7	36.7	54.0
HHV	BTU/lb	6590	13115	7645	12400

	Lignite A	Subbituminous	Bituminous
Ash Softening Temperature (°F)	1850	2100	2400

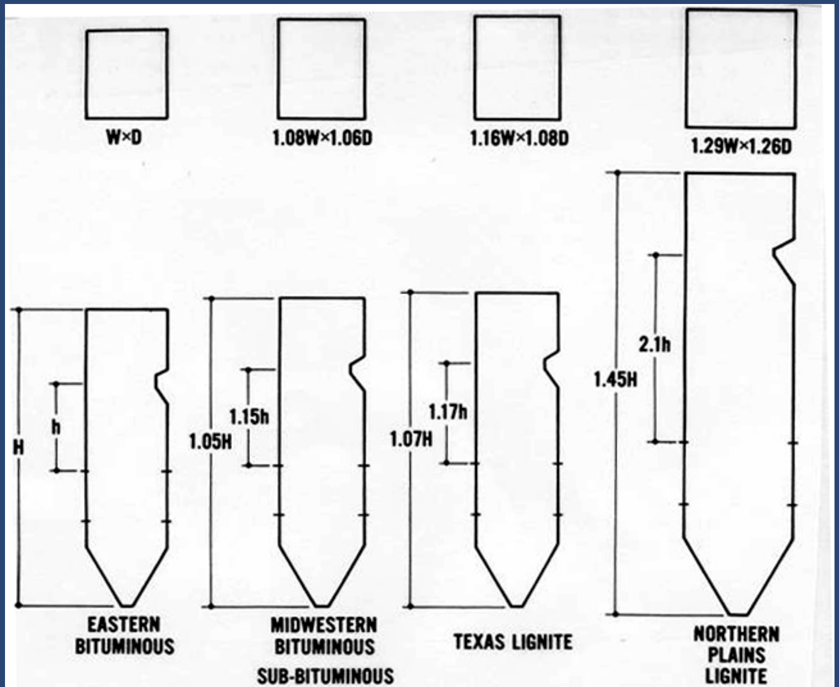


Fig. 3: Effect of coal rank on furnace sizing (constant fuel fired)

TIPS Furnace Design Considerations

- Six Issues
  - Residence time
  - Heating surface area
  - Ash
  - Temperature moderation
  - Upsets
  - Air startup or load

- Residence time
  - Density ratio is ~130 (FBC) ~ 80 (PC)
  - Could probably feed granular
  - Residence time is not an issue therefore a large furnace is not required for residence time reasons

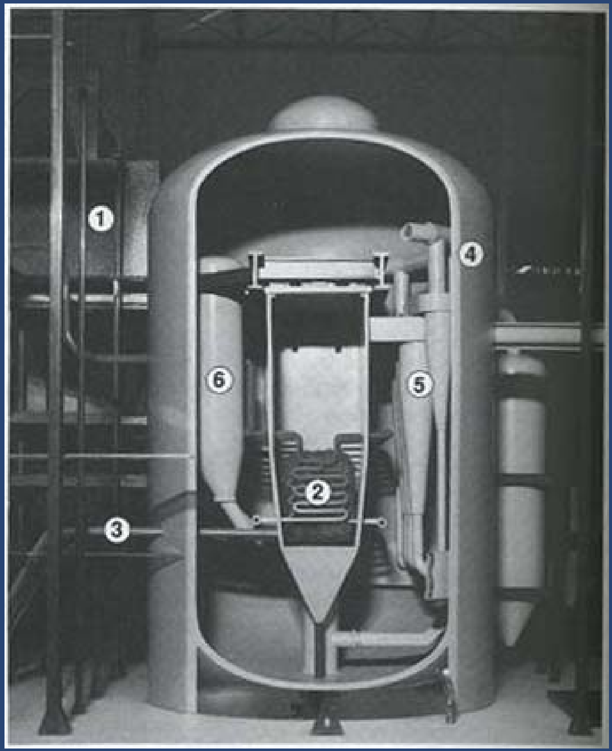
- Heating Surface
  - Many furnace designs use a suspended waterwall screen or generating bank (Recovery boilers, bark, lower pressure process boilers, etc.)

TIPS Furnace Design Considerations

- Ash
  - Need to deal with it
  - Using techniques commonly employed with gasifier designs
    - Wet slag
    - Dry - FBC to reduce the ash to below ash fluid temperatures
- Temperature Moderation
  - FGR, Bed cooling, In-bed heat exchangers
- Upset conditions
- Air startup or load
  - Do not know yet

Furnace Technology

- Wet
  - Smaller furnace & simpler design
  - 70% ash removal in furnace
  - Can fire fewer coals
  - Higher temperatures in convective sections (less surface but molten deposits)
  - Running ash problems
  - Less tolerance of upset
- Dry (Our preferred route)
  - More expensive capital
  - Higher thermal capacitance
  - Lower temperatures in convective pass (more surface but dry deposits)
  - Can moderate furnace temperature using FGR, bed material and in bed heat exchangers
  - Wider fuel range possible
  - BFBC preferred to CFBC
  - Probably higher system reliability



- PFBC installations in Japan, USA, Sweden and Spain