Gas-Turbine Performance Improvements Through the Use of Multiple Turbine Interstage Burners

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April 22, 2005
Introduction

• What?
  – The use of interstage burners to increase engine efficiency by burning fuel at higher pressure and temperature.

• Why?
  – Original analysis thought to be incomplete. Paper considers various cooling flows in turbine and variable specific heats.

• How?
  – Prepare computer code that is validated against previously existing model.
Approach: Model

- Program used 1st Law analysis.
- Included following assumptions:
  - No heat loss from compressor or turbine.
  - Air mixture of N₂ and O₂ only.
  - Complete combustion.
  - Perfect mixing in stator and rotor sections.
  - Neglect pumping power for steam cooling flows.
  - Cooling flows introduced behind each stator and rotor.
  - Heat exchanger assumed for closed-loop steam cooling.
Approach: Model

• Invoke 1st Law for open system:

\[
\frac{dE_{CV}}{dt} = \left[m \left( h + \frac{V^2}{2} + gz \right)\right]_e - \left[m \left( h + \frac{V^2}{2} + gz \right)\right]_i + Q_{CV} - W_{CV}
\]

• Applying assumptions and considering steady state:

\[
\dot{Q}_{CV} - \dot{W}_{CV} = \dot{H}_e - \dot{H}_i = \sum P N_e \left\{ h_f + \left[ h(T_e) - h(T_{ref}) \right] \right\} - \sum R N_i \left\{ h_f + \left[ h(T_i) - h(T_{ref}) \right] \right\}
\]

• Net Power given by:

\[
P_{net} = P_t - P_c = \sum_{j=1}^{N_{stages}} \left( \dot{H}_{RI_j} - \dot{H}_{RE_j} \right) - \left( \dot{H}_{CI} - \dot{H}_{CE} \right)
\]
Approach: Model

• $N_{\text{stages}}$ from:

\[
\left( \frac{\Pi_{t_{\text{max}}}}{\Pi_{t_{\text{max}}}} \right)^{N_{\text{stages}}} = \frac{\Pi_{t}}{\Pi_c \Pi_b}
\]

• Combustion reaction modeled as:

\[
C_xH_y + a \times (O_2 + 3.76 \times N_2) + b \times H_2O + c \times CO_2 \rightarrow \\
u \times CO_2 + v \times H_2O + 3.76 \times a \times N_2 + w \times O_2
\]

• Efficiency given by:

\[
\eta_{th} = \left( \frac{P_{net}}{100} \right) / \dot{Q}_{fuel}
\]

\[
\dot{Q}_{fuel} = \eta_b \times m_{fuel} \times LHV_{CH4}
\]
Results: Open-Loop Air Cooling vs. Steam Cooling

- Steam has two advantages:
  - Can be provided by inexpensive external pump.
  - Increases core mass flow, which increases power.
- Two disadvantages:
  - Steam recovery.
  - Availability of pure water; leads to cost increase.
- Steam displays better performance.
Results: Open-Loop Air Cooling vs. Steam Cooling

Fig. 11 Net power output $P_{net}$ vs number of MIBs for open-loop air and steam cooling.

Fig. 12 Efficiency vs number of MIBs for open-loop air and steam cooling.
Results: Open-Loop vs. Closed-Loop Steam Cooling

• Advantage:
  – Closed loop superior since cooling steam recycled and no mixing is involved.

• Disadvantage:
  – Causes “mechanical difficulty” and “complicated design criteria” since internal to turbine airfoils.

• Open-Loop performs better than Closed-Loop.
Results: Open-Loop vs. Closed-Loop Steam Cooling

Fig. 14  Net power output vs number of MIBs for open-loop and closed-loop steam cooling.

Fig. 15  Efficiency vs number of MIBs for open-loop and closed-loop steam cooling.
Results: Comparison of Three Options

- Open-Loop steam provides most power and highest efficiency.
- Two main burners appear sufficient for optimum performance.
Results: Comparison of Three Options

Fig. 16 Net power output vs number of MIBs for all three types of cooling: open-loop air, open-loop steam, and closed-loop steam cooling.

Fig. 17 Efficiency vs number of MIBs for all three types of cooling: open-loop air, open-loop steam, and closed-loop steam cooling.
Final Remarks

• Applying interstage burners may be difficult.
  – Cost of design and production may be high.
  – Actual design and sizing of parts presents problems.
  – Time required for mixing and burning of fuels