

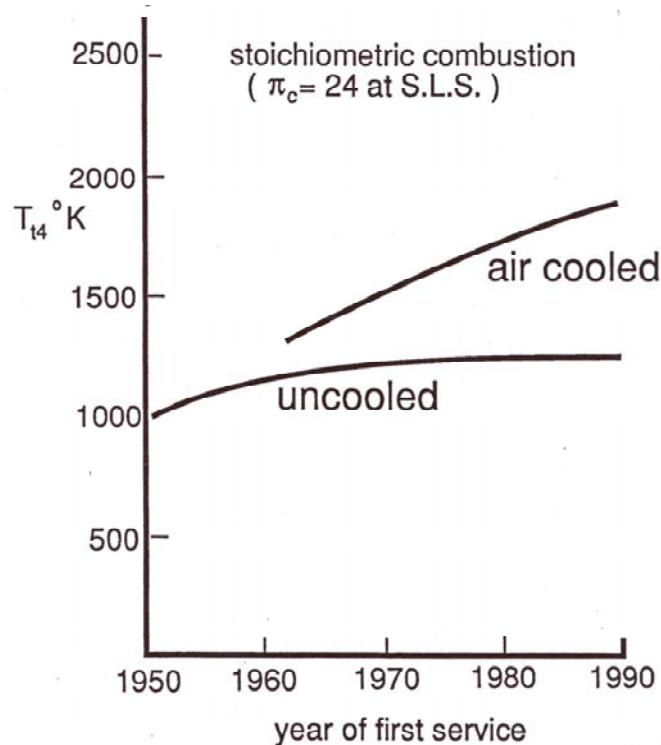
16.50 Lecture 29

Subjects: Turbine cooling; General trends and systems; Internal cooling

Turbine cooling trends:

As we have learned from our performance analyses for turbojets and turbofans, the thrust per unit of airflow of the aircraft engines increases monotonically with turbine inlet temperature ratio, which we have designated as θ_t . Though it is less obvious, the thermal efficiency and specific impulse also increase due to the increase in θ_t . Thus, there is a powerful incentive to increase the turbine inlet temperature.

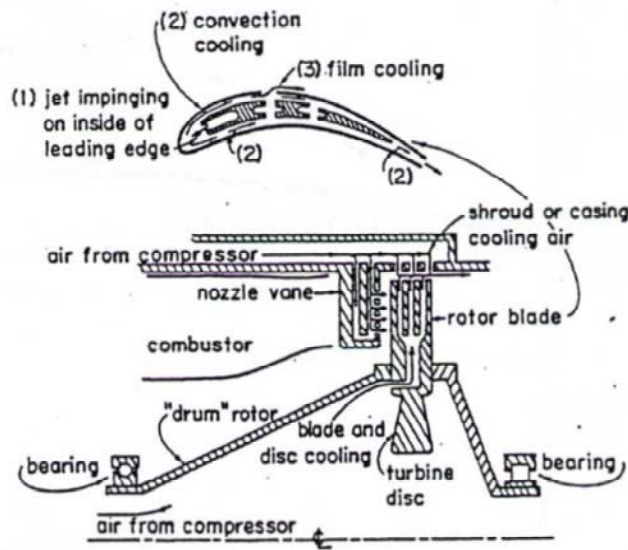
The trend of temperature increase with time is shown in the figure:



From Kerrebrock, Jack L. *Aircraft Engines and Gas Turbines*. 2nd edition. MIT Press, 1992. © Massachusetts Institute of Technology. Used with permission.

In the early period, the increase was limited by metallurgical progress in developing oxidation-resistant materials, primarily Nickel and Cobalt based alloys, that could operate for long times at high temperatures. Beginning in the mid-60's, the technology of air cooling was introduced, and most advancement since then has been due to more refined cooling techniques, although the introduction of directionally-solidified and single-crystal blade materials has allowed some increase in metal temperature.

Cooling Systems: The general scheme for air cooling of the “hot section” of an engine is shown in the figure below:



From Kerrebrock, Jack L. *Aircraft Engines and Gas Turbines*. 2nd edition. MIT Press, 1992. © Massachusetts Institute of Technology. Used with permission.

In most all cases the cooling air is drawn from the compressor discharge because it must be at a higher pressure than that of the part of the flow path to be cooled. This leads to the important condition that the cooling air temperature is the compressor discharge temperature. As shown in the diagram, some of the air is used to cool the turbine nozzles, by a combination of internal convection cooling and film cooling, processes that will be discussed in detail below. Another portion of the cooling air is transferred onto the rotor and used to cool the rotating blades and their supporting disc. Here again a combination of internal convection and film cooling is used.

Internal Convection Cooling:

In this form of cooling, the blade temperature is maintained below that of the hot gas passing through the turbine by a flow of compressor-discharge air through passages internal to the blade, as suggested in the diagram. To model this process we must therefore model first the heat transfer to the outside of the blade from the hot gas, then the heat transfer on the inside to the coolant. The objective in cooling design usually is to maintain the blade temperature nearly constant in the presence of a variation of the heat flux to its surface from the hot gas.

External Heat Transfer:

Let us look first at the heat transfer to the outside of blade. We can write it as

$$q_w = St[\rho u c_p (T_r - T_w)]$$

where ρu is the mass flow density in the hot gas, T_r is the “recovery temperature” and T_w is the wall temperature. The definition of T_r is the temperature the wall would reach if adiabatic, and it is close to the external stagnation temperature. S_t is defined by this relation, but what is its physical significance? We have

$$\frac{cq_w}{\rho u c_p (T_r - T_w) s} = \sigma S_t = \text{fraction of heat flowing thru the blade row which enters the blade.}$$

Here as before c is the blade chord and s is the blade spacing.

Fortunately, S_t is a small number because the boundary layers on the blades are very thick compared to the blade chord. In fact S_t depends on the details of the boundary layer behavior, and of course, is not a constant, but for our purposes here we can think of S_t as being an average value for the blade surface. To estimate its magnitude we can model the blades as flat plates, in which case the local S_t is given approximately by:

$$2 St = C_f = \frac{0.66}{\sqrt{Re_x}} \quad (\text{laminar})$$

$$2 St = C_f = \frac{.0592}{(Re_x)^{1/2}} \quad (\text{turbulent})$$

where Re_x is the Reynolds number based on distance from the leading edge of the plate. One important difficulty for turbine cooling arises because transition from laminar to turbulent flow occurs at some Reynolds number in the range of 3×10^5 to 10^6 . Looking at the expressions for S_t we see that for example if the transition occurs at $Re_x = 10^6$, then

$$S_t = 0.66 \times 10^{-3} \quad (\text{laminar})$$

$$S_t = 0.037 \quad (\text{turbulent})$$

So the heat transfer jumps suddenly by a large factor at the point of transition.

To get an idea of the magnitude of Re_x in an engine let us look at some typical numbers.

For $p_{t4} = 20$ atm, $\theta_t = 6$, $T_t = 6(298) = 1788$ K, $Re_x = 3 \times 10^7/m$ at $M = 1$, so for a blade that has a chord of 4 cm, Re_x based on chord is 1.2×10^6 and we would expect transition on the blade surface. Actually external flow turbulence tends to promote the transition so that it will probably occur at a lower value than this. But the exact location of the transition is difficult to predict.

This gives rise to a major problem in scheduling the internal cooling system so that internal cooling matches the external heat transfer.

Internal cooling rate:

For the internal cooling flow we model the flow as that through a long thin passage, for which

$$2St_{int} = Cf_{int} = 0.023 \frac{1}{(Re_D)^{1/2}}$$

One important question to be addressed is how much cooling air is required. Forming a heat balance such that the heat flux into the blade equals that absorbed by the cooling flow,

$$2cq_w = 2\sigma St_e [\rho u c_p (T_r - T_w) s] \leq \dot{m}_c c_p (T_w - T_c)$$

$$\frac{\dot{m}_c}{\rho u s} \geq 2\sigma S_{te} \frac{T_r - T_w}{T_w - T_c}$$

For $T_r - T_w = 200^*K$, $T_w - T_c = 400^*K$, and $\sigma=1$,

$$\frac{\dot{m}_c}{\rho u s} \geq 2\sigma (.005) \left(\frac{1}{2}\right) \cong .005$$

Actually a ratio more nearly .01 is required, because the cooling air is not heated all the way to the blade temperature. This is per blade row, not counting casing cooling. For a two-stage turbine, including these effects we may need 2-4% of the air flow.

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