Waste Heat Recovery
Technology Overview
Gas/Electric Partnership 2009

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Agenda

- What is Waste Heat Recovery (WHR)?
- WHR Applications
  - Exhaust heat electric power generation (ORC, steam)
  - Turboexpanders
  - Turbine inlet cooling – refrigeration cycle
  - Turbochargers
  - Preheating fuel (GT and recips)
  - GT Regenerator
- Summary of Concepts
What is Waste Heat Recovery?

- Using the remaining heat/thermal energy in the exhaust stream to create useful energy

**Useful Energy**

- Electricity
- Power/Torque
- Preheat
- Low Grade Steam
- Hot Water

**Common Heat Losses**

- Gas Turbine Exhaust * 72%
- IC Engine*
  - Exhaust 35%
  - Jacket Cooling 18%
  - Lube Cooling 20%
  - IC Engine Total 73%  

Rankine Cycle (Power Plant)
Rankine Cycle with Gas Turbine Exhaust as Heat Source

- Steam cycles require 24 hr supervision per federal regulation
- Organic fluid is combustible, potential for exhaust air mixing with organic fluid is dangerous

Effects based on location and season

Gas Turbine
Evaporator
Turbine
Condenser
Generator
Pump
Atmosphere
Organic Rankine Cycle (ORC)

- ORC does not require 24 hr supervision
- More economical than steam cycle
- Equipment is physically smaller for ORC vs. steam

Low DP on Exhaust Side (minimize back pressure on turbine)

Heat transfer fluid to prevent mixing of organic fluid and exhaust air

Effects based on location and season

ORC does not require 24 hr supervision
- More economical than steam cycle
- Equipment is physically smaller for ORC vs. steam
Exhaust Heat Electric Power Generation

- ORC Common Applications: Geothermal, solar panels, biomass, and cement plants
- ORC Manufacturers: Infinity Turbine, ORMAT, TURBODEN, Turbo Thermal Corp., etc...

<table>
<thead>
<tr>
<th>Economical Considerations*</th>
<th></th>
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<tbody>
<tr>
<td>Capital Cost</td>
<td>$2000 to $2,500/kW</td>
</tr>
<tr>
<td>Operating Cost</td>
<td>$0.001 to $0.005/kWh</td>
</tr>
<tr>
<td>Overall Cost to Operate and Own</td>
<td>$0.035 to $0.040/kWh</td>
</tr>
<tr>
<td>Current Electricity Purchase Prices</td>
<td>$0.035 to $0.050/kWh</td>
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</tbody>
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*Note: This does not include cost of installation of power lines to site*

Exhaust Heat Electric Power Generation

- **Compressor Stations Applications**
  - Proximity to power grid

- **INGAA White Paper Criteria for ORC**
  - Station Capacity > 15,000 hp
  - 5,250 hrs / 12 months
  - 50 stations of 473 meet criteria

- **6.5 MW ORC Cycle Plant**
  - **Gold Creek Compressor Station, Canada**
  - Courtesy of ORMAT

- **7 existing ORC applications (~5.5 MW)**
- **6 planned ORC applications (~5.4 MW)**

Integral component to any exhaust heat recovery system

Gas Turbines and IC Engines

Require Low DP, avoid back pressure on engines

Current Industry Technology

- HRSG – Combined Cycle Plant (Waste Heat Recovery on a large scale!)
- Cogeneration – Use of waste heat to generate low grade steam or hot water
- Regenerator – Preheat GT inlet air to combustor
Applications

- Exhaust Heat Electric Power Generation (Steam, ORC)
- Cogeneration (production of low grade steam and hot water)
- GT Regenerator (preheat GT inlet air to combustor)
- Preheat GT fuel
- Generate torque through expansion of high pressure gas
- Applications: LNG and hydrocarbon processing applications (steady flows and pressure ratio)
- Natural Gas Industry: Pressure regulation from transmission pipelines to distribution lines

**Existing Pressure Regulator**

\[ P_1, T_1 \rightarrow P_2, T_2 \]

\[ T_3 < T_2 \]

*Turboexpanders require either pre or post gas heating to avoid crossing dew point*

**Proposed Turboexpander**

\[ P_1, T_1 \rightarrow P_2, T_3 \]
Turboexpanders

- Turboexpander capital cost
  - $600 to $2300/kWh (average of $1450/kWh)
- High flow variability on pipelines
  - Not a constant energy source
- Increased additional O&M cost at regulating station
- Several installations in US in past, but since have been shutdown due to economics
Technical Premise: Inlet Air Cooling

Power Augmentation Concepts for WHR:

- Turbine Inlet Air Cooling
- Gas Turbine Regeneration
- Pre-heating Fuel
- Turbocharging IC engines

Fuel

\[ M_{\text{fuel}} = 1-2\% \text{ of } M_{\text{air}} \]

Air at Ambient Temp

\[ T_{3 \text{ Max Temp}} \sim 2500^\circ \text{F} \]

Turbine Inlet Air Cooling

Waste Heat Recovery Step

Gas Turbine Regeneration

Pre-heating Fuel

Turbocharging IC engines

\[ M_{\text{air}}(h_{2} - h_{1}) = P_{\text{comp}} \]

\[ M_{\text{fuel}}(q_{\text{LHV}}) = M_{\text{air}}(h_{3} - h_{2}) = P_{\text{burn}} \]

\[ M_{\text{air+fuel}}(h_{3} - h_{4}) = P_{\text{turb}} \]

\[ P_{\text{tot}}^* = P_{\text{turb}} + P_{\text{burn}} - P_{\text{comp}}^* \]
**Technical Premise: Gas Turbine Regen**

- **Air at Ambient Temp**
- **Fuel** $M_{fuel} = 1\text{–}2\%$ of $M_{air}$
- **Higher h3 or less fuel to reach h3**
- **Add hot air to h2**
- **T3 Max Temp** $\sim 2500 \, ^\circ F$

### Power Augmentation Concepts for WHR:

- **Turbine Inlet Air Cooling**
- **Gas Turbine Regeneration**
- **Pre-heating Fuel**
- **Turbocharging IC engines**

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**Diagram Details:**

1. **M_{air} (h_2-h_1) = P_{comp}**
2. **M_{air}^{*}(\Delta h^{*}) = M_{fuel}^{*} (LHV)**
3. **M_{air+fuel} (h_3-h_4) = P_{turb}**
4. **P_{tot}* = P_{turb} + P_{burn}^{*} - P_{comp}**
5. **T3 Max Temp Limit**

**Equations:**

- $M_{air} (h_2-h_1) = P_{comp}$
- $M_{air}^{*}(\Delta h^{*}) = M_{fuel}^{*} (LHV)$
- $M_{air+fuel} (h_3-h_4) = P_{turb}$
- $P_{tot}* = P_{turb} + P_{burn}^{*} - P_{comp}**$
Technical Premise: Pre-heating Fuel

Power Augmentation Concepts for WHR:
- Turbine Inlet Air Cooling
- Gas Turbine Regeneration
- Pre-heating Fuel

Preheating Fuel can also be easily applied (more effectively at times) for reciprocating engines.
Technical Premise

- Turbocharging IC engines

![Diagram of Turbocharging IC engines](www02.abb.com)

Specific Volume, v

Pressure

Waste Heat Recovery Step

 Courtesy of ABB (www02.abb.com)
• Ongoing program at DOE NETL / Caterpillar to investigate recovery of exhaust energy electrically using high speed generator.

• ABB: Variable turbine geometry used in recovery of waste heat from 2 stroke engines.

[Graph and diagram of turbocharger components.]

Courtesy of DOE / OSTI Information Bridge Website

Courtesy of ABB website
Summary Points

• Effectiveness and cost to operator for many of the WHR concepts are site dependent.

• Technology advancements in compressed energy storage will aid many WHR options, especially turboexpander or steam drive.

• Operators need to assess options, based on lifecycle costs, capital costs and power grid considerations for a given site.

• Combinations of these technologies may prove to be the most useful to operators and should be considered. Examples: Turbine inlet air cooling and pre-heating fuel or Turboexpander and waste heat exchanger.
Questions?

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