

Effect of Cooling Air Mass Flow on Turbine Efficiency in the AL-31F Engine

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Abstract:

This paper evaluates the effect of cooling air mass flow on turbine efficiency in the AL-31F engine using an energy balance and the turbine stage work equation. The analysis covers corrected low-pressure spool speeds from 70 to 105 percent and compares an uncooled reference with cooling cases labeled 1 and 3 percent. The 3 percent case produces a larger efficiency penalty throughout the investigated range. Approximate relative reductions read from the calculated curves are 6–9 percent and 1–2 percent for secondary efficiency in the 3 and 1 percent cases, respectively. The corresponding reductions in effective efficiency are approximately 7–9 percent and 1.5–2 percent. The efficiency curves show local variations with speed, including a recovery near the 100 percent operating point. Including the available energy of the coolant lowers effective efficiency relative to secondary efficiency. The results describe aerodynamic and energy penalties associated with cooling; determining an optimum coolant flow additionally requires a validated heat transfer model and material temperature limits.

Keywords—AL-31F; cooled turbine; cooling air mass flow; mixing loss; turbine efficiency.

I. INTRODUCTION

Increasing the gas temperature upstream of a turbine raises the available work of the gas stream while increasing the thermal load on vanes, blades and discs [1]. The AL-31F turbine comprises one high-pressure stage and one low-pressure stage. Its air cooling system follows an open arrangement: air extracted from the compressor cools the components and then enters the main gas stream. Coolant injection therefore changes both the thermal condition of the components and the mass flow, momentum and mixing losses of the working fluid.

An efficiency assessment must distinguish the thermal protection provided by cooling from its aerodynamic and energy effects. This study formulates a consistent stage energy balance, distinguishes secondary and effective efficiencies, and analyzes calculated results as a function of corrected spool speed. The scope is a stage-level aerodynamic and energy analysis. The reported values are calculation results rather than engine measurements; blade temperatures, thermal stresses and service life are not inferred from the efficiency curves. These quantities require a separate thermal and structural assessment [2].

II. MODEL AND METHODOLOGY

A. Flow Definitions and Operating Range

Three stations are considered: upstream of the stator, upstream of the rotor, and downstream of the rotor. G_g is the main gas mass flow and $G_{c,i}$ is the coolant mass flow through channel i ; both are expressed in kg/s. Subscripts S and R identify injection through the stator vanes and rotor blades, respectively. The relative coolant-flow ratio and mass balances are

$$\begin{aligned}\bar{g}_{c,i} &= \frac{G_{c,i}}{G_g} \\ G_1 &= G_g + G_{c,S} \\ G_2 &= G_1 + G_{c,R}\end{aligned}\quad (1)$$

Results are reported over corrected low-pressure (LP) spool speeds of 70–105%, with reference values tabulated at 5% intervals. The uncooled case is compared with two cooling cases identified by the relative coolant-flow labels of 1% and 3%. The reference operating point is at an altitude of 0 m and Mach number 0, with an ambient temperature of 288 K, an ambient pressure of 101325 Pa, and a turbine inlet temperature of 1650 K. This inlet temperature is not imposed over the entire speed range. Comparisons between cooling cases require the same operating point and coolant-flow normalization.

B. Stage Power and Efficiency Definitions

For a constant mean diameter, angular momentum conservation gives the stage power as

$$N_T = u(G_1 C_{1u} + G_2 C_{2u}) \quad (2)$$

Here, N_T is stage power in W, u is the blade speed in m/s, and C_{1u} and C_{2u} are the magnitudes of the tangential components of absolute velocity. The positive sign assumes that the rotor-exit tangential velocity is directed opposite to rotation. If signed velocity components are used, the corresponding algebraic difference must be applied.

Secondary efficiency, η_{sec} , is referenced to the available energy of the main gas stream. Effective efficiency, η_{eff} , also includes the available energy of the coolant. With both energy terms defined on the same state basis,

$$\begin{aligned}\eta_{sec} &= \frac{N_T}{G_g H_g} \\ \eta_{eff} &= \frac{N_T}{G_g H_g + \sum_i G_{c,i} H_{c,i}} = k_E \eta_{sec}\end{aligned}\quad (3)$$

The energy correction factor is

$$k_E = \left(1 + \sum_i \bar{g}_{c,i} \frac{H_{c,i}}{H_g}\right)^{-1} \quad (4)$$

H_g and $H_{c,i}$ denote the available specific adiabatic energies of the main gas and coolant streams, respectively, in J/kg. For positive coolant available energy, k_E is less than unity, and effective efficiency is lower than secondary efficiency. The same expressions on a stagnation-state basis use H_g^* and $H_{c,i}^*$, giving η_{sec}^* and η_{eff}^* . An asterisk denotes a stagnation quantity. Static-state and stagnation-state quantities are kept separate throughout the analysis; thermophysical and gas-dynamic functions provide the theoretical basis for these energy terms [3].

C. Loss Representation

The blade-row energy balance gives the velocity coefficient in the form

$$\varphi = \frac{c_1}{c_{g,ad}} = \sqrt{\frac{1 - \zeta_{p,0} - \zeta_{mix} + \zeta_{inj} - \zeta_Q - \Delta\zeta_p}{1 + \bar{g}_c}} \quad (5)$$

$C_{g,ad}$ is the adiabatic velocity of the main gas stream. $\zeta_{p,0}$ is the uncooled profile-loss coefficient, ζ_{mix} is the mixing-loss coefficient, ζ_{inj} represents the energy contribution of coolant injection, ζ_Q represents heat exchange, and $\Delta\zeta_p$ is the change in profile loss caused by cooling. All coefficients must use a consistent energy normalization. The sign and magnitude of the profile-loss change depend on the injection geometry: in some arrangements, injection can reduce trailing-edge losses.

D. Reporting Efficiency Reductions

At a given corrected speed, relative and absolute efficiency reductions are distinguished as follows:

$$\begin{aligned} \delta_\eta &= \frac{\eta_0 - \eta_c}{\eta_0} 100\% \\ \Delta\eta &= \eta_0 - \eta_c \end{aligned} \quad (6)$$

η_0 and η_c are the uncooled and cooled efficiencies, respectively. δ_η is a relative reduction expressed in percent; $100\Delta\eta$ is an absolute change expressed in percentage points. Reference values are taken from the calculation table. The reduction ranges are read approximately from the calculated curves and are not treated as exact values at individual operating points.

III. RESULTS AND DISCUSSION

A. Uncooled Reference Case

Table I and Fig. 1 show an overall decrease in secondary efficiency on a static-state basis, from 0.8770 at 70% corrected LP spool speed to 0.7960 at 105%. The trend is not monotonic: efficiency rises locally from 0.7964 at 95% to 0.8108 at 100% before decreasing again. The stagnation-state efficiency follows a similar pattern.

TABLE I. PARAMETERS OF THE UNCOOLED TURBINE STAGE

LP speed (%)	Static η_{sec}	Stagnation η_{sec}^*	Friction loss $\zeta_{f,0}$	Velocity φ_0
70	0.8770	0.8757	0.0288	0.9446
75	0.8595	0.8580	0.0287	0.9446
80	0.8575	0.8567	0.0279	0.9450
85	0.8083	0.8081	0.0260	0.9460
90	0.8047	0.8046	0.0245	0.9467
95	0.7964	0.7963	0.0244	0.9468
100	0.8108	0.8099	0.0237	0.9471
105	0.7960	0.7957	0.0243	0.9468

Note: $\zeta_{f,0}$ is the uncooled friction-loss coefficient and φ_0 is the corresponding velocity coefficient.

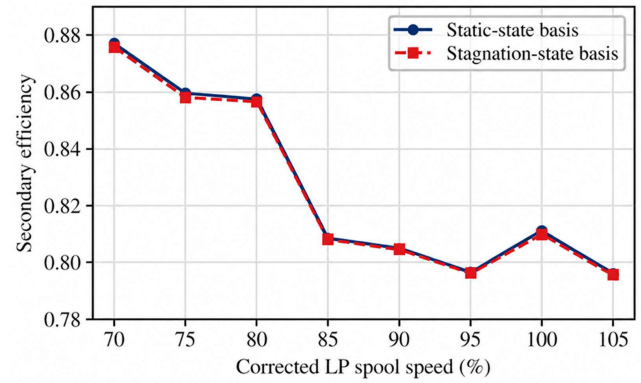


Fig. 1. Secondary efficiency of the uncooled turbine stage on static-state and stagnation-state bases, plotted from Table I.

The friction-loss coefficient decreases from 0.0288 at 70% to 0.0237 at 100%, then rises slightly to 0.0243 at 105%. The velocity coefficient changes only within 0.9446–0.9471. Efficiency does not follow friction loss alone because it also depends on the velocity triangles, stage work and energy used for normalization. The uncooled values provide a speed-dependent reference rather than a direct measure of the cooling penalty.

B. Influence of Coolant Flow

Fig. 2 shows a greater relative reduction in secondary efficiency for the 3% cooling case than for the 1% case throughout the investigated speed range. The 3% curve rises clearly over approximately 80–85%, varies more slowly over 85–95%, decreases locally near 100%, and then rises towards the upper end of the range. The 1% curve varies less strongly. These local changes preclude a simple linear description of reduction versus corrected speed. Approximate reduction ranges for both efficiency definitions are summarized in Table II.

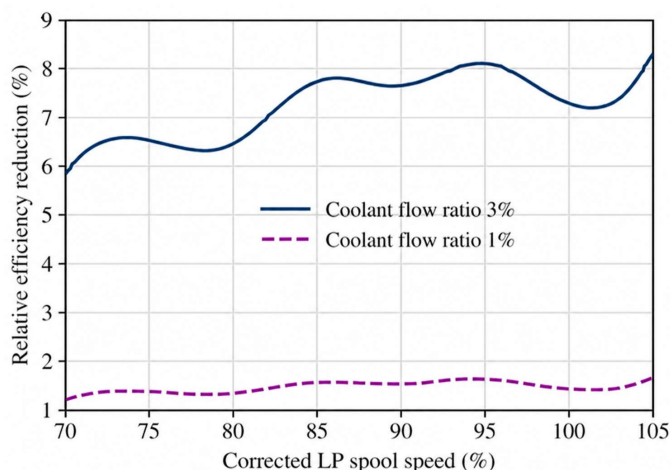


Fig. 2. Relative reduction in secondary efficiency on a static-state basis. Curves are reproduced approximately from the calculation plots.

TABLE II. APPROXIMATE RELATIVE EFFICIENCY REDUCTIONS

Coolant flow label	Secondary efficiency Static-state basis	Effective efficiency Static-state basis
1%	1–2%	1.5–2%
3%	6–9%	7–9%

At the same cooling-case label, effective efficiency shows a larger reduction than secondary efficiency (Fig. 3 and Table II). This agrees with the inclusion of coolant available energy in the denominator of (3). The reduction combines mixing losses, changes in profile loss and mass flow, and the energy of the injected coolant. The same extracted air flow can produce different results if its state or injection location changes.

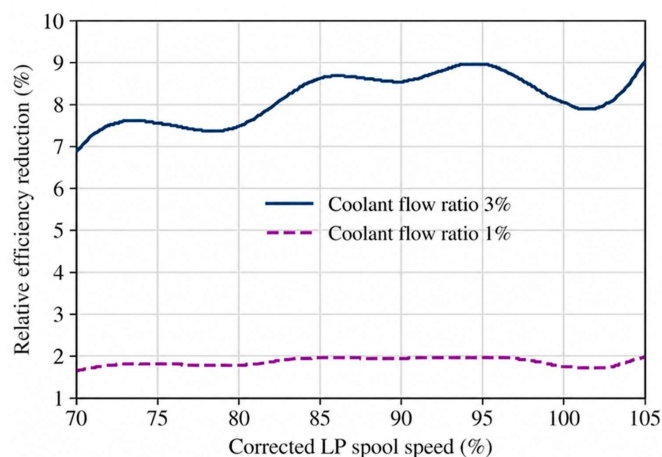


Fig. 3. Relative reduction in effective efficiency on a static-state basis. Curves are reproduced approximately from the calculation plots.

C. Engineering Implications and Limitations

Coolant-flow selection must account for both thermal protection and aerodynamic penalties. The present efficiency curves do not determine blade metal temperatures, thermal stresses or service life. Their numerical values depend on boundary conditions, component matching and empirical loss coefficients. The curve-based ranges in Table II are descriptive; they do not replace pointwise cooled-efficiency data. Channel flow allocation and coolant states must also be specified for reproducible calculations. Determining an

optimum cooling flow, or extending the results to flight conditions, requires a heat transfer model, uncertainty and sensitivity assessments, and appropriate validation.

IV. CONCLUSIONS

The stage energy balance distinguishes secondary efficiency, referenced to the main gas stream, from effective efficiency, which includes coolant available energy. Mixing, profile-loss changes and the energy of coolant injection must be evaluated using a consistent normalization.

Over corrected LP spool speeds of 70–105%, the 3% cooling case produces a greater penalty than the 1% case. Approximate relative reductions on a static-state basis are 6–9% and 1–2% for secondary efficiency, and 7–9% and 1.5–2% for effective efficiency, respectively. Both efficiency and efficiency reduction exhibit local variations with speed.

These results support aerodynamic loss analysis within the stated model. An optimum coolant flow cannot be established from efficiency curves alone; it must be assessed together with material temperature limits using a validated thermal model.

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