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

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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 N_2 and O_2 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:

$$\frac{dE_{CV}}{dt} = \left[\dot{m}\left(h + \frac{V^2}{2} + gz \right) \right]_i - \left[\dot{m}\left(h + \frac{V^2}{2} + gz \right) \right]_e + \dot{Q}_{CV} - \dot{W}_{CV}$$

- Applying assumptions and considering steady state:

$$\dot{Q}_{CV} - \dot{W}_{CV} = \dot{H}_e - \dot{H}_i = \sum_P \dot{N}_e \left\{ \bar{h}_f^0 + \left[\bar{h}(T_e) - \bar{h}(T_{ref}) \right] \right\} - \sum_R \dot{N}_i \left\{ \bar{h}_f^0 + \left[\bar{h}(T_i) - \bar{h}(T_{ref}) \right] \right\}$$

- 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_{stages} from:

$$\left(\Pi_{t\_stage\_\max}\right)^{Nstages} = \Pi_t = 1/\Pi_c \Pi_b$$

- Combustion reaction modeled as:

C_xH_y + a x (O_2 + 3.76 x N_2) + b x H_2O + c x CO_2->
u x CO_2 + v x H_2O + 3.76 x a x N_2 + w x O_2

- Efficiency given by:

$$\eta_{th} = (P_{net} \times 100) / \dot{Q}_{fuel}$$

$$\dot{Q}_{fuel} = \eta_b \times \dot{m}_{fuel} \times LHV_{CH4}$$

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

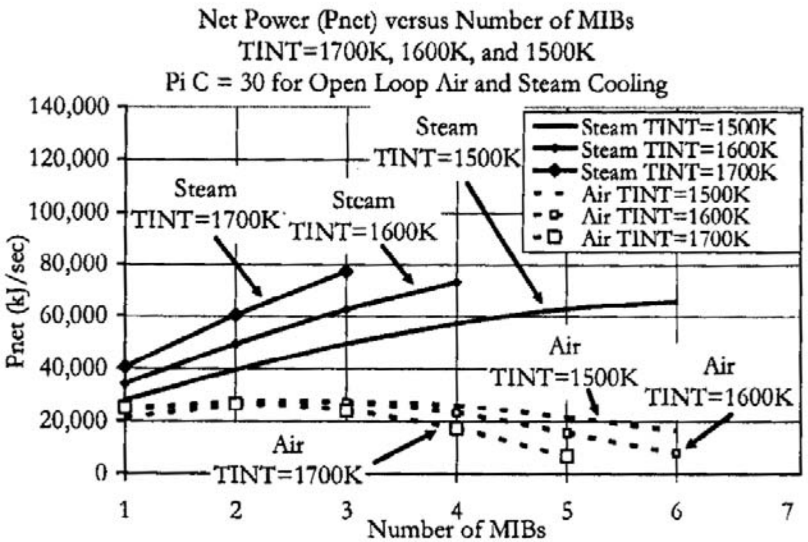

Fig. 11 Net power output P_{net} vs number of MIBs for open-loop air and steam cooling.

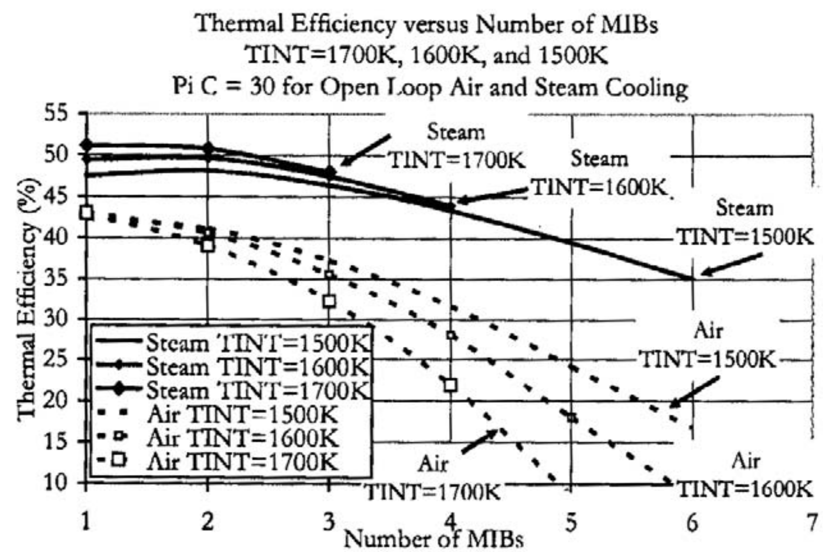

Fig. 12 Efficiency vs number of MIBs for open-loop air and steam cooling.

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

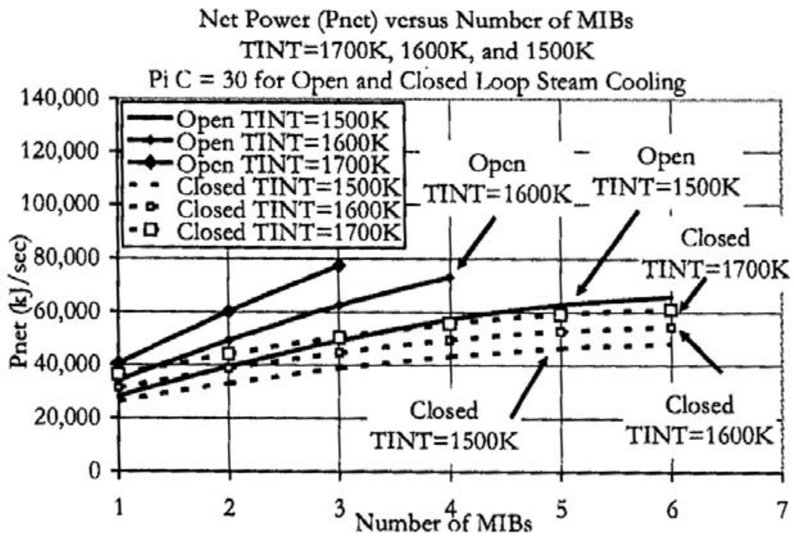

Fig. 14 Net power output vs number of MIBs for open-loop and closed-loop steam cooling.

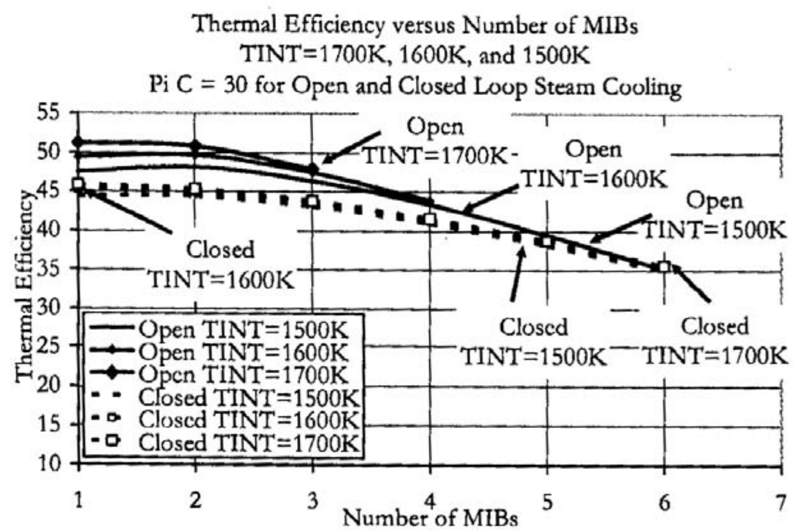

Fig. 15 Efficiency vs number of MIBs for open-loop and closed-loop steam cooling.

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

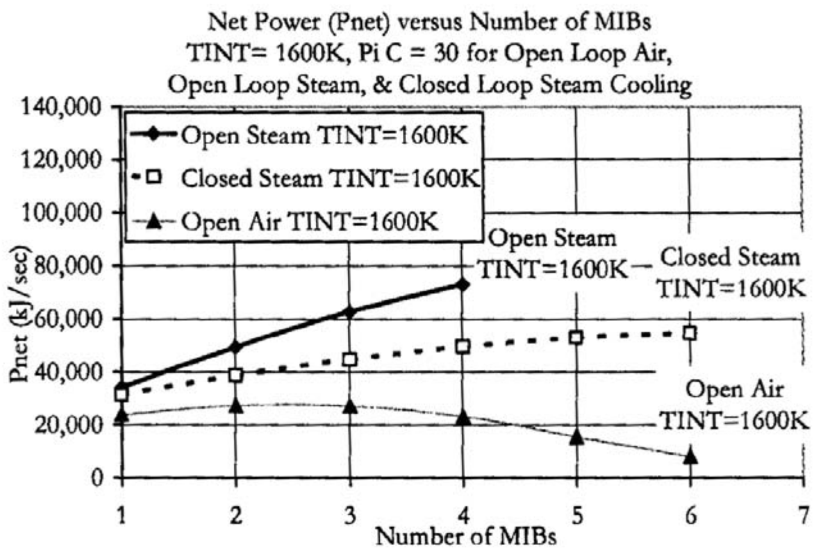

Fig. 16 Net power output vs number of MIBs for all three types of cooling: open-loop air, open-loop steam, and closed-loop steam cooling.

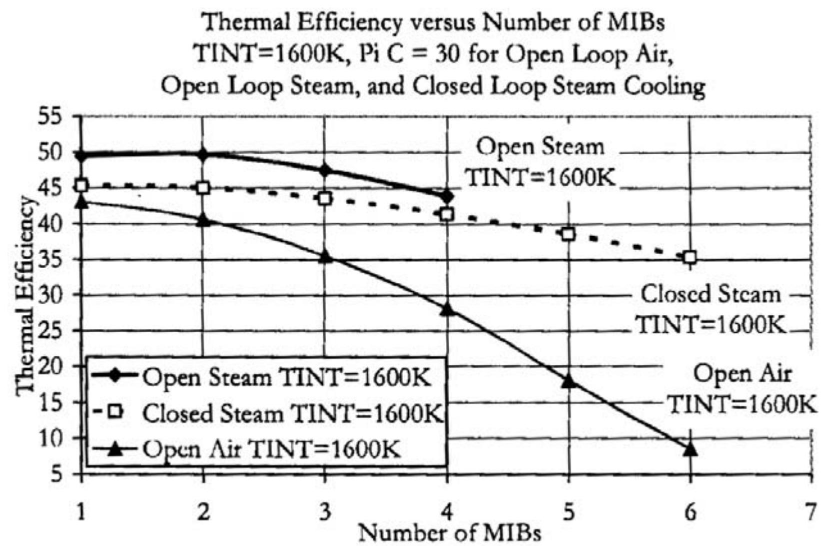

Fig. 17 Efficiency vs number of MIBs for all three types of cooling: open-loop air, open-loop steam, and closed-loop steam cooling.

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