Course-PM – TME210 – Turbomachinery

2019-09-01 – Final
2019-10-10 – Update on industrial lecture 3.

Aim of course

The course aims at providing fundamental knowledge about the design and industrial application of turbomachinery. This involves developing an insight into applied thermodynamics and aerodynamics, as well as to apply this knowledge to a number of technology areas.

Learning goals

- Explain how turbomachinery is applied in various fields of power generation such as nuclear and combined cycle power plants, wind and hydropower engineering and process industry.
- Formulate turbomachinery design criteria for a range of applications.
- Carry out preliminary design of a range of turbomachines
- Be able to apply commercial tools to outline more detailed turbomachinery design

Contents

The course aims at giving a broad introduction to the field of turbomachinery. This is primarily done by describing the work principle and underlying theory of a number of turbomachinery components. The equations describing the energy transfer between the fluid and the rotating component are applied to centrifugal and axial pumps, fans, axial compressors, gas and steam turbines, hydraulic turbines and wind turbines.

Course responsible

Lecturer/Examiner: Tomas Grönstedt, Fluid mechanics, 031-7721409, tomas.gronstedt@chalmers.se
Lecturer: Håkan Nilsson, Fluid mechanics, 031-7721414, hakan.nilsson@chalmers.se
Lecturer: Hamid Abedi, Fluid mechanics, 031-772 1390, abedih@chalmers.se
Course assistant, Daniel Lindblad, Fluid Mechanics, 031-7725078, daniel.lindblad@chalmers.se
Assistant, Olidan visit: **Vinicius Tavares Silva**, Fluid Mechanics, vincius@chalmers.se
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Literature

"Fluid Mechanics and Thermodynamics of Turbomachinery", S. L. Dixon and C. Hall, 7th edition, ISBN: 978-0-12-415954-9, available from the Cremona book shop for 538 SEK.
An E-book is also available (free of charge) at http://www.lib.chalmers.se

Examination

Completed warm up exercise, hand in problems (up to 10 bonus credits), high pressure turbine rotor design lab (computer lab), water turbine lab and participation in study visit is compulsory. Written five hour exam consisting of four calculation problems and two theory problems (total 60 credits with 24, 36, 48 as grading limits). One of the two theory problems are selected from a list. The exam is an open book exam; that is the course book can be used when solving the problems. The theory part of the exam is closed book.

Week 1 (36):

Lect1, 2019-09-03 – EF, 10.00 - 11.45: Course presentation. Chapter 1: Turbomachinery classification and usage of turbomachinery. Coordinate systems. Fundamental laws. Compressible flow relations, thermodynamic properties of fluids and efficiency definitions.

Lect2, 2019-09-04 – EF, 08.00 - 09.45: Chapter 2: Dimensional analysis and turbomachinery type selection. Chapter 3: 2D flow and cascades. *Distribution of* ***hand in problem*** **1** (should be handed in 2019-09-11).

Ex1, 2019-09-06 – EC, 08.00 - 09.45: Problems: 1.3, 1.6, 2.1, 2.5, and 2.6
Lect3, 2019-09-06 – EC, 10.00 - 11.45: Chapter 3: 2D flow and cascades, some definitions and intro.

Chapter 1	
1.1 Definition of a turbomachine	I
1.2 Coordinate system	VI
1.3 Fundamental laws	I
1.4 Equation of continuity	VI
1.5 First law of thermodynamics	VI
1.6 The momentum equation	VI
1.7 The second law of thermodynamics – entropy	VI
1.8 The Bernoulli equation	I
1.9 The thermodynamic properties of fluids	VI
1.10 Compressible flow relations	VI
1.11 Definitions of efficiency	I
1.12 Small stage or polytropic efficiency	I
1.13 The inherent unsteadiness of the flow within turbomachines	R
Recommended problems: 1.1a, 1.1b, 1.2a, 1.2b, 1.8, 1.9, 1.11	
Chapter 2	
2.1 Dimensional analysis and performance laws	I
2.2 Incompressible fluid analysis	VI
2.3 Performance characteristics for low speed machines	I
2.4 Compressible fluid analysis	VI
2.5 Performance characteristics for high speed machines	I
2.6 Specific speed and specific diameter	VI
2.7 Cavitation	I
Recommended problems: 2.2, 2.4, 2.10	
Chapter 3	
3.1 Introduction	I
3.2 Cascade geometry	VI

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Week 2 (37):

Lect3B, 2019-09-10 – EF, 08.00 – 09.45: Chapter 3 continued: Cascade flows and cascade forces, diffusion, incidence effects, turbine cascades, loss correlations. *Distribution of **hand in problem 2*** (should be handed in 2019-09-18).
Ex2, 2019-09-10 – EF, 10.00 – 11.45: Problems: 3.2, 3.4

Ex3, 2019-09-11 – EF, 08.00 – 09.45: Problems: 3.7 and 3.9.

Lect4, 2019-09-13 – EC, 08.00 – 09.45: Chapter 4: Velocity diagrams, stage parameters, repeating stages, degree of reaction, preliminary axial turbine design, effect of reaction on efficiency, efficiency correlations, stresses in turbine rotor blades, blade cooling.
Ex4, 2019-09-13 – EC, 10.00 – 11.45: Problems: 4.6, 4.9a, 4.10.

Chapter 3 continued	
3.3 Cascade flow characteristics	VI
3.4 Analysis of cascade forces	I
3.5 Compressor cascade performance	VI
3.6 Turbine cascades	VI
3.7 Cascade computational analysis	I
Recommended problems: 3.3b, 3.3c, 3.5a, 3.5b, 3.6	
Chapter 4	
4.1 Introduction	I
4.2 Velocity diagrams of the axial-turbine stage	I
4.3 Turbine stage design parameters	VI
4.4 Thermodynamics of the axial-turbine stage	VI
4.5 Repeating stage turbines	I
4.6 Stage losses and efficiency	VI
4.7 Preliminary axial turbine design	VI
4.8 Styles of turbine	VI
4.9 Effect of reaction of efficiency	VI
4.10 Diffusion within blade rows	I
4.11 The efficiency correlation of smith	VI
4.12 Design point efficiency of a turbine stage	VI
4.13 Stresses in turbine rotor blades	VI
4.14 Turbine blade cooling	I
4.15 Turbine flow characteristics	I
Recommended problems: 4.4, 4.8, 4.11, 4.12	

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Week 3 (38):

Lect5, 2019-09-17 – EF, 10.00-11.45: Chapter 5: mean line analysis of compressor flows, velocity diagrams of the compressor stage, mean line calculations and preliminary design, stall and surge. *Distribution of* ***hand in problem 3 (should be handed in 2019-09-26).***

Computer lab, ED3582, 2019-09-18 – MT13, 08.00-11.45: Simulation lab hand out: High pressure turbine rotor design exercise **(report should be handed in 2019-10-02).**

Ex5, 2019-09-20 – EF, 10.00-11.45: Problems: 5.5, 5.10a & 5.10b, 5.12

Chapter 5	
5.1 Introduction	I
5.2 Mean-line analysis of the compressor stage	I
5.3 Velocity diagrams of the compressor stage	I
5.4 Thermodynamics of the compressor stage	I
5.5 Stage loss relationships and efficiency	VI
5.6 Mean-line calculation through a compressor rotor	VI
5.7 Preliminary compressor stage design	VI
5.8 Simplified off-design performance	R
5.9 Multi-stage compressor performance	I
5.10 High Mach number compressor stages	VI
5.11 Stall and surge phenomena in compressors	VI
5.12 Low speed ducted fans	I
Recommended problems: 5.1, 5.3, 5.4, 5.6	

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Week 4 (39):

Computer lab, 2019-09-23 – F-T7203, 13.15-17:00: High pressure turbine rotor design exercise.

Computer lab, 2019-09-25 – MT14, 08.00-11:45: High pressure turbine rotor design exercise.

Computer lab, 2019-09-26 – MT14, 08.00-11:45: High pressure turbine rotor design exercise.

Steam turbine lecture, 2019-09-27 – EC, 08.00 - 09.45: Tomas Grönstedt. Introduction to steam turbine design. Learning material for steam turbines is: slides, revision questions, theory questions, one problem on exercise.
Steam turbine exercise, 2019-09-27 – EC, 10.00 – 11.45: Steam turbine exercise.

Steam turbines	
Revision questions + slide material	I
Recommended problems: 1.8, 1.9	

Week 5 (40):

Lect6, 2019-10-01 – EF, 08.00 – 09.45: Chapter 6: Three-dimensional flow in axial turbomachines
Ex6,   2019-10-01 – EF, 10.00 – 11.45: Problems: 6.2, 6.4 and 6.7.

Lect7, 2019-10-02 – EF, 08.00 – 09.45: Chapter 7: centrifugal pumps, fans and compressors.
Distribution of ***hand in problem 4*** (should be **handed in 2019-10-09)**.
Ex7, 2019-10-02 – ML1, 10.00 - 11.45: 7.1, 7.4 and 7.8.

Lect8, 2019-10-04 – EC, 08.00 – 08.45: Chapter 8: radial-flow turbines.
Ex8, 2019-10-04 – EC, 09.00 - 10.45: 8.1, 8.8 and 8.12.
Industrial lecture, 2019-10-04 – EC, 11.00 - 11.45: Industrial lecturer 1. GKN Aerospace, space applications and fluid mechanics. Alexandre Capitao Patrao.

Chapter 6	
6.1 Introduction	I
6.2 Theory of radial equilibrium	VI
6.3 The indirect problem	I
6.4 The direct problem	I
6.5 Compressible flow through a fixed blade row	I
6.6 Constant specific mass flow	R
6.7 Off-design performance of a stage	R
6.8 Free-vortex turbine stage	R
6.9 Actuator Disc Approach	NI
6.10 Computational through-flow methods	I
6.11 3D flow features	VI
6.12 3D design	VI
6.13 The application of 3D computational fluid dynamics	I
Recommended problems: 6.5, 6.6, 6.12a, 6.15 (see lecture notes)	
Chapter 7	
7.1 Introduction	I
7.2 Some definitions	I
7.3 Thermodynamic analysis of a centrifugal compressor	VI
7.4 Inlet velocity limitations at the compressor eye	I
7.5 Design of a pump inlet	I
7.6 Design of a centrifugal compressor inlet	I
7.7 Slip factor	I
7.8 A unified correlation for slip factor	I
7.9 Head increase of a centrifugal pump	VI
7.10 Performance of a centrifugal compressors	VI (determinin
7.11 The diffuser system	I
7.12 Diffuser performance parameters	I
7.13 Choking in a compressor stage	R
Recommended problems: 7.2, 7.3, 7.11, 7.13, 7.14	

Chapter 8	
8.1 Introduction	I
8.2 Types of IFR turbines	I
8.3 Thermodynamics of the 90° IFR turbine	VI
8.4 Basic design of the rotor	VI
8.5 Nominal design point efficiency	NI
8.6 Some Mach number relations	NI
8.7 The scroll and stator blades	I
8.8 Optimum efficiency considerations	I
8.9 Criterion for minimum number of blades	I
8.10 Design considerations for rotor exit	I
8.11 Significance and application of specific speed	NI
8.12 Optimum design selection of 90° IFR turbine	NI
8.13 Clearance and windage losses	I
8.14 Cooled 90° IFR turbine	NI
Recommended problems: 8.2, 8.6, 8.7, 8.9	

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Week 6 (41):

Lect9 & 10, 2019-10-08 – EF, 08.00 - 11.45: Håkan Nilsson. Chapter 9: Hydraulic turbines, a national and international perspective. Hydraulic turbine fundamentals. Hydraulic turbine types, size and efficiency, additional topics. Information about hydraulic turbine lab. *Distribution of* ***hand in problem 5*** (should be **handed in 2019-10-16)**.

Preparations for Francis turbine lab should be done before lab 2019-10-11 and 2019-10-14.

Ex9, 2019-10-09 – EF, 08.00 - 09.45: Problems: 9.4, 9.15
Ex10, 2019-10-09 – ML1, 10.00 - 11.45: Problems: 9.14, 9.17.

Industrial lecture 2, 2019-10-11 – EB, 10.00-10.45: Industrial lecturer 2. Martin Ottersten, Fan flows and indoor climate, Swegon.

Industrial lecture 3, 2019-10-11 – EB, 11.00-11.45: Industrial lecturer 3. Amir Baniameri, Sulzer Turbomachinery, Pumps and their application in practice.

Francis turbine lab, 2019-10-11 and 14 – course lab, 1h per group (the post lab hand-in, which is a minor task, should be handed in 2019-10-18).

Chapter 9	
9.1 Introduction	I
9.2 Hydraulic turbines	I
9.3 The Pelton turbine	VI
9.4 Reaction turbines	I
9.5 The Francis turbine	VI
9.6 The Kaplan turbine	VI
9.7 Effect of size on turbomachine efficiency	I
9.8 Cavitation in hydraulic turbines	I
9.9 Application of CFD to the design of hydraulic turbines	I
9.10 The Wells turbine	NI
9.11 Tidal power	R
Recommended problems: 9.9, 9.10, 9.11, 9.13, 9.18	

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Week 7 (42):

Francis turbine lab, 2019-10-11 and 2019-10-14 – course lab, 1h per group

Study visit, 2019-10-15: 08.00-13.30: - Hydraulic power plant study visit (Olidan and Höjom in Trollhättan). Bus at 08.00 from Chalmers library.

Lect11, 2019-10-16 – EF, 08.00-09.45: Chapter 10: classification of basic wind turbine types, estimating power output, actuator disc approach and the blade element momentum method. Blade selection criteria. Hamid Abedi.

Ex11, 2019-10-18 – EC: 08.00-09.45: Problems: 10.5, 10.8. Hamid Abedi.

Chapter 10	
10.1 Introduction	I
10.2 Types of wind turbine	I
10.3 Performance measurement of wind turbines	VI
10.4 Annual energy output	I
10.5 Statistical analysis of wind data	I
10.6 Actuator disc approach	VI
10.7 Blade element theory	VI
10.8 The BEM method	VI
10.9 Rotor configurations	I. Rotor optimum design criteria is R
10.10 The power output at optimum conditions	R
10.11 HAWT blade selection	I
10.12 Developments in blade manufacture	I
10.13 Control methods	I
10.14 Blade tip shapes	I
10.15 Performance testing	I
10.16 Performance prediction codes	R
10.17 Environmental considerations	I
10.18 The largest wind turbines	I
10.19 Final remarks	I
Recommended problems: 10.2, 10.3, 10.4	

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Week 8 (43):

Ex12, 2019-10-22 – EF: 08.00-11.45: Old exams tutorial.
Ex13, 2019-10-25 – EC: 08.00-11.45: Old exams tutorial.

Week 9 (44):

Written exam, 2019-11-01 08.30-13.30 (5 hours),
Re-exam, 2020-01-07, 08.30-13.30 (5 hours)

Todo:

Check book prices.
Industriföreläsningar.