Version RJM/2

EGT3
ENGINEERING TRIPOS PART IIB

Tuesday X April 2023   2 to 3.40

Module 4A3

TURBOMACHINERY 1

*Answer not more than **two** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Attachment: Excerpt from Compressible Flow Data Book (pages 1-20 of 38 pages).
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

You may not remove any stationery from the Examination Room.

1 (a) A two-dimensional linear turbine cascade operates with air. The blade exit Mach number is 0.95. The opening-to-pitch ratio of the blade row is $o/s = 0.30$ and it has a stagnation pressure loss coefficient of $Y_p = (p_{01} - p_{02})/(p_{01} - p_2) = 0.035$. Assume that all loss occurs downstream of the choked throat, the blade height is constant through the cascade and that the growth of the endwall boundary layers is negligible. Show that the blade exit flow angle is 72.22°. [30%]

(b) At the inlet of the cascade the flow angle is $-30°$. The pitch to axial chord ratio of the blades is 1.0. Calculate the Zweifel loading coefficient for the blade. The Zweifel loading coefficient for a turbine is defined as

$$Z = \frac{\dot{m}\left|V_{\theta 2} - V_{\theta 1}\right|}{\left(p_{01} - p_2\right)c_x h}$$

If you wanted to reduce the loss coefficient of this blade row, would you lower or raise its pitch to axial chord ratio? Explain the physical cause of the reduction in loss. [25%]

(c) The blade design tested in the cascade is used as the rotor in a turbine. The working fluid of the turbine is air. At the design condition, the rotor relative flow angles and Mach numbers are matched to those of the cascade. At the inlet of the rotor the flow angle and stagnation temperature in the absolute frame are $-75°$ and 1000 K. Calculate the blade speed. [25%]

(d) The turbine rotates at 6000 rpm. The axial chord of the rotor is 50 mm. Calculate the number of blades in the rotor of the turbine. [20%]

Assume air behaves as a perfect gas with $\gamma = 1.4$ and $c_p = 1005$ J kg^{-1} K^{-1}.

2 (a) For an axial flow turbine with repeating stages derive the relationship

$$\psi = 2\left(1 - \Lambda - \phi \tan\alpha_1\right)$$

relating the stage loading ψ, the reaction Λ, the flow coefficient ϕ and the interstage swirl α_1. Hence explain two design choices which can be used to increase the stage loading of a turbine. [30%]

(b) A high pressure steam turbine has an overall enthalpy drop of 400 kJ kg $^{-1}$. It is composed of repeating stages each with the same mean line radius and blade speed of 200 m s $^{-1}$.

(i) An initial turbine is designed with 50% reaction, a flow coefficient of 0.4 and no interstage swirl. Calculate the number of stages required. [20%]

(ii) The turbine is redesigned with four less stages. A reaction of 30% is chosen and a flow coefficient of 0.4. Calculate the interstage swirl which is required. [20%]

(iii) Explain an advantage of 50% reaction design and an advantage of the 30% reaction design. [10%]

(c) The 30% reaction turbine in part (b) has a mass flow rate of 30 kg s $^{-1}$. The rotational speed is 3000 rpm and the density of the steam at the inlet is 1.7 kg m $^{-3}$. Determine the mean radius, and the hub to tip ratio of the stator in the first stage of the turbine. What does this mean for the way in which the design of the stator blade varies across its span? [20%]

3 A single shaft gas turbine, shown in Fig. 1, is used to provide power for an industrial process. The inlet guide vane of the compressor is choked with throat area A_1 and the turbine stator is choked with throat area A_3. Both compressor and turbine can be treated as isentropic. Assume that the working fluid is air throughout. The pressure losses in the combustor, compressor inlet and turbine exhaust can be neglected, as can the mechanical losses.

(a) Draw a $T-s$ diagram of the cycle and write a relationship for the power output as a function of the stagnation temperatures at the stations 1 to 4 and the mass flow rate $\dot{m}$. [10%]

(b) Determine relationships for p_{02}/p_{01} and T_{04}/T_{01} in terms of the compressor inlet temperature T_{01} the turbine inlet temperature T03, and the compressor and turbine throat areas A_1 and A_3. [25%]

(c) Using the relationships derived in part (b), develop a relationship for the power output of the gas turbine in terms of the gas turbine's inlet temperature T_{01} and pressure p_{01}, the turbine inlet temperature T_{03}, and the compressor and turbine throat areas A_1 and A_3. [20%]

(d) Errors in the manufacturing process cause the compressor inlet guide vane throat area A_1 and the turbine stator throat area A_3 to differ from the design intent. During operation the turbine inlet temperature T_{03} and the shaft speed are maintained at the design intent. The inlet guide vane to the compressor and the turbine stator remains choked. Sketch the characteristic of a high-speed multistage compressor. Mark on the characteristic the effect of the change in areas A_1 and A_3 on the compressor operating point. Describe two methods of maintaining the design intent compressor stall margin and the practical implications of their implementation. [25%]

(e) Describe how changes in the areas A_1 and A_3 described in part (d) affect the power output of the turbine. How might the turbine inlet temperature T_{03} be changed to keep the work constant. Discuss two practical implications of this change. [20%]

Assume air behaves as a perfect gas with γ = 1.4 and c_p = 1005 J kg^{-1} K^{-1}.

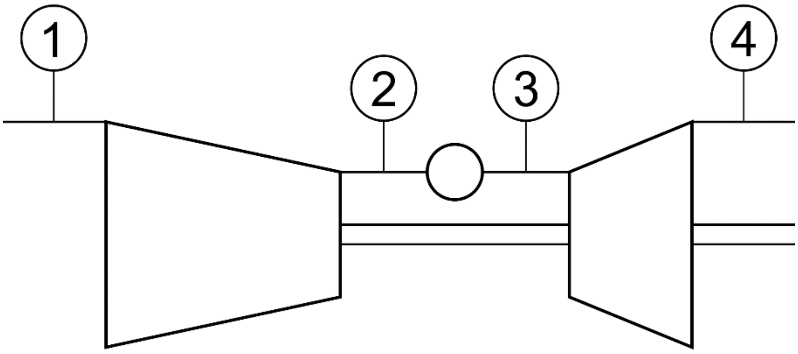

Fig. 1

END OF PAPER

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