Ramjet engine

To ram means to force in. In ramjet air is forced into the engine air intake by the sheer drive of the speed of flight. Ramjet, in principle, can work at subsonic speed but it can be practical only at supersonic speed.

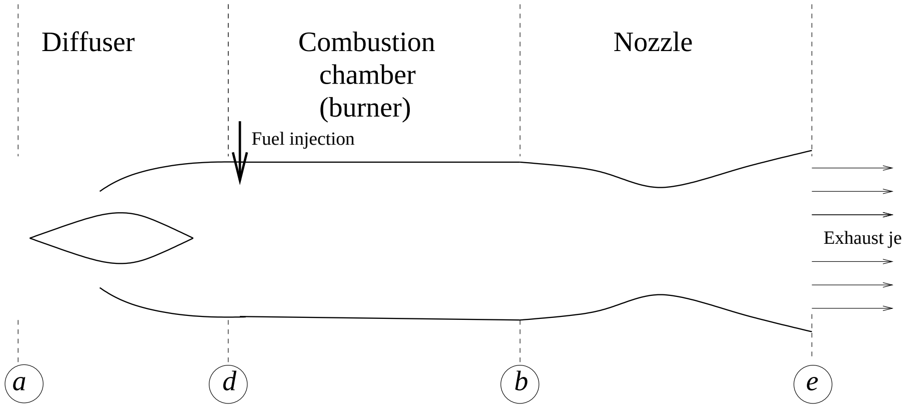

Figure 1: The ramjet.

In a ramjet, air undergoes compression in the diffuser, then fuel is added and burnt in the burner, and then the combustion products expand through the nozzle. It is helpful to consider first a simplified model of an **ideal ramjet**. For ideal ramjet it is assumed that compression and expansion processes are reversible and adiabatic, that combustion occurs at constant pressure, that the air/combustion products properties (specific heat ratio γ and the gas constant R) are constant throughout the engine, and, although this is not necessary, that the outlet pressure is equal to the ambient pressure, in other words, that the nozzle is in the design regime. The usual tool for analysis of the processes in engines is the so-called enthalpy-entropy diagram.

The thermodynamic state of air is determined by two independent parameters. If a point in $h-s$ diagram is given then all other parameters, like pressure, temperature, density, internal energy etc can be calculated. When a unit mass of air moves through the engine the properties are changing and the point that indicates the state is moving accordingly. The use of the enthalpy h and entropy s is especially convenient for the following reasons. In adiabatic reversible process s remains constant, and, therefore, the path of such a process is a vertical line in $h-s$ diagram. Since irreversibility usually lead to deterioration of performance, engines are designed so as to be as close to reversible processes as possible. If the process is irreversible then entropy at the end of it is greater than entropy at the end of the corresponding reversible process. Therefore, in $h-s$ diagram it is easy to anticipate the effect of irreversibility on the shape of the diagram. The advantage of using enthalpy as the other parameter follows from the form of the energy conservation law for open steady-state system:

$$\frac{\dot{W}}{\dot{m}} = \frac{\dot{Q}}{\dot{m}} - h_{0\text{out}} + h_{0\text{in}} = \frac{\dot{Q}}{\dot{m}} - (h_{\text{out}} + \frac{u_{\text{out}}^2}{2}) + (h_{\text{in}} + \frac{u_{\text{in}}^2}{2})$$

where $\frac{\dot{W}}{\dot{m}}$ and $\frac{\dot{Q}}{\dot{m}}$ are respectively the work done by and the heat added to a unit mass of air passing from station "in" to station "out". Therefore, changes in h can readily be interpreted as work done, heat added, or kinetic energy variation. For a perfect gas $h = c_p T$, therefore, one can consider h axis as approximate temperature axis. Therefore, a restriction of the maximum temperature in the engine can be interpreted as a restriction on maximum h.

In a diffuser no heat is added to air and no work is done, but the velocity decreases. Therefore, h increases, as shown in Fig. 2 by a straight line a-d, with $h_d - h_a$ equal to the kinetic energy of a unit mass in the incoming flow. Then, heat is added in the combustion process d-b. Heat addition leads to an increase in s in accordance with the formula $dQ = Tds$ for reversible processes. Therefore, d-b goes in the direction of increasing s along the curve $p = const$. Along this curve $h_b - h_d$ represents the amount of heat added per unit mass of air. In the nozzle no heat is added and no work is done, therefore, the total enthalpy is constant, but kinetic energy increases and h decreases, with $h_b - h_e$ giving the kinetic energy of a unit mass in the exhaust jet.

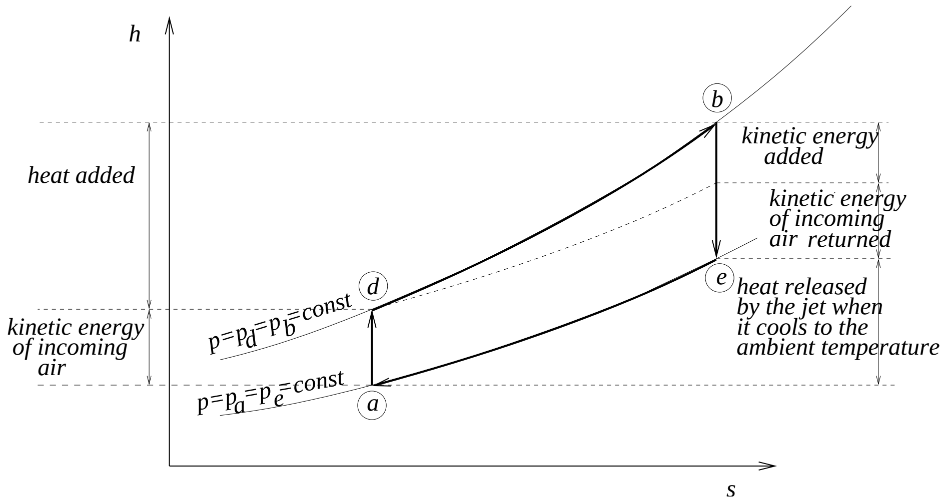

Figure 2: Enthalpy-entropy diagram for an ideal ramjet

For a perfect gas in $h-s$ diagram the $p = const$ curves have the form $h = Const\,\exp(s/c_p)$, and, therefore, the distance b-e is greater than d-a. This is a very important feature. It is also true for real gases even though the curves may be not exactly exponential. Therefore, the exhaust velocity is greater than the flight velocity, and thrust is created.

Naturally, exhaust gases do not go back into the air intake. However, they do cool down to the ambient temperature. This process occurs at constant pressure $p = p_a$ and is shown as curve e-a in the figure. The enthalpy difference $h_e - h_a$ is the amount of heat per unit mass released by the jet when it cools down. We can see that only part of the heat added in the combustion process turns into the useful kinetic energy.

It is possible now to analyse the effects of various parameters on the engine performance.

Decreasing the flight speed, that is decreasing the Mach number, decreases the kinetic energy $h_d - h_a$ (see Fig. 2). Imagine that it became very small. Then d-b will almost coincide with a-e. As a result, the added kinetic energy will become very small. At the same time the heat released by the jet will be almost equal to the heat added in the burner and will remain finite. That is burning a finite amount of fuel will produce almost no thrust, that is the thrust specific fuel consumption, TSFC, will become quite high. Also, since the added kinetic energy is small, specific thrust, that is thrust-to-air-mass-flow rate ratio will also be small. Then, for producing finite thrust the air mass flow rate has to be large, and, accordingly, the engine size has to be quite large. This is why ramjet is not practical at small Mach numbers.

If, for a fixed Mach number, that is fixed $h_d - h_a$, the added heat $h_b - h_d$ is increased the kinetic energy added will also be increased (see again Fig. 2). Therefore, the specific thrust will be increased thus allowing smaller engine for the same thrust. The thermal efficiency will not be affected strongly as one can also see from the figure. However, an increase in h_b means increase in the maximum temperature, and this is limited by the material properties of the engine walls.

Suppose that the maximum temperature, and, hence, h_b is fixed. Consider the variation of the specific thrust and TSFC with the Mach number M. At small M, point d is close to point a, and, as discussed, TSFC is high and specific thrust is small. An increase in M reduces TSFC. As for the specific thrust, one has to take into account that with h_b fixed increase in h_d results in a decrease in the amount of heat added. For small M this effect is, clearly (see the figure again) is less important and specific thrust increases with M. However, when h_d approaches h_b, the kinetic energy added, being only a fraction of the added heat, tends to zero. Accordingly, the specific thrust also tends to zero. Therefore, specific thrust has a maximum at some value of M between zero and that value of M at which isentropic compression in the diffuser leads to temperature attaining the maximum allowed value.

It is possible to calculate all characteristics of an ideal ramjet. However, the use of $h-s$ diagram makes it possible to achieve an intuitive understanding of the engine performance, as this was illustrated above. One can now, for example, anticipate the rationale of the turbojet. Try it.