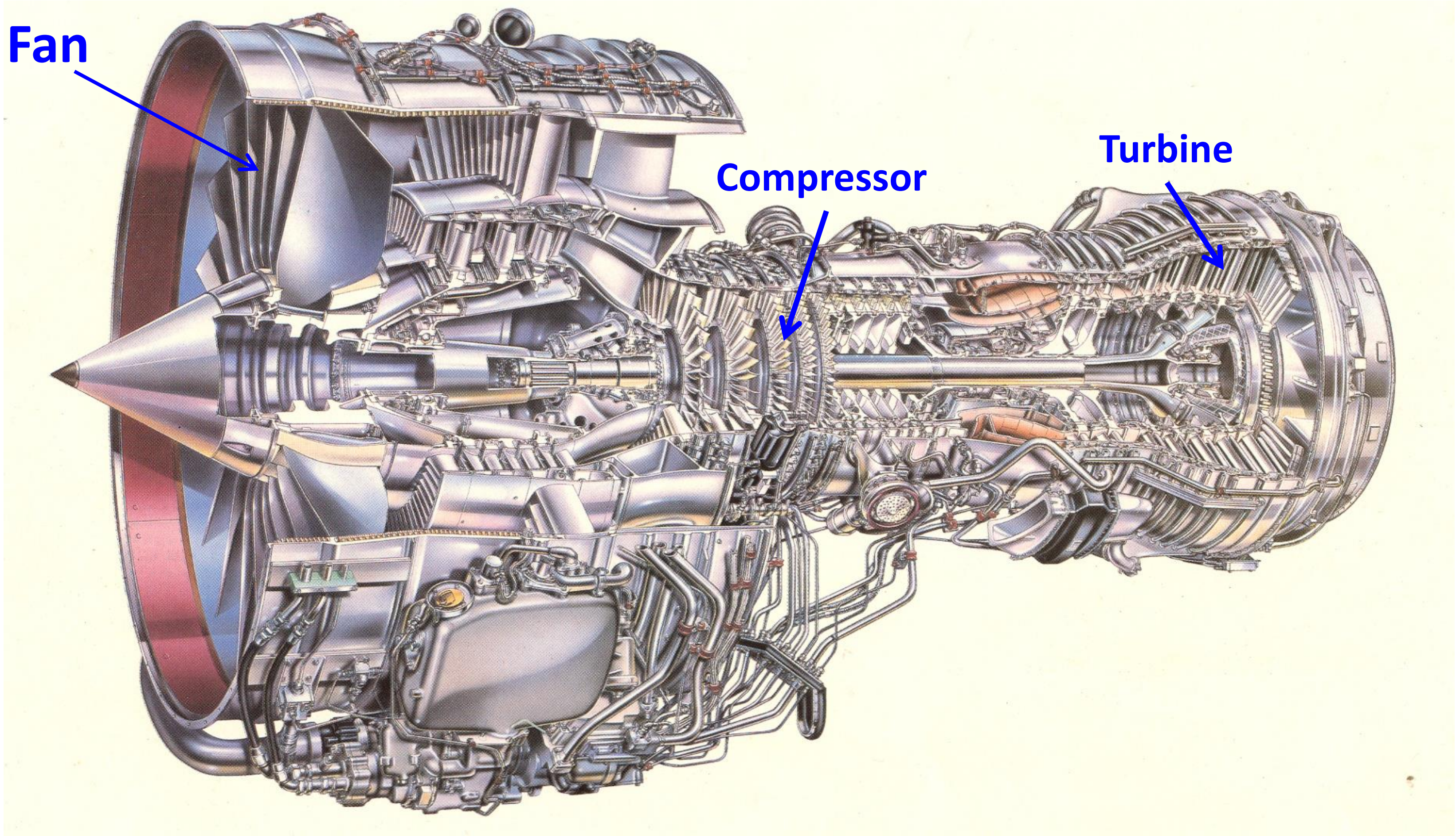
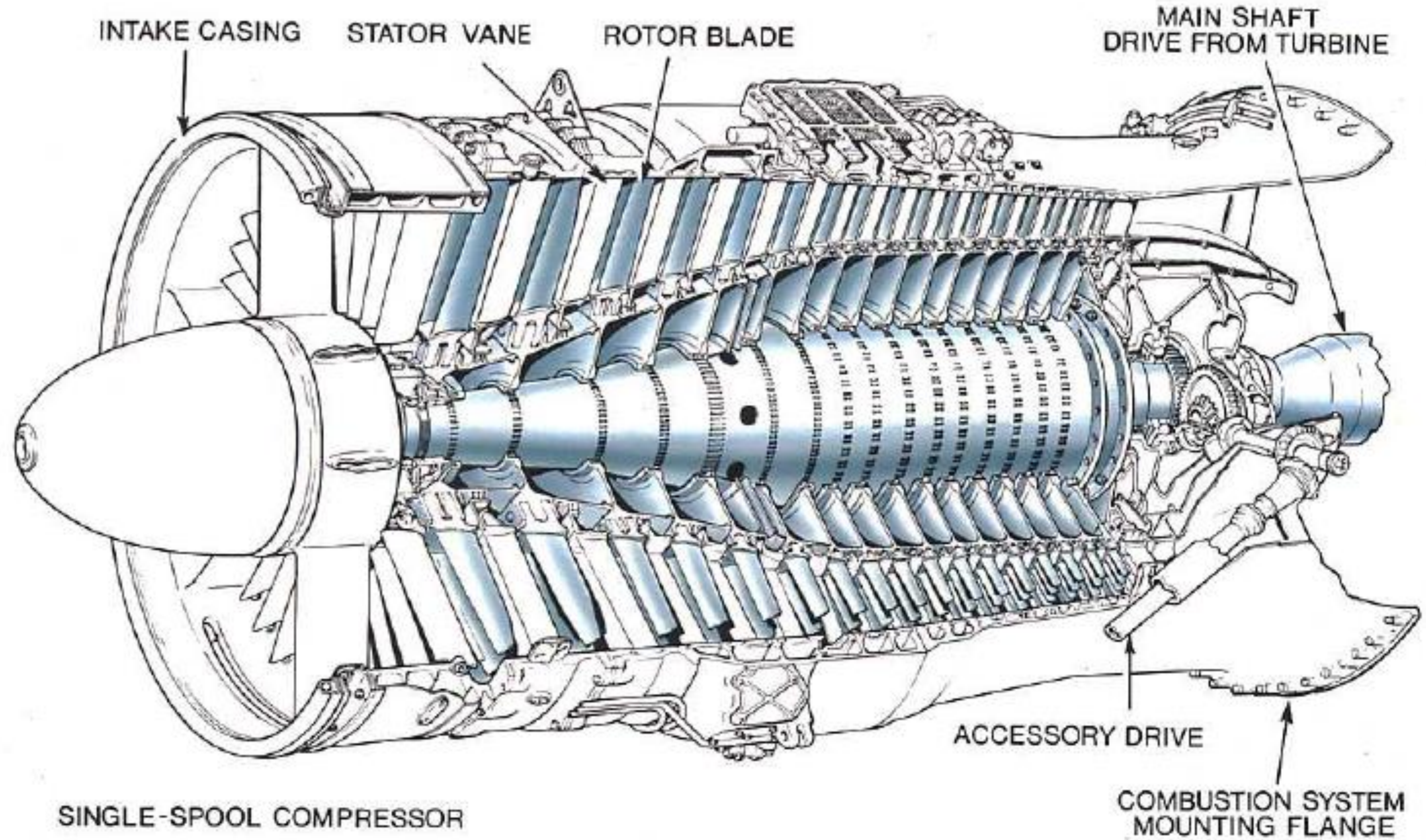
- Recap: Lecture 1: 21st July 2015, 1530-hrs.
  - Introduction
  - Aims of the course
  - Course contents
  - Text books/references
  - Evaluation scheme and course schedule

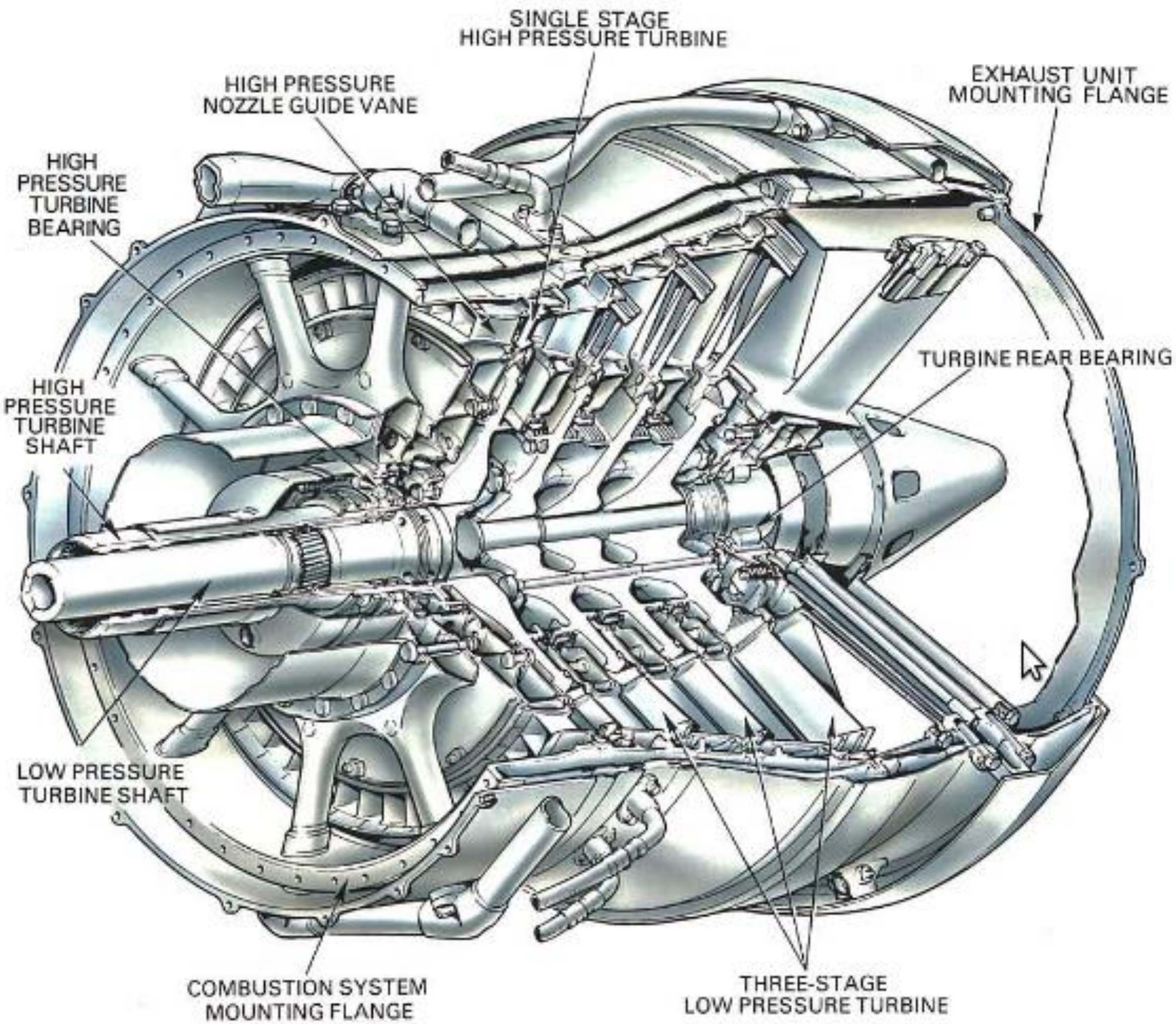


A modern high bypass turbofan engine



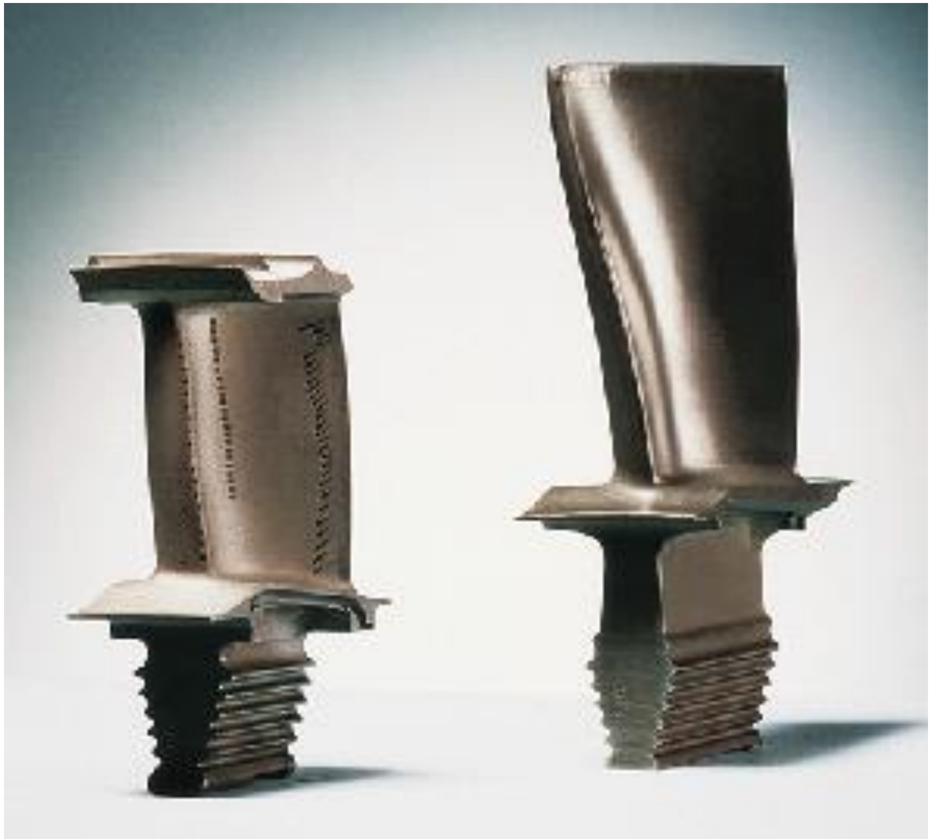
Typical multi-stage axial flow compressor

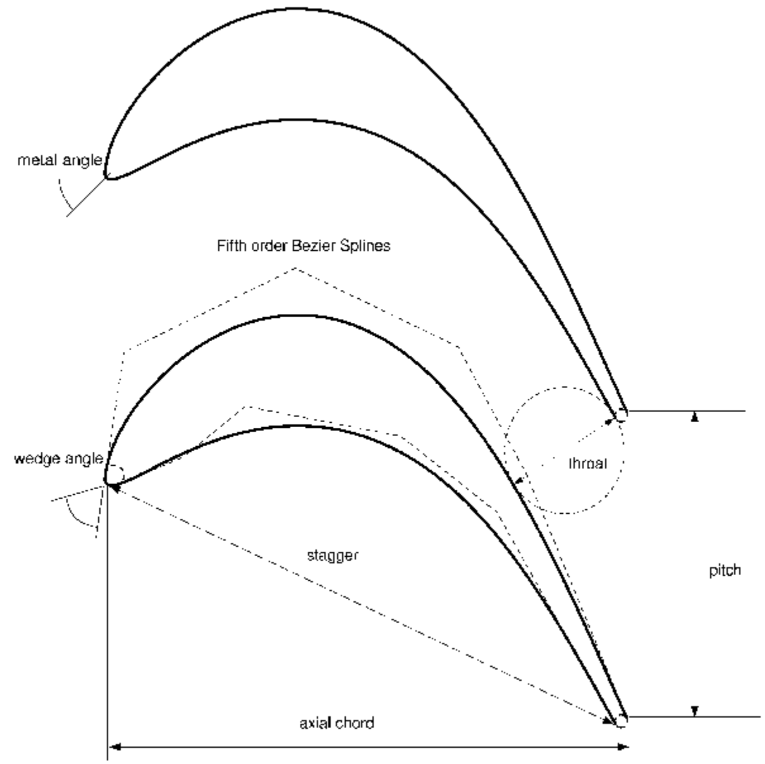
Source: *The Jet Engine*, Roll Royce Plc, 1996



A twin turbine and shaft system

Source: The Jet Engine, Rolls Royce, 1996





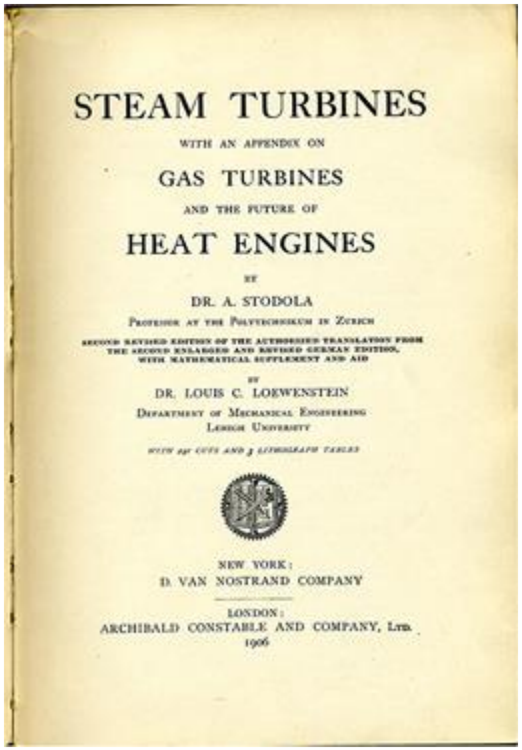
Turbine nozzle and rotor blade geometries

Source: Mitsubishi Heavy Industries, Ltd.

Centrifugal compressor

	787 Engines: GEnx-1B Trent 1000	767 Engines: GE CF6-80C2 RR RB211-524G/H
Bypass Ratio	~10	~5
Overall Pressure Ratio	~50	~33
Thrust Class	53,000–74,000 lbf	53,000–63,000 lbf
Fan Diameter	111–112 in	86–93 in
Specific Fuel Consumption	15% lower	Base
Noise	ICAO Chapter 4	ICAO Chapter 3
Emissions	CAEP/8 (2014)	CAEP/2

Source: http://www.boeing.com/commercial/aeromagazine/articles/2012_q3/2/



STEAM TURBINES

WITH AN APPENDIX ON

GAS TURBINES

AND THE FUTURE OF

HEAT ENGINES

BY

DR. A. STODOLA

PROFESSOR AT THE POLYTECHNIKUM IN ZURICH

SECOND REVISED EDITION OF THE AUTHORIZED TRANSLATION FROM THE SECOND ENLARGED AND REVISED GERMAN EDITION, WITH MATHEMATICAL SUPPLEMENT AND AID

BY

DR. LOUIS C. LOEWENSTEIN

DEPARTMENT OF MECHANICAL ENGINEERING
LEHIGH UNIVERSITY

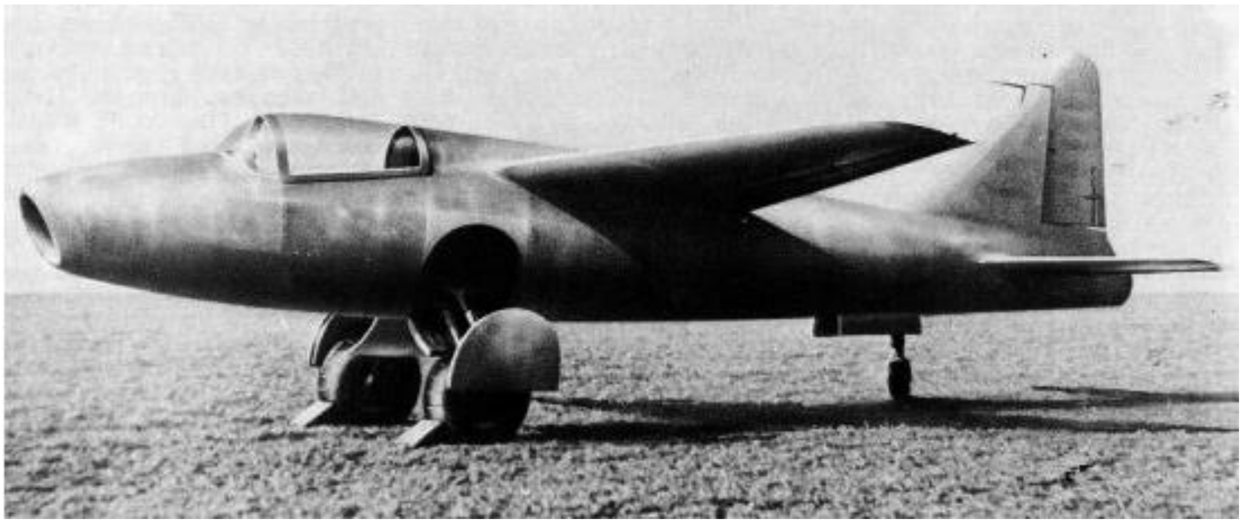
WITH [illegible] CUTS AND 3 LITHOGRAPH TABLES

NEW YORK:
D. VAN NOSTRAND COMPANY

LONDON:
ARCHIBALD CONSTABLE AND COMPANY, LTD.
1906

Commissioning of world's first industrial gas turbine, Neuchatel, 1939 (Stodola at age 80)

Frank Whittle and Hans von Ohain



First turbojet-powered aircraft – Ohain’s engine on He 178 (1939)

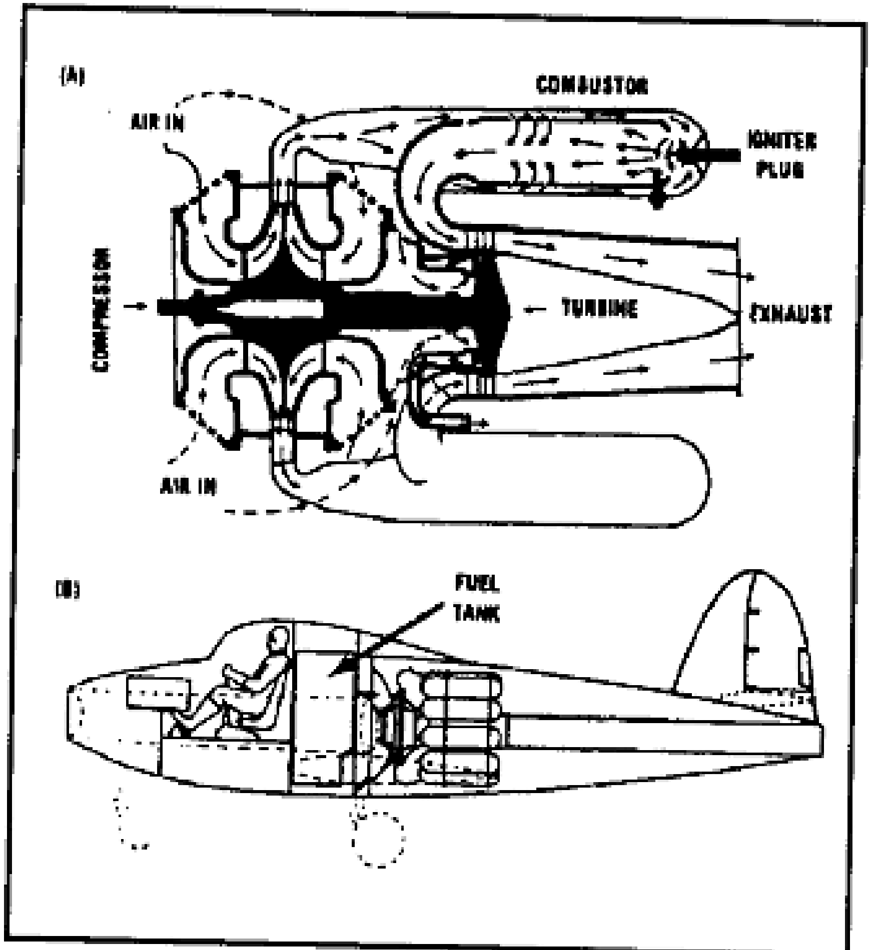
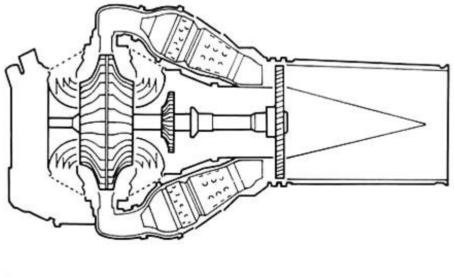
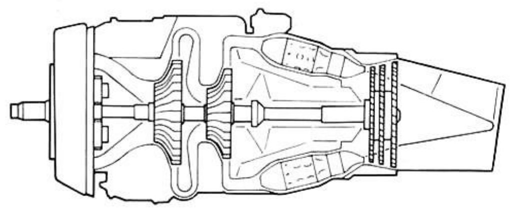


Figure 2-5. A – Whittle's Reverse-Flow Combustion Chamber. B – Fuselage Arrangement of the E28/39 Experimental

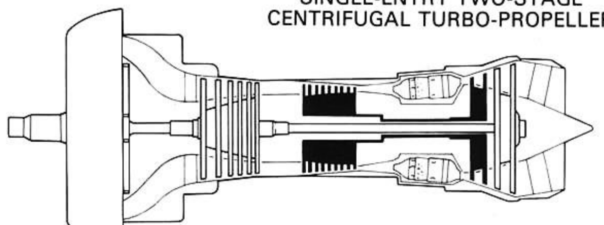
Powered the Gloster E28/39 Britain on 15 May 1941.



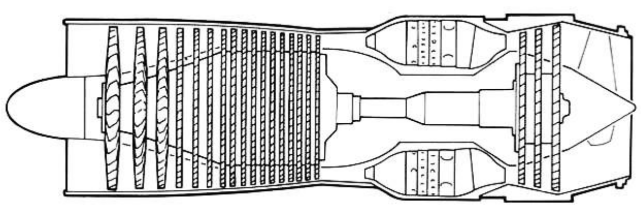
DOUBLE-ENTRY SINGLE-STAGE
CENTRIFUGAL TURBO-JET



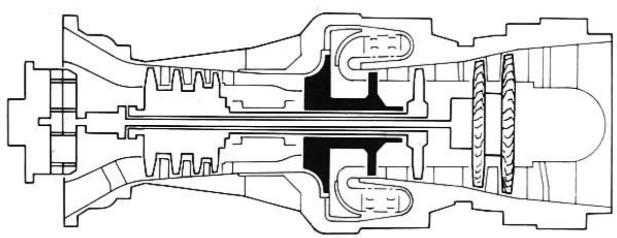
SINGLE-ENTRY TWO-STAGE
CENTRIFUGAL TURBO-PROPELLER



TWIN-SPOOL AXIAL FLOW TURBO-PROPELLER



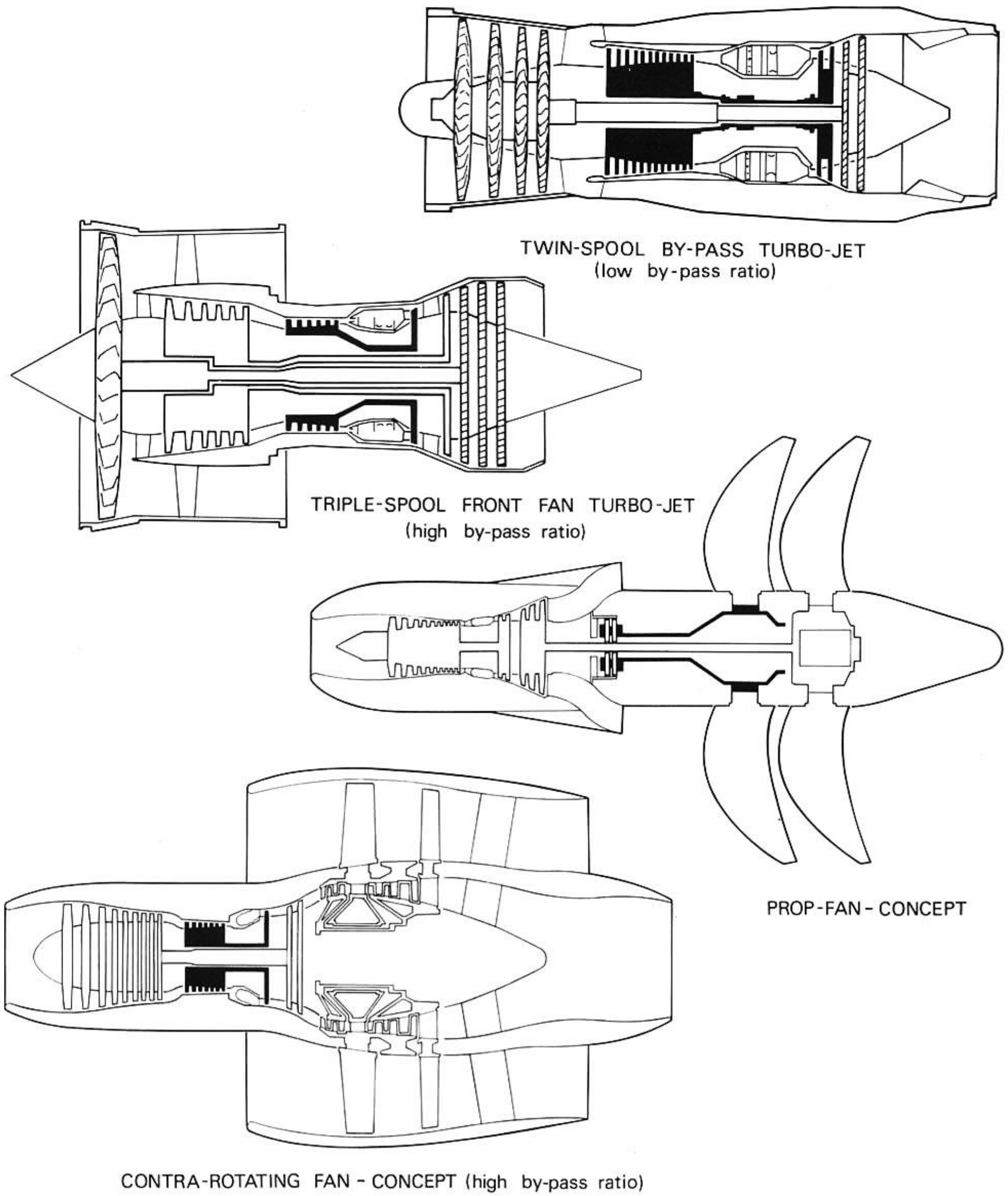
SINGLE-SPOOL AXIAL FLOW TURBO-JET



TWIN-SPOOL TURBO-SHAFT (with free-power turbine)

Types of Gas Turbine Engines

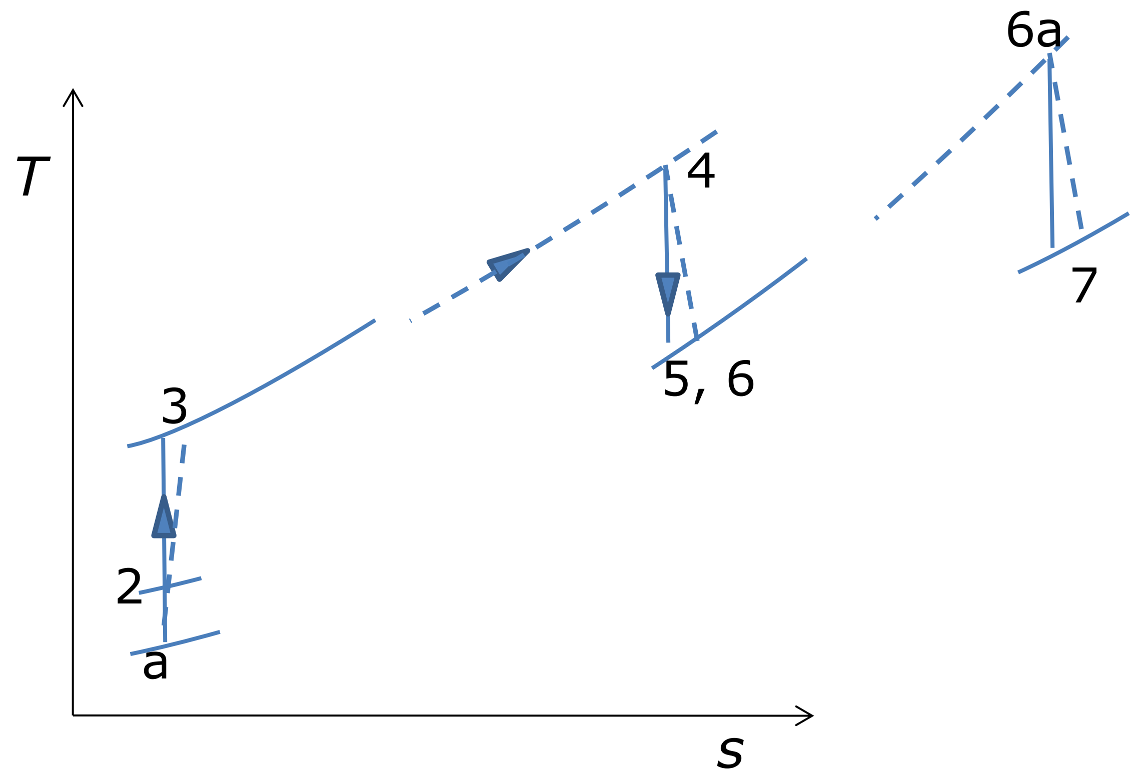
Courtesy: The Jet Engine: Rolls Royce, 1996



Types of Gas Turbine Engines

Courtesy: The Jet Engine: Rolls Royce, 1996

Real cycle for turbojet engines



Real turbojet cycle (with afterburning) on a T-s diagram

Review of Thermodynamic Concepts

Total energy of a system

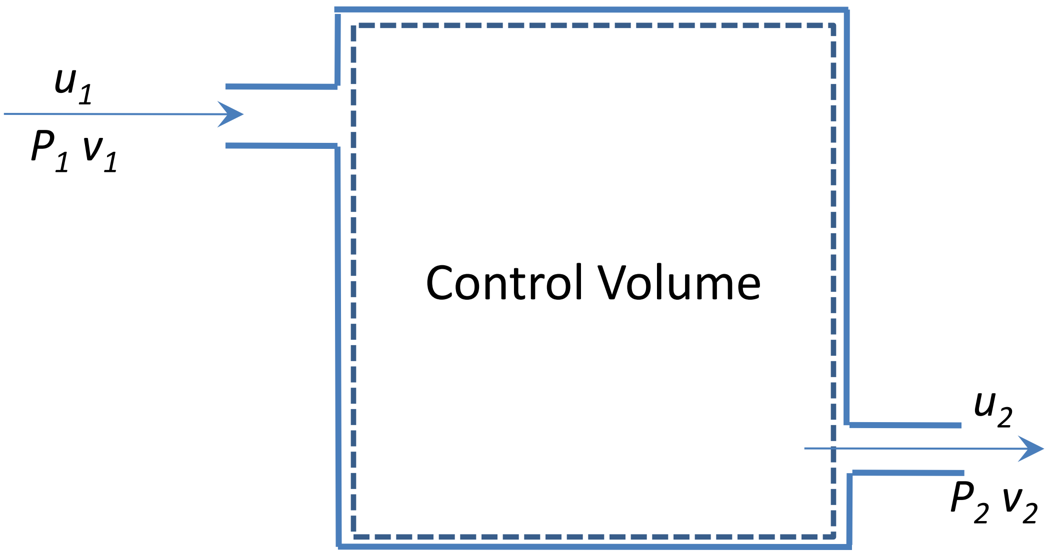
- In the absence of magnetic, electric, and surface tension effects, the total energy of a system consists of the kinetic, potential, and internal energies

$$E = U + KE + PE = U + \frac{mV^2}{2} + mgz \quad \text{(kJ)}$$

or, on a unit mass basis

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

Enthalpy



The combination u+Pv is frequently encountered in the analysis of control volumes

Enthalpy

- The combination of internal energy *u* and *Pv* is often encountered in the analysis of control volumes
- Enthalpy is a combination property

$$\text{Enthalpy}, h = u + Pv \quad (\text{kJ/kg})$$

$$H = U + PV \quad (\text{kJ})$$

- Enthalpy is also often referred to as heat content
- Process in which enthalpy is constant: isenthalpic process

Entropy

- Entropy is an extensive property of a system and sometimes is referred to as total entropy. Entropy per unit mass, designated *s*, is an intensive property and has the unit kJ/kg.K
- The entropy change of a system during a process can be determined by

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right)_{\text{int. } rev.} \qquad \text{(kJ/kg)}$$

Entropy

- Entropy is a property, and like all other properties, it has fixed values at fixed states.

- Therefore, the entropy change dS between two specified states is the same no matter what path, reversible or irreversible.

Temperature-entropy plot

$$dS = \frac{dQ_{rev}}{T}$$

$$\text{If the process is reversible and adiabatic, } dQ_{rev} = 0$$

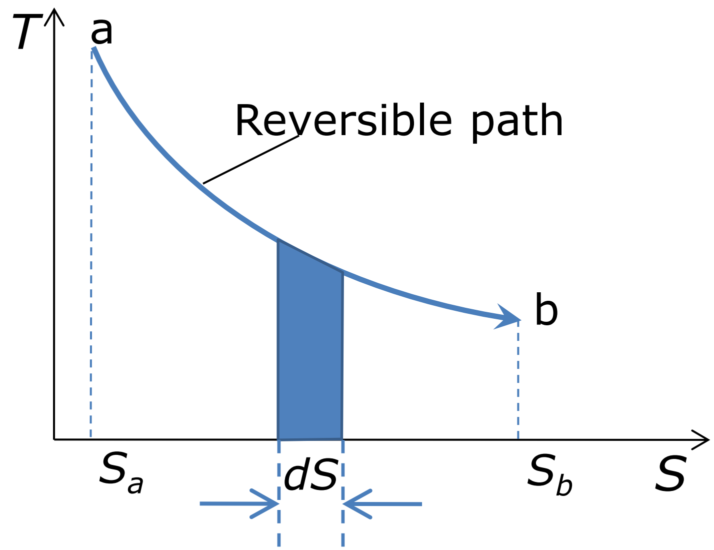
$$\therefore\ dS = 0 \quad or \quad S = \text{constant}$$

- A reversible adiabatic process is, therefore, and isentropic process.

$$dQ_{rev} = TdS$$

$$or,\ Q_{rev} = \int TdS$$

Temperature-entropy plot



$$Q_{rev} = \int_a^b TdS = T\left(S_b - S_a\right)$$

- The area under the reversible path on the T-S plot represents heat transfer during that process.

Isentropic processes

- A process where, $\Delta s=0$
- An isentropic process can serve as an appropriate model for actual processes.
- Isentropic processes enable us to define efficiencies for processes to compare the actual performance of these devices to the performance under idealized conditions.
- A reversible adiabatic process is necessarily isentropic, but an isentropic process is not necessarily a reversible adiabatic process.

TdS equations

- From the first law for an internally reversible process, we know that

$$dQ_{\mathrm{int}\,rev} - dW_{\mathrm{int}\,rev,out} = dU$$

$$\text{Since, } dQ_{\mathrm{int}\,rev} = TdS \text{ and } dW_{\mathrm{int}\,rev,out} = PdV$$

$$TdS = dU + PdV \;\; or,\, Tds = du + Pdv$$

- This is known as the first TdS equation.

TdS equations

- From the definition of enthalpy, we know that,

$$h = u + Pv$$

$$\text{or, } dh = du + Pdv + vdP$$

$$\text{since, } Tds = du + Pdv,$$

$$Tds = dh - vdP$$

- This is known as the second TdS equation.

Entropy change of ideal gases

- For ideal gases we know that,

$$du = c_v dT, \ P = RT / v$$

From the TdS relations,

$$ds = c_v \frac{dT}{T} + R\frac{dv}{v}$$

- The entropy change for a process,

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\ln\frac{v_2}{v_1}$$

Entropy change of ideal gases

If we use these relations,

$$dh = c_p dT,\ v = RT / P$$

Then, from the TdS relations,

$$s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\ln\frac{P_2}{P_1}$$

- Usually, we assume average values of c_p and c_v in the above equations and thus can replace $c_p(T)$ with $c_{p,av}$ and $c_v(T)$ with $c_{v,av}$.

Energy analysis of steady flow systems

- For single entry and exit devices,

$$\dot{Q}-\dot{W}=\dot{m}\left[h_2-h_1+\frac{V_2^{\,2}-V_1^{\,2}}{2}+g(z_2-z_1)\right]$$

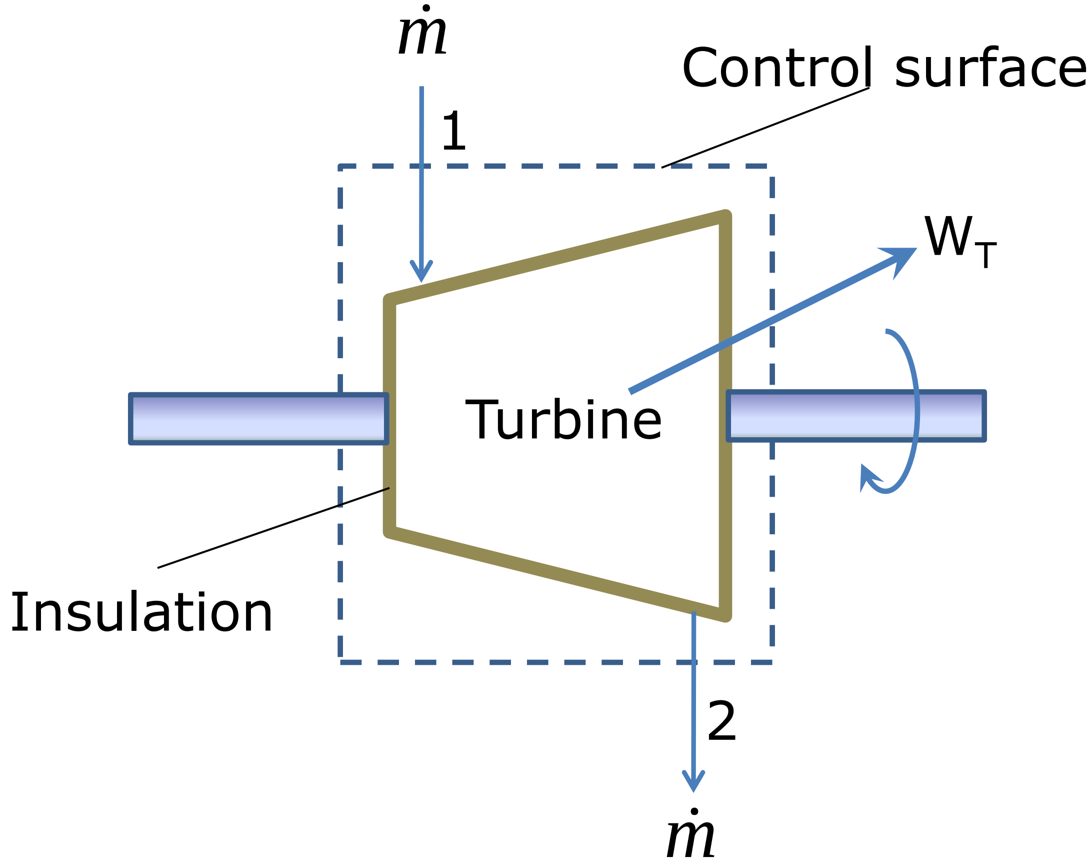
or per unit mass,

$$\dot{q}-\dot{w}=h_2-h_1+\frac{V_2^{\,2}-V_1^{\,2}}{2}+g(z_2-z_1)$$

Turbines and compressors

- Pumps, compressors and fans: used to increase the pressure of a fluid and require work input.
- Turbines generate work.
- Q, KE and PE may or may not be zero.
- Usually PE is negligibly small.

Turbines and compressors



Turbines and compressors

- For a turbine for eg., the energy equation would be:

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

If KE and PE are negligible,

$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

Stagnation properties

- Enthalpy represents the total energy of a fluid in the absence of potential and kinetic energies.
- For high speed flows, though potential energy may be negligible, but not kinetic energy.
- Combination of enthalpy and KE is called stagnation enthalpy (or total enthalpy)

$$h_0 = h + V^2/2 \qquad \text{(kJ/kg)}$$

Stagnation enthalpy Static enthalpy Kinetic energy

Stagnation properties

- Consider a steady flow through a duct (no shaft work, heat transfer etc.).
- The steady flow energy equation for this is: $h_1 + V_1^2/2 = h_2 + V_2^2/2$

  or, $h_{01} = h_{02}$

- That is in the absence of any heat and work interactions, the stagnation enthalpy remains a constant during a steady flow process.

Stagnation properties

- If the fluid were brought to rest at state 2,

$$h_1 + V_1^2/2 = h_2 = h_{02}$$

- The stagnation enthalpy represents the enthalpy of a fluid when it is brought to rest adiabatically.
- During a stagnation process, the kinetic energy of a fluid is converted to enthalpy (internal energy + flow energy), which results in an increase in the fluid temperature and pressure.

Stagnation properties

- When the fluid is approximated as an ideal gas with constant specific heats,

$$c_p T_0 = c_p T + V^2/2$$

$$\text{or,} \quad T_0 = T + V^2/2c_p$$

- T_0 is called the stagnation temperature and represents the temperature an ideal gas attains when it is brought to rest adiabatically.
- The term $V^2/2c_p$ corresponds to the temperature rise during such a process and is called the dynamic temperature.

Stagnation properties

- The pressure a fluid attains when brought to rest isentropically is called the stagnation pressure, P_0.
- For ideal gases, from isentropic relations,

$$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\gamma/(\gamma-1)}$$

Similarly, for density we have,

$$\frac{\rho_0}{\rho} = \left(\frac{T_0}{T}\right)^{1/(\gamma-1)}$$