16.50 Lecture 34

Subjects: Combustors; Afterburners

Combustors:

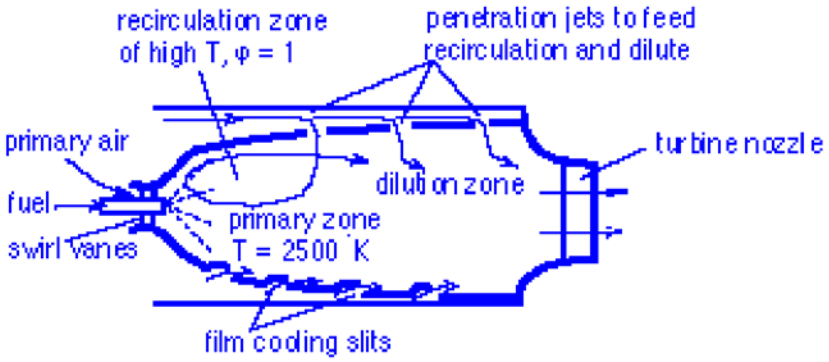
The combustor of an aircraft engine releases an enormous amount of heat per unit volume, second only to high-pressure rocket engines. In designing the combustor we must implement solutions to the following difficulties:

a) The gas temperature at the outlet is well above the limits of the materials from which the combustor is built.

b) Kerosene-air mixtures will only burn in a narrow range of mixtures near stoichiometric.

c) The overall mixture is very lean, and varies over a wide range with changes in the power setting of the engine.

These requirements are met by introducing the fuel as a spray into a primary zone where the combustion is near stoichiometric and is stabilized by a recirculating flow generated by a set of jets from the periphery. The gas leaving the primary zone is then cooled by mixing with additional air before it exits to the turbine nozzles.



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There are also a number of "secondary" requirements to be met, some of which are quite challenging too:

-The burner must be dimensioned to assure re-starting at high altitude, when pressure, and hence chemical rates, are low. Designs that are optimized for cruise may not meet this requirement.
-The combustor must have an operating life of over 20,000 h., or some 5,000 cycles.
-Pollutant formation must be below legally allowed limits (see next lecture).
-The total pressure drop must be small, despite the strong flow turbulence that is purposely introduced for enhanced mixing.
-The temperature profile at combustor exit must be uniform (or sometimes must meet some prescribed radial profile).

Now let us look at some of the fundamental phenomena involved in the combustion process. The fuels used commonly in aircraft engines (kerosene, JP-4), react with air only in gaseous form, so they must be atomized, vaporized, and mixed with the air, starting from liquid form. Even then, the fuels burn only in nearly stoichiometric proportions, so we have to first burn with such proportions, then mix with air to get the desired temperature.

As an example, take a stoichiometric mixture of octane (C_3H_8) and oxygen:

$$C_3H_8 + 5\ 0_2 \rightarrow 3CO_2 + 4H_20$$

$$\left(\frac{fuel}{air}\right)_{stoich} = \frac{3(12)+8}{5(32)}(0.23) = 0.0633$$

whereas normal fuel/air ratios in jet engines are around 0.03. The ratio of fuel to stoichiometric fuel is called the "fuel equivalence ratio", φ, and is here seen to be as as low as 0.3/0.66=0.45. Normal hydrocarbon fuels do not ignite this far from stoichiometry, even at the relatively high compressor discharge temperture.

In the molecular mixture, the reaction proceeds by molecular collisions. There is an activation energy, A, and the kinetic energy of impact between the reacting molecules $\frac{1}{2}$ mv^2 must exceed A in order that a reaction to occur. Since the molecules have a kinetic energy distribution according to Boltzmann

$$f\left(\tfrac{v^2}{2}\right) \propto e^{-\frac{mv^2}{2R_gT}}$$

the fraction of molecules with $m\frac{v^2}{2} > A$ is $\propto e^{-\frac{A}{RT}}$. The number of such collisions per unit volume and time, called the reaction rate, is

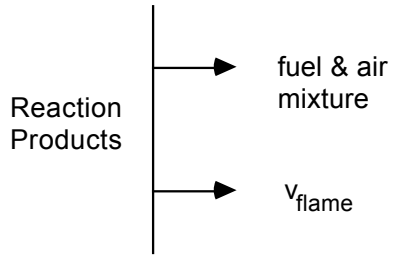
$$\text{reaction rate} \propto n_{0_2}\ \ n_{fuel}\ \ n \ldots e^{-A/RT}$$

so for a given fuel-air mixture we find

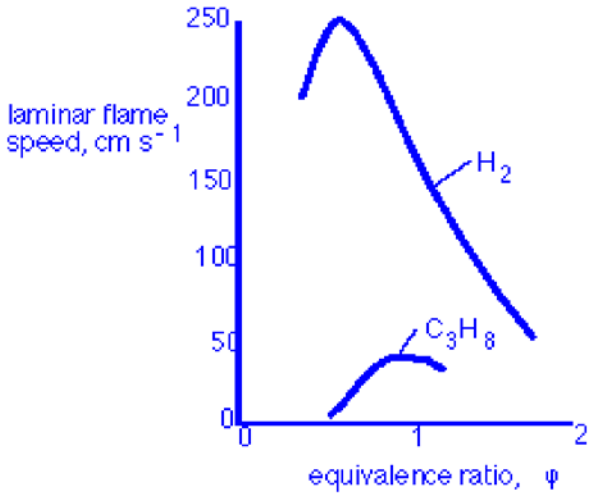
$$\text{reaction rate} \propto p^n e^{-A/RT}$$

where n=2 if 2 molecules are involved, 3 if 3 molecules are involved, etc.

Combustion in premixed gases is the simplest to visualize and in a sense the easiest to experiment on, although is not often the actual mechanism in practical combustion systems. We imagine a flame front propagating into the premixed fuel and air



The rates of propagation of such flames are determined by a balance between reaction time and products diffusion time, and are roughly as shown in the figure:



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This however is the laminar rate. Turbulence increases the rate by at least two mechanisms.

a) stretching of the flame front
b) wrinkling of the flame front

Both of these mechanisms are promoted by a high level of fluid turbulence that is generated by the jets of air entering the primary zone and the mixing zone.

Combustor sizing:

The chemical energy density in the burner is the mass of fuel per unit volume, times the fuel heat value, $E/V = \rho_a fh$. If the time to full combustion, t_{burn} is known, we can then calculate the power density as

$$P/V = \frac{\rho_a fh}{t_{burn}}$$

The burning time must be estimated differently for design (or cruise) conditions and for low-pressure conditions.

(a) For design conditions the pressure and temperature are fast enough that the rate-limiting step is not the reaction itself, but the turbulent mixing of the fuel and air, or of the rich primary burnt gas with the dilution air. Let l_t be a caracteristic turbulent eddy size (of the order of the combustor diameter or width), and u_t some characteristic eddy velocity (some fraction of the mean flow velocity in the burner). Then we estimate $t_{burn} \approx l_t/u_t$. For a numerical estimate, take ρ_a=3 kg/m^3, f=0.027, h=43MJ/kg, u_t=u_x=50 m/s and l_t=0.1 m. We then calculate a power density

$$P/V = 1.7 \times 10^9 \text{ W/m}^3$$

which is of the right order, and obviously very high.

We can now calculate the combustor volume $V_c=P_{th}/(P/V)$, where the total thermal power is $P_{th} = \dot{m}_a fh$, and the airflow can be expressed as $\dot{m}_a = \rho_a u_x A_c$. Substituting and simplifying, the combustor <u>length,</u> $L_c=V_c/A_c$ is found to be

$$L_c \approx \frac{u_x}{u_t} l_t$$

which simply says that the combustor length scales with its width, or with whatever determines the eddy size. We could call this "photographic scaling".

(b) <u>At low pressure</u>, chemical reactions limit the combustion time, and assuming a bi-molecular reaction mechanism,

$$t_{burn} = \frac{n_{products}}{\dot{n}_{producs}} = \frac{n_{products}}{R(T)n_1 n_2} \propto \frac{C(T)}{\rho_a}$$

The power per unit volume is now proportional to the air density, and repeating the steps of case (a), we arrive at a combustor length estimate

$$L_c \approx C(T)\frac{u_x}{\rho_a}$$

which is independent of width or any other size parameter. In other words, <u>the chemically-limited combustor length is independent of engine size</u>.

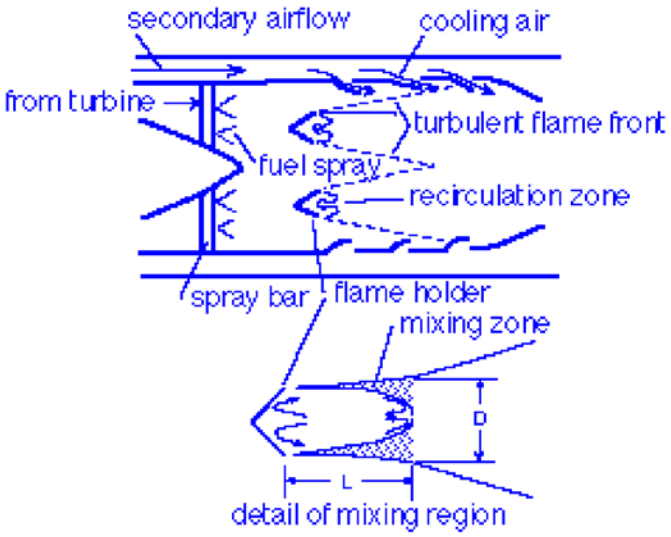
Roughly speaking, the larger of the two estimates must be chosen in order to satisfy conditions both at design and at low pressure. For a given engine family, the smaller engines will be chemically limited and will all tend to have equal length combustors (so the combustor is most prominent in the smallest of them), but at some larger size, length will need to be increased in proportion to width in order to obtain sufficient mixing.

<u>Afterburners:</u>

The afterburner faces a different set of requirements

a) High outlet temperature
b) High flow Mach number
c) Low pressure drop required when non-afterburning
d) Accepts flow from both core and fan

In afterburners the flame needs to be stabilized by bluff bodies, usually triangular in shape as indicated in the diagram. This is because the flame speed, even accounting for turbulent effects, is not as large as the mean flow speed, and the flame would be carried away without some recirculatory zone where combustion has time to occur.



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The requirement for stability is that the fuel-air mixture spend a certain time, τ_c, that is required for the chemical reactions to initiate, in the mixing layer adjacent the recirculating wake. So the flow time τ_f must be greater than this "chemical time" τ_c. From the flow geometry,

$$\tau_f = \frac{L}{V}$$

So we require

$$\frac{L}{V} > \tau_c$$

The length/breadth of the wake region is nearly independent of the absolute breadth, so we can say that $L = (\frac{L}{D})D$, and we see that a certain <u>size</u> of flame holder is required such that

$$\frac{D}{V}(\frac{L}{D}) > \tau_c$$

Since V and τ_c are independent of engine size, we find that D is as well. This is an example of <u>lack of geometric scaling</u>, analogous to the low-pressure scaling for the main combustor.

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