by the turbine exhaust before reaching the combustion chamber. The effectiveness of the regenerator is 80%. The maximum temperature after constant-pressure combustion is 677°C and the efficiency of the turbine is 80%. Neglecting all losses except mentioned, and assuming the working fluid throughout the cycle to have the characteristics of air

(i) Sketch the cycle on the T-s diagram.

(ii) Calculate the efficiency of the cycle.

Ans: (i) 23.7%

6.2 A simple gas turbine takes in air at 1.0 bar and 27°C and compresses to a pressure of 6 bar with the isentropic efficiency of compression being 85%. The air passes to the combustion chamber, and after combustion the gases enter the turbine at a temperature of 560°C and expand to 1.00 bar, the turbine efficiency being 80%. Neglecting the change of mass flow rate due to fuel, calculate the flow of air in kg per second for a net output of 1500 kW making the following assumptions: Loss of pressure in combustion chamber = 0.08 bar.
Ans: (i) 42.67 kg/s

6.3 The axial compressor of a gas turbine delivers 20 kg/s of air at a pressure ratio of 5.0 with an isentropic efficiency of 80%. Inlet temperature and pressure are 22°C and 1 bar. Calculate the power required by the compressor.

After heating at constant-pressure to 870°C the gas is expanded to 1 bar through a turbine with efficiency of 85%. The turbine is direct coupled to the compressor and to an airscrew reduction gear which has an efficiency of 95%. What power is available for the airscrew?
Ans: (i) 4332.56 kW (ii) 2852.17 kW

6.4 For a gas turbine operating at a pressure ratio of 8.7 the maximum temperature ratio to be maintained such that the turbine just supports the compressor, which is given by $t_{min} = 3.0$. If the compressor inlet total temperature and the turbine efficiency are respectively 300 K and 0.75, find the following:

(i) the compressor efficiency

(ii) the temperature ratio at which the compressor work is 80% of the power produced by turbine. Also find the corresponding heat addition and Net work output per unit mass flow in the gas turbine. Take $C_{pa} = 1.005$ kJ/kg K and $C_{pg} = 1.147$ kJ/kg K.

(iii) for the temperature ratio found at (ii) find the required compressor pressure ratio at which the compressor work and turbine work are equal. Take $\gamma_g = \gamma_a$ and $C_{pg} = C_{pa}$.

Ans: (i) 0.8 (ii) (a) 3 (b) 396.06 kW (c) 64.29 kW (iii) 12.33

6.5 In a gas turbine the pressure ratio of r is achieved by two stage compression with intercooling. If η_1 is the efficiency of LP compressor, η_2 is the efficiency of the HP compressor and ϵ is the effectiveness of the intercooler. Derive an expression for the above for stage pressure ratios in terms of overall pressure ratio between first stage and second stage such that work of compressor is minimum.

If the efficiencies of the HP and LP compressors are respectively 0.75 and 0.85, and if the effectiveness of the intercooler is 80%, find the work of compression assuming the inlet temperature at LP compressor as 300 K. The total pressure ratio for overall compression ratio is 11.3137. *Ans:* (i) $c_{01} = \left[c\left(\frac{\eta_1+\epsilon-1}{\eta_2+\epsilon-1}\right)\right]^{\frac{1}{2}}$ (ii) $c_{02} = \left[c\left(\frac{\eta_2+\epsilon-1}{\eta_1+\epsilon-1}\right)\right]^{\frac{1}{2}}$ (iii) 327.368 kJ/kg

6.6 A simple gas turbine with heat-exchanger has a compressor and turbine having respective isentropic efficiencies η_C and η_T. Show that the combined effect of small pressure drops Δp_{hg} (in gas-side of heat-exchanger) and Δp (total in combustion chamber and air-side of heat-exchanger) is to reduce the specific work output by an amount given by

$$\left(\frac{\gamma-1}{\gamma}\right) \times \left(\frac{C_p T_{03} \eta_T}{r^{\frac{\gamma-1}{\gamma}} p_{01}}\right)\left(\Delta p_{hg} + \frac{\Delta p}{r}\right)$$

where T_{03} is turbine inlet temperature, p_{01} is compressor inlet pressure and r, the compressor pressure ratio. Assume that C_p and γ are constant throughout the cycle.

6.7 In a gas turbine plant, air is compressed from state (p_{01}, T_{01}) to a pressure rp_{01} and heated to temperature T_{03}. The air is then expanded in two stages with reheat to T_{03} between the turbines. The isentropic efficiencies of the compressor and each turbine are η_C and η_T. If xp_{01} is the intermediate pressure between the turbines, show that, for given values $p_{01}, T_{01}, T_{03}, \eta_C, \eta_T$ and r, the specific work output is a maximum when $x = \sqrt{r}$.

If this division of the expansion between the turbines is maintained, show that:

(i) when r is varied, the specific work output is a maximum with r given by

$$r^{3/2} = \left(\frac{\eta_C \eta_T T_{03}}{T_{01}}\right)^{\gamma/(\gamma-1)}$$

(ii) when a perfect heat-exchanger is added, the cycle efficiency is given by

$$\eta = 1 - \frac{T_{01} r^{(\gamma-1)/2\gamma}\left(r^{(\gamma-1)/2\gamma} + 1\right)}{2\eta_C \eta_T T_{03}}$$

Assume that the working fluid is a perfect gas with constant specific heats, and that pressure losses in the heater, reheater, and heat-exchanger are negligible.

6.8 A peak load generator is to be powered by a simple gas turbine with free power turbine delivering 20 MW of shaft power. The following data are applicable:

Compressor pressure ratio	:	11.0
Compressor isentropic efficiency	:	0.82
Combustion chamber pressure loss	:	0.4 bar
Combustion efficiency	:	0.99
Turbine inlet temperature	:	1150 K
Power turbine isentropic efficiency	:	0.89
Mechanical efficiency (each shaft)	:	0.98
Ambient conditions p_a, T_a	:	1 bar, 300 K

Assume gas generator turbine isentropic efficiency = 0.87, Draw the schematic diagram of the cycle. If the calorific value of the fuel = 43 MJ/kg, calculate the air mass flow required and the specific fuel consumption. *Ans:* (i) 130.51 kg/s (ii) 0.3726 kg/kW h

6.9 A gas turbine is to consist of a compressor, combustion chamber, turbine and heat-exchanger. It is proposed to examine the advantage of bleeding off a fraction $\left(\frac{\Delta m}{m}\right)$ of the air delivered by the compressor and using it to cool the turbine blades. By so doing the maximum permissible cycle temperature may be increased from T to $(T + \Delta T)$. The gain in efficiency due to the increase of temperature will be offset by a loss due to the decrease in effective air flow through the turbine. Show that, on the following assumptions, there is no net gain in efficiency when

$$\frac{\Delta m}{m} = \frac{\left(\frac{\Delta T}{T}\right)}{\left(1 + \frac{\Delta T}{T}\right)}$$

and that this result is independent of the compressor and turbine efficiencies. Assumptions:

(i) No pressure loss in combustion chamber or heat exchanger.

(ii) Working fluid is air throughout and the specific heats are constant.

(iii) Air bled for cooling purposes does no work in the turbine.

(iv) Temperature of the air entering the combustion chamber is equal to that of the turbine exhaust.

A plant of this kind operates with an inlet temperature of 288 K, a pressure ratio of 6.0, a turbine isentropic efficiency of 90 per cent and a compressor isentropic efficiency of 87 per cent. Heat transfer calculations indicate that if 5 per cent of the compressor delivery is bled off for cooling purposes, the maximum temperature of the cycle can be raised from 1000 to 1250 K. Find the percentage increase in (a) efficiency, and (b) specific work output, which is achieved by the combined bleeding and cooling process. Make the same assumptions as before and take $\gamma = 1.4$ throughout. *Ans:* (i)25.1% (ii) 48.55%

6.10 The efficiencies of the compressor and turbine of a gas turbine are $\eta_C = 0.80$ and $\eta_T = 0.75$ respectively. If the temperature ratio is 4 and the inlet total temperature of air 300 K, find the optimum pressure ratio, and corresponding Net work output, work ratio, heat addition and efficiency. *Ans:* (i) 4.626 (ii) 158.96 kJ/kg (iii) 0.43 (iv) 796.16 kJ/kg (v) 19.96%

6.11 An auxiliary gas turbine for use on a large airliner uses a single-shaft configuration with air bled from the compressor discharge for aircraft services. The unit must provide 1.5 kg/s bleed air and a shaft power of 200 kW. Calculate (a) the total compressor air mass flow and (b) the power available with no bleed flow, assuming the following:

Compressor pressure ratio	:	3.80
Compressor isentropic efficiency	:	0.85
Combustion pressure loss	:	0.12 bar
Turbine inlet temperature	:	1050 K
Turbine isentropic efficiency	:	0.88
Mechanical efficiency (compressor rotor)	:	0.99
Mechanical efficiency (driven load)	:	0.98
Ambient conditions	:	1 bar, 288 K

Ans: (i) 4.97 kg/s (ii) 630.9 kW

6.12 In a simple gas turbine plant air enters the compressor at 1 bar and 15°C and leaves at 6 bar. It is then heated in combustion chamber to 700°C and then enters the turbine and expands to atmospheric pressure. The isentropic efficiency of compressor and turbine are 0.80 and 0.85 respectively and the combustion efficiency is 0.90. The fall in pressure in the combustion chamber is 0.1 bar. Determine

(i) air-fuel ratio,

(ii) work ratio,

(iii) thermal efficiency,

(iv) air rate in kg per shaft kilowatt power, and

(v) specific fuel consumption.

Take calorific value of the fuel equal 42000 kJ/kg.

Ans: (i) 73.219:1 (ii) 0.2831 (iii) 16.89% (iv) 0.0105 kg/kW
(v) 0.5158 kg/kW h

6.13 An industrial gas turbine takes in air at 1 bar and 27°C and compresses it to 5.5 times the original pressure. The temperatures at the salient points are compressor outlet, 251°C, turbine inlet 760°C and turbine outlet 447°C. Calculate (i) the compressor and (ii) turbine efficiencies.

Compare the ideal cycle and the practical cycle considering component efficiencies for the following

(iii) work ratio,

(iv) thermal efficiency,

(v) optimum pressure ratio for maximum output.

Ans: (i) 0.842 (ii) 0.88 (iii) 0.47; 0.37 (iv) 0.308; 0.229 (v) 8.7; 5.7

6.14 Deduce an expression for the specific output (kJ/kg of working fluid) of a simple constant-pressure gas turbine in terms of temperatures at the beginning of compression and at the beginning of expansion, the isentropic efficiencies of the compressor and turbine, the pressure ratio and the isentropic index. The specific heat at constant-pressure may be assumed constant, and the weight of the fuel added may be neglected.

Hence determine the pressure ratio at which the specific output is maximum for the following operating conditions. Temperature at compressor inlet is 15°C, temperature at turbine inlet is 630°C and the isentropic efficiency for compressor and turbine is 0.85 and 0.90 respectively.

Neglect the effect of fuel flow and assume constant C_p of air. Determine in kg/kW-h the air flow and the specific fuel consumption, if 1 kg/s of fuel is flowing with the calorific value of 42000 kJ/kg.

$$Ans:\ \text{(i)}\ W_N = C_p\eta_T T_{03}\left[1 - \frac{1}{\left(r_p^{\frac{\gamma-1}{\gamma}}\right)}\right] - \frac{C_p}{\eta_C}T_{01}\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)$$

(ii) 4.62 (iii) 35.1 kg/kW h (iv) 0.362 kg/kW h

6.15 In a gas turbine plant, comprising a single stage compressor, combustion chamber and turbine, the compressor takes in air at 15°C and compresses it to 4 times the initial pressure with an isentropic efficiency of 85 per cent. The fuel-air ratio is 0.0125 and the calorific value of the fuel is 42000 kJ/kg. If the isentropic efficiency of the turbine is 82 per cent, find the amount of air intake for a power output of 260 kW and also the overall thermal efficiency. Take the mass of the fuel into account. The turbine inlet temperature is 1000 K.

Ans: (i) 2.33 kg/s (ii) 21.3%

6.16 At design speed the following data apply to a gas turbine set employing a separate power turbine, heat exchanger, reheater and intercooler between two-stage compression.

Efficiency of compression in each stage	:	80%
Isentropic efficiency of compressor turbine	:	87%
Isentropic efficiency of power turbine	:	80%
Transmission efficiency	:	99%
Pressure ratio in each stage of compression	:	2:1
Pressure loss in intercooler	:	0.07 bar
Temperature after intercooling	:	300 K
Thermal ratio of heat exchanger	:	0.75
Pressure loss in combustion chamber	:	0.15 bar
Combustion efficiency of reheater	:	98%