VON KARMAN INSTITUTE FOR FLUID DYNAMICS

RESEARCH MASTER IN FLUID DYNAMICS

Level master after master

COURSE SYLLABUS AND REGULATIONS

2015- 2016

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INTRODUCTION

The von Karman Institute for Fluid Dynamics (VKI), founded by Professor Theodore von Kármán in 1956, is an international association with the following aims:

- To promote the training of scientists and engineers from the NATO countries in the field of fluid dynamics,
- To contribute to the dissemination of knowledge in the field of fluid dynamics,
- To undertake, to instigate and to promote studies and research in the field of theoretical, experimental and computational fluid dynamics.

The educational and research programs of the Institute are organised within the following areas of specialisation:

- Aeronautics and Aerospace,
- Environmental and Applied Fluid Dynamics,
- Turbomachinery and Propulsion.

The VKI operates a comprehensive range of experimental and computational facilities covering virtually all aspects of the above fields. Necessary support is provided by facility engineers, electronic and photographic laboratories, a computing centre, a technical library, a computer-aided drawing/design office and well-equipped workshops.

One of the main programs offered by the Institute is the one-year post-graduate “Research Master in Fluid Dynamics” at the level “Master after Master” (former VKI Diploma Course). Approximately thirty-five engineers and scientists drawn from ten or more countries attend this program. They are offered a wide selection of specialized courses on various aspects of fluid dynamics and are given the opportunity to perform personal research projects under close guidance by members of the faculty. The projects may be experimental, theoretical, or computational in nature. Thus, the VKI Research Master in Fluid Dynamics Course complements, rather than duplicates, the teaching programs of universities.

This syllabus presents pertinent information regarding the VKI Research Master (RM) in Fluid Dynamics. Admission, diploma requirements and regulations are reviewed first. Then the course syllabus for the current academic year is presented. A description of research activities provides an indication of the diverse possibilities for the individual research project. The major facilities available for the research project are described and a list of the faculty members is included.

Further information on the VKI Research Master in Fluid Dynamics can be obtained from our Secretariat: secretariat@vki.ac.be or on our website: http://www.vki.ac.be.

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REGULATIONS OF THE RESEARCH MASTER PROGRAM

The following chapters describe the rules about the jury, admission conditions, educational organization, evaluation processes, conditions to receive the diploma, relation between staff and students and the way complaints and conflicts will be handled. They also describe the organizations involved in Quality Assurance and the Accreditation of the program according to the Bologna Process organizing the Higher Education Area in Europe.

Any change/update of the regulations is the prerogative of the Educational Committee and must be submitted to the Board of Directors for approval.

Chapter I Admission requirements

Admission to the VKI RM program is decided by the faculty of the department in which the student wants to continue his/her studies on the basis of a file prepared by the student. Admission requirements are:

- A five-year engineering or science degree (3-year B.Sc. + 2-year M.Sc.) from a European university or a M.Sc. from an American, Canadian or Turkish University.

- A working knowledge of the English language. Students who did not obtain their degree from a university with lectures in English have to deliver proof of having studied in English or an English language test-result from an international organization. There is no test required for students from the European Union (EU) or students who have successfully followed courses in English of minimum 15 ECTS equivalent. Derogations from these rules can be granted by the heads of departments on the basis of a judgement of the application file.

- Endorsement of the applicant by an STO National Delegate. Citizenship of one of the NATO countries is imposed by the financing organization. Non-NATO nationals residing in NATO countries will be considered for admission if they are recommended by the STO National Delegate of their country of residence on the ground that their attendance at VKI would be beneficial to that country.

- Recommendations by 3 professors from a university where the candidate has studied previously.

There is no tuition fee for students from the countries financing the VKI.

Chapter II Study program

The VKI Master after Master program comprises a balanced combination of lectures and individual research. All teaching activities are in English.

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Each student will select one of the following areas of specialization offered by VKI: Aeronautics and Aerospace, Environmental and Applied Fluid Dynamics or Turbomachinery and Propulsion.

The study program and project are defined during a first meeting of the students with the faculty of the department of his/her choice. A minimum total study load of 60.5 ECTS (30.5 ECTS course work and 30 ECTS project) is required. Selection is based on the detailed description of the general and optional courses, defined and made available before the start of each academic year. The student can add optional courses as determined by his or her needs.

The outcome is the definition of the official study program of each student, written in a document (one copy for the student, one for the supervisor and one for the VKI secretariat). The study program of all students is submitted for approval to the faculty at the first faculty meeting following its definition. Later changes are possible only in function of the project evolution and with the agreement of the entire faculty of the department.

Students who have a job can spread the program over two years. The yearly program is defined in agreement with the Educational Committee taking into account the other (professional) activities of the student. They have to satisfy all requirements in terms of evaluation teams and public presentations.

Except on the days shown as holidays on the calendar, the Institute is open from Monday to Friday. Normal working hours are from 8.10 to 12.15, and from 13.00 to 16.55. All students are requested to be present at VKI during these hours, unless prior arrangements are made with their supervisor. A detailed schedule of courses and laboratory sessions will be announced before the start of every trimester.

Students may also have access to their desk or to the computer center during nights, weekends, or other holiday periods. For safety reasons, students are not allowed to be alone in the laboratories outside normal working hours. The presence of at least one other researcher or technician is required. Furthermore all safety instructions, given by the VKI Safety Officer and the Laboratory Industrial Engineer must be rigorously respected. Under no circumstances are students authorized to operate large facilities or noise-producing facilities outside normal working hours.

Chapter III Master Thesis

In addition to the courses, each student is required to carry out a Master Thesis project. It consists of an independent research project. It must exhibit originality and be more than a routine test or computation. Originality is understood to mean a contribution to the field, e.g., the study of a new phenomenon, the interpretation of the results of an experiment, modeling a complex flow, or a significant modification or development of a new computational method or experimental technique. A list of possible projects is published at the start of the academic year. A final selection by the student must be made before 30 October.

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A full-time faculty member will be designated as supervisor. In some cases, the faculty supervisor will be assisted by a researcher (a post-doctoral researcher, a PhD candidate or a research engineer) working in a field that is related to the student's Master Thesis project. They will assist the student in a more detailed definition of the project, identify problems to solve, define goals, and assist the students in defining the approaches, tools and test cases.

The student should also report on progress or any unexpected problems at regular intervals as defined by the supervisor. If the student is carrying out an experimental project, the supervisor will organize the contacts with the department's Industrial Engineer, responsible for the technical aspects of the work and for the technical coordination with other VKI services (metal and wood workshops, electronic and photo labs, etc.).

The supervisor is also responsible for the establishment of the Project Evaluation Team (PET) within the first month of the year. In addition to the supervisor, the team will have at least one faculty member from the other two departments. They are selected for their interest in and knowledge of the research subject. The PET supervises the evolution of the project and is the main evaluating body.

Chapter IV Exams

Examinations are organized for each course and will take place between two and three weeks after the last lecture. The examination procedure (oral/written, open book/closed book…) must be announced to the students at the start of the course.

The detailed time schedule of examinations must be announced at least two weeks before the exam takes place. Any changes must be announced sufficiently in advance and take into account the other workload of students and professors.

If for a serious and exceptional reason a student does not participate in an exam, he should contact the examiner who will set a new date in common agreement. If this agreement cannot be reached, the Ombudsperson should be contacted to start mediation.

An examiner who, for circumstances beyond his control, cannot give the exam, will inform the Ombudsperson immediately and define a new timetable in common agreement with the students involved or organize a written exam at the time scheduled in the original timetable.

If an examiner does not appear within 30 minutes after the set time, the student should immediately inform the Ombudsperson who will schedule a new time, giving priority to the preferences of the student.

The examiner can split the evaluation between a formal exam and exercise. The method of examination and the weight of the different components must be communicated to the student at the start of the course.

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Test exams may be organized to allow the student to become familiar with the VKI examination techniques and criteria. The student has the right to repeat the test exam if he wishes to do so or may request to consider the score as final. In the latter case he will not be tested again on the same content. If partial evaluations of large courses are organized, the final grade will be the average of the partial results weighted by the respective course hours.

Within 2 weeks after the exam, the grades must be communicated to the student and to the secretariat, who will store them in a safe place. The secretariat will acknowledge in writing having received the grades. The further handling of the grades is under the supervision of the Dean of Faculty.

Grades of less than 50% are considered unsatisfactory and a repeat exam will be organized within four weeks of the publication of the initial results. The student can sit the exam maximum two times and this possibility to repeat an exam replaces the exams that are traditionally organized in September. At this second exam, a maximum mark of 60% can be awarded. If the exam consists of different parts with different examiners, this 50% passing rule and the 60% rule apply to the global results of all exams and exercises.

Oral exams are public. The public cannot intervene during the exam. The copies of the written exam can be consulted after being corrected. In critical cases the student or professor may request the presence of a second professor to be indicated by the Dean of Faculty. A professor cannot participate in an exam of a relative up to the fourth degree.

Chapter V Master Thesis evaluation

A special evaluation procedure is put forward for the Master Thesis project and the general course “Presentation, Reporting and Management”.

At the **end of the first trimester, each student will present to the PET a progress report.** He/she will describe his/her understanding of the problem and proposed solution method, together with a summary of the work already accomplished on the project; i.e. the results of the literature search, time schedule and planning. A thorough discussion with the PET members will help the student to ensure that the proposed solution is realistic and that the pathway to a successful conclusion has been defined.

A second presentation will be made to the PET at the end of the second trimester. Again, a thorough appraisal of the progress will be made including recommendations for future work. A report relative to the literature survey associated with the research project will also be presented. A **“PET bibliography grade”** will be assigned to this report by the faculty members of the PET as part of the course “Presenting, Reporting and Research Management”.

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A **first public presentation of 15 minutes duration and 5 minutes discussion is also made towards the end of March** to gain practice in the art of public speaking; no grade is assigned.

The complete Master Project report (one paper and one electronic copy) must be submitted on the date specified at the start of the academic year. The word "complete" means that the text and figures will be as close as possible to a final report. All chapters must be included, but updates to incorporate last minute data or calculations can be made before graduation day.

This report must describe completely the research, including definition of the problem, methodology, results and their uncertainty, their analysis, conclusions and recommendations for future work. It must contain all information necessary to repeat the experiments and calculations in order to reproduce the same results. Therefore it must include a full description of the hardware or software developed during the stay at VKI, if any, and its use. In particular, mechanical drawings of hardware should be included in appendix, or alternatively the VKI Design Office drawing number must be indicated in the text, to fully specify the hardware. These requirements apply only if the same information is not given in a previous VKI report, which has then to be referenced.

A **detailed final presentation of the project to the PET will be made in mid-June**, followed by a full and careful assessment of the work by the PET members. As a result of the final evaluation session, the team members may propose optional or mandatory changes to the report. The latter concern the language and organization of the report, missing information or further explanations, and must be carried out before graduation day. A second **public presentation** of 20 minutes duration followed by 10 minutes for questions and discussions will be made **in late June**. A **"Faculty presentation grade"** will be assigned by each member of the faculty together with a **"Faculty project grade"** on the basis of the results presented in the public presentation.

The PET grades and public presentation grades are given as follows:

1. Grades given by the Project Evaluation Team (PET) members:

    Report grade: after reading the report, minimum 2 reviewers (they all have to be members of the PET) and the supervisor will give an individual report grade. The average of these grades (called *report grade*) counts for 1 ECTS in the PRM course. All faculty members present in the PET have the right to be reviewer. All reviewers have to be designated at the latest on the day of the delivery of the reports.

    PET project grade: at the end of the Evaluation Team (ET) meeting in which the project was presented and discussed, the Project Evaluation Team will issue the *PET project grade,* which counts for 23 ECTS. This grade is made according to a well-defined scale available on VKI intranet. A consensus grade should be privileged. If no consensus can be reached, the grade is obtained by averaging the individual grades of the faculty members present at the PET

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meeting. A dedicated form has to be signed by all PET members. It is the responsibility of the faculty members to also take into account the opinions of the non-faculty members of the PET.

2. Grades given during the final Public Presentation by all faculty:

<u>Faculty presentation grade:</u> During the final Public Presentation, each faculty member will give an individual grade for the quality of the presentation. The average of these grades counts for 2 ECTS in the PRM course.

<u>Faculty project grade:</u> During the final Public Presentation, each faculty member will also give an individual grade for the quality of the project. The average of these grades (called *faculty project grade*) counts for 7 ECTS in the project grade.

Summary: PRM grade and Project grade

The final grade for the PRM course (5 ECTS) will be established from the *bibliography grade* (1 ECTS) issued by the PET members at midterm, the *planning grade* issued by Prof. Carbonaro in June (1 ECTS), the *report grade* issued by the PET reviewers in June (1 ECTS) and the *faculty presentation grade* issued by the faculty members at the June public presentation (2 ECTS).

The final *project grade* (30 ECTS) will be established from the *PET project grade* (23 ECTS) issued at the June ET and the *faculty project grade* (7 ECTS) issued at the June Public presentation.

The overall grade for the Research Master will be the average of the *course grades* and the final *project grade*.

Definition of PRM and Project grades

Summary table of grading Project and PRM course		PRM (ECTS)	Project (ECTS)
PET Meeting Midterm	Bibliographic Report (PET)	1	
PET Meeting June (fac. Members of PET)	Project Report	1	
	Project Planning	1	
	Project Evaluation		23
Public Presentation June (all Fac. Members)	Presentation Quality	2	
	Project Quality		7
	TOTAL	5	30

Deliberations of the PET are confidential. Only the results and conclusions are communicated to the student. The supervisor is encouraged to communicate to the students the arguments that have lead to the grading without revealing the secret of the deliberation.

The dates of the evaluation meetings and public presentations of the Master Thesis are fixed at the start of each trimester.

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If because of circumstances beyond the student's control (sickness, major equipment failure or non availability of important equipment) the project cannot be finished within the schedule, the jury may agree to postpone the deadlines for the report and presentations.

Chapter VI Complaints

The student can within a period of five days after the exam took place or the results have been communicated to the student, complain in writing to the Ombudsperson(s) about any irregularity in the way the courses are given or the exam has been organized. Only complaints relating to violation of the administrative rules (e.g. as described in the present syllabus) or to an erroneous transmission of information to the secretariat are receivable. The quote that was given to the student by the examiner or decision taken by the Project Evaluation Team cannot be the object of a complaint. The examiner will be available during five days following the announcement of the results for explanations about the grade and to discuss any possible material errors in the communication or transmission of results.

One of the Ombudspersons (see Chapter XI-Ombudspersons) will examine the complaint together with the official student representative and they will communicate their decision in writing to the student within 5 days after receiving the complaint. In conflicts of greater importance or when the student does not agree with the decision of the Ombudsperson, the problem will be presented to the whole faculty at the next faculty meeting. After gaining advice of an independent external expert in educational matters and hearing of the student, the faculty will take a motivated decision and communicate it to the student.

The same procedure applies for matters related to the Master Thesis (i.e decisions of the PET).

Chapter VII Jury

The jury is composed of all the full time faculty members and is presided by the Dean of Faculty. The Dean can be replaced by a faculty member for some specific matters. The youngest faculty member present is the secretary of the jury. The jury meets in June after completion of the final project presentations.

The jury can take valid decisions if a minimum of 60% of the faculty members are present. Absent faculty members cannot be replaced. The decisions of the jury are adopted by a majority of the votes cast. Each member of the jury has one vote. The jury can define additional rules if it feels needed.

The jury verifies that the student satisfies all legal conditions and those defined by the regulations, and that the study load is in agreement with the required number of ECTS in the student's study program. The diploma "Master after Master" will be awarded on the basis of the results of the exams.

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A professor cannot participate in the deliberation of a relative up to the fourth degree.

Deliberations and votes of the jury are confidential. Only the results and conclusions are made public.

Chapter VIII Diploma

The diploma will be awarded by decision of the Jury to the student who obtained a grade of 50% or higher in each course of his/her study program and achieved an average result of 60% or more in both the course work and the research project. The overall course grade is the average of the individual course grades weighted by the corresponding ECTS. The overall grade for the year is a weighted average of the course work and the research project in proportion to the respective ECTS.

Students who did not obtain a grade above 50% in all courses will be the object of a deliberation and vote by the jury. A majority of 60% of the votes cast is required to grant the diploma.

The secretariat provides the detailed results of all the exams and Master Thesis evaluations and the averaged values to the members of the jury in a form that facilitates the deliberation. The averages are weighted by the corresponding ECTS. Students not satisfying the diploma requirements mentioned before are highlighted.

Students with results of 80% or more in each category (courses and project) will receive the diploma with honors. The jury may in exceptional cases deviate from this rule if a small shortcoming on courses is compensated by a high grade for the project. Such a decision requires a more than two thirds majority of the votes and must be motivated.

The decisions of the jury are final and announced ad valvas.

Each student receives a copy of a summary sheet listing all course and Master Thesis project grades; this sheet is referred to as a “transcript of grades”. The results of the deliberation are written in the official VKI register of diplomas and signed by all the members of the jury.

Complaints related to erroneous transmission of results or erroneous calculations can be considered if received before the official diploma ceremony. Any correction requires a decision of the jury.

Complaints related to non-respect of the regulations must be submitted to the Ombudsperson within a period of five days after the decision of the jury has been communicated. In cases where the Ombudsperson considers the complaint justified and of sufficient importance, he can call for a new meeting of the jury to reconsider the decision. The latter will be officially communicated to the student.

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Chapter IX Awards

In order to encourage excellence, the VKI has created the following special awards for the RM students:

- The Theodore von Karman Prize for the best overall performance in course work and Master Thesis.
- The Belgian Government Prize for second best overall performance in course work and Master Thesis.
- Prince Alexander of Belgium Award for the best project presentation.
- Prize for Excellence in Experimental Work.
- Prize for Excellence in Numerical Work.
- The Alumni Award for Best Collaboration which recognizes the importance attached by the VKI to team spirit and collaboration.

All prizes are decided by the Jury during its deliberation meeting in June, except for the Alumni Award for the best collaboration.

The Alumni Award for Best Collaboration is decided by the RM members during a secret vote organized in collaboration with the Alumni Association during the period May - June.

Chapter X Class Representative

The VKI encourages students to select a representative to facilitate the planning of social activities (particularly those taking place at the VKI or under the sponsorship of the VKI) as well as to provide a formal mechanism by which problems may be brought to the attention of the Direction, the Faculty or the Ombudspersons, in order to improve the quality of life at the VKI. This representative will be a member of the Educational Committee and as such have the possibility to discuss policies which may improve the educational the system of the Research Master.

It is also encouraged to have a representative of the RM members per department who reports to the Heads of department or the Ombudspersons about any problem related to the department.

All representatives should be selected by the middle of November at the latest.

Chapter XI Ombudspersons

Two ombudspersons among VKI staff (one inside and one outside the Faculty) are nominated at the start of the academic year for a period of one year by the

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educational committee. The name, telephone number and email address of the ombudspersons are announced ad valves and on the Intranet.

The ombudspersons can intervene in all educational matters to solve problems of a more personal nature (see Chapter VI-Complaints). The non-faculty ombudsperson can also be present at the deliberations but is not entitled to vote.

The ombudspersons have access to all information related to education and will be consulted when modifying the present regulations. They must respect the confidential character of the information they receive and are obliged to exercise discretion.

Chapter XII Fraud and Plagiarism

Fraud and plagiarism (related to exams or reports) must be reported together with any available proof to the Dean of Faculty as soon as it is detected. The student will be interrogated by the members of the Educational Committee in presence of the Ombudsperson and the examiner or supervisor (in case of plagiarism). The student will have the possibility to be assisted by a third person for his/her defense. The Educational Committee will communicate its conclusions in a written report to the jury and to the student. The student has the right to continue the exams during this period.

Based on this report the jury will take a decision. If detected before the deliberation the jury may refuse the student's further participation in the educational program. If detected after the deliberation, the jury may take correcting measures on previous decisions concerning the diploma.

Chapter XIII Quality Assurance

The VKI is officially recognized by the Belgian and NATO authorities (STO) as an establishment for Higher Education. The Research Master in Fluid Dynamics has been officially accredited according to Belgian law as a master after master program following the European standard (Bologna Process), which implies a regular and thorough screening of the program by an independent organization (see Chapter XIV-Accreditation).

Furthermore, the quality of the RM program is continuously monitored both internally and by external organizations.

Internal quality assurance

The education at VKI is subject to several systematic evaluations. Besides the permanent concern of the faculty about educational quality, there are also organizational measures for a more structured monitoring of the quality of the education provided at VKI.

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The Educational Committee is responsible for the active promotion of teaching competences within the VKI and carries out a systematic evaluation of the quality of the teaching activities. The purpose is an optimization of the education process by measuring the student's perception of the quality of the education. Participation in these evaluations is mandatory for VKI students. Specific criteria are: quality of lecturing, availability and quality of didactic materials, evaluation method, respect of course and examination schedules, supervision of Master Thesis Project. The committee ensures remediation when educational problems are detected.

External quality assurance

The following are independent organizations evaluating the VKI performance in terms of education and research

The Technical Advisory Committee (TAC), composed of senior professors and heads of large research centres is established by NATO-STO. It was formed at the invitation of the NATO Council (C-R (83) 30 dated 25 July 1983) to make a yearly assessment of the importance for NATO and NATO countries of the von Karman Institute's activities conducted in accordance with its Charter. The TAC meets annually at the VKI and on this occasion the VKI management and faculty members present the results of the past activities, the new orientations in research, a five year development and investment plan and the expected impact on the VKI educational programs. The outcome is an evaluation report to NATO.

The NATO Working Group on the Financing of the VKI, composed of representatives of the ambassadors at NATO, evaluates the VKI activities in terms of education, research and service to the financing countries on the basis of an extensive report of activities. The committee makes recommendations to the financing countries.

Chapter XIV Accreditation

The VKI Research Master follows the standard for master programs defined in the Bologna Process organizing the Higher Education Area in Europe. According to this framework it has been officially accredited by the Dutch-Flemish Accreditation Agency NVAO as a Master after Master with a duration of 1 academic year and a study load of 60 ECTS credits.

The accreditation started for the academic year 2010-2011 and is presently valid until the academic year 2020-2021 included (prolongation approved in 2014). Before 2010 the program was called "Diploma Course of the von Karman Institute". It has been continuously in operation since 1956.

The European Qualifications Framework (EQF) level of the program is 7 (for more details, see http://ec.europa.eu/ploteus/en/content/descriptors-page).

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FINANCIAL ASPECTS

TUITION FEES

Tuition is free for citizens of the following NATO countries which contribute to the operating budget of the VKI:

Belgium	Germany	Norway
Czech Republic	Hungary	Portugal
Croatia	Iceland	Romania
France	Italy	Turkey
Greece	Luxembourg	

as well as for citizens of the following new NATO countries : Albania, Bulgaria, Estonia, Latvia, Lithuania, Slovakia and Slovenia.

Information on tuition fees applicable to citizens of other countries may be obtained by contacting the Secretariat of the Institute.

COST- OF- LIVING FELLOWSHIP

Grants are available to citizens of the above listed countries who have been accepted into the Research Master in Fluid Dynamics and have demonstrated no other means of support.

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1. COURSE PROGRAM 2015-2016

Attendees of the VKI Research Master in Fluid Dynamics follow a series of lectures entitled "Theoretical and Experimental Fluid Dynamics" described on the next pages and then make a selection among the three areas of specialization (see chart on next page). Further specialization in certain fields is also possible. The final program of courses for each attendee is formulated following discussions with the department members and the supervisor, for a total of minimum 30,5 ECTS.

An essential aspect of the VKI Research Master in Fluid Dynamics is the independent research project counting for 30 ECTS.

The detailed program is presented on the pages that follow.

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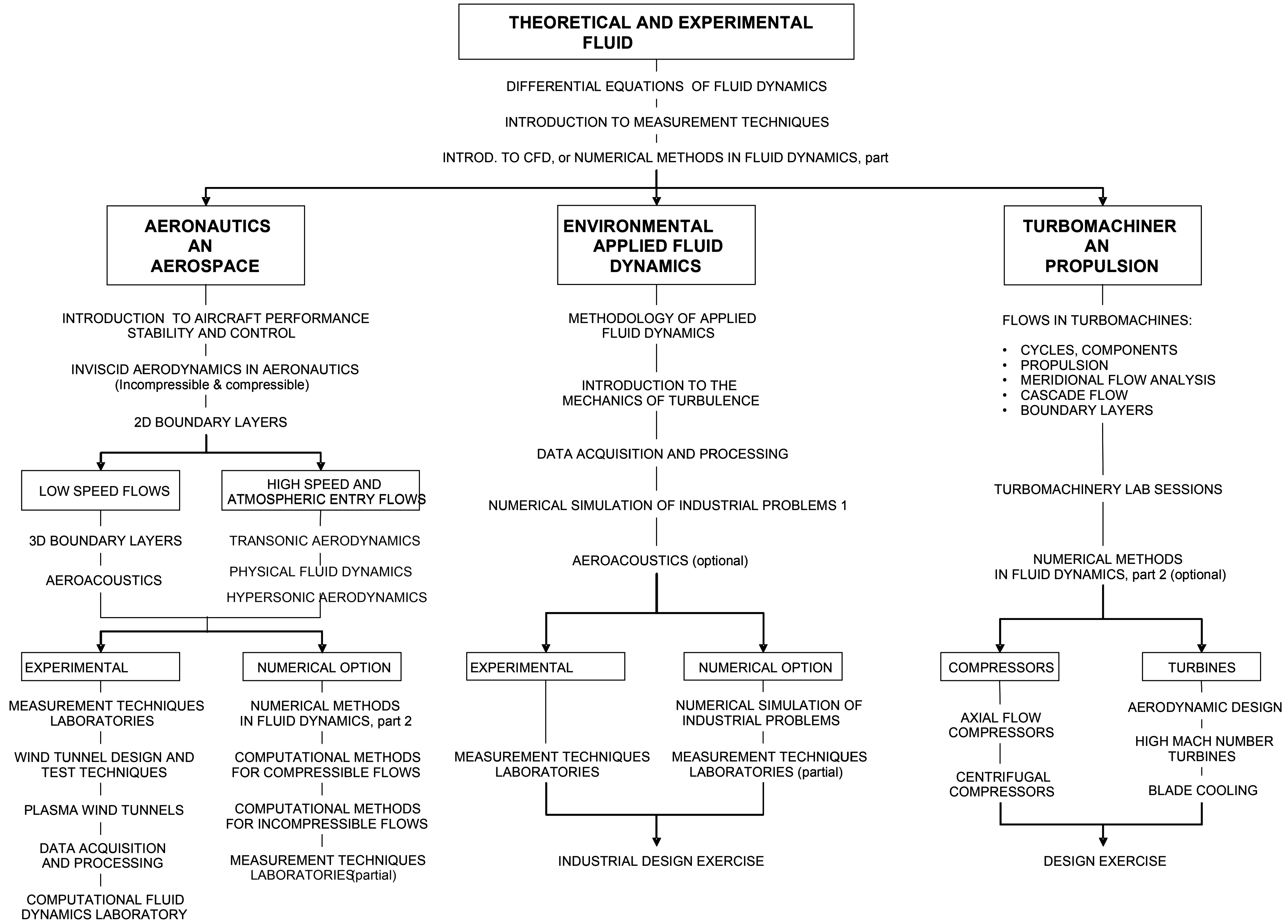
Mandatory number of ECTS : MINIMUM 30

Course Abbreviation and Title		Lecturer	AR		EA		TU	
			Exper. Option	Num. Option	Exper. Option	Num. Option	Exper. Option	Num. Option
			Nbr ECTS	Nbr ECTS	Nbr ECTS	Nbr ECTS	Nbr ECTS	Nbr ECTS
COMMON COURSES								
DEFM	Differential equations of Fluid Dynamics	Buchlin	1,25	1,25	1,25	1,25	1,25	1,25
IMT	Introd. to Measurement Techniques in Fluid Dynamics LS	Faculty (T. Arts coordinator)	2,50	2,50	2,50	2,50	2,50	2,50
PRM	Presenting, Reporting and Research Management	Faculty	5,00	5,00	5,00	5,00	5,00	5,00
NMFD-1	Numerical methods in Fluid Dynamics, part 1	Deconinck		1,25		1,25		1,25
	TOTAL		**8,75**	**10,00**	**8,75**	**10,00**	**8,75**	**10,00**
SPECIALIZED COURSES AR								
GENERAL COURSES AR								
APSC	Aircraft Performance, Stability and Control	Carbonaro	2,00	2,00				
IAAI	Inviscid Aerodynamics in Aeronautics, Incompressible flow	Bottin	2,50	2,50				
IAAC	Inviscid Aerodynamics in Aeronautics, Compressible flow	Magin	2,00	2,00				
2DBL	Two-dimensional Boundary layers	Degrez	4,00	4,00				
IGT	Introduction to Ground Testing facilities	Faculty (Chazot coordinator)	1,25					
CFD Lab	Computational Fluid Dynamics Laboratory	Deconinck	1,50					
ICFD	Introd. to Computational Fluid Dynamics Lecture Series	Peric (Deconinck coordinator)	1.25					
MT Labs	Advanced Measurement Techniques Laboratories	EA Faculty/Chazot (Van Beeck coordinator)	6,00	1,50				
NMFD-2	Numerical methods for Fluid Dynamics, part 2	Deconinck		3,00				
CMCF-T	Computational Methods for Compressible Flow - Theory	Deconinck/Magin		1,50				
CMCF-L	Computational Methods for Compressible Flow - Lab	Deconinck/Magin		2,50				
	TOTAL		**19,25**	**19,00**				
OPTIONAL COURSES AR (minimum 2 courses to be selected)								
PCMAF	Physico-chemical models for Athmospheric entry Flow	Magin	3,00	3,00				
PCMAF (optional part)	Physico-chemical models for Athmospheric entry Flow (optional partl)	Magin	1,00	1,00				
3DBL	Boundary Layers and flow separation in 3 dimensions	Degrez	1,25	1,25				
ACOUS	Introduction to Aeroacoustics	Schram	2,00	2,00				
TRANS	Transonic Aerodynamics	Chazot	1,00	1,00				
HYP	Hypersonic Aerodynamics	Chazot	2,00	2,00				
PWT	Design and operation of plasma wind tunnels	Chazot	1,00					
WTAD	Low Speed Wind Tunnels Analysis and Design	Bottin	1,00					
DAP	Data Acquisition and Processing	Schram	2,00					
CMIF-T	Computational Methods for Incompressible Flow - Theory	Deconinck		1,50				
CMIF-L	Computational Methods for Incompressible Flow - Lab	Deconinck		2,50				
	MINIMUM TOTAL		**2,00**	**2,00**				
SPECIALIZED COURSES EA								
MAFD	Methodology of Applied Fluid Dynamics	EA faculty			5,00	5,00		
IDE	Industrial Design Exercise	EA faculty			3,50	3,50		
TURB	Introduction to the Mechanics of Turbulence Modeling	Benocci / Van Beeck			2,50	2,50		
DAP	Data Acquisition and Processing	Schram			2,00	2,00		
NSIP1	Numerical Simulation of Industrial Problems 1	Benocci / Van Beeck			2,75	2,75		
NSIP2	Numerical Simulation of Industrial Problems 2	Benocci / Van Beeck				3,50		
MT Labs	Advanced Measurement Techniques Laboratories	EA Faculty/Chazot (Van Beeck coordinator)			6,00	1,50		
	TOTAL				**21,75**	**20,75**		
SPECIALIZED COURSES TU								
FTM	Flow in Turbomachines	Arts / Verstraete					8,00	8,00
DE	Design exercise	Arts / Breugelmans					5,00	2,00
TU Labs	Turbomachinery Laboratory Sessions	TU Faculty					3,00	3,00
ACT (*)	Advanced Course on Turbines	Lavagnoli / Arts / Sieverding					4,50	4,50
ACC (*)	Advanced Course on Compressors	Fontaneto / Verstraete / Van den Braembussche / Breugelmans					4,50	4,50
ICFD	Introd. to Computational Fluid Dynamics Lecture Series	Peric					1,25	
NMFD-2	Numerical methods for Fluid Dynamics, part 2	Deconinck						3,00
	TOTAL						**21,75**	**20,50**
(*)	One of ACT or ACC has to be selected.							
	GRAND TOTAL		**30,00**	**31,00**	**30,50**	**30,75**	**30,50**	**30,50**
OPTIONAL COURSES all dept								
ICFD	Introd. to Computational Fluid Dynamics Lecture Series	Peric (Deconinck coordinator)		1,25	1,25	1,25		1,25
MT Labs	Advanced Measurement Techniques Laboratories	EA faculty / Chazot				1,50	1,50	1.50
ACOUS	Introduction to Aeroacoustics	Schram			2,00	2,00	2,00	2,00
TURB	Introduction to the Mechanics of Turbulence Modeling	Benocci / Van Beeck	2,50	2,50		2,50	2,50	2,50
DAP	Data Acquisition and Processing	Schram		2,00		2,00	2,00	2,00
PWT	Design and operation of plasma wind tunnels	Chazot		1,00	1,00	1,00		1,00
NMFD-2	Numerical methods for Fluid Dynamics, part 2	Deconinck				3,00		
CMIF-T	Computational Methods for Incompressible Flow - Theory	Deconinck				1,50		1,50
CMIF-L	Computational Methods for Incompressible Flow - Lab	Deconinck				2,50		2,50
CMCF-T	Computational Methods for Compressible Flow - Theory	Deconinck/Magin				1,50		1,50
CMCF-L	Computational Methods for Compressible Flow - Lab	Deconinck/Magin				2,50		2,50
2DBL	Two-dimensional Boundary layers	Degrez			3,25	3,25		
3DBL	Boundary Layers and flow separation in 3 dimensions	Degrez			1,25	1,25		
WTAD	Low Speed Wind Tunnel Analysis and Design	Bottin			1,00	1,00		
IGT	Introduction to Ground Testing facilities	Faculty (O. Chazot coordinator)			1,25		1,25	



THEORETICAL AND EXPERIMENTAL FLUID
DIFFERENTIAL EQUATIONS OF FLUID DYNAMICS
INTRODUCTION TO MEASUREMENT TECHNIQUES
INTROD. TO CFD, or NUMERICAL METHODS IN FLUID DYNAMICS, part
AERONAUTICS AN AEROSPACE
INTRODUCTION TO AIRCRAFT PERFORMANCE STABILITY AND CONTROL
INVISCID AERODYNAMICS IN AERONAUTICS (Incompressible & compressible)
2D BOUNDARY LAYERS
LOW SPEED FLOWS
3D BOUNDARY LAYERS
AEROACOUSTICS
HIGH SPEED AND ATMOSPHERIC ENTRY FLOWS
TRANSONIC AERODYNAMICS
PHYSICAL FLUID DYNAMICS
HYPERSONIC AERODYNAMICS
EXPERIMENTAL
MEASUREMENT TECHNIQUES LABORATORIES
WIND TUNNEL DESIGN AND TEST TECHNIQUES
PLASMA WIND TUNNELS
DATA ACQUISITION AND PROCESSING
COMPUTATIONAL FLUID DYNAMICS LABORATORY
NUMERICAL OPTION
NUMERICAL METHODS IN FLUID DYNAMICS, part 2
COMPUTATIONAL METHODS FOR COMPRESSIBLE FLOWS
COMPUTATIONAL METHODS FOR INCOMPRESSIBLE FLOWS
MEASUREMENT TECHNIQUES LABORATORIES(partial)
ENVIRONMENTAL APPLIED FLUID DYNAMICS
METHODOLOGY OF APPLIED FLUID DYNAMICS
INTRODUCTION TO THE MECHANICS OF TURBULENCE
DATA ACQUISITION AND PROCESSING
NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS 1
AEROACOUSTICS (optional)
EXPERIMENTAL
MEASUREMENT TECHNIQUES LABORATORIES
NUMERICAL OPTION
NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS
MEASUREMENT TECHNIQUES LABORATORIES (partial)
INDUSTRIAL DESIGN EXERCISE
TURBOMACHINER AN PROPULSION
FLOWS IN TURBOMACHINES:
• CYCLES, COMPONENTS
• PROPULSION
• MERIDIONAL FLOW ANALYSIS
• CASCADE FLOW
• BOUNDARY LAYERS
TURBOMACHINERY LAB SESSIONS
NUMERICAL METHODS IN FLUID DYNAMICS, part 2 (optional)
COMPRESSORS
AXIAL FLOW COMPRESSORS
CENTRIFUGAL COMPRESSORS
TURBINES
AERODYNAMIC DESIGN
HIGH MACH NUMBER TURBINES
BLADE COOLING
DESIGN EXERCISE

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2. GENERAL COURSES

Differential equations of fluid dynamics	DEFM - 1.25 ECTS
Introduction to measurement techniques in fluid dynamics (LS)	IMT - 2.5 ECTS
Presenting, reporting and research management	PRM – 5.0 ECTS
NUMERICAL OPTION Numerical methods in fluid dynamics NMFD1 NMFD2	 NMFD – 4.25 ECTS 1.25 ECTS 3.0 ECTS

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DIFFERENTIAL EQUATIONS OF FLUID DYNAMICS (DEFM - 1.25 ECTS)

J.-M. BUCHLIN

This is a formal course, organized as a refresher to ensure that all students have the basic knowledge to follow the other courses.

Learning outcomes

Students should master the basic laws of fluid dynamics valid for all applications i.e. the universal conservation equations, stress tensor and heat flux vector, the Newton-Navier viscous stresses, the Fourier law and their range of validity.

The relative importance of the different terms in the Navier-Stokes equations, their mathematical properties and impact of boundary conditions should be understood.

The shortcomings of the limiting cases (incompressible, inviscid flows, Stokes flow, flows with low viscosity, unsteady flows) should be known.

The student should also master the use of the similarity parameters (Strouhal, Mach, Reynolds, Prandtl numbers, etc.) and understand their limitations.

Teaching forms

Formal lectures 90 %, summary exercise 10%

Course notes

A Review of the Differential Equations of Fluid Dynamics, J.M. Buchlin, VKI-CN 195

Literature

Bibliography in VKI-CN 195

Evaluation

The learning outcome is verified by a written (open book) exam. Criteria are the understanding of the basic equations and the capacity to apply them in practical cases. Memorization of the equations is not required and the VKI-CN-195 can be used to copy complex equations if needed.

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INTRODUCTION TO MEASUREMENT TECHNIQUES IN FLUID DYNAMICS

(IMT - 2.5 ECTS)
FACULTY

The course, mandatory for both numerical and experimental options, consists of lectures (70%) and "hands-on" laboratory sessions (30%) and provides an insight into different basic measurement techniques for fluid dynamics. Each technique is presented by a VKI faculty member who is experienced in that technique.

Learning outcomes

At the end of this course students should have a good knowledge of the different experimental techniques available for fluid dynamic research. He/she should be able to select the appropriate measurement technique (Pressure probes and transducers, temperature measurements inclusive infrared thermography, Laser velocimetry and optical density and spectroscopic measurement techniques, hot wire anemometry, flow visualization) to solve a given experimental problem. He/she should be able to implement the technique, understand its limitations, be able to estimate its accuracy and make the necessary corrections.

Teaching approaches

Formal lectures 21h

Lab sessions 8 h

Lecturers

Profs. T. Arts, (course coordinator), J.M. Buchlin, M. Carbonaro, O. Chazot, M.R. Vetrano, C. Schram, V. Van der Haegen

Course notes

Measurement Techniques in Fluid Dynamics – An Introduction, Third revised edition, VKI, 1991, 383 pgs.

Literature

Extended bibliography in Course notes

Evaluation

The objectives are verified by a single open book exam organized by the course coordinator based upon the questions he receives from the other lecturers. The

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student has to propose a solution for some practical measurement problems within a limited amount of time. The open book evaluation technique is selected because it is the closest to the real world application where the scientist has to select and apply the most appropriate technique to solve a problem. Evaluation criteria are the student's ability to select the best technique, to define the measurement chain and corresponding data processing procedure, to provide a critical evaluation of the application limits and a correct estimation of the accuracy. The weighting of the questions is proportional with the number of lecture hours for each part and indicated on the questions.

PRESENTING, REPORTING AND RESEARCH MANAGEMENT

(PRM – 5.0 ECTS)
FACULTY

This course intends to teach the skills that are needed for a successful completion of research projects in the domain of fluid dynamics and is considered as one of the specifics of the VKI teaching program. It covers all aspects from the conception of a research project up to the delivery of the final report, taking into account risk management and IP rights.

Learning outcomes

Students should be able to function as a member of an international team working on a large project or on a complex facility.

They should be able to consult the scientific databases and capable of writing a bibliographic report i.e. frame their own proposed approach in the relevant literature, evaluate the different approaches, select the way to follow for the project, motivate this choice and make conclusions. They must also be able to present and defend their project as well for specialists as for a non-specialist audience.

In terms of project management, students should be able to define a research strategy. They should master planning software (not simply excel) including the techniques for project breakdown into major tasks and subtasks. They should be able to create the critical tasks path of the project, define milestones and deadlines taking into account the availability of resources (facilities, instrumentation and computers). They should be able to specify the follow-up and updating of the planning, conduct project reviews, evaluate the risks and manage documentation.

Students should be able to communicate verbally and in writing with colleagues and non-specialist audiences, about the research strategy, solutions and results, in a multi-disciplinary working environment. They should master the use of visual aids, the art of presentation of scientific research and the techniques for a high quality scientific report.

The students should also have insight into the functioning of large international collaborative projects. They must understand the way the supranational research is

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structured in Europe, especially with respect to Aeronautics, Space, Transportation and Energy (EU framework programs) and ESA (European Space programs). The different mechanisms such as ITN, CSA, Marie Curie, Erasmus Mundus for EU and TRP, GSTP, mandatory programs for ESA will be understood.

Teaching forms

Formal lectures (35%), Seminars (15%), Home work (Literature reading and reporting) (25%), Project work (proposal writing and planning (25%)).

Lecturers

Profs. H. Deconinck (coordinator), M. Carbonaro, C. Schram, J. Muylaert

Seminars can be given by experts from Industry and Organizations (for example the European Patent Office or the European Commission).

Evaluation

The evaluation is based on the final bibliographic report (20%) graded by the PET members, on the Master Thesis planning presented at the 3 PET meetings (20%) graded by Prof. Carbonaro and PET, on the written project report (20%) graded by the PET members and on the public oral presentation (40%) graded by the entire Faculty.

Course notes

PowerPoint slides by all teachers

Literature

- Getting the Message Across, in SCIENTIAE, April/June 1979, pgs. 16-22
- A Guide to Presenting Technical Information Effective Graphic Communication, Matthews, Clifford, John Wiley & Sons, June 2000
- Web sites indicated on the PowerPoint slides

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NUMERICAL OPTION

Students following a numerical option also follow:

NUMERICAL METHODS IN FLUID DYNAMICS (NMFD – 4.25 ECTS)

H. DECONINCK

This course consists of two parts: one at introductory level (NMFD1) and one at advanced level (NMFD2). The reason for splitting the course into two parts is as follows: the first part is mandatory for all students having selected the numerical option, while the second part is mandatory for the students of the AR and TU department who follow the numerical option, but not for the EA students. Indeed, the second part (NMFD2) has a strong component oriented towards hyperbolic conservation laws (essential for compressible flow) and is therefore less important for students of the EA department because they are mostly interested in incompressible flows.

NMFD1 (NMFD1 – 1.25 ECTS)

H. DECONINCK

The first part (NMFD1) has similar objectives to the “Introduction to Computational Fluid Dynamics Lecture Series” but is oriented towards students who will make a numerical project, hence it is more oriented towards future development of CFD methods rather than the application of CFD codes and using existing CFD tools. Hence, this course aims to give the broad view that prepares for making the best choice of algorithms and methods to accomplish a specific flow simulation and prepares the student for a more specialized numerical study (either independently or in other CFD courses, or by following NMFD2).

At the end of NMFD1 the student should have an understanding of the basic principles of Computational Fluid Dynamics (CFD), how the equations for incompressible and compressible flows (introduced in previous mandatory course DEFM) are numerically modeled and how the different formulations (implicit/explicit) influence accuracy and stability. He/she should know the fundamental differences between convection/propagation and diffusion with respect to their numerical treatment. He/she will understand the principles of discretization methods based on functional (Finite Elements, Spectral methods) and pointwise or cell-averaged (Finite Differences, Finite Volumes) representation of the discrete solution. He/she will acquire a global view on the formulations used to obtain the discrete system of equations like strong differential form (for finite differences), weak formulation, integral conservation law, method of weighted residuals (for finite elements) and the consequences for boundary conditions (weak, strong).

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He/she will understand the concepts of consistency, stability and convergence of discrete solutions, linked by the Lax-Wendroff theorem and master the stability theory for the Method of Lines (stability of Ordinary Differential Equations in time obtained after semi-discretization in space). Finally he will learn the particularities of the treatment of incompressible flow with respect to the solenoidal constraint for the velocity and pressure stabilization (by staggered grid formulation or using different finite element spaces for velocity and pressure).

NMFD2 (NMFD2 – 3.0 ECTS)
H. DECONINCK

The second part is a natural continuation of the first part, but goes much more in detail. At the end of the course the student should be able to follow the global CFD literature, choose an algorithm and develop independently a CFD method for a particular application. The following objectives should be reached for a successful completion of this course:

- master the theory of Partial Differential Equations, including the classification of PDEs based on the theory of characteristics. Master the specific properties of hyperbolic, elliptic and parabolic equations and the link with initial versus boundary value problem and diffusion versus propagation. Understand the concept of well-posedness with respect to boundary and initial conditions (Hadamard). Have a detailed understanding of the theory of hyperbolic conservation laws including weak solutions, jump relations, concept of mathematical entropy condition, boundary conditions,

- know the main discretization techniques based on finite difference, finite volume, finite element and spectral methods, including a discussion of the relationship between the various methods,

- have a deep understanding of the concepts of consistency, stability and convergence, stability theory (von Neumann analysis), Lax-Wendroff theorem, equivalent differential equation of a scheme, concepts of artificial dissipation and upwinding and the relation between both,

- master the principles of monotone schemes for hyperbolic conservation laws based of TVD and positivity (LED) conditions,

- be familiar with the classical finite difference and stabilized finite element schemes (SUPG, GLS) for hyperbolic and parabolic problems. Be familiar with classical time integration schemes (explicit and implicit) and their stability properties,

- have a good understanding of the boundary value problems, with emphasis on iterative methods for solving linear systems, including relaxation methods (SOR, Gauss-Seidel), conjugategradient like (Krylov subspace) methods and multigrid methods.

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Course notes

- Numerical Methods for Fluid Dynamics 1, H. Deconinck and T. Horváth, VKI-CN 226
- Numerical Techniques for Solving Partial Differential Equations, H. Deconinck, VKI-CN 142
- Numerical Methods in Fluid Dynamics 2, Exercises, H. Deconinck, VKI-CN 182
- Numerical Methods in Fluid Dynamics 2, Solutions to exercises, H. Deconinck, VKI-CN 183.

Literature

- Introduction to CFD, G. Degrez, VKI-CN 153
- Overview of Grid generation Methods, H. Deconinck, VKI-CN 146
- Numerical Solution of Time-Dependent Advection-.Diffusion-Reaction Equations, W. Hundsdorf and J.G. Verwer, Springer Series in Computational Mathematics, 2003
- Fundamentals of Computational Fluid Dynamics, Springer Verlag, H. Lomax, Thomas H. Pulliam, David W. Zingg
- Difference Methods for Initial-Value Problems, Robert D. Richtmyer, K. W. Morton
- Numerical Computation of Internal and External Flows, Ch. Hirsch,Butterworth-Heinemann
- Numerical Methods for Conservation Laws (Paperback), Randall J. LeVeque, Birkhauser
- Finite Element Methods for Flow Problems, J Donea, Antonio Huerta, John Wiley

Evaluation

Evaluation of the first part (NMFD1) is by a written exam in 2 parts: a closed book exam with questions about theory (weight 50%) and an open book exam with practical exercises (weight 50%) (4 hours in total).

The evaluation of the second part (NMFD2) is by a written open book exam consisting of exercises which require both a good understanding of the theory and the capacity to set up, analyze and solve a CFD problem.

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3. SPECIALIZATION IN AERONAUTICS/AEROSPACE

GENERAL COURSES IN AERONAUTICS/AEROSPACE	
Aircraft performance, stability and control	APSC - 2.0 ECTS
Inviscid aerodynamics in aeronautics	IAAI – 4.5 ECTS
A. Incompressible inviscid flows	IAAI – 2.5 ECTS
B. Compressible inviscid flows	IAAC – 2.0 ECTS
Two dimensional boundary layers	2DBL – 4.0 ECTS
COURSES EXPERIMENTAL OPTION	
Introduction to Ground Testing facilities	IGT – 1.25 ECTS
Computational fluid dynamics laboratory	CFD Lab - 1.5 ECTS
Introduction to computational fluid dynamics (LS)	ICFD - 1.25 ECTS
Advanced measurement techniques laboratories	MT Labs 6.0 ECTS
COURSES NUMERICAL OPTION	
Numerical methods in fluid dynamics	NMFD2 - 3 ECTS
Computational methods for compressible flows	CMCF – 4.0 ECTS
Advanced measurement techniques laboratories	MT Labs 1.5 ECTS
OPTIONAL COURSES IN AERONAUTICS/AEROSPACE	
A. For all options	
Physico-chemical models for atmospheric entry flow	PCMAF – 3 + 1(opt.) ECTS
Boundary layers and flow separation in 3D	3DBL - 1.25 ECTS
Introduction to aeroacoustics	ACOUS - 2 ECTS
Transonic aerodynamics	TRANS - 1 ECTS
Hypersonic aerodynamics	HYP - 2 ECTS
B. For the experimental option	

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Design and operation of plasma wind tunnels	PWT – 1.0 ECTS
Low speed wind tunnel analysis and design	WTAD – 1.0 ECTS
Data acquisition and processing	DAP - 2 ECTS
C. For the numerical option	
Computational methods for compressible flows	CMCF - 1.5 to 4 ECTS

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The aim of this series of courses is to provide the student with an overall appreciation of the role of aerodynamics in aeronautics/aerospace, as well as providing the required background to study a particular topic in greater depth. The common part of the program is designed to achieve the first objective. It comprises courses devoted to some areas of flight dynamics as well as courses dealing with the theory of inviscid and viscous flows for the different speed regimes. At the end of these courses, the attendee should be aware of the problems and methods encountered in aeronautical aerodynamics and re-entry aerothermodynamics. He should also understand the compromises and trade-offs that are necessary for any aircraft, missile or spacecraft design. After completion of this general program, the attendee can select more specialized courses in either high speed or low speed aerodynamics within the experimental or numerical approach.

Students with a good background in aeronautics may replace one or more of the general courses by some optional courses.

3.1 GENERAL COURSES IN AERONAUTICS/AEROSPACE

AIRCRAFT PERFORMANCE, STABILITY AND CONTROL (APSC - 2.0 ECTS)

M. CARBONARO

The course consists of formal lectures on flight mechanics, but also includes computerized demonstrations and exercises.

Learning objectives

At the end of this course students should have a good knowledge of the basic concepts of flight mechanics such as: lift and drag characteristics of airborne vehicles, their relation to the power required for flight and general performance for horizontal, climbing, gliding or accelerated flight. The student should be able to predict the velocity-flight envelope of a propeller-driven and of a jet-driven aircraft, as well as ceilings, climb rate, range and endurance. The student should also be able to understand and explain aspects of maneuvering performance and of aircraft stability and control.

Teaching forms

18 hours formal lectures, during which about 1 hour is devoted to a demonstration of performance prediction using an excel sheet. A 1 ½ hour seminar on a commercial software package for aircraft design and performance prediction is given by an external lecturer.

An individual homework exercise is to be carried out by each student.

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Course notes

- Introduction to Aircraft Performance, Stability and Control, M. Carbonaro, (PowerPoint slides)

Literature

- Introduction to Flight, John Anderson, McGraw-Hill Science/Engineering/Math; 6th edition, October 25, 2007

- Theory of Wing Sections: Including a Summary of Airfoil Data, Ira H. Abbott and A. E. von Doenhoff, Dover Publications, 31. December 1960.

Evaluation

The exam is based on an individual homework consisting in predicting the performances of a given aircraft or in a generic aircraft design problem, followed by a closed book written exam based on a list of 28 questions covering all the course subjects (weight is 50% for each).

INVISCID AERODYNAMICS IN AERONAUTICS (IAAI – 4.5 ECTS)
B. BOTTIN, T. Magin

This course is oriented towards students without background in classical aerodynamics.

There are two parts, one covering incompressible and one covering compressible flow. At the end of these courses the student should understand the physics of incompressible and compressible flows and be capable of using these theories in the interpretation of wind tunnel experiments or CFD simulations. Depending on the student's background he/she may be dispensed of following one or both parts of the basic course. In that case he/she should select optional courses in agreement with the faculty of the AR department.

A. INCOMPRESSIBLE INVISCID FLOWS (IAAI - 2.5 ECTS)
B. BOTTIN

This tutorial course gives insight into the characteristics of lifting airfoils in two-dimensional flows.

Learning objectives

The student should have a firm physical understanding of the methodology used for incompressible flow analyses (superposition principle, the relation between circulation and lift).

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The student should also understand the limitations and possibilities of linearized theories for thin airfoils and three dimensional wings. He/she should be able to use these methods to solve typical problems encountered during the design phase of aerodynamic surfaces. A good understanding of the underlying principles of numerical panel methods for wing sections (2D and 3D) and the ability to use state-of-the-art software to analyze practical cases is also required.

Course notes

- Inviscid Aerodynamics in Aeronautics / Incompressible Case (partial notes), B. Bottin, VKI CN 173

Literature

- *Theoretical aerodynamics*. Milne-Thomson, L.M., Mc-Millan, 1948. Also Dover, New York, 1973. {VKI reference number: 08.126}

- *Hydrodynamics in theory and application*. Robertson, J.M., Prentice-Hall, Englewood Cliffs, 1965. {VKI reference number: 08.311}

- *Fundamentals of aerodynamics*. Anderson, J.D.Jr., 3rd Edition. McGraw-Hill, New York, 2001. {VKI reference number: 08.456}

- A. *Low-speed aerodynamics from wing theory to panel methods*. 2nd Edition. Katz, J. & Plotkin, Cambridge University Press, Cambridge, 2001. {VKI reference number: 08.624}

Evaluation

The evaluation consists of two open book exercises and an oral interview. The former allows to verify that the student is capable of applying the techniques, the latter allows to verify that the student has understood the theoretical basis and its limitations.

The first exercise is a mid-course homework (weighting 4/20). The final evaluation is based on the individual solution of a complete problem (open book) by the student and an oral interview about the proposed solution (weighting 16/20).

The total weight of this first incompressible part is 62%.

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B. COMPRESSIBLE INVISCID FLOWS (IAAC – 2.0 ECTS)

T. MAGIN

Learning objectives

At the end of the course the student should master the classical theory of compressible gas dynamics including for steady and unsteady flow: oblique shock theory, Prandtl-Meyer expansion theory, numerical method of characteristics (MOC), shock/expansion method, small disturbance theory applied to supersonic wing and slender bodies, the Riemann problem for unsteady flow (shock tube problem, piston problem). He/she should be able to apply this understanding in the practice of external and internal aerodynamical engineering: for example to interpret physical data (e.g. Schlieren pictures from a supersonic wind tunnel or iso-plots from CFD), to carry out a simple design of a supersonic nozzle, to estimate the lift and drag of a supersonic wing, to model the functioning of short duration supersonic wind tunnels.

Course notes

- Inviscid Compressible Aerodynamics, G. Degrez, IVK-CN 145.

Literature

- Gas Dynamics, Maurice Joseph Zucrow, Joe D. Hoffman

- Compressible Fluid Dynamics, Philip A. Thompson

- Supersonic Flow and Shock Waves (Applied Mathematical Sciences)

  Richard Courant, K.O. Friedrichs.

Evaluation

The exam consists of oral questions about the theory and a small exercise/project (e.g. using the MOC to design a 2D nozzle or to solve a shock tube or piston problem). The ratio is 2/3 for the theoretical questions (1.3 ECTS) and 1/3 for the exercise (0.7 ECTS) giving in total 2.0 ECTS.

TWO DIMENSIONAL BOUNDARY LAYERS (2DBL – 4.0 ECTS)

G. DEGREZ

The detailed description is given in the section Optional Courses for all departments.

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The attendees of the Aeronautics/Aerospace program will specialize in one of the following two subgroups:

- Experimental option
- Numerical option

3.2 COURSES EXPERIMENTAL OPTION

INTRODUCTION TO GROUND TESTING FACILITIES (IGT – 1.25 ECTS)
FACULTY, O. CHAZOT (coordinator)

The detailed description is given in the section Optional Courses for all departments.

COMPUTATIONAL FLUID DYNAMICS LABORATORY (CFD Lab-1.5 ECTS)
H. DECONINCK

The purpose of this activity is to acquaint experimentalists with the basic use of CFD tools for investigating fluid flow problems.

Learning outcomes

Students should be able to compute a simple flow (e.g. one of the flows investigated experimentally in the measurement technique labs) using either by an in-house or a commercial CFD package. Issues to become familiar with include amongst others: the influence of the discretization scheme on the computational results, the iterative convergence and grid sensitivity.

Teaching forms

Formal lectures (25%), exercices on computer (75%)

Course notes

Not applicable

Literature

- Computational fluid dynamics - An introduction, edited by Wendt, J.F., ed. Springer, 3rd edition, 2009, isbn-13 978-3-540-85055-7, A von Karman Institute Book

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Evaluation

Evaluations are based on a written report, presenting/discussing the simulation results of the ERCOFTAC database test cases. Criteria are the student's capability: to define the calculation domain and the quality of the grid, to generate the correct boundary conditions based on available data, to evaluate the influence of the RANS one and two equation turbulence models and wall treatments, to investigate the influence of the order of numerical discretization and grid refinement (grid dependency) on convergence and accuracy, to evaluate acceleration techniques and convergence criteria.

INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS (ICFD - 1.25 ECTS)

The detailed description is given in the section Optional Courses for all departments.

ADVANCED MEASUREMENT TECHNIQUES LABORATORIES

(MT Labs 1.5 – 6.0 ECTS)

The detailed description is given in the section Optional Courses for all departments. Students following the experimental option have to choose all four sections of this course.

3.3 COURSES NUMERICAL OPTION

NUMERICAL METHODS IN FLUID DYNAMICS, PART 2 (NMFD2 - 3 ECTS)

H. DECONINCK

The detailed description is given in the section General Courses.

COMPUTATIONAL METHODS FOR COMPRESSIBLE FLOWS

(CMCF – 4.0 ECTS)

Both parts of this course, theory and Lab sessions, are mandatory for the numerical option in Aeronautics and Aerospace, and fully described in the Optional Courses for all departments.

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ADVANCED MEASUREMENT TECHNIQUES LABORATORIES

(MT Labs 1.5 – 6.0 ECTS)

The detailed description is given in the section Optional Courses for all departments. Students following the numerical option have to choose minimum one of the four sections of this course.

3.4 OPTIONAL COURSES IN AERONAUTICS/AEROSPACE

Students should take an equivalent of minimum 2 ECTS of the following optional courses, depending on the project.

A. FOR ALL OPTIONS

PHYSICO-CHEMICAL MODELS FOR ATMOSPHERIC ENTRY FLOW

(PCMAF – 3+1(optional) ECTS)
T. MAGIN

Addressed primarily to engineers, this course is an introduction to the basic tools of quantum mechanics, statistical physics, kinetic theory, and collisional and radiative elementary processes, used to model and understand chemically reacting and plasma flows encountered in hypersonic and combustion applications. A series of practical problems encountered in aerospace missions is also discussed, focusing on the simulation of atmospheric entry flows and ground testing. An optional laboratory session is proposed to the student to apply some of the theoretical concepts to interpret experimental data.

Learning objectives

The learning objective is to make the student aware of the specificities of aerospace flow modeling from the continuum to the rarefied regime. They should master the techniques to derive conservation equations from kinetic theory. They should understand the role of thermo-chemical non-equilibrium effects in compressed and expanding flows. They should assimilate the concept of coupling the radiation field to the flow field in atmospheric entry flows. They should know how and where to find basic data for thermodynamic and transport properties, as well as reaction rate coefficients. Students should also be able to use a library for high enthalpy and plasma flows focusing on computational fluid dynamics applications such as the VKI MUTATION++ library.

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Teaching methods

-3 ECTS: Course: 26h theory + 4h exercises (take-home assignment)

-1 ECTS (optional): Optical Emission Spectroscopy laboratory: 4h demonstration +6h data processing (laboratory report)

Lecturers

Prof. T. Magin

Course notes

- Physical Gas Dynamics, T. Magin, VKI-CN 213.
- Collection of slides: Introduction, Quantum theory, Statistical thermodynamics, Radiation, Kinetic theory, T. Magin

Literature

Basic level

– J. D. Anderson, Hypersonic and high-temperature gas dynamics, American Institute of Aeronautics and Astronautics, 2006

– G. Vincenti, C. H. Kruger, Introduction to physical gas dynamics, Wiley, 1965

– D. A. McQuarrie, J. D. Simon, Physical chemistry: a molecular approach, University Science Books, 1997

Intermediate level

– Mayer and Mayer, Statistical mechanics, Wiley, 1977

– J. H. Ferziger and H. G. Kaper, Mathematical theory of transport processes in gases, North-Holland, 1972

– M. Mitchner, C. H. Kruger, Partially ionized gases, Wiley, 1973

– Park, Nonequilibrium hypersonic aerothermodynamics, Wiley, 1989

– G. A. Bird, Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Oxford University Press, 1994

Advanced level

V. Giovangigli, Multicomponent Flow Modeling, Springer, 1999

– L. C. Woods, The Thermodynamics of Fluid Systems, Oxford University Press, 1975

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Evaluation

Evaluation (3 ECTS) is based on the correction of one take-home assignment (50%), as well as on one oral exam (50%) including the explanation of an original paper selected from the literature. Evaluation of the laboratory (1 ECTS) is based on the correction of the laboratory report.

The take-home assignment allows the student to apply some of the theoretical concepts learned in class in order to solve practical problems encountered by aerospace engineers. For example, previous homework assignments focused on a recent aerospace mission: predicting nonequilibrium radiative heat fluxes during the entry of the Huygens probe into Titan's atmosphere, and on ground testing in the VKI facilities: studying a Pitot measurement in the Plasmatron facility, rebuilding from experimental measurements the free stream conditions at the exit of a nozzle in the VKI free piston high speed Longshot wind tunnel, studying the ablation phenomenon of a carbon phenolic ablators tested in the Plasmatron facility.

The laboratory session is an introduction to optical emission spectroscopy allowing students to directly apply theoretical aspects of quantum mechanics introduced in class. Experimental measurements are carried out in a lab demonstration by teaching assistants who operate the VKI small inductively coupled plasma wind-tunnel. Students are requested to process the experimental data by means of two software: Mutation++, in-house library for high enthalpy and plasma flow properties, and Specair, online spectroscopic database.

A typical oral examination lasts approximately one hour. A few days before the exam, the students helped by the teacher select a paper among legacy and state-of-the-art literature. The main ideas of the paper are reviewed by the student during the exam, and are compared to the state-of-the-art concepts explained in class. This starts as a basis for discussion about this part of the course. A series of short questions about the other parts of the course allow for a more complete evaluation of the students.

BOUNDARY LAYERS AND FLOW SEPARATION IN THREE DIMENSIONS

(3DBL - 1.25 ECTS)
G. DEGREZ

The detailed description is given in the section Optional Courses for all departments.

INTRODUCTION TO AEROACOUSTICS (ACOUS - 2 ECTS)

C. SCHRAM

The detailed description is given in the section Optional Courses for all departments.

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TRANSONIC AERODYNAMICS (TRANS - 1 ECTS)

O.CHAZOT

This is a basic course on the typical features of transonic flows. It is organized in three main parts: Transonic phenomenology where the specific aspects of transonic flows are presented with a focus on shock structure and shock-boundary layer interactions. Transonic theory which presents how this particular flow regime could be modeled and its essential differences with the subsonic and supersonic regimes. Transonic testing that describes the main issue for the design of transonic wind tunnels.

Learning outcome

After successful completion of this course, students should be aware of the specific problems of transonic flows over airfoils and bodies and master the transonic similarity rules, as well as the solution techniques for the transonic full potential and small disturbance equations. They should also understand the conditions for shock-free supercritical flows, law of stabilization around M = 1 and specificities of the drag at transonic speeds. Students should also have a detailed understanding of the flow physics in transonic regime with its particular features. They should gain basic knowledge on transonic testing.

Teaching forms

Formal courses (8.0 h) and guided exercise (2.0 h)

Evaluation

Evaluation consists of two parts:

- a common exercise in the class guided by the professor and

- a written exam, closed book, at the end of the course period, focussing on typical transonic flow problems. The evaluation criteria are based on the understanding of basic transonic phenomenology, by reading Schlieren pictures, and theoretical results together with classical applications.

Course notes

- Elements of Transonic Aerodynamics G. Degrez, VKI-CN 194

- Handwritten notes by O. Chazot

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Literature

- Elements of Gasdynamics, H.W. Liepmann and A. Roshko, GALCIT Aeronautical series, John Wiley, 1957.

- Bibliography of VKI-CN 194

HYPERSONIC AERODYNAMICS (HYP - 2 ECTS)

O. CHAZOT

This course describes the main features of hypersonic flows and aerothermodynamics. It is organized in coordination with PWT course dedicated to Plasma wind tunnels for aerothermodynamics studies.

Learning objectives

The objective of this course is to ensure that the student has a good understanding of the specificities of inviscid and viscous hypersonic flows such as: Newtonian flow, shock expansion, tangent wedge and cone, similarity rules, small disturbance theory, strong and weak viscous interactions. The student must have a good insight into the physics of the hypersonic boundary layers and the consequences of high temperature (i.e. dissociation, non-equilibrium, etc.). He/she should become familiar with the classical hypersonic literature and also be able to select the appropriate experimental techniques and interpretation of high enthalpy experiments.

Teaching forms

Formal Courses (10h), Seminars (6h), Reading and reporting on specialized literature (4h).

Course notes

- Hypersonic Aerodynamics, R. Korkegi VKI-CN 9

- Fundamentals of Hypersonic Flow – Aerothermodynamics, D. Fletcher, VKI CN 190

- Handwritten notes, O. Chazot

Literature

- Hypersonic and High temperature gasdynamics, Anderson J.D., MCGraw-Hill, 1989

- Introduction to physical Gasdynamics, W.G. Vincenti & C.H. Kruger, John Wiley and sons, 1965

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Evaluation

A closed book oral exam evaluating the understanding of the basic hypersonic theory.

The second part of the evaluation is based on a three-page synthesis report including comments about a reference publication in hypersonic aerothermodynamics selected from a list provided at the end of the course period. Criteria are the understanding of major features of hypersonic flows, the development of ground test facilities and the extrapolation to real reentry flows.

B. FOR THE EXPERIMENTAL OPTION

DESIGN AND OPERATION OF PLASMA WIND TUNNELS (PWT – 1.0 ECTS)
O. CHAZOT

The detailed description is given in the section **Optional Courses for all departments.**

LOW SPEED WIND TUNNEL ANALYSIS and DESIGN (WTAD – 1.0 ECTS)
B. BOTTIN

The detailed description is given in the section **Optional Courses for all departments**.

DATA ACQUISITION AND PROCESSING (DAP – 2.0 ECTS)
C. SCHRAM

The detailed description is given in the section **Optional Courses for all departments**.

C. FOR THE NUMERICAL OPTION

COMPUTATIONAL METHODS FOR COMPRESSIBLE FLOWS (CMCF - 1.5 to 4 ECTS)
H. DECONINCK, T.MAGIN

A full description of this course is given in the **Optional Courses for all departments.**

PROFILES

Two specific examples of profiles are proposed to help students in choosing a coherent package of courses.

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1. Profile AeroThermoDynamics

Course	Credits		Notes
ATD Courses	**9**		
Compressible Inviscid Flows	2		
Physico-chemical Models for Atmospheric Entry Flows	3+1		
Hypersonics	2		
Plasma Wind Tunnels operation and design	1		
Experimental Option	**10.75**		
Measurement Techniques laboratories	6		
Introduction to Ground testing facilities	1.25		
Data Acquisition and Processing	2		
CFD lab	1.5		
Numerical Option		**8.5**	
Measurement Techniques laboratories		1.5	
Numerical Methods for Fluid Dynamics (part2)		3	
Computational Methods for Compressible Flows (Theory/Lab)		4	
Total	**19.75**	**17.5**	+ general courses

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2. Profile Aerodynamics

Course	Credits	Notes
Inviscid flow	4.5	
Subsonic aerodynamics	2.50	This is the IAAI course
Supersonic aerodynamics	2.0	This is the IAAC course
Viscous flow	4	
2D boundary layers	4.0	This is the 2DBL course
Introductory CFD	2.75	
Introduction to CFD	1.25	This is the LS Intro CFD or the NMFD1 course
CFD lab	1.50	Emphasis on turbulence models and practical use, which are necessary to fulfil the CFD lab according to the criteria issued in the brochure. An exercise just as it is now, on the correct use of CFD and not just fancy colours.
Aircraft Perf, Stab, Ctl	2	This is the APSC course.
Ground testing module	7.25	
Introduction to Ground Testing facilities	1.25	This is the IGT course.
Low-speed Wind tunnels	1.50	Dimensional analysis and the design of low speed facilities, i.e. essentially WTAD.
High-speed & plasma WT	1.50	This would cover hypersonic and plasma tunnels.
MT Labs (2 labs)	3.00	At least 2 MT labs are necessary. Suggest the classical Pitot-LDV BL exploration and the strain-gage balance labs.
Specific aerodynamics	4.5	
Transonic regime	1.00	The TRANS course.
Hypersonic regime	1.50	Hypersonic regime specifics, i.e. HYP course minus the facility-related problems, now bundled in PWT.
Aeroacoustics	2.00	The ACOUS course.
Total	25.0	+ 8,75 from common courses (Exp Option).

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4. SPECIALIZATION IN ENVIRONMENTAL AND APPLIED FLUID DYNAMICS

GENERAL COURSES IN ENVIRONMENTAL AND APPLIED FLUID DYNAMICS	
Methodology of applied fluid dynamics	MAFD - 5 ECTS
Industrial design exercise	IDE - 3.5 ECTS
Introduction to the mechanics of turbulence	TURB - 2.50 ECTS
Data acquisition and processing	DAP - 2 ECTS
COURSES EXPERIMENTAL OPTION	
Advanced measurement techniques laboratories	MT Labs - 6.0 ECTS
COURSES NUMERICAL OPTION	
Numerical methods in fluid dynamics	NMFD1 – 1.25 ECTS
Numerical simulation of industrial problems 1	NSIP1 - 2.75 ECTS
Numerical simulation of industrial problems 2	NSIP2 - 3.5 ECTS

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The objective of these lectures is to train attendees in handling and solving the wide variety of problems that may occur in environmental and industrial fluid dynamics. The main objective is to acquire a good insight into both fundamental and applied fluid dynamics. The teaching is closely related to the research activities carried out by staff members of the Department.

Each course member will make a selection with his/her supervisor among the courses below in function of his/her project.

4.1 GENERAL COURSES IN ENVIRONMENTAL AND APPLIED FLUID DYNAMICS

METHODOLOGY OF APPLIED FLUID DYNAMICS (MAFD - 5 ECTS)

EA FACULTY

The objective of this course is to train students in dealing with industrial fluid dynamics problems. It is a combination of tutorials, courses and seminars, providing insight into typical industrial fluid dynamic problems and solution techniques, and exercises in learning the methodology. Sessions are organized for treating samples followed by four exercises on real problems; each of them takes four successive sessions; one to introduce the problem to the students, two for the students to work under supervision of a professor and one for the debriefing and comments.

Learning outcomes

After completing the course, the student should be able to analyze a problem and make a complete research proposal. He/she must have the skills needed to perform a good analysis and diagnosis on the types of engineering and research problems which he/she may be faced with during his or her professional career, and devise ways to solve them.

To achieve this objective the student must be able to apply efficiently the methodology, i.e.

- to identify the fluid dynamic aspects of the industrial problem
- to select the most convenient type of investigation
- to estimate the resources in terms of required manpower and technical facilities
- to establish a research program
- to establish a time schedule and estimate a cost
- to put together a contract proposal.

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In addition to these competencies, the student must also have a good knowledge of typical industrial fluid dynamic problems and have an insight into the possible solution methods.

Teaching forms

Formal lectures on methodology in applied fluid dynamics illustrated by examples (20%)

Exercises (40%)

Courses and seminars relevant for learning the methodology of applied fluid dynamics on specific problems in Fluid Dynamics (MAFD-TCS) (40%) i.e.:

- Fundamentals of Aeroacoustics;
- Fundamentals of Boundary layer theory;
- Fundamental and Applied Heat transfer;
- External compressible flows;
- Macroscopic Balances;
- Dimensional Analysis and Model Theory;
- Bluff-body Aerodynamics;
- Internal Compressible flows;
- Incompressible internal flows;
- Pollutant dispersal in the atmosphere;
- Introduction to Two-Phase Flows;
- Optics & lasers;
- Transport Phenomena in Liquid Sprays;
- Flow induced oscillations;
- Wind Tunnel Design;
- Applied research in Coating Processes.

Lecturers

EA-Faculty – Profs Buchlin, Benocci, van Beeck, Rambaud, Schram, Vetrano

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Course notes

- Syllabus of MAFD course,
- Flow charts of systematic procedure,
- Slides on examples and exercises,
- MAFD-TCS slides.

Literature

Each MAFD-TCS course has a complete list of references.

Evaluation

The examination is based on the proposed investigation methodology to a typical problem elaborated by small groups of 2 to 3 students supervised by a faculty member.

A first part is a written report prepared by each group, containing a complete industrial proposal. Evaluation criteria are: clarity and conciseness of the report, completeness of the technical description, time schedule and estimation of cost in terms of manpower, adequacy of the proposed investigation.

A second part is based on an internal technical report, intended for the research institute supervisor. Evaluation criteria are: the motivation for selecting a given investigation methodology, its appropriateness, the demonstration that the technical proposal is feasible and that timelines and cost are estimated realistically.

An oral presentation of the problem and research proposal is given by each group, followed by questions from the faculty. An individual oral examination is then held with all the faculty members of the department who agree on a common grade. Evaluation criteria are relevance and sound founding of the proposed technical investigation (correct measurement technique or adequate numerical solution) and capability of the student to justify his/her choices and explain his/her approach to the problem.

The final grade for MAFD is a weighted average of the written reports (40%) and oral examination (60%) grades.

INDUSTRIAL DESIGN EXERCISE (IDE - 3.5 ECTS)
EA FACULTY

The objective of the industrial design exercise is to solve, within a limited amount of time, a realistic industrial problem related to fluid dynamics in a manner fitting the purpose. It is the follow-up of the MAFD course. The subject of the exercise is

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selected in relation to the options and the research project in which the students are already involved.

Learning objectives

The main objective is to allow the student to get better acquainted with the methodology techniques that he has been taught in the course of MAFD by putting them into practice.

The student must be able to propose a complete solution for a typical research problem of fluid dynamics taking into account the context of a complex industrial engineering system. He/she must be able to select an adequate methodology and solve the problem in the allocated time.

Course notes

- Same as MAFD course notes.

Literature

- Ad-hoc, depending on an assigned exercise, different for each student.

Evaluation

The first part of the evaluation is based on a written report describing the proposed solution of the industrial problem assigned to an individual student. Evaluation is by the supervising faculty member. Criteria are:

- the quality of the report (clarity, conciseness, structure, completeness)
- the appropriateness of the selected solution
- definition of the limits of application and estimation of uncertainty
- quality of proposal for future work that could be done if more time would be available
- presentation and discussion of the results, and conclusions.

The second part is an oral presentation, given to all EA faculty members and EA research engineers followed by questions from the EA faculty. Evaluation criteria are the relevance and sound founding of the proposed technical solution (correct measurement technique or adequate numerical solution).

The final grade for IDE is a weighted average of report (50%) and presentation (50%) grades, the latter being an average of the grades given by each EA faculty member.

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INTRODUCTION TO THE MECHANICS OF TURBULENCE (TURB - 2.50 ECTS)
C. BENOCCI
J. VAN BEECK

The detailed description is given in the section Optional Courses for all departments.

DATA ACQUISITION AND PROCESSING (DAP - 2 ECTS)
C. SCHRAM

The detailed description is given in the section Optional Courses for all departments.

4.2 COURSES EXPERIMENTAL OPTION

ADVANCED MEASUREMENT TECHNIQUES LABORATORIES (MT Labs - 6.0 ECTS)
J. VAN BEECK,J-M. BUCHLIN,M.VETRANO, C. SCHRAM, O. CHAZOT

The detailed description is given in the section Optional Courses for all departments.

Students following the experimental option have to choose minimum one of the four labs. The objective is to help them in the physical understanding of fluid mechanics.

4.3 COURSES NUMERICAL OPTION

NUMERICAL METHODS IN FLUID DYNAMICS (NMFD1 – 1.25 ECTS)
H. DECONINCK

The detailed description is given in the section General Courses.

NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS 1 (NSIP1 - 2.75 ECTS)
J. VAN BEECK
C. BENOCCI
Prof. Em. Ch HIRSCH

The objective of the course is to familiarize the student with the numerical solution of industrial and environmental flow problems through the application of a commercial flow solver and to lead him/her to acquire the critical sense and physical feeling necessary to evaluate the relevant numerical results. The course is composed of seminars, where the capabilities and the limitations of numerical simulation in industrial environmental problems are discussed.

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Learning outcomes

After the course the student should master the “best practice” rules for CFD predictions and should be able:

- to understand the different CFD models and approximations, which are a necessary part of this class of simulation,

- to perform a critical evaluation of the numerical results, assess their uncertainty and to define the logical approach to improve them.

A large part of this course consists of a practical exercise whereby the student simulates a simple turbulent shear layer and compares his/her numerical results to his/her own corresponding experimental results, obtained during the MT labs prior to the NSIP1 course.

Teaching forms

Formal lectures 30%, Exercises 60%, Seminar 10%

Evaluation

The evaluation is based on the report of the common work of a group of students (typically 2-3), and on an individual interview. The final mark is determined by 40% of the report mark and 60% of the interview mark.

Course notes

- Numerical simulation of industrial flows – slides, C. Benocci, VKI-CN 181.

- User manual for OpenFoam flow solver

- User Manual for FINE (NUMECA) Flow solver

Literature

- Model Evaluation guidance and protocol document, Editors: Rex Britter and Michael Schatzmann, ISBN 3-00-018312-4, Copyright COST Office, 2007

- ERCOFTAC Special Interest Group on “Quality and Trust in Industrial CFD”, Best Practice Guidelines, Editors: Michael Casey and Torsten Wintergeste, Fluid Dynamics Laboratory Sulzer Innotec, Version 1.0, January 2000, Copyright European Research Community On Flow, Turbulence And Combustion

-Quantification of uncertainty in computational fluid dynamics, Roache P.J., Ann. Rev. Fluid Mech. Vol. 29, pp 123-160, 1997.

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NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS 2 (NSIP2 - 3.5 ECTS)

J. VAN BEECK

C. BENOCCI

At the end of the project-oriented course NSIP2, the student should be familiar with the simulation of complex industrial and environmental flow problems using a general commercial flow solver, and have acquired the critical sense and physical feeling necessary to evaluate the numerical results. This is achieved by a practical but complex exercise, performed individually, in which the numerical results have to be compared with experimental ones, LES or DNS data from the literature. The main objective is the understanding of the models and the approximations, which are a necessary part of this class of simulation.

Lecturer

Prof. Benocci, Prof. Van Beeck,

Assistants for the exercises: L. Koloszar, Ph. Planquart, K. Myrillas

Teaching Forms

Exercises 100%

Evaluation

Evaluation is based on a report which is prepared by each student individually. The student is requested to simulate individually a bench-mark case selected from the ERCOFTAC database, using a RANS or URANS approach. The student has to investigate the influence of the computational domain, grid refinement, boundary conditions, discretization order, CFL number, convergence criteria, and turbulence model. Critical analysis of the simulated flow field quantities and assessment of the differences between simulation and experimental data is required for all parameters that were varied during the numerical modelling. The mark is 100% based on the report evaluated by both lecturers.

Course notes

- Numerical simulation of industrial flows – slides, C. Benocci, VKI-CN 181

- User manual for ANSYS and OpenFoam.

Literature

Same as Numerical Simulation of Industrial Problems 1 (NSIP1).

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5. SPECIALIZATION IN TURBOMACHINERY AND PROPULSION

GENERAL COURSES IN TURBOMACHINERY AND PROPULSION	
Flow in turbomachines	FTM - 8.0 ECTS
Design exercise	DE - 5.0 ECTS
Laboratory sessions	TU Labs - 3.0 ECTS
SPECIALIZATION IN TURBINES	
Advanced course in turbines	ACT - 4.5 ECTS
SPECIALIZATION IN COMPRESSORS	
Advanced course in compressors	ACC - 4.5 ECTS
OPTIONAL COURSES IN TUBOMACHINERY AND PROPULSION	
Introduction to computational fluid dynamics	ICFD - 1.25 ECTS
Numerical option students making the reduced design exercise follow also:	
Numerical methods in fluid dynamics, part 2	NMFD2 – 3.0 ECTS

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The main objective of these specialized courses is to familiarize the students with the main theories and tools for the interpretation of numerical and experimental results and the design techniques for advanced turbomachinery components. The first part provides the basis for the more specialized studies in turbines or compressors in the second part of this course program. The formal lectures are completed with the aero-design of advanced turbomachinery components to put the learned lessons into practice. The targeted courses prepare the student for a position in a turbomachinery research center or the R&D department of a turbomachinery manufacturer.

5.1 GENERAL COURSES IN TURBOMACHINERY AND PROPULSION

FLOW IN TURBOMACHINES

(FTM - 8.0 ECTS)
T. ARTS
T. VERSTRAETE

This basic course is mandatory for all Turbomachinery students (compressor and turbine specialization). The course starts with a detailed cycle analysis, a description of the component overall characteristics and a one dimensional flow analysis. It further provides a general description of the flow in Turbomachines using the S1/S2 model, based on the superposition of two 2D flows. It is the first step towards the understanding of the more complex 3D flows and the basis for the traditional turbomachinery design. Boundary layer issues and heat transfer are finally addressed at the end of this course.

Learning outcomes

At the end of this course the student should have acquired the necessary knowledge and competences for the design of gasturbines and their turbomachinery components. He/she should have a good understanding of the thermodynamic principles governing the flow and master the analysis and design methods, specific for the turbomachinery components.

In particular he/she should have a good understanding of the thermodynamic cycles and the fundamentals of propulsion in addition to a good knowledge of turbopropulsion elements, the laws of similitude and the prediction correlations. He/she should have an insight into the influence of the cycle characteristics on the performance of the individual turbomachinery components, the thermal efficiency of jet engines, gas turbines and steam turbine.

Starting from the engine specifications the student should be able to make a one-dimensional layout of a jet engine, specify the cycle characteristics, and predict the

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performance and its changes with operating conditions. The student should also be able to implement these design requirements into an optimization strategy. By this the student should have a good insight into the different propulsion systems for subsonic to hypersonic flow speed.

The S1-S2 model is the basis of turbomachinery analysis and design. Its correct use for a more detailed layout of a multistage compressor or turbine (i.e. the prediction of the performance and the specification of blade shapes) and the understanding of its limitations, are the objectives of the next and major part of the course. This results in 2 main and parallel courses related to respectively the meridional and blade to blade flow.

The main objective of the meridional flow study is to get a physical understanding of the theoretical relations on which the axi-symmetric flow model is based and to be able to apply them. The student must understand the influence of the design strategy (vortex law) on velocity triangles, degree of reaction, pressure, temperature and density gradients, efficiency and some basic aspects of manufacturing. The following more detailed aspects should also be understood: influence of radial enthalpy and entropy gradients, impact of streamwise curvature, relative motion and blade forces.

The main objective of the blade to blade flow study is a good understanding of the limitations of the experimental and numerical data for the turbomachinery blade design and a mastering of the analysis and design techniques. Students should be aware of the main differences between external flows and turbomachinery flows as there are: the impact of rotation, periodicity of the flow and unsteady blade row interaction. They should understand the limitations when using simplified numerical predictions or experimental data obtained in non rotating cascades. Students should also master the performance and loss prediction correlations in compressors and turbines, understand the physical phenomena occurring in turbomachines on which they are based (secondary flows, impact of Reynolds- and Mach number on operating range, etc.) and be available to implement them in a design strategy.

Students should also have a good knowledge of the numerical techniques that are at their disposal and of the modern design methods (inverse design and optimization methods) that presently are the subject of intensive research.

At the end of the courses FTR and FTC the student should be able to make a first lay-out of a multistage compressor or turbine and predict the performance based on the S1-S2 model, the analytical relations and performance correlations.

The objective of a last part is to make students familiar with the specificities of the boundary layers in turbines and compressors, as there are: basic transition and turbulence modeling and their relation to stage interaction, heat transfer in turbines, film cooling and internal convection cooling.

Teaching forms

Formal lectures (98%), computerized demo (2%)

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The practical application of the course is in the Design Exercise (DE 5. ECTS)

Seminars on more advanced cycles "High Speed Propulsion" by Hon. Prof. F. Breugelmans (6 h)

Course notes

- Turbomachinery Cycles and Components, R. Denos, VKI-CN 163

- Thermodynamic Cycles in Turbomachinery, PowerPoint slides by G. Paniagua

- Turbomachinery Components, PowerPoint slides by G. Paniagua

- Meridional Flow in Axial Turbomachines, J. Chauvin, VKI-CN 99

- Flow in turbomachines and turbomachinery component characteristics,

F. Breugelmans, VKI-CN 83

- Aerodynamic design of a gas turbine, McDonald, P.W., VKI-CN 95

- Radial equilibrium in Turbomachines, T. Arts, (handwritten notes)

- Boundary layers, R. Kiock, VKI-CN 118

- Introduction to heat transfer phenomena in gas Turbines, T Arts, M. Lambert & , Rutherford, VKI-CN 127

- Blade to Blade flow in Turbomachinery, R.A. Van den Braembussche, VKI CN 172

- Compressor Cascade Flow and Losses, R.A. Van den Braembussche, PowerPoint slides

- Inverse Design Methods for Axial and Radial Turbomachines,
R.A. Van den Braembussche, VKI Preprint 1994-35

- Fast Multidisciplinary Optimization of Turbomachinery Components,
R.A. Van den Braembussche, VKI LS 2004-07 (part of)

- Handwritten notes on introduction to numerical methods in Turbomachines,
R.A. Van den Braembussche.

Literature

- Convective Heat and Mass Transfer, Kays & Crawford (Book)

- Boundary-Layer Theory, H. Schlichting, Springer, 8th edition, 2000, Corr. 2nd printing edition, 1 Oct 1999

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- Viscous Fluid Flow, Frank White, McGraw-Hill Science/Engineering/Math, 3rd Revised edition, 1 avril 2005

- Optimization and Computational Fluid Dynamics, Ed. D. Thevenin and G. Janiga, Springer Verlag, ISBN: 978-3-540-72152-9

- Aerothermodynamics and Flow in Turbomachines, M.H. Vavra, R.E. Krieger Publishing Co.

- Aerodynamic Design of Axial compressors, NASA SP 36, Compressor and Turbine Research Division, NACA Lewis Research Center.

Evaluation

The evaluation is done by an oral exam for each of the three large parts of the course (open and closed book including exercises). The evaluation of the fourth part (boundary layers) is incorporated into the second part. The weighting (3/20 for cycles, 10/20 for meridional flow and boundary layers, 7/20 for blade to blade flow) is proportional to the number of lecture hours and communicated to the students in advance. A test exam is planned early in the year for FTR and FTC, to familiarize the students with the VKI evaluation criteria and techniques. Students can decide to keep the points for the final grade or to repeat the exam at the end of the course.

The evaluation aims to measure the student's knowledge of the flow phenomena, his/her capacity to apply the techniques and understanding of the consequences of the approximations that are involved. The ultimate test will be by a separate Design Exercise (2 or 5 ECTS depending if the student is following the numerical or experimental option).

More detailed evaluation criteria related to each part of the course are:

- the student's understanding of the Joule cycle, his/her ability to explain the differences between the ideal cycle and the real one and to propose and justify possible improvements to the gasturbine lay-out and components.

- the student's understanding of the different meridional flow concepts addressed during the teaching, his/her ability to select the appropriate design options, to propose solutions to the different problems and restriction of the design space. The understanding of the impact of boundary layers and heat transfer on the flow pattern and performance are also evaluated.

- the student's understanding of the limitations of applicability of experimental and numerical data, its use in the design of compressors and turbines are the main evaluation criteria of the blade to blade part of the course.

The final evaluation will be the design exercise (see DE 3.5 ECTS).

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<u>DESIGN EXERCISE</u> (DE - 5. ECTS)

T. ARTS
F. BREUGELMANS
F. FONTANETO

The objective of this individual exercise is to further familiarize students with the turbomachinery design and analysis methods by applying them for the design of a complete turbomachinery component. It is the final hands-on illustration/evaluation of the different basic and advanced turbomachinery lectures (FTM, ACC or ACT). The component (compressor or turbine) to be designed depends on the option chosen for specialization.

Students making a numerical project may decide to limit the design exercise the first part (2.0 ECTS) and complement their curriculum with the course “Numerical Methods for Fluid Dynamics, part2” described in the section Optional Courses for all departments.

<u>Learning outcomes</u>

The student must be capable of defining the aerodynamic path and of specifying the blading in function of the design point, by means of the techniques specified in the courses. Only the overall boundary conditions (total inlet conditions, total pressure ratio, mass flow or power) of a turbine or (inlet conditions, mass flow and pressure ratio) for a compressor, are specified. Any other required input and design choice has to be defined and justified by the student.

The student should be able to address following successive steps of the design:

- global cycle analysis (compressor-turbine matching)
- 1D mean radius analysis of the turbine (selection/optimization of exit static conditions, degree of reaction, exit flow angles of vane and blade, rotational speed). Definition of the number of stages and cross sections (passage convergence or divergence)
- ISRE analysis. Selection of an exit vortex law for both vane and blade complying with the requirements on exit swirl, rotational speed, blade turning and cross section divergence
- NISRE analysis. Selection of a loss model. Definition of profile, secondary and leakage losses. Effect of Mach and Reynolds number. Calculation of radial profiles of kinematic and thermodynamic radial gradients. Need to comply with requirements on exit swirl, rotational speed, blade turning and cross section divergence
- Presentation, analysis and justification of final velocity triangles.

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There is no pre-established software available for this part of the exercise. The main emphasis is put on a correct physical understanding of the implications of the choices made.

The design has to be complemented by an off-design performance prediction. Finally the student must be able to design/select the blades and analyze them by Navier-Stokes solvers to confirm the local energy exchange and verify the optimality of the blade velocity distribution.

Teaching forms

Exercise 100%

Course notes

-All Turbomachinery course notes used in FTM

Literature

Not applicable

LABORATORY SESSIONS (TU Labs - 3.0 ECTS)
TU FACULTY

This course comprises a series of lab sessions that are defined to provide a better understanding of the flow physics and theories presented in the courses FTM, ACC and ACT.

Learning outcomes

The student should demonstrate mastery of the following measurement techniques:

- measurement of the steady flow in a cascades by pressure probes
- heat transfer and gas temperature measurements related to hot turbine blades
- unsteady flow measurements during surge and stall by hot wire.

For each technique he/she should

- understand the limitations and field of application,
- be able to select the appropriate data acquisition systems
- show the capability to develop data reduction techniques

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- be able to estimate the accuracy
- show the capability to link the results to the physics of the problems.

Teaching forms

Practical exercises on existing facilities

Course notes

- Handouts for TU-labs, PowerPoint slides by G. Paniagua

Evaluation

The evaluation is based on the test report. The main criteria, specified in the handouts, are:

- completeness of the report
- quality of uncertainty analysis
- validation of the results by linking them with physical flow models
- depth in the interpretation of the flow data
- recognition of the design options in the measurement results.

5.2 SPECIALIZATION IN TURBINES

ADVANCED COURSE IN TURBINES (ACT - 4.5 ECTS)

S. LAVAGNOLI, T. ARTS
C.H. SIEVERDING

This advanced course is the follow-up of the turbomachinery course FTM and followed only by students who have selected the turbine option. It provides a detailed overview of the advanced design and analysis methods for the different types of turbines. Honorary professors with a long experience and broad expertise in this field play a non negligible role in this specialized teaching.

Learning outcomes

At the end of this course the student should

- have a good knowledge of the evolution of the different architectures of turbomachines as prime mover in conversion and propulsion systems from

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1900 to today as driven by a combination of the inventive spirit of gifted engineers, the gradual evolution of more and more complex experimental and analytical models and finally the irresistible progress of advanced numerical methods,

- master in much more detail than taught in the FTM course, the design practice for turbine blades and stages, have a feeling for the hierarchy of importance of different design aspects and be able to judge what appears right or wrong in a turbine design,

- have a sound understanding of the basic physics of the complex flow through turbine bladings including aspects of transonic and supersonic flow, boundary layer transition and separation and three dimensional flows. They should know how to improve the turbine design by using this knowledge for an improved flow control,

- be able to evaluate the impact of the aerodynamics on the thermal aspects such as the appearance of condensation in last stages of steam turbines and the need of cooling of blades in the first stages of gas turbines and appreciate the effect of cooling systems and blade materials on turbine lifetime,

- understand the underlying physics and be able to make use of the art of bending the blades in tangential and/or axial direction to generate blade forces effecting the three-dimensional flow for improved flow control, in particular in the endwall regions,

- understand how the unsteady flows through the combination of most advanced time resolved experimental and numerical methods can help in improving both performance and life time of turbomachines,

- have insight into how the short and long term research efforts are of particular importance to the future development of more efficient turbomachines with the aim of reducing their impact on the environment and have a feeling for top priorities in research in a competitive environment.

Teaching forms

Formal lectures.

The practical application of the course is in the Design Exercise (DE 5. ECTS).

Course notes

- Rocket Engines: Turbomachinery, PowerPoint slides by G. Paniagua

- Contra-rotating Turbines Study, PowerPoint slides by G. Paniagua

- Unsteady flows in Turbines, G. Paniagua, VKI-CN 206

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- Development of Steam and Gas Turbines and 1D stage Design and Analysis, C. Sieverding, VKI-CN 199

- Turbine Blade Design, C. Sieverding, VKI-CN 200

- Compressible flow theory, C. Sieverding, VKI-CN 201

- Transonic Gas Turbine Stages, C. Sieverding, VKI-CN 202

- Transonic Flow in Last Stage of Large Steam Turbines, C. Sieverding, VKI-CN 203

- Secondary Flows in Turbine Blade Passages, C. Sieverding, VKI-CN 204

- Full Three-dimensional Blade Design, C. Sieverding, VKI-CN 205

- Axial Performance Prediction Methods, C. Sieverding, VKI-CN 207

- Comparison of Axial Turbine Loss Correlations, C. Sieverding, VKI-CN 208

- Introduction to Heat transfer Phenomena in gas Turbines, T. Arts, VKI-CN 127

Literature

Untersuchungen und Berechnung axialer Turbinenstufen, Dejc, E., Trojanovskij, B.M. & Naumann, W., Berlin : Verlag Technik, 1973.

Thermische Turbomaschinen: Zweiter Band. Geänderte Betriebsbedingungen, Regelung, mechanische Probleme, Temperaturprobleme, Volume 2, Walter Traupel, Springer, 4th edition, 2000.

Evaluation

The evaluation consists of an individual oral (one hour) closed book exam covering 3 selected chapters of the six main chapters of the course (two imposed by the evaluator, one freely chosen by the student). The chapters imposed are communicated to the students at the end of the course. The choice of the freely selected chapter is announced by the student at the beginning of the exam.

The evaluation criteria are the degree in which the student:

- masters the design methodology and his/her discernment of selecting the most appropriate solution, his/her knowledge of the most appropriate stage performance evaluation methods,

- understands the basic physics of the flows in turbine bladings and their consequence on optimal blade designs,

- understands and is able to apply the various means for reducing the impact of secondary and tip clearance flows on turbine performance,

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- is able to estimate the impact of the selected solutions on the overall aero-thermal performance of the turbine stage(s),
- has a comprehension of the unsteady flow phenomena caused by blade row interaction and his/her appreciation of the importance of unsteady effects with respect to steady state stage performance data.

5.3 SPECIALIZATION IN COMPRESSORS

ADVANCED COURSE IN COMPRESSORS (ACC - 4.5 ECTS)

F. FONTANETO, T. VERSTRAETE
F. BREUGELMANS
R. VAN DEN BRAEMBUSSCHE

This advanced course is the follow-up of the basic turbomachinery course FTM and is followed only by students who have selected the compressor option. Presented are the theory and models that have been established for the detailed design and analysis of the different components of radial and axial compressors and an overview of the computer-based optimization methods for radial compressors. Emphasis is on the physics of the flow in relation to the equations that govern them and on the way geometrical changes influence the performance. The course intends to give a good basis for people interested in designing different types of compressors.

This course is composed of two parts corresponding to the main types of compressors. The first part provides the theory and models that have been established for radial compressors. This second one is similar to the first one but aims for an up-to-date understanding of the flow mechanisms governing advanced axial compressors (subsonic, transonic and supersonic).

Learning outcomes

The learning objective of the first part is to make the student aware of the specificities of radial compressors. They should understand the role of radius change and flow separation on the transformation of energy and pressure rise, the mechanisms governing the flow in radial vaneless and vaned diffusers, return channels and volutes. The student should also understand the mutual interaction of these components. He/she should master the specific performance prediction models with special attention to range, understand the specificities of the secondary flow in radial turbomachines and its impact on stability (surge and stall). He/she should know the specific problems related to the different fields of application (industry, power generation or aeronautics), and understand the impact of Reynolds number or gas composition on performance.

This first part of the course is also offered to external participants from industry and research centers and PhD students preparing a thesis related to radial compressors.

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At the end of the second part of the course student should have a clear idea of the specificities of multistage, low speed, transonic and supersonic axial compressors and understand how the different operating conditions influence the design. The impact of flow unsteadiness, secondary flows and casing treatment, inlet distortion and erosion, on the stability (surge and stall) and advantages of variable geometry and bleeding should be understood. Students should master the design methodologies that are specific for high speed applications including the stage matching techniques. They should be aware of the differences between the aero and industrial applications and the impact of gas composition.

The students should also understand the problems that are specific for supersonic compressors such as: 3D shock losses and unique incidence and their impact on blade shape and range. They should also understand the different design philosophies. The second part of the course makes extensive use of conference articles and journal papers to illustrate the topics that are discussed.

Teaching methods

Part 1 (ARCC): tutorials 30h, exercises 4h

Part 2 (AACC): tutorials 20h, seminars 6h

The practical application of the course is in the Design Exercise (DE 5. ECTS)

Course notes

- Centrifugal Compressors, Analysis & Design, R.A. Van den Braembussche, VKI CN 192

- Multidisciplinary Optimization of Turbomachinery Components using Differential Evolution, T. Verstraete, VKI CN 218

- Centrifugal Compressors, R.A. Van den Braembussche, PowerPoint Slides

- Collection of PowerPoint slides J.F. Brouckaert

- Mechanical Factors affecting Surge line, F. Breugelmans VKI-CN 96

- Off-design Performance of Axial Compressors, J. Chauvin VKI-CN 100

- Transonic Compressor Cascades, H. Griepentrog, VKI-CN 73.

Literature

- Extensive bibliography in CN 192 and CN218

- Effect of Mach number on the Flow and Application of Compressibility Corrections in a Two-Dimensional Subsonic-Transonic Compressor Cascade having Varied Porous-wall Suction at the Trailing Edge, W.B. Briggs, NACA TN 2649

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- Performance of Controlled Diffusion Blades, H. Starken, VKI-LS 1992-02 (part of)

- Loss Development in Transonic Compressor Cascades, H. Starken, VKI-LS 1998-03 (part of)

- Investigation of the Axial Velocity Density Ratio in a High Turning Cascade, H. Starken, F. Breugelmans, P. Schimming, ASME 75-GT-25

- Design of Compressor Blades Suitable for Transonic Axial-Flow Compressors, M.P. Boyce ASME 67-GT-47

- A shock Loss Model for Supercritical Subsonic Flows in Transonic Axial Compressors, R.J. Dunker, AGARD …… paper 27

- The Cascade and Stator Section Performance of a 48^o Cambered DCA Airfoil – Comparison with 2D Flow Calculations in the Compressible Flow Regime, F. Breugelmans, VLI-LS 59

- Single Stage Experimental Evaluation of High Mach Number Compressible Rotor Blading, Part I Design of Rotor Blading, D.R. Steyler & L.H. Smith. NACA RM

- Design Methodology for Advance HP Compressor First Stages, M. Goutines, VKI LS 1988-03, (part of)

- Analysis of 3D Viscous Flow in Transonic Compressors, W.N. Dawes, VKI-LS February 1988) (part of)

- Fan and LP Compressor Design: General; Considerations, (slides), J. Lepine, VKI-LS 2003-06, (part of)

- LP Compressor Design, (slides), J. Lepine, VKI-LS 2003-06, (part of)

- Shock Structure Measured in a Transonic Fan Using Laser Anemometry, J. Wood et al. AGARD CP-401, paper 2

- Transonic Investigation of an Axial-Flow Compressor Rotor with a Hub-tip ratio of 0.75 and Blades having NACA A_2I_{8b} mean lines, NACA RM L57H08, P.T. Bernot & M. Savage

- Single Stage Experimental Evaluation of High Mach Number Compressible Rotor Blading, Part 4 Performance of Rotor 2D, K.W. Krabacher & J.P. Gostelow

- Axial Compressor Performance Predictions, AGARD (part of).

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5.4 OPTIONAL COURSES IN THE TURBOMACHINERY DEPARTMENT

Students following the experimental option have to take following course:

INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS (ICFD - 1.25 ECTS)
M. PERIC

The detailed description is given in the section **Optional Courses for all departments**.

Students selecting the Numerical option and making the reduced Design Exercise (1.5 ECTS) have to take following course:

NUMERICAL METHODS IN FLUID DYNAMICS, PART 2 (NMFD2 - 3 ECTS)
H. DECONINCK

The detailed description is given in the section **Optional Courses for all departments**.

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6. OPTIONAL COURSES FOR ALL AREAS OF SPECIALIZATION

Introduction to computational fluid dynamics (lecture series)	ICFD - 1.25 ECTS
Advanced measurement techniques laboratories	MT Labs – 1,5 - 6.0 ECTS
Introduction to aeroacoustics	ACOUS - 2 ECTS
Introduction to the mechanics of turbulence modelling	TURB - 2.50 ECTS
Data acquisition and processing	DAP - 2 ECTS
Design and operation of plasma wind tunnels	PWT – 1.0 ECTS
Numerical methods in fluid dynamics, part 2	NMFD2 - 3 ECTS
Computational methods for incompressible flows	CMIF - 1.5 to 4.0 ECTS
A. Lectures	1.5 ECTS
B. Exercises	2.5 ECTS
Computational methods for compressible flows	CMCF - 1.5 to 4.0 ECTS
A. Lectures	1.5 ECTS
B. Exercises - Project	2.5 ECTS
Two-dimensional boundary layers	2DBL – 4.0 ECTS
Boundary layers and flow separation in three dimensions	3DBL - 1.25 ECTS
Low speed wind tunnel analysis and design	WTAD - 1 ECTS
Introduction to Ground testing facilities	IGT – 1.25 ECTS

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The following courses are optional and in function of their projects, students may select, in agreement with their supervisor, one or more optional courses available to all areas of specialization.

INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS LS (ICFD - 1.25 ECTS)

M. PÉRIC
(VKI coordinator H. DECONINCK)

This three-day course has the same objectives as the course on "Numerical Methods in Fluid Dynamics, part 1: Introduction" but is oriented to students who will follow the experimental option and hence will not continue with a more advanced CFD course. Emphasis is also put on the relation between the flow physics and the modeling.

Learning outcomes

At the end of the course the student should have an understanding of the basic philosophy of Computational Fluid Dynamics (CFD). He/she should know how the equations for incompressible and compressible flows, explained in the theoretical courses, are numerically modeled and how the different formulations (implicit/explicit) influence accuracy and stability. He/she should understand the CFD vocabulary.

This course is included in the VKI lectures series program and attracts every year between 30 and 40 external participants from industry and research centers.

Teaching forms

Formal lectures 15 hours

Course notes

- Computational fluid dynamics - An introduction, Edited by Wendt, J.F., ed. Springer, 3rd edition, 2009, isbn-13 978-3-540-85055-7, A von Karman Institute Book

Literature

References in the course notes

Evaluation

The evaluation is done by an oral closed book exam.

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ADVANCED MEASUREMENT TECHNIQUES LABORATORIES

(MT Labs – 1,5 - 6.0 ECTS)
J. VAN BEECK,J-M. BUCHLIN,M. VETRANO, C. SCHRAM, O. CHAZOT

This course intends to provide the in-depth knowledge of typical measurement techniques to students who plan to use them in their project.

Learning objectives

After conducting these laboratory experiments the student should have an in-depth knowledge of and the skills required to apply following modern measurement techniques with application to fluid dynamics:

- Calibration of a three-component internal strain gauge balance and its use for force measurements on a typical aircraft/missile configuration,
- Laser Doppler velocimetry and its use to measure mean velocities and turbulence levels in a boundary layer flow,
- Hot wire anemometry and pressure probes to measure mean velocities and turbulence levels in a boundary layer flow,
- Infrared radiometry applied to heat transfer on a body in hypersonic flow.

In particular he/she should understand the limits of application, master the calibration, be able to perform the data reduction and be capable of estimating the accuracy.

Course notes

- Guidelines for the Measurement Techniques laboratories, J. Anthoine & O. Chazot, VKI-CN 191

Literature

- Measurement Techniques in Fluid Dynamics – An Introduction, Third revised edition, VKI, 1991, 383 pgs

Evaluation

Each group of students is asked to prepare a report about each lab and the evaluation is based on the grade given by the supervisor to this report. Emphasis is put on critical analysis of the results including uncertainty.

A second evaluation is by an individual oral examination of each student by a college of faculty members. Criteria are the understanding of the techniques, calibration and

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error estimation and their application to specific problems. The final grade is based on a weighted average of these grades (60% for oral examination and 40% for reports).

INTRODUCTION TO AEROACOUSTICS

(ACOUS - 2 ECTS)
C. SCHRAM

The purpose of this course is to provide students with some basic knowledge of physical acoustics and aero-acoustics. The main fields of application encompass low-Mach number flows in ground and air transportation, such as cooling fan noise, airframe noise, and ducted systems amongst others. This course is continuously updated following the research activities at the VKI.

Learning objectives

The students should understand the fundamentals of acoustics such as: units and assessment of noise, aerodynamic noise generation. They should understand 2D and 3D wave propagation and dissipation, Lighthill's formulation and vorticity formulation applied to jet noise, resonators and flow-acoustic coupling.

Course notes

- An Introduction to Linear Acoustics and Flow Noise at Low Mach Numbers,
C. Schram, VKI-CN 222

Literature

Bibliography in VKI-CN 222

Evaluation

The evaluation consists of a written exam focusing on practical questions and exercises involving the implementation of the theoretical aspects covered by the course.

INTRODUCTION TO THE MECHANICS OF TURBULENCE MODELING

(TURB - 2.50 ECTS)
C. BENOCCI
J. VAN BEECK

This is a formal course organized to ensure that all students of the EA department have a basic understanding of the physics of turbulence and its simulation by computational means. It is an optional course for students of the other departments.

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Learning outcomes

At the end of this series of tutorials the student should have an insight into the mathematical tools for the statistical description of turbulence, including transition, turbulent stresses, kinetic energy equation, vortex dynamics in turbulent flows, correlations, spectral analysis, notions of homogeneous and isotropic turbulence.

He/she should have an understanding of the basics of turbulence modeling and be able to select the appropriate model for each application and assess the capabilities and limitations of the chosen model.

Teaching forms

Formal courses 100%

Lecturer

Prof. C. Benocci (course responsible), J.P.A.J. van Beeck

Course notes

- Concepts of Turbulence modeling, C. Benocci and D. Olivari, VKI-CN 158
- An Introduction to Mechanics of Turbulence, D. Olivari and C. Benocci, VKI-CN 157
- Introduction to mechanics of turbulence: Spectral analysis of turbulent flows, C. Benocci and J. Van Beeck, VKI-CN 168
- Introduction to the Physics and Simulation of Turbulence, J.H. Ferziger, VKI-CN 156.

Literature

Turbulent Flows, S.B Pope (2000) Cambridge University Press

Large Eddy Simulation and related techniques, Theory and Application, VKI Lecture Series 2012-03, C. Benocci & J. Van Beeck editors

Introduction to the modeling of turbulence, VKI Lecture Series 2004-06, C. Benocci & J. Van Beeck editors.

Evaluation

Evaluation is by a written closed book exam measuring the objectives are reached i.e. a theoretical knowledge about the mechanics of turbulence and its modeling.

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DATA ACQUISITION AND PROCESSING (DAP - 2 ECTS)

C. SCHRAM

This course teaches the basic techniques for acquiring experimental data under a digitized form and the numerical techniques for processing them.

Learning outcomes

After successful completion of this course the student should understand the consequences of the measurement chain and numerical data processing techniques (digital filtering, numerical modeling of probe transfer function and digital compensation of signals …). In particular he/she should be aware of the restrictions and errors due to the discretization. He/she should also understand the advanced techniques for unsteady flow measurements (wavelets, POD decomposition, etc.).

The final outcome is the student's capability to define and set up the appropriate measurement chain for a specific problem and the knowledge and competence needed to correctly perform the analysis of the results collected in the research project (TU students) or obtained in the laboratory sessions of the "Advanced Experimental Techniques course (MT labs 1.5 ECTS)".

Teaching forms

Formal lectures (85%) and computerized exercises (15%)

Lecturer

Prof. C. Schram, faculty

Course notes

- Data acquisition and processing, PowerPoint slides by G. Paniagua

- Measurement Techniques in Fluid Dynamics – An Introduction, Third revised edition, VKI, 1991, 383 pgs. (last chapter)

- Fundamentals of Data Acquisition and processing, R. Denos, VKI-CN 171.

- Introduction to Advanced Data Processing, Mike Bilka, VKI-CN 197.

Literature

Bibliography in VKI-CN 171, VKI-CN 197

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Evaluation

The evaluation is based on a written closed book exam measuring the understanding of the concepts explained during the courses (weight 16/20) and by a multiple choice test evaluating the understanding of the advanced data processing techniques for unsteady flows (4/20).

DESIGN AND OPERATION OF PLASMA WIND TUNNELS (PWT – 1.0 ECTS)

O. CHAZOT

This course describes the basic features of Plasma wind tunnels and related ground testing.

Learning objectives

At the end of this course the student should have a general knowledge of what is specific for plasma facilities and plasma reactors used for aerothermodynamics research. It includes:

- basic operations of high frequency generators,

- Inductively Coupled Plasma torches design,

- characteristics of plasma flows,

- operation of plasma wind tunnels,

- application of aerothermodynamics testing in Plasmatron facilities.

Teaching forms

Formal lectures (6h), seminar (2h), Lab demonstration (2h)

Course notes

- PowerPoint Slides Plasma Windtunnel - Design Operation and Application

Literature

No good reference available (except in Russian)

Evaluation

Evaluation consists of a written exam with theoretical questions on the course contents and the preliminary design and performance evaluation of a plasma wind

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tunnel. The evaluation criteria are along the understanding of plasma wind tunnel operation, thermal plasma flow features and typical measurements techniques applicable.

NUMERICAL METHODS IN FLUID DYNAMICS, PART 2 (NMFD2 - 3 ECTS)

H. DECONINCK

Learning objectives

This second part is a natural continuation of the first part, but goes much more in detail. At the end of the course the student should be able to follow the global CFD literature, choose an algorithm and develop independently a CFD method for a particular application. The following objectives should be reached for a successful completion of this course:

- master the theory of Partial Differential Equations, including the classification of PDEs based on the theory of characteristics. Master the specific properties of hyperbolic, elliptic and parabolic equations and the link with initial versus boundary value problem and diffusion versus propagation. Understand the concept of well-posedness with respect to boundary and initial conditions (Hadamard). Have a detailed understanding of the theory of hyperbolic conservation laws including weak solutions, jump relations, concept of mathematical entropy condition, boundary conditions,

- know the main discretization techniques based on finite difference, finite volume, finite element and spectral methods, including a discussion of the relationship between the various methods,

- have a deep understanding of the concepts of consistency, stability and convergence, stability theory (von Neumann analysis), Lax-Wendroff theorem, equivalent differential equation of a scheme, concepts of artificial dissipation and upwinding and the relation between both,

- master the principles of monotone schemes for hyperbolic conservation laws based of TVD and positivity (LED) conditions,

- be familiar with the classical finite difference and stabilized finite element schemes (SUPG, GLS) for hyperbolic and parabolic problems. Be familiar with classical time integration schemes (explicit and implicit) and their stability properties,

- have a good understanding of the boundary value problems, with emphasis on iterative methods for solving linear systems, including relaxation methods (SOR, Gauss-Seidel), conjugategradient like (Krylov subspace) methods and multigrid methods.

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Course notes

- Numerical Techniques for Solving Partial Differential Equations, H. Deconinck, VKI-CN 142

- Numerical Methods in Fluid Dynamics 2, Exercises, H. Deconinck, VKI-CN 182

- Numerical Methods in Fluid Dynamics 2, Solutions to exercises, H. Deconinck, VKI-CN 183

Literature

- Numerical Solution of Time-Dependent Advection-.Diffusion-Reaction Equations, W. Hundsdorf and J.G. Verwer, Springer Series in Computational Mathematics, 2003

- Fundamentals of Computational Fluid Dynamics, H. Lomax Thomas H. Pulliam David W. Zingg, Springer Verlag

- Difference Methods for Initial-Value Problems, Robert D. Richtmyer, K. W. Morton

- Numerical Computation of Internal and External Flows, Ch. Hirsch,Butterworth-Heinemann

- Numerical Methods for Conservation Laws (Paperback), Randall J. LeVeque, Birkhauser, - Finite Element Methods for Flow Problems, J Donea, Antonio Huerta, John Wiley.

Evaluation

The evaluation of NMFD2 is made by a written open book exam consisting of exercises which require both a good understanding of the theory and the capacity to set up, analyze and solve a CFD problem.

COMPUTATIONAL METHODS FOR INCOMPRESSIBLE FLOWS (CMIF - 1.5 to 4.0 ECTS)

H. DECONINCK

This course consists of lectures (1.5 ECTS) and exercises (2.5 ECTS). Students may choose to attend only the lectures.

A. LECTURES (1.5 ECTS)

Learning outcomes

The student must master the different discretization methods applied to the steady convection diffusion equation, with emphasis on monotonicity and accuracy. This

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includes finite difference, upwind finite volume schemes (including monotone schemes such as MUSCL TVD) and SUPG finite element schemes.

They should understand the incompressibility condition and the role of the pressure in incompressible flows. They should also be able to solve problems governed by the full incompressible Navier-Stokes equations and master:

- the projection method, including the different ways of coupling the velocity and pressure field (SIMPLE, SIMPLEC, SIMPLER, PISO),

- the different ways to stabilize the pressure (Brezzi-Babuska condition),

- staggered grid approaches for finite differences and non collocated finite element methods in u-v-p formulation,

- finite volume methods based on the artificial compressibility method and Lagrangian Augmented.

They should have a basic knowledge of:

- turbulence models for incompressible solvers (with focus on k-epsilon and Large Eddy Simulation),

- multiphase models for incompressible solver (with focus on VOF).

<u>Teaching forms</u>

Formal lectures (100%)

<u>Course notes</u>

- Computational Methods for Incompressible Flows, PowerPoint slides by P. Rambaud

<u>Literature</u>

Computational methods for fluid dynamics, Ferziger, J.H.; Peric, M., 3rd Edition Springer, 2002,

<u>Evaluation</u>

Evaluation is done through a written exam trying to measure the theoretical understanding of the different techniques.

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B. EXERCISES (2.5 ECTS)

The exercises consist of short problems to illustrate the theory.

Learning outcomes

The student should be able to use a commercial code and an open source code to solve a specific problem by means of the different techniques presented in the lecture part. Modifications of the open source code written in Matlab will be required.

Teaching forms

Exercises (100%)

Course notes

- MatLab program to be modified

Literature

- Computational methods for fluid dynamics, Ferziger, J.H.; Peric, M., 3rd Edition Springer, 2002.

Evaluation

Evaluation is based on a report showing the sensibilities of the solutions and potential benefits from modifications implemented in the solvers.

COMPUTATIONAL METHODS FOR COMPRESSIBLE FLOWS (CMCF - 1.5 to 4.0 ECTS)

H. DECONINCK
T. MAGIN

This course consists of lectures (1.5 ECTS) and exercises (2.5 ECTS). Students may choose to attend only the lectures. This is a specialized course oriented towards the development of new advanced algorithms and software for compressible flow with application to both aeronautics and turbomachines. The student is supposed to have completed the NMFD1 and NMFD2 courses before starting this one.

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A. LECTURES 1.5 ECTS

Learning outcomes

A successful completion of this course requests that the student has an in-depth knowledge of the modern explicit and implicit Finite-Difference, Finite Volume and Finite Element techniques for the solution of compressible Euler and Navier-Stokes equations, including:

- Finite Volume methods on structured and unstructured grids,

- the mixed fourth/second order artificial diffusion scheme of Jameson, Schmidt and Turkel,

- upwind schemes based on Godunov's method (Riemann solvers), including Flux Difference (Roe, Liu) and Flux Vector Splitting (Steger-Warming, van Leer) schemes,

- second order high resolution TVD and LED schemes combined with central and upwind discretization based on MUSCL reconstruction, flux limiting using classical limiters,

- multidimensional upwind Residual Distribution methods on unstructured grids,

- stabilized (continuous) Least Squares Galerkin Finite Element methods, SUPG stabilization, shock capturing stabilization,

- basics of Discontinuous Galerkin Finite Element methods for compressible flow and the link with Finite Volume Methods,

- explicit time integration based on multi-stage schemes,

- implicit time integration methods, Newton and quasi-Newton methods combined with iterative solvers including relaxation methods (SGS), multigrid methods, Krylov subspace methods.

Specificities of external flows (airfoils) and internal flows (nozzles, turbo-machinery cascades) should be understood.

Teaching forms

Tutorials 100%

Course notes

- Computational Methods for Compressible Flow, H. Deconinck, VKI-CN 147

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Literature

- Finite Volume Methods for Hyperbolic Problems, Randall J LeVeque, Cambridge University press

- Numerical Methods for Conservation Laws (Paperback), Randall J. LeVeque, Birkhauser

- Numerical Computation of Internal and External Flows, Ch. Hirsch, Butterworth-Heinemann

- Riemann Solvers and Numerical Methods for Fluid Dynamics: A Practical Introduction, Eleuterio F. Toro, Springer

Evaluation

The evaluation is based on an oral exam with questions verifying the theoretical knowledge, and the explanation of an original paper from literature (given to the students a few days before the exam). Weight is 2/3 for the oral questions and 1/3 for the literature paper.

B. EXERCISE - PROJECT 2.5 ECTS

For a CFD course at this advanced level it is essential to be able to convert the theory into a working computer code. Students with a good background (e.g. programming experience in a previous master thesis) can be allowed to skip this part. This is evaluated at the beginning of the year when the course program is defined.

Learning outcomes

Completing the programming exercise serves two purposes: first, it completes the process of mastering the theory because understanding a CFD algorithm in all its facets can only be obtained by programming and testing the method in a working program. For example, use of memory, speed of the algorithms, complexity of programming (e.g. implicit versus explicit) are important elements which the student will acquire through the programming exercise. Second, the principles of incremental programming and debugging will be acquired by students who are inexperienced in programming. This experience is then further developed in the master project.

Teaching forms

Exercises 100%

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Course notes

Not applicable

Literature

See theory

TWO-DIMENSIONAL BOUNDARY LAYERS (2DBL – 4.0 ECTS)
G. DEGREZ

This is the basic boundary layer course for AR students.

Learning objectives

At the end of this course, the student should have a good knowledge of the different boundary layer concepts together with the equations and master the solution techniques for incompressible and compressible boundary layers. In particular he/she should:

- know the Blasius' solution for flat plate flow, Falkner-Skan self-similar flows,

- understand the influence of pressure gradient,

- know the criteria for instability and transition (Orr-Sommerfeld equation, initial instability and growth of 3D perturbations, turbulent spots; by-pass mechanisms, receptivity) for laminar boundary layers,

- have a physical understanding of the turbulent boundary layers, know the Reynolds-averaged turbulent boundary layer equations and turbulence models,

- understand the concept of integral methods and the effect of boundary layers on outer flowviscous/inviscid interaction.

Course notes

- Laminar Boundary Layers, G. Degrez, VKI-CN 143

- 2D Boundary layers – Transition and turbulent Flows, G. Degrez, VKI-CN 143 Part

  II, (Draft)

Literature

- Modeling & Computation of Boundary-Layer Flows: Laminar, Turbulent &

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- Transitional Boundary Layers in Incompressible Flows. Solutions Manual &
- Computer Programs, Cebeci, T. & Cousteix, J., Springer, 1st edition, June 15, 2001.

Evaluation

Evaluation is based on 3 homework assignments and a written exam. The homework (weight 9/20) intends to verify if the students are able to apply the knowledge presented in the course. The written exam (weight 11/20) has 2 parts: closed book (6/20) to verify the knowledge related aspects, and open book (5/20) is a further evaluation of the student's competence to apply that knowledge.

BOUNDARY LAYERS AND FLOW SEPARATION IN THREE DIMENSIONS

(3DBL - 1.25 ECTS)
G. DEGREZ

The aim of this optional course is to provide a deep insight into the specificities of three-dimensional boundary layers, i.e. the impact of cross flows, how they occur on flat plates with parabolic free stream and in flows over sheared wings (infinite swept wings). It is complementary to the course on 2D boundary layers.

Learning objectives

At the end of this course the student should have a good understanding of the boundary layer equations in surface-oriented coordinate systems, the nature of integral equations and singular points. He should also have clear insight into flow separation, the corresponding streamlines and skin friction lines, the critical points, the topological rules and their evolution with parameters, the dynamical constraints of flow patterns and vortical structures. He should be able to interpret results of 3D transonic flow calculations and surface flow visualizations.

Course notes

- Three Dimensional Boundary Layers and Separation, G. Degrez, VKI-CN 154

Literature

Bibliography listed in VKI-CN 154

Evaluation

Evaluation is based on a written exam. A closed book part (weight 10/20) verifies the knowledge-related topics; the open book part verifies the student's capacity to apply that knowledge to practical cases (weight 10/20).

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LOW SPEED WIND TUNNELS ANALYSIS AND DESIGN (WTAD - 1 ECTS)
B. BOTTIN

This course focuses on the different aspects of subsonic wind tunnel design i.e. industrial requirements, configuration types, sizing and geometrical and performance requirements.

Learning objectives

The objective is to make the student aware of the different non-dimensional parameters that are important in wind tunnel testing. He/she should know the different aspects of open and closed tunnels of conventional, pressurized and cryogenic operation, their power requirements and the parameters that affect the Reynolds and Mach numbers. He/she should be able to specify/select individual wind tunnel components, such as test section, diffusers, fan, corner vanes, wide angle diffusers, settling chamber, screens and honeycombs, contraction and heat exchangers. He/she should be capable of estimating the impact of design options on power and turbulence reduction requirements.

Course notes

- From Subsonic to Supersonic Wind Tunnels: Similarity Laws, Tunnel Types and Components

- Design Considerations, B. Bottin, VKI CN 151.

Literature

Bibliography in VKI-CN 151

Evaluation

The evaluation consists of an individual design of a new wind tunnel (open book), followed by an oral interview. Justification of the selected design options is the major evaluation criterion.

INTRODUCTION TO GROUND TESTING FACILITIES LECTURE SERIES
(IGT – 1.25 ECTS)
FACULTY, O. CHAZOT (coordinator)

The course, dedicated for both numerical and experimental options, consists of lectures (80%) and “hands-on” laboratory sessions (20%). It provides a general understanding of the design, operation and application of ground testing facilities from all speed regimes. Experimental methodology is exposed as well as the

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interpretation of the data and their extrapolation to a real situation. The course includes an on-site presentation of the VKI facilities during a lab visit.

Learning outcomes

At the end of this course students should have a good knowledge of the different ground testing facilities available for fluid dynamic research at all speed regimes. He/she should be able to select the appropriate ground testing environment to study a given experimental problem. He/she should be able to understand its operation and its limitations, be able to carry out the data interpretation and the corresponding flight extrapolation.

Teaching forms

Formal lectures 15 h

Lab sessions 3 h

Lecturers

Profs. O. Chazot, (course coordinator), T. Arts, B. Bottin, J.M. Buchlin, M. Carbonaro, C. Schram, J. Vanbeeck.

Course notes

Lecture series folder with courses notes and slides.

Literature

References in the course notes

Evaluation

The evaluation is done by an oral closed book exam.

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LECTURE SERIES 2015-2016

1. Introduction to Measurement Techniques

   05-09 October 2015

2. Introduction to Ground Testing Facilities

   03-05 November 2015

3. Progress in Simulation, Control and Reduction of Ventilation Noise

   16-19 November 2015

4. Space debris reentry and mitigation (VKI/STO-AVT-262)

   30 November – 4 December 2015

5. Introduction to Computational Fluid Dynamics

   25-29 January 2016

6. Electric Propulsion Systems : from recent research developments to industrial space applications (VKI/STO-AVT-263)

   1-5 February 2016

7. Large Eddy Simulation

   9-13 May 2016

8. Introduction to Optimization and Multidisciplinary Design

   23-27 May 2016

9. Liquid Fragmentation in Gas Flow: Theoretical & Experimental Approach

   13-17 June 2016

10. Measurement, Simulation and Control of Subsonic and Supersonic Jet Noise

    29-30 September 2016

NOTE: The dates and events mentioned above are subject to change; please consult the VKI website for the latest information.

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VKI FACILITIES, INSTRUMENTATION AND COMPUTATIONAL AIDS

The information contained in the brochure entitled "Von Karman Institute, Test Facilities and Technical Support", 50^{TH} anniversary edition 2006 is updated and summarized here below:

MAIN FACILITIES

Low Speed Wind Tunnel L-1A: An open-jet test facility for aeronautical and industrial research and development. Test section diameter 3 m, length 4.5 m; velocity up to 60 m/s (Mach number 0.2).

Low Speed Wind Engineering Facility L-1B: A closed test section wind tunnel of 3 m x 2 m section. The length of the test section of 15m allows simulation of atmospheric boundary layers, for studies of urban microclimates and pollutant dispersal, and wind effects on buildings and structures. A special test section is available for model studies of vehicle aerodynamics. Velocity from 1 to 50 m/sec.

Low Speed Wind Tunnel L-2A: A small size, open circuit, multipurpose facility for the study of aircraft and capsule wakes, aerofoils, junction flows, jet interactions and vortical flows; section 0.28 m x 0.28 m, velocity up to 45 m/s, turbulence level 0.2%.

Low Speed Wind Tunnel L-2B: A moderate size, open circuit, multipurpose facility for the study of low speed flows: aeroelasticity, turbulence, unsteady flows, wind effects on buildings and structures, urban microclimate and pollutant dispersal, car aerodynamics. Velocity up to 30 m/s, section 0.38 m x 0.38 m equipped with moving ground belt.

Low Speed Wind Tunnels L-7 and L7+: Two small, low cost, portable, low speed facilities, specially designed for student training in lab. Section 0.16 m x 0.16 m, velocity up to 20 m/s, turbulence level 0.2%; and 0.27 m x 0.36 m, 16 m/s, 0,5%.

Low Speed Wind Tunnels L-10 and L-12: Two small, low cost, portable, low speed facilities, using L-7 design, especially devoted to student training. Section 0.2 m x 0.2 m, velocity up to 15 m/s, turbulence level 0.3%.

Low Speed Wind Tunnels L-11: A small, low cost, portable, low speed facility, similar to L-10, recently rebuilt to allow injection of water droplets to study particles-turbulence interactions, as well as slag entrapment in a 2D-cold flow model of a solid propellant rocket engine with submerged nozzle. Section 0.2 m x 0.2 m, velocity up to 15 m/s.

Low Speed Wind Tunnel for study of impinging jets : A duplication of the L-10 wind tunnel, adapted to accommodate an array of nozzles (perforated plate) to create air jets impinging on a heated plate. Infrared Thermography measurements, flow rate between 0.1 and 0.25 m^3/s.

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Myrrha Basic sEt-up for Liquid fLow Experiments - MyrrhaBelle : A water-scaled model of the primary circuit allows high-resolution flow field and temperature characterization for forced, mixed and natural convection regimes.

SHaking Apparatus for Kinetic Experiments of Sloshing Project with EArthquake REproduction - ShakeSpeare: A 3D sloshing table allows the investigation on the consequences of liquid sloshing due to seismic activity on the different internal structures of the MYRRHA reactor.

Ultrasonic Imaging System–Taupe: Due to the opaque nature of the liquid metal coolant, ultrasonic imaging systems can be useful to help the fuel loading process in the reactor pool and inspect the internal structures to ensure safe and proper operation of the reactor. Within this objective, the VKI has started the development of a method for the reconstruction of images based on the signal delivered by ultrasonic transducers. An experimental investigation will also start on the effect of thermal and velocity gradient on the propagation of ultrasonic waves.

Cryogenic Facilities: The laboratory is composed by two main facilities. A large multipurpose facility, the “CryoLine,” which allows the characterization of cryogenic valves and the study of cryogenic water hammer and chill-down phenomena. A fully customized cryostat, certified for microgravity conditions,“CryME” for the characterization of cryogenic sloshing, boiling and thermal stratification on earth and in microgravity conditions.

Cold Wind Tunnel CWT-1: A thermally insulated low speed facility designed for the study and aerodynamic certification of aircraft de/anti-icing fluids, and the impact of ice crystals and droplets on aircrafts and wind turbine blades. Possible cooling down to -40°C by liquid nitrogen sprays. Presently used at ambient temperature for general studies. Section 0.1 m x 0.3 m with 1.6 m length, optical access, maximum speed 75 m/s. The wind tunnel is equipped with injection points for water droplets that freeze depending on operating conditions and droplet size.

Adaptive Wall Wind Tunnel T'3: A small, cryogenic, pressurizable, adaptive wall wind tunnel, on loan from ONERA to VKI. Presently run in non-cryogenic mode, for wall interference-free aerofoil testing, at Reynolds numbers from 2×10^5 to 1×10^6. Test section 0.1 m x 0.12 m, speed up to 80 m/s.

Supersonic Wind Tunnel S-1: Continuous flow facility with low stagnation pressure for fundamental and applied research on aircraft/missile/shell shapes in transonic and supersonic regimes. Recently improved for transonic airfoil testing. Mach numbers from 0.4 to 1.0 and 2.25 in a 0.36 m x 0.4 m test section. Reynolds number 1×10^6/m. Equipped with a schlieren/shadowgraph imaging system, and a high accuracy Laser Doppler Velocimetry traversing table. Incorporates as an option a turbine blade cascade test section, located in the first corner, for low Reynolds number and high subsonic Mach number testing.

Supersonic Wind Tunnel S-4: High stagnation pressure intermittent facility for basic and applied research. Mach number 3.5 in an 80 mm x 100 mm test section, with a

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schlieren/shadowgraph imaging system, and PIV capability. Reynolds number to 1 x 10^8/m.

Hypersonic Tunnel H-3: High stagnation pressure blow-down facility for studies of boundary layer heat transfer, separation and transition, shock wave boundary layer interaction, simulation of ablation, aerodynamic loads. Mach number 6 in a 120mm diameter free jet, with a schlieren/shadowgraph imaging system, and infrared measurements capability. Reynolds number from 3 x 106/m to 30 x 106/m.

Hypersonic "Longshot" Tunnel: Very high stagnation pressure, short duration high Mach number facility for studies of laminar and turbulent heat transfer, transition, static and dynamic stability, flow fields around bodies and forces/moments measurements. Mach number 14 to 20 in a 250 mm diameter free jet, with a schlieren/shadowgraph imaging system. Reynolds number 3 x 107/m at Mach 15. Operation with nitrogen (? = 1.41) or CO2 (? = 1.33), for Earth and Mars entry simulation.

The "Minitorch": A small, 15 KW, inductively heated plasma jet facility for instrumentation studies and training. Frequency of induction heating 27 MHz, jet diameter 30 mm, discharging in a 300 mm diameter, 1.2 m long test section, where pressure can be varied from 30 mbar to atmospheric. By addition of a Laval nozzle, a supersonic plasma jet (Ma = 2.2) can be obtained. Argon, air or other gases (CO_2) can be used. Particles addition for simulation of dusty Mars atmosphere, and model pre-cooling to simulate Mars entry initial conditions. Recently added capability of simulation of Titan atmosphere radiation for the Huygens entry.

The "Plasmatron": A high enthalpy facility generating an argon, air or CO_2 plasma jet in a vacuum test section. The plasma is generated by electrical induction heating at 400 kHz, 2 kV, 8 kA to yield better purity than arcjets. Electrical supply power 1.2 MW (most powerful ICP in the world). Jet diameter is 80 or 160 mm, plasma temperatures up to 8.000°K, test chamber pressure from 1 to 200 mbar. Application to space re-entry materials testing, as well as to fundamental studies on plasma flow dynamics.

Water Tunnel WT-1: Continuous closed loop facility using water for flow visualization over small models. PIV and LDV measurements are also possible. Section 0.12 m x 0.24 m, length 0.9 m, full optical access, velocity up to 0,15 m/s.

Water Tables: Two free surface water tables (1.4 m x 0.9 m, and 3 m x 0.8 m) using the hydraulic analogy for the visualization of 2-D internal and external sub-critical (Froude number less than 1) and super-critical flows (Froude number from 1 to 4).

Water Spray Test Facility WS-1: A facility for tests of water nozzles and study of interactions between single and multiple sprays and surrounding gas for pollutant abatement. Equipped with a 1 l/s, 8 bar pump and a 3 m x 4 m water collecting pool. Also used to study the infra-red radiation shielding properties of a water spray curtain.

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Wind Gallery WG-1: A specially designed very low speed wind tunnel for the investigation of dispersion of gases and absorption by water curtains: ejector driven, equipped with liquid drainage, 1 m x 1,3 m test section, 11 m long, speed V < 4m/s. Optional addition of rough floor for simulation of atmospheric flows.

Plate Galvanization Simulation Facility "Essor": Consists of a water bath through which a 0.9m wide rubber belt is drawn, to simulate a steel strip coated with liquid zinc. Equipped with an air knife to study control of residual film thickness. Belt velocity up to 4 m/s (presently disassembled).

Jet-Wiping Facility “Ondule”: Facility for the study of plane jet wiping of surfaces covered with viscous liquids, using a rotating transparent cylinder dipping in liquid bath, and wiped by a turbulent plane jet generated by a 2-D slot nozzle. Equipped to allow optical non-intrusive measurements of liquid film characteristics.

Multi-Jet Cooling Facility “Drever”: Facility for the study of fast metal strips cooling in galvanizing plants, using planar jets (more than 50 different nozzles), at velocities up to 100 m/s. Also used for metal strip vibrations studies.

Continuous Casting Simulation Facilities "Vulcain & Pluton": Water-based facilities for the study of continuous casting of steel. Simulation of flow in the mould (1/2 scale) and in the ladle and tundish above it (1/4 scale). Full optical access for flow visualization and non-intrusive measurements.

High-Speed Train Simulation Facility: A crossbow launcher facility used to propel train models at high speed on steel wires, to study pressure fluctuations at entrance of tunnels and underground stations. Train tunnel at 1/87 scale, tunnel length 6m, train velocity up to 150 km/h.

Aeroacoustics Facility “Acous”: For the study of coherent structures in shear layers, and of noise generation, with application to aircraft turbojet engines. Consists of 40mm and 20mm diameter steel nozzles, supplied by air ejectors through acoustically damped 0.5m x 0.5m x 2m settling chambers, and mounted inside a 4m x 3m x 3m acoustically insulated room. Fitted with loudspeakers for acoustic jets excitation. Jets velocity up to 75 m/s.

Solid Propulsion Facility "Booster": A cold flow model of a solid propellant rocket motor combustion chamber, used to study the aeroacoustics instabilities, which lead to pressure and thrust fluctuations. Axisymmetric 76 mm-diameter test section with porous walls for radial injection of cold air, in turn feeding interchangeable nozzles fitted with moveable needle to vary the throat area. Air flow rates up to 0.3 kg/s.

Biological Flows Facility "Bio": Transparent scaled-up model of human lung bifurcations, using water-glycerol mixtures to simulate respiratory flows, specially designed for non-intrusive optical diagnostics.

Low Speed Cascade Tunnel C-1: Continuous facility for the study of flows in low speed turbomachinery blading. Section 120 mm x 500 mm, velocity up to 100 m/s, blade Reynolds number from $5x10^4$ to $8x10^5$.

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<u>High Speed Cascade Tunnel C-3</u>: Intermittent facility for the study of flows in subsonic, transonic and supersonic blade cascades up to Mach 2.2. Test sections of 100 mm x 250 mm, or 200 mm x 400 mm for large subsonic model testing, inlet angle continuously adjustable. Test durations up to 10 minutes.

<u>Jet Calibration facility C-4</u>: Vertical jet axis used to calibrate directional probes in the transonic domain, benefiting from the same 40 bar air supply system as the C3 facility. Calibration nozzle outlet diameter is 50 mm. The accuracy in the angle calibration is better than +/- 0.5 deg. Test duration up to 10 minutes.

<u>Shock Tube ST-2</u>: small shock tube from Snecma (groupe Safran) installed at the VKI for frequency response characterization of pressure transducers and lines. Length 8000 mm, diameter 100 mm, operating pressure 2 bar.

<u>Compression Tube CT-2</u>: Short duration hot compressible flow facility for studying heat transfer and film cooling effectiveness on turbine blades. Stagnation pressure and temperature ranging respectively between 0.1 to 5 bar and 300 to 600°K; flow duration 0.1 to 1.0 sec; test section 100mm x 200mm.

<u>Compression Tube Turbine Facility CT-3</u>: Short duration facility for testing full scale advanced high-pressure cooled nozzle guide vanes, blade rows and complete1 and ½ stages of transonic turbines. Full simulation of Mach and Re numbers and temperature ratios; maximum outer diameter: 800 mm, maximum power: 2-3 MW. .Equipped with opto-electronic data transmission system to allow unsteady measurements on the rotating frame.

<u>Internal Cooling Channels LC1, LC2, LC3</u>: Steady state or short duration test sections simulating a turbine cooling passage. Test section 50 mm x 50 mm and 100 mm x 100 mm; velocities up to 15 m/s; provision for wall surface (20 … 60°C) or flow heating (20 … 60°C).

<u>Rotating Channel Facility RC-1</u>: Facility to perform aero-thermal studies of low Reynolds number flows in ducts in presence of strong Coriolis forces, wall roughness and heat transfer. For application to micro gas turbines and HP turbines cooling channels. Consists of a 2.5 m diameter rotating disk, up to 160 RPM, fitted with a transparent channel and optical measurement technique (time-resolved PIV).

<u>Low Speed Compressor Facility R-1</u>: Open-loop continuous facility for the study of rotating stall and flow distortions in axial compressors. 50 KW motor, rotor tip diameter 700mm, blade height 75mm.

<u>High Speed Compressor Facility R-2</u>: Open loop continuous facility for testing axial flow compressor stages. 185 KW motor, 10000 rpm, rotor diameter up to 50mm.

<u>High Speed Compressor Facility R-4</u>: Closed loop continuous facility for testing axial and radial compressor stages. 500 KW motor, 25000 max rpm, axial rotor diameter up to 400mm. It has been refurbished and is now being equipped with a booster test section.

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Low Speed Turbine Facility T-1: Open loop continuous facility for low speed flow studies in turbine stators, single stage rotors, and 1½ stages. Maximum air supply of 7 m3/s at 16 kPa.

QB50 Satellite Lab: Laboratory consists of a 25sqm satellite integration room used to assemble and test nanosatellites and a satellite ground station allowing to control satellites from VKI and operates the QB50 mission.

Bleve and Boilover ExperimentaL setup – BABELs: This facility has been designed to perform small scale hazardous experiments like fires or explosions in a secure environment. The facility consists of a cylindrical chamber of 2m diameter, and 3m high, with round-shaped flanges, and made out of steel with a rated pressure of 0.5MPa. The setup has 3 series of 7 optical accesses of 0.15m in diameter separated by 90 degrees and an elliptical door of 0.57m x 0.77m. The setup allows air venting through openings in its bottom and upper parts, the last one being ended by an exhaust vent that can be used after each test to remove smoke or gas from the chamber. The setup also includes a ladder, and a circumferential walking area is located at mid-height for better accessibility to the upper optical accesses.

NanoLab: The laboratory is composed of two main facilities: a cleanroom (2.5m² and a height of 2m designed to work either as an ISO Class 5 cleanroom or as an ISO Class 4 containment enclosure and a MBraun glovebox (internal dimensions 1950(W)x780(D)x900(H) (mm) and can be operated at over or under pressure: 15 to +15 mbarg) and one instrument: Thermal Analyzer STA 449 F3 Jupiter from Netzsch.

INSTRUMENTATION

Pulsed and CW Lasers: A number of He-Ne continuous lasers are available (power range from 1 to 35 mW). Four continuous Argon lasers, with power up to 5 W, are also available for visualisations, Laser Doppler Velocimetry, Rainbow Interferometry, Particle Image Velocimetry and Doppler Global Velocimetry. Three mini-YAG, for Particle Image Velocimetry, producing double pulses of 10 ns duration with spacing as low as 200 ns, at repetition frequency of 10 Hz and output energy ranging between 150 and 180 mJoule. One of these lasers can emit in the UV range as well as in the visible range. Two old Nd-YAG lasers with energy of 150 to 400 mJ are also available. A fourth mini-YAG is part of a micro-PIV system.

Laser Doppler Velocimetry: Five complete optical systems for LDV measurements are available: three modular multipurpose systems, a TSI two-component dual color backscatter system, and two phase Doppler analysers (PDA) measuring particle size (from 1µm to 10mm) and velocity. Various accessories such as Bragg cells or beam expanders may be added to the modular optics. Five period counters are available for the Doppler signal processing. One of these accepts Doppler frequencies up to 200 MHz, and the four others operate in a range of 10 kHz to 20 MHz. The PDA have a range of 1 kHz to 30 MHz. The TSI LDV is equipped with an IFA processor working in the frequency domain.

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Several traversing tables are available for use with these LDV systems. Four of them are motorised and allow displacements along three axes. Among these, a traversing table is fully computer-controlled. Airflow seeding systems include four oil-smoke generators together with a pressurized Laskin's nozzle system and several atomizers for aerosol generation.

Particle Image Velocimetry: Over the past twenty years a large number of developments in this domain have been made at the VKI. Several home-made systems are available. The three Nd-Yag pulsed lasers described above are available for PIV. Three PCO cameras are used for PIV. They have a resolution of 1280X1024, a 12-bit output and are capable of a time interval of 200 ns between the grabbing of the two images. Each camera is associated with a frame grabber installed on a PC computer. The PCO cameras can be combined for stereoscopic measurements. PIV processing is mostly performed using the VKI-developed software WIDIM, but another processing technique also developed at VKI, the Particle Tracking Velocimetry or PTV is also available for multiphase flows. A micro-PIV system that includes a mini-YAG laser connected to a microscope through a fiber optics and a PIV camera is also available. It is used to measure single or two-phase flows in channels ranging from 25 micrometer to 2 mm.

Hot Wire Anemometers: More than 20 VKI-designed and constructed systems are available, some including a linearizer, and some without, but with a signal conditioning filter/amplifier for data acquisition. A commercial state-of-the-art 4-channel hot wire anemometry system was very recently purchased.

Microcomputers/Acquisition: More than 20 PC's equipped with multichannel analog and digital interface boards, with 12 bit resolution and acquisition frequencies ranging from 4 KHz to 1 MHz. A 96 channel, multiplexed, 100 KHz A/D 12 bit converter, PC based data acquisition system is available for the Plasmatron. Four 8-channel, 1 MHz systems are available in the TU department.

Transient Recorders: Two 32-channel non-multiplexed systems are available for the Longshot facility which may be used individually or in tandem; controlled by a PC; 50 kHz sampling rate per channel. Three additional systems for the CT2/CT3 lab, also PC-controlled, have respectively a channel capacity, max sampling frequency and memory depth per channel of: 32 channels at 1 MHz/ch 16 bits, 64 channels at 300 kHz/ch and 64 k; 8 channels at 1 MHz/ch and 256 k; 48 channels at 50 kHz/ch and 128k.

Infrared radiometer system: 2 infrared cameras, operating in the 8 to 12 µm and in the 8 to 9 µm wavelength range, for remote, non-intrusive surface temperature mapping.

Optical pressure measurements: A UV light source, optical bench and calibration set-up for pressure sensitive paints. Compact UV light sources are now available for installation in facilities. Improved paints and a 12-bit video camera are also available.

Image Acquisition and Processing: A number of video cameras, recorders and PC video acquistion/processing boards are available for use in optical/visualization

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experiments. A high speed camera with variable framing rate up to 100 kHz is also available for recording of transient phenomena.

Emission Spectrometer System: A spectrograph with a focal length of 1m equipped with 2 gratings (1200 gr/mm with spectral range 400-1200 nm and 3600 gr/mm with spectral range 150-450 nm) and with a LN2-cooled array of CCD detectors (800 x 2000 pixels) is available for the Plasma Facilities. Commercial software allows performing data acquisition and part of the processing on line. A new compact, fast-sample spectrometer that covers the spectral range from 200 to 900 nm provides complementary capability for temporally resolved measurements at lower spectral resolution. Two new compact, fast-sample spectrometers that cover the spectral range from 200 to 900 nm provide complementary capability for temporally resolved measurements at lower spectral resolution.

Laser Spectroscopy Optical Laboratory: A third Nd:YAG laser is used to pump a high spectral resolution, tunable dye laser for spectroscopic experiments. This laser is also equipped with frequency tripling to obtain UV radiation for single-photon excitation of molecular species and multi-photon excitation of atomic species. Dedicated instrumentation includes fast digital oscilloscopes and a multi-channel, gated integrator detection system and a small flow reactor for calibration of fluorescence signals to allow absolute species concentration measurements.

VKI COMPUTER CENTER

The IT infrastructure in VKI consists of a wired gigabit and a fast wireless network (802.11 b/g/n) connecting four high performance clusters, desktop workstations, and network resources like dedicated file servers, web servers, CAD hardware, printers, scanners, security cameras, access control systems, environmental sensors and so on.

The VKI local area network is connected via optical fiber to its internet service provider, Belnet, the high bandwidth Belgian national research network managed by the Federal Office for Science Policy, via a leased line provided by the Proximus Company.

IT Infrastructure

The wired network has a backbone made of fully gigabit Ethernet-compliant HP Procurve switches and CAT6 cabling between buildings and main network resources. The switches are trunked (via LACP) together for increased bandwidth and link resilience. LACP trunking insure bandwidth in excess of 2 Gbit/s between all the important nodes (file servers, database servers, virtualization hosts), with a reduced speed of 100 Mbit/s for non essential edge network clients.

A wireless network consisting of two VLANS, one for the visitors (using a captive portal for authentication), one for the authenticated users (using 802.1x) offers a complete coverage in essential areas, thanks to seven access points directly connected to the network backbone. 802.1x authentication is being deployed for ethernet connections as well for increased security and manageability.

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Important data is stored in central servers that are the object of incremental backups every night, for a capacity of over 30 TBs. This data is protected in addition by physical protections against hardware failure including RAID5/6 (depending from the server) configurations with hot spares.

CAD resources consist of several Windows and GNU/Linux workstations with 19" or 21” monitors, digitizing tablets and two HP plotters (a B/W and a photo quality color) for A0 paper format.

Licenses control and monitoring is provided to check licenses availability to users and housekeeping.

Workstations and User PC's

Many workstations are publicly available for designated purposes: over 25 GNU/Linux workstations offer ample development capacity for students and researchers to prepare their simulations for the HPC clusters or to process their experimental data. These machines are accessible as well from laptops via remote connection (cli:ssh/graphicts:X2go). The hardware ranges from baseline P4s, to Dual Opterons and Intel Octacores, all running a 64bit OS and with an average of 2GB RAM for core.

Dedicated workstations assigned to users (researchers and PhDs) are around fifty, and range from P4s to Dual Intel Xeon Octacores with 196GB of RAM for heavy meshing and simulations.

The total number of workstations located in offices, labs and public rooms is around 200. Normal productivity stations offer the Microsoft branded OS and office productivity suite, and will be more and more based on a thinclient-server architecture to reduce costs and reduce environmental footprint reducing electrical comsumption.

Parallel Computer Platforms

The main High Performance Computing (HPC) platform for students and researchers, often the first contact with the HPC world, is a BEOWULF, Ethernet-based parallel computer. Commodity workstations, connected via gigabit Ethernet, run under a 64bit GNU/Linux OS using the ROCKS software stack for node provisioning and the SGE Sun Grid Engine queuing system for jobs management. Currently, it counts around 200 cores and 0.4 TB of RAM. The hardware is heterogeneous, it counts Intel dual and quad cores for main parallel jobs.

A second, denser HPC rack mounted cluster from SGI with 48 processors (including three rack-mounted units with four Intel Xeon quads each) connected via infiniband has been bought, using a financing from LMSintl, to run aeroacoustic simulations.

The last generation HPC solution is provided by a 512-cores, 1TB RAM and 12TBs storage infiniband blade cluster used for massively parallel jobs of great scientific interest and scale. This cluster is reserved to advanced research and studies.

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The state-of-the-art HPC solution is provided by a 1792-cores, 7.2TB RAM and 72TBs storage infiniband (FDR) blade cluster used for massively parallel jobs of great scientific interest and even bigger scale than the ones allowed by the last generation cluster. This cluster is reserved for advanced research and studies.

Software

VKI researchers and students have access to dedicated commercial scientific computing packages (e.g. Matlab, Mathcad, Tecplot, EcoSimPro, C/C++ and Fortan compilers) and to a series of commercial and open source CFD solvers (such as Fluent, CFX, Fine, OpenFOAM, CFD++). A number of in-house developed CFD codes are used for dedicated applications in optimization, plasma flows, aeronautics, turbomachinery, multiphase flow, turbulence modeling, large eddy simulation and aeroacoustics, exploiting the parallel computing capacity without licenses restrictions. Access to Computer Aided Design (CAD) is available in various services and in public rooms, by means of Autodesk INVENTOR running under a network license for 30 concurrent users.

Internet

The VKI maintains a highly visible web site (http://www.vki.ac.be), which contains detailed information about the VKI's educational programs (including Lecture Series), laboratories, ongoing research and noteworthy events. An SSL/VPN-OpenVPN service is installed to provide secure access to the VKI network for VKI personnel needing to remotely connect through Internet.

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