

Research Master in Fluid Dynamics

Course Syllabus and Regulations

Academic Year 2026–2027

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Part I

Introduction

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

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

The educational and research programs of VKI are organized into three main areas of specialization corresponding to the three departments of VKI:

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

VKI operates a comprehensive range of experimental and computational facilities covering virtually all aspects of the above fields. Necessary support is provided by the facilities and test setup service, test engineers, electronic and instrumentation laboratories, a a technical library, a design office and well-equipped workshops, and an IT and computer sciences center.

One of the main educational programs offered by VKI is the one-year postgraduate "Research Master in Fluid Dynamics" at advanced master level (formerly called "VKI Diploma Course"). Approximately thirty-five engineers and scientists drawn from the 15 countries that financially support VKI 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 faculty members, research experts and research engineers. The individual research projects may be experimental, theoretical, or computational in nature. The VKI Research Master in Fluid Dynamics Course complements the teaching programs of universities.

This syllabus presents pertinent information regarding the VKI Research Master (RM) in Fluid Dynamics. First, admission, diploma requirements and regulations are reviewed. Subsequently, 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.

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

Part II

Academic Regulations and Program Structure

CHAPTER 1

Regulations of the Research Master Program

This section describes the regulations concerning admission, educational organization, evaluation processes, diploma requirements, and the relationship between staff and students.

1.1 Admission Requirements

Admission to the VKI Research Master program is decided by the faculty of the department in which the student wishes to continue their studies. The admission requirements are:

- A five-year engineering or science degree (e.g., 3-year B.Sc. + 2-year M.Sc.),
- A working knowledge of English. Students who did not obtain their degree from a university with lectures in English must provide proof of English proficiency,
- Endorsement by an STO National Delegate, initiated by VKI,
- Recommendations by 3 professors from a university where the candidate has studied previously.

No tuition fee is required for students from countries that finance VKI.

1.2 Research Master Program

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

Each student will select one of the following areas of specialization, corresponding with the three VKI departments:

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

The course work and individual research project are defined during the first meeting of the student with the faculty of the department of their choice. A minimum total study load of 60.0 ECTS is required (30.0 ECTS for the course work and 30.0 ECTS for the individual research project).

1.2.1 Course work

Course 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 their 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 of the academic year. Later changes are possible only in function of the project evolution and with the agreement of the faculty supervisor and corresponding head of department.

A detailed schedule of courses and laboratory sessions will be announced in the MS Teams Calendar "Course Schedule".

Students who have a job can spread the program over two years. In such case, the yearly program is defined in agreement with the Faculty considering the other (professional) activities of the student. They must satisfy all requirements in terms of evaluation teams and public presentations.

1.2.2 Research project

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, theoretical approach, or experimental technique. A list of projects is published at the start of the academic year. A final selection by the student must be made by mid-October.

A faculty member will be designated as faculty supervisor. In most cases, the faculty supervisor will be assisted by a research supervisor (post-doctoral researcher, PhD candidate, (senior) research engineer, research expert) 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 engineers, 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 faculty supervisor is also responsible for the establishment of the Project Evaluation Team (PET) within the first month of the academic 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.

1.3 Research Master Evaluation

1.3.1 Course work evaluation

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 consider the other workload of students and professors.

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

An examiner who, for circumstances beyond their control, cannot give the exam, will inform the dean or head of department immediately and define a new timetable in common agreement with the students and examiner involved.

If an examiner does not appear within 30 minutes after the set time, the student(s) should immediately inform the dean or head of department who will schedule a new time, giving priority to the preferences of the student(s).

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.

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. Grades are represented over 100 using a 3-digit system. This involves expressing the grade to 1 decimal place, for example, 80.0 instead of just 80. Within 2 weeks after the exam (4 weeks for courses with more than 1 examiner), the grades must be communicated to the student(s) by the VKI secretariat, who will store them in a safe place for at least 5 years.

Grades of less than 50.0% are considered unsatisfactory and a repeat exam will be organized within four weeks of the publication of the initial results. This possibility to repeat an exam replaces the exams that are traditionally organized in September at a university. At this repeat exam, a maximum mark of 60.0% can be awarded. If the repeat exam consists of different parts with different examiners, the 50.0% passing rule and the 60.0% maximum mark rule apply to the global results.

Oral exams are always organized with the presence of a third person in addition to the main course examiner. The copies of the written exam can be consulted after being corrected for a period of 5 days. 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. Upon failure of a repeat exam, further participation of the RM program will require assessment by the faculty and be decided on a case by case to terminate the RM Program or continue only for the research project.

1.3.2 Master Thesis evaluation

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

addresses key non-technical subjects required for scientific and R&D related professional practice and provides lectures and exercises in presenting, scientific writing, data management, leadership, and project management. It is within this course module, that the concept of peer reviewing is practiced in the RM program.

At the **end of the first trimester, each student will go through a first status review of their research project with the Project Evaluation Team (PET).** For each research project a specific PET is set up with the student's supervisor, further faculty members and advisors working in the field of the project. **A week before the PET meeting, the student submits a research proposal**, which details the literature review and scientific gap, work packages, the timeline in a Gantt chart and an initial risk assessment with potential mitigations. During the PET meeting, the student will present their understanding of the problem and the proposed solution method which is substantiated by the literature search and supported by the project planning. A detailed discussion with the PET members will help the student to ensure that the proposed solution approach is realistic and that the pathway to a successful conclusion has been defined. In addition, the student will receive a research proposal review report from one randomly assigned peer. The feedback from the PET and from the peers will help the student to create the final version of the project planning report which is due one week after the PET. This report will be evaluated by assigned faculty members from the PET and forms the basis for the **"Research Proposal report grade"** (3 ECTS).

At the end of the second trimester, a second PET review will take place. The student will prepare thoroughly an update of their project in terms of solution methodology and advancement, results obtained, deviations from original plan due to issues encountered, accompanied with an updated Gantt Chart, risk assessment, and an outlook to the remainder of the project. The project update needs to be provided three working days before the PET review. A thorough appraisal of the student's progress including recommendations for future work will be provided at this point. The faculty members of the PET **evaluate project quality, management and execution** achieved up to this phase of the research project (5 ECTS). The evaluation of the updated project planning report will become part of this grade.

A **first public presentation of 15 minutes duration and 5 minutes discussion is made towards the end of March** to gain practice in the art of public speaking. The presentation will be evaluated with 1.0 ECTS by the faculty. Two randomly assigned student peers will provide a structured peer evaluation highlighting strong elements and possible suggestions for further improvement in public speaking. The evaluation of the presentation is based on the instructions and criteria discussed in the PRM lecture "Presenting".

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, and this version is graded by at least 2 PET members. The report comprises three parts: editorial notes, a scientific draft paper, and a comprehensive appendix. All parts with all chapters must be included, but updates to incorporate last minute data or calculations can be made before graduation day.

The **scientific draft paper** highlights the research work accomplished in the format of a typical journal paper. The purpose of the **appendix** is to provide all the information necessary to repeat the experiments and calculations to reproduce the same results. Therefore, it must include a full description of the data obtained, hardware or software developed during the stay at VKI, if any, and its use. In particular, mechanical drawings of hardware should be provided, 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. The **editorial notes** provide a link between the contents of the scientific draft paper and the appendix by giving background information which is typically not described in a journal paper.

A **detailed final presentation of the project to PET will be made in mid-June**, followed by a detailed and comprehensive evaluation of the work by the PET members. As a result of the final evaluation session, team members can propose optional or mandatory changes to any of the three parts of the report. The latter concerns the language and organization of the text, missing information, or further explanations, and must be carried out before graduation day. The PET faculty members will assign a grade for project quality, management, and execution (10 ECTS). A second **public presentation** of 20 minutes duration followed by 10 minutes for questions and discussions will be made **in late June**. The public presentation is the basis for the evaluation (5 ECTS) of the overall achievement of the project by the faculty members.

The PET grades and faculty grades are given as follows and summarized in the overview table below:

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

   Report grade: after reading the report (the draft paper, editorial notes, and the appendix), a minimum of 2 reviewers (must be members of the PET) and the supervisor will give an individual report grade. The average of these grades (called report grade) counts for 10 ECTS of the project grade. 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 report.

   PET project quality, management and execution grade: At the end of the Project Evaluation Team (PET) meeting in which the project is presented and discussed in detail, the PET will issue another contributor to the PET project grade, which counts for 10 ECTS. This grade is established through a well-defined grading grid along specific predefined criteria. The grade is obtained by averaging the individual evaluation of the faculty members present at the PET meeting. A dedicated form must be filled out and signed by all PET members. It is the responsibility of the faculty members to also consider the opinions of the nonfaculty members of the PET.

2. Faculty project grade given by faculty members, who were not part of the student's project evaluation team:

   In the **public presentation**, the student will present their project results to a larger audience which includes attendants who have not followed the course

of the student's project. This situation resembles a conference presentation to a professional audience or a scientific evaluation jury. Faculty members who have not been following and supporting the work as PET members before will be asked to evaluate the overall project achievement with a weight of 5 ECTS in the project grade against the criteria of the presentation clarity, structure and style as well as the scientific content.

The final grade for the PRM course (4.0 ECTS) will be established as an average of the Research Proposal grade (3.0 ECTS), and the mid-term presentation grade (1.0 ECTS). The total project grade (30 ECTS) will be derived from the report grade with 10 ECTS, the project quality, management, and execution grade of the PET scoring for 5 ECTS at the end of the mid-term and for another 10 ECTS in June plus a faculty evaluated project achievement grade scoring for 5 ECTS.

Summary table of grading Project and PRM course		**PRM grade (ECTS)**	**Project grade (ECTS)**
Research Proposal	Report graded by PET readers and peers	3	
Midterm PET meeting	Project quality, management & execution (graded by PET)		5
Midterm Public Presentation	Presentation (graded by peers and faculty members)	1	
Final PET Meeting	Project Report (graded by minimum 2 readers of PET)		10
	Project quality, management & execution (graded by PET)		10
Final Public Presentation	Project achievement including presentation (graded by all faculty members)		5
	Total ECTS	4	**30**

Table 1.1: Summary of grading for PRM course and Master Thesis project

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 led 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.

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.

1.3.3 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 grade given to the student by the examiner, or the

academic judgement embodied in a decision of the Project Evaluation Team, cannot be the object of a complaint; only procedural irregularities in how the exam, course, or evaluation was conducted can be complained about. 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 Section 2.8, Ombudspersons) will examine the complaint together with the official student representative(s) 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).

1.3.4 Diploma Requirements

The diploma will be awarded by decision of the Jury to the student who

1. Obtained a grade of 50.0% or higher in each course of their study program,

2. Obtained an average result of 60.0% or more in the course work,

3. Obtained an average result of 60.0% or more for the research project (30.0 ECTS),

4. Obtained 30.0 ECTS or more on the course work,

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 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 agrees 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. 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.

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.

The secretariat provides the detailed results of all the exams and Master Thesis evaluations and the average 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 average results of 80.0% 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 faculty 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 register of diplomas by the Flemish Government 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, they can call for a new meeting of the jury to reconsider the decision. The latter will be officially communicated to the student.

1.3.5 Awards

In order to encourage excellence, 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.
- Prize for Excellence in Machine Learning techniques applied to Fluid Dynamics.
- 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, which decided by the RM members during a secret vote organized in collaboration with the Alumni Association during the period May - June.

Both the diploma and the prizes are handed out to the students during the VKI diploma ceremony which is organized on the last Friday morning of the academic year (end June, early July).

1.4 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 their 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.

1.5 Academic authorities

The following authorities and bodies are involved either in the direction, delivery, or oversight of the Institute's academic programmes.

- **Managing Director:** Mr. Peter Grognard, Managing Director since February 2018, is responsible for the Institute's overall management, including institutional development, international relations, and business development.
- **Dean of the Faculty:** Prof. Jeroen van Beeck, Dean of the Faculty since 2018, holds primary academic responsibility for the Institute's educational programs, including the design, coherence, and quality of the course curriculum, the award of the VKI Diploma/Research Master degree, and academic decisions concerning the student body. Prof. van Beeck also serves as Head of the Environmental and Applied Fluid Dynamics Department.
- **Heads of Department:** Course units and research projects within each area of specialisation are supervised under the academic responsibility of the respective Head of Department:
  - **Aeronautics and Aerospace Department** — Prof. Olivier Chazot
  - **Environmental and Applied Fluid Dynamics Department** — Prof. Jeroen van Beeck (also Dean of the Faculty)
  - **Turbomachinery and Propulsion Department** — Prof. Tom Verstraete
- **Faculty** Beyond department leadership, teaching and research supervision are carried out by the wider VKI Faculty, supported by research experts, with recognised expertise in their respective fields. The complete list of the VKI faculty is provided in Appendix 9.
- **Educational committee** 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 educational committee is composed of the all the faculty members, the members of the

project office involved in the teaching, the secretariat, and the class representatives. The educational committee meets once a year.

- **The Scientific Advisory Committee (SAC)**, composed of senior professors and heads of large research centers, 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 SAC 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.

- **External Accreditation Authority** 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 2027-2028 included (prolongation approved in 2021). 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).

1.6 Quality Assurance

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

Furthermore, the quality of the RM program is monitored both internally and by external organizations. Students must evaluate each course via a survey sent by the secretariat. During a yearly educational committee meeting, the evaluations are reviewed, and actions are formulated to aim at continuously improving the quality of the program.

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.

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. The educational committee meets once a year, because already in the Faculty meetings all academic items are discussed monthly.

1.7 Use of generative AI in course work

Generative AI and large language models such as ChatGPT are advancing rapidly, and their use is growing across every field of human activity. Generative AI can yield substantial benefits, but careless use also carries a real risk of harm – for example through breaches of confidentiality, plagiarism, or reliance on inaccurate output. In the RM course, the use of generative AI is generally allowed, but all use must adhere to the following principles:

1. **Authorship and accountability.** The author remains fully responsible and accountable for the content produced, and must adhere to all applicable policies, laws, rules, and guidelines (e.g. IP rights, data security, personal privacy, compliance with IT and communication rules). ChatGPT or other generative AI tools can take neither authorship nor responsibility for the work.

2. **Confidentiality.** The use of AI on sensitive data, topics, or projects covered by a non-disclosure agreement is explicitly forbidden. When in doubt, consult your supervisor.

3. **Attribution.** In any original student text, such as reports, articles, or course deliverables, the use of generative AI must be indicated and specified (topic and purpose), following the template in Section 1.7.1. When in doubt, declare your usage: over-reporting is never a problem, under-reporting is.

4. **Originality.** To prevent copyright infringement, the output of LLM tools such as ChatGPT must never be copied and pasted into original work; it must be reformulated in the author's own words and critically checked, not merely paraphrased.

5. Paraphrasing someone else's published text with AI and presenting it as your own is not allowed and is considered plagiarism.

6. **Verification.** LLMs can provide false or unethical information. The user is responsible for verifying the accuracy and compliance of any AI-assisted content.

7. **Exams.** Unless explicitly allowed by the course instructor, the use of generative AI tools is forbidden in written and oral exams.

Failure to comply with these guidelines will be investigated according to the Fraud and Plagiarism procedure defined in Section 1.4.

1.7.1 Template for declaring AI usage in reports and deliverables

Select the appropriate bold sentences and include them in your deliverable in a dedicated subsection.

The content in this deliverable is my own (unless otherwise specified) and generative AI has only been used in accordance with the VKI guidelines. I have reviewed and edited the content as needed and take full responsibility for the content of this deliverable. (this statement is mandatory)

Insert either option 1 or option 2 at the end of your deliverable. Replace *GenAI* by the appropriate tool used: ChatGPT, Gemini, Claude, ...

1. **I did not use generative AI assistance tools during the research and writing process of this deliverable, except for minor language assistance.**[1]
2. **I used generative AI assistance tools during the research and writing process of this deliverable. More specifically:**
    - *GenAI* **was used as a search engine to explore a particular topic.** If yes, specify further.
    - *GenAI* **was used to support my literature overview.** If yes, specify further.
    - *GenAI* **was used to generate code.** If yes, specify further.
    - *GenAI* **was used to generate visuals.** If yes, specify further.
    - *GenAI* **was used to generate research ideas.** If yes, specify further.
    - ... (any other usage)

[1] Minor language assistance is defined as post-processing of self-written text, proofreading, feedback on structure, etc.

CHAPTER 2

Resources and services related to the Research Master Program

2.1 International student exchange and liaison office

The office is involved in supporting students throughout their journey at the Institute. They handle applications, manage the administrative steps required for their arrival, coordinate with IT, the library, and reception to ensure a smooth welcome, and assist them with practical matters such as accommodation, registration at the local commune, health insurance, public transportation, or tax declarations. For Research Master's students, the office also supports the setup of their program and organization of key moments such as their first day and graduation ceremony. The office accompanies students, answers questions, solves problems, and tries to be a reliable point of reference.

2.2 Class Representatives

The VKI encourages students to select class representatives, one from each of the three academic departments, to facilitate the planning of social activities (particularly those taking place at the VKI or under the sponsorship of the VKI), to organize peer group activities, 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.

- The class representatives work as a team to represent the interests of the class and to foster team building, mutual trust and support in the class.
- Also, the class representatives are the go-to person for any issues of members of their class section. They coordinate educational activities such as the peer-to-peer evaluation of the literature survey.
- The class representatives are members of the Educational Committee giving the opportunity to contribute to policies which may improve the educational system of the Research Master.
- The class representatives report to the Dean, the Heads of Department and the Ombudsperson. Specifically, the class representatives are encouraged to discuss department-related problems (e.g. relating to specific course and project work) with the respective Head of Department in a day-to-day fashion.

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

2.3 Sport and Leisure facilities

The von Karman Institute allows to play different sport activities during the breaks with a basketball and volleyball field, as well as two table tennis tables.

During the year, several activities are also dedicated to promote the strong collaborative spirit, distinctive of VKI. During the first week, the beer and cheese evening allows the research master to get to know each other, but also VKI and Belgium through a quizz, also played by the VKI faculty and project office. The VKI St-Eloi allows to engage in fun activities in the morning such as walk, run, bike, chess, darts, petanque, as well as the famous VKI challenge. The activities are followed by a nice lunch shared by VKI as a whole. Finally, the research master celebrates their graduation during a ceremony on the last Friday of June (or 1st Friday of July), allowing them to celebrate the hard work of the year, followed by a family barbecue on the Friday evening.

2.4 Badge and presence on VKI site

When on site, the Phd candidates are obliged to badge for security reasons. This badging is not linked to the time-sheet system. In order to record your arrival or departure, you must read-in your badge at the entrance to one of the following buildings:

- Building A
- Building B
- Building D
- Workshop
- Computer Center

All students have a strictly personal badge that must be used to record each time the candidate enters or leaves the site. The data collected are confidential and can only be accessed by the HR department and by IT staff in case of a technical problem. The collected data is stored for a period of 5 years. If the student has forgotten your badge, he/she must request a temporary one-day badge from the Library. With this temporary badge she/he will need to record her/his presence as soon as possible.

Students may also have access to their desk or to the computer center during evenings, weekends, or other holiday periods. For safety reasons, students are not allowed to work in the laboratories outside normal working hours. Furthermore, all safety instructions given by the VKI Chief Operating Officer and the faculty member with expertise in Laboratory Safety must be rigorously respected. Under no circumstances are students authorized to operate large facilities or noise-producing facilities outside normal working hours.

2.5 Financial Aspects

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



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. Information on tuition fees applicable to citizens of other countries can be obtained by contacting the Secretariat of VKI (secretariat@vki.ac.be).

2.6 Learning facilities

2.6.1 Experimental facilities

The von Karman Institute for Fluid Dynamics operates one of the most extensive and technically diverse sets of experimental facilities among fluid dynamics research centers worldwide, with around fifty wind tunnels and test rigs supporting both its research and its academic programs.

Its high-speed wind tunnel portfolio spans transonic and supersonic testing up to hypersonic regimes. The S-1 facility is a continuous closed-circuit transonic/supersonic tunnel driven by a 615 kW axial compressor, offering interchangeable test sections that reach Mach 2.25 and a variable-Mach transonic section, but that can also study turbine flows at transonic conditions, and the aerothermal characterization of heat exchangers at Mach 0.1-0.6. The H-3 facility is one of only a handful of European wind tunnels capable of replicating the aerothermal environment experienced by launchers, re-entry vehicles, and space debris, while the Long-Shot free-piston tunnel reaches Mach 14 for the study of hypersonic flight conditions.

Among the low-speed wind tunnels, L-1 is the Institute's largest, with a 3-metre-diameter, 4.5-metre-long open-jet test section driven by contra-rotating fans on a 580 kW motor, covering velocities from 2 to 60 m/s at low turbulence. Originally built for aircraft model testing, it has since been adapted with interchangeable inserts for a wide range of applications — from cyclist and road-vehicle aerodynamics to wind-turbine and street-furniture testing.

For entry and re-entry research, VKI's plasma facilities are a distinguishing asset, most notably the 1.2 MW Plasmatron — an inductively coupled plasma wind tunnel used to reproduce the boundary-layer heating a spacecraft encounters during atmospheric entry, supporting thermal-protection-material testing and space-debris demise studies.

The turbomachinery facilities include CT-3, the world's largest isentropic light-piston compression tube, which uses a piston driven by high-pressure air to generate short, engine-representative flow pulses through a research turbine stage, allowing Reynolds and Mach numbers to be matched independently to real aero-engine conditions. Its smaller counterpart, CT-2, operates on the same isentropic-compression principle — a lightweight piston driven down a pressurized cylinder

to heat and accelerate the gas ahead of it — but feeds a two-dimensional linear cascade rather than a full annular turbine stage, making it well suited to detailed aerothermal studies of individual compressor or turbine vane and blade profiles under matched engine-representative Mach, Reynolds, and gas-to-wall temperature ratios. Alongside these, R-4 is a high-speed, closed-loop compressor test rig — pressurizable from vacuum to 3 bar and driven by a 500 kW motor up to 25,000 rpm — used to study axial and radial compressor performance across a range of simulated flight conditions.

Beyond these signature facilities, VKI also maintains water tunnels and two-phase flow rigs, icing wind tunnels, aeroacoustics chambers, cryogenics and seismic testing facilities, and industrial test rigs. Together, these facilities allow VKI to cover an unusually wide range of flow regimes — from low-speed aerodynamics to hypersonic and plasma flows — within a single research and teaching institution.

A more comprehensive list of the facilities can be found in the brochure entitled "Von Karman Institute, Test Facilities and Technical Support" (50th anniversary edition, 2006).

2.6.2 VKI Computer Center

The IT infrastructure at VKI consists of a wired Gigabit Ethernet network and a wireless network (802.11 b/g/n) connecting a high-performance computing cluster, high-end workstations, desktop computers, and network resources such as dedicated file servers, web servers, CAD hardware, printers, scanners, security cameras, access-control systems, environmental sensors, and other devices.

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, through a leased line provided by Proximus.

2.6.2.1 IT Infrastructure

The wired network has a backbone consisting of fully 10-Gigabit or 1-Gigabit Ethernet-compliant HP ProCurve switches and CAT6/CAT6A cabling between buildings and the main network resources. The switches are trunked together using LACP to provide increased bandwidth and link resilience. Depending on the link, LACP trunking provides aggregate bandwidth in excess of 30 Gbps between important nodes, such as file servers, database servers, and virtualization hosts, with reduced aggregate speeds of approximately 3–4 Gbps at the network edges and down to 100 Mbit/s for non-essential edge-network clients.

The wireless network consists of two VLANs and multiple SSIDs: one for visitors, using a captive portal for authentication, and several for authenticated users, using 802.1X. It provides coverage throughout the essential areas, laboratories, and other locations through more than 30 access points directly connected to the network backbone. Students have dedicated SSIDs, including Eduroam and networks for undergraduate and graduate students, although they are encouraged to use wired connectivity in their study rooms.

802.1X authentication is also being progressively deployed for Ethernet connections throughout the premises in order to improve security and manageability. The first deployment uses captive-portal-based authentication in the RM and Stag

Rooms.

Important data is stored on central servers and is backed up incrementally every night, or every other night depending on the system, with an overall storage capacity of several hundred terabytes.

Individual high-end workstations can also be equipped with hundreds of terabytes of local storage. Until late 2025, storage prices remained sufficiently competitive for such configurations to be economically viable.

In addition to backups, data is protected against hardware failures through redundant storage configurations. These include RAID5 or RAID6, depending on the server, generally with hot spares, and, in more recent systems, ZFS RAIDZ1 or RAIDZ2 configurations.

CAD resources consist of several Windows and GNU/Linux workstations equipped with HiDPI monitors and digitizing tablets, together with two HP plotters: one black-and-white and one photo-quality colour plotter, both supporting A0 paper format.

License-control and monitoring systems are used to provide users with information about software-license availability and to facilitate license management and housekeeping.

2.6.2.2 Workstations and User PCs

Many workstations are publicly available for designated purposes. More than 20 freely accessible GNU/Linux workstations provide substantial development capacity for students and researchers to prepare simulations for the HPC clusters or to process experimental data.

These machines can also be accessed remotely from laptops and other computers using command-line SSH or graphical remote-access solutions such as NoMachine and ThinLinc.

The hardware of these public machines ranges from AMD Ryzen 7 5700X systems with 8 cores and 16 threads to AMD EPYC 9554P systems with 64 cores and 128 threads. Some machines are equipped with conventional graphics cards for visualization, while others include data-center-class GPUs such as the NVIDIA A2000 with 12 GB of VRAM, allowing users to become familiar with CUDA and GPU programming.

Dedicated "private" workstations assigned to selected users, including researchers and PhD students, number approximately one hundred. Their hardware ranges from low-end desktop systems to dual-socket AMD Turin EPYC 9555 workstations, with 64 cores and 128 threads per processor, as well as several dual-socket AMD EPYC 9654 systems with 96 cores and 192 threads per processor.

The total number of workstations located in offices, laboratories, and public rooms is approximately 200–250.

Standard productivity workstations are equipped with the Microsoft Windows operating system and Microsoft Office productivity software.

2.6.2.3 GPU Computing

Although GPU computing is not yet essential for all workloads, it is becoming increasingly commonplace. Multiple machines are equipped with data-center-class

GPUs such as the NVIDIA A100 with 40 or 80 GB of memory, as well as NVIDIA H200 GPUs.

Public computers in the `gpulinX` series are equipped with NVIDIA A2000 GPUs with 12 GB of VRAM, providing an accessible platform for users who want to get started with GPU computing.

Multi-GPU configurations, both homogeneous and heterogeneous, are also available. AMD Instinct data-center-class GPUs are available for testing and development as well.

2.6.2.4 Parallel Computer Platforms

The Frankenstein in-house cluster at VKI is a high-performance computing cluster that entered service in the second half of 2019. It was initially based on AMD Naples EPYC 7551 processors and was designed to support computationally intensive workloads, particularly CFD calculations.

At the current stage, the cluster is equipped with 22 blades, including:

- 6 nodes with dual AMD Naples EPYC 7551 processors, each with 32 cores and 64 threads, and 1 TB of RAM distributed across 32 DIMMs running at 2133 MHz and using 8 memory channels;
- 14 nodes with dual AMD Rome EPYC 7742 processors, each with 64 cores and 128 threads, and 1 TB of RAM distributed across 32 DIMMs running at 3200 MHz and using 8 memory channels;
- 2 nodes with dual AMD Rome EPYC 7763 processors, each with 64 cores and 128 threads, and 1 TB of RAM distributed across 32 DIMMs running at 3200 MHz and using 8 memory channels;

Dual-rail InfiniBand connectivity is used for MPI communications between the compute nodes. Each rail uses 4× EDR InfiniBand, with a theoretical maximum link speed of 100 Gbps per EDR link.

2.7 Diversity and Inclusion

VKI appreciates the importance of an inclusive community that is not only free from discrimination but is also able and willing to do more - in other words, a community perceiving differences as an ethical value and a valuable resource that can yield positive benefits. VKI is committed to promote the diversity of our community (staff and students), fostering a culture of respect and providing equality, fairness and inclusion for everyone, no matter his/her background, characteristics or preferences.

Therefore, the VKI has developped a Gender Equality, Diversity and Inclusion Plan (GEP). The GEP of the von Karman Institute for Fluid Dynamics is a document with which the Institute aims to implement actions and projects to reduce gender inequalities and to enhance diversity with regards, for example, to age, culture, physical ability, sexual orientation, multilingualism, etc. This document is available both on the VKI public website and intranet.

The Gender and Diversity Working Group oversees the implementation of the VKI GEP Actions. This group involves researchers, students and staff members interested in reflecting and managing actions. Prof. Delphine Laboureur has been

elected Gender and Diversity Officer. The officer oversees equality, gender and diversity policies. She / he ensures the harmonization, clarification, and fairness of management practices within the institution. She / he develops the institutional policy of equal opportunity at work in partnership with the relevant services. She / he supervises the "Gender and Diversity" working group. Alice Fischer has been elected gender and diversity representative for the Postdoc and PhD community. Every year, a gender and diversity representative for the research master is also elected, simultaneously with the class representatives. She/he will support the committee in the implementation of the gender equality plan by providing the point of view of the research master community.

Capacity-building trainings offered to RM students include harassment awareness, the gender dimension in research, one soft-skills session grouped with the PhD symposium, and an RM survey and discussion session.

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

The ombudspersons can intervene in all educational matters to solve problems of a more personal nature. 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.

2.9 Confidential Counselor

A confidential counselor is a legally defined function within an organization or institution. It is a neutral, designated contact person whom employees or students can turn to for support regarding psychosocial problems, conflicts, or unacceptable behavior. The three confidential counselors available at VKI are announced *ad valvas*, and can be addressed in English, French or Dutch. Similar to the ombudsperson, the counselor will respect the confidentiality of all conversations with the person seeking support. The counselor should be contacted for all problems that put the psychological well-being within the institute at risk. Help can be provided though different forms, going from providing a listening ear, to more formal actions such as interventions with a third party. This always requires the agreement of the requester, and has as sole purpose to resolve problems and conflicts. The confidential counselor can be reached by direct contact, but also at safe@vki.ac.be, or anonymously through the mailbox in the VKI canteen.

Part III

Course Program 2026-2027

CHAPTER 3

Overview of the Course Program 2026-2027

The course program for each student is defined through discussions with department members and the faculty supervisor and must include a minimum of 30 ECTS. Of these, 12 ECTS are assigned to a series of mandatory common courses designed to provide a solid foundation in the core areas of fluid dynamics research and project management.

The distribution of the common mandatory courses accross the whole RM programme, together with the general and optional courses for each department is illustrated in Figure 3.1.

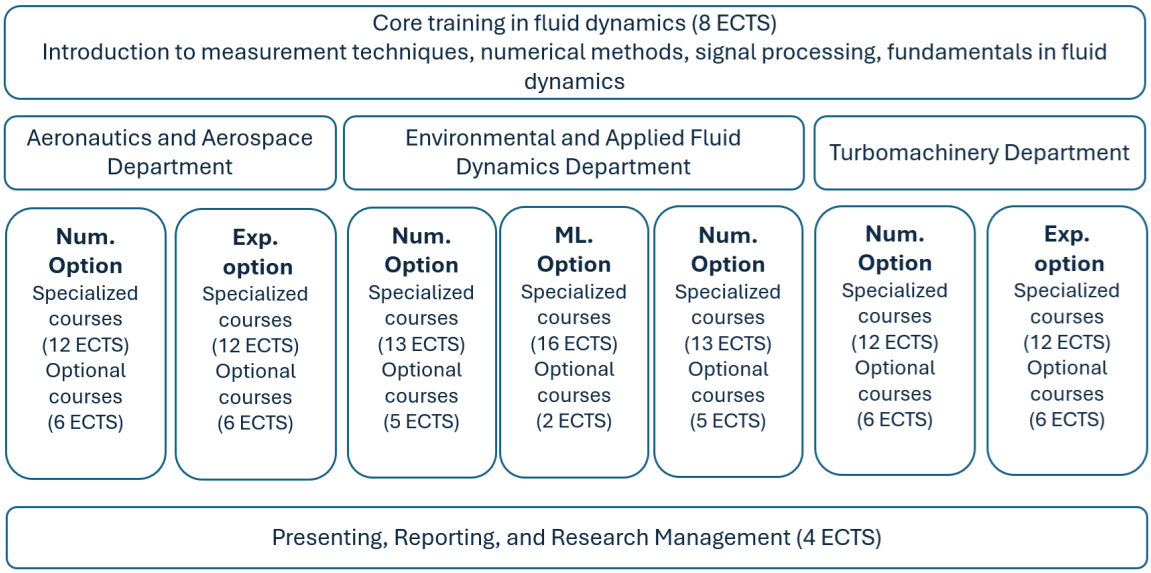


Figure 3.1: Course program overview with number of ECTS per departments

In addition to the core "pillar courses", each department will offer specialized activities such as numerical simulations, experimental laboratories, and design exercises. These activities provide students with the opportunity to apply and test their acquired knowledge in the context of the department's specific research domains. The overview of the full course program, i.e. the mandatory common, and departmental and specialization specific and optional courses are explained in full detail in chapters 4 to 6.

CHAPTER 4

Common Mandatory Courses

The course program includes a minimum of 30 ECTS of coursework. Of these, 12 ECTS consist of common courses which provide foundation in fluid dynamic research and project management. These are mandatory to all students and are described in this section. Other general courses that can be selected as optional courses are described in chapter 6.

Abbreviation	**Course title**	**Lecturers/ Coordinator**	**ECTS**		
			EXP	**NUM**	**ML**
FFD	Fundamentals of Fluid Dynamics	Faculty (M. A. Mendez coordinator)	3	3	3
IMT	Introduction to Measurement Techniques in Fluid Dynamics LS	Faculty (F. Fontaneto & D. Laboureur coordinator)	2	2	2
INM	Introduction to Numerical Methods	P. Schrooyen	1.5	1.5	1.5
SP	Signal Processing	C. Schram & M. A. Mendez	1.5	1.5	1.5
PRM	Project Mgt.: Presenting, Reporting and Research Management	Faculty (C. Schram & D. Laboureur coordinator)	4	4	4
TOTAL			**12**	**12**	**12**

Table 4.1: General courses required for all specializations and departments, mandatory for all Research Master students.

4.1 FUNDAMENTALS OF FLUID DYNAMICS (FFD – 3.0 ECTS)

Lecturers: M.A. Mendez (coordinator), O. Chazot, G. Degrez, D. Laboureur

This course reviews the fundamentals of a broad spectrum of fluid dynamics topics, starting from first principles and building toward more advanced concepts. We begin with the derivation of conservation laws in both integral and differential forms, followed by constitutive laws and flow kinematics. We then explore classical models of fluid flows—such as incompressible, inviscid, and Stokes flows—and study dimensionless analysis, similarity, and scaling laws. Building from the fundamentals, the course then progresses toward more advanced topics, including boundary layers, compressible flows, vorticity and potential flows, special forms of the energy equation, wave propagation in fluids, and the use of eigenfunctions for analyzing linear stability problems. Students will gain a solid understanding of the laws governing fluid dynamics, their engineering applications, their range of validity, mathematical properties, scaling behavior, and the influence of boundary conditions. By the end of the course, students will also have a broad overview of specialized topics in fluid dynamics and will be equipped to effectively formulate and tackle problems of research interest.

Teaching forms: Formal lectures 70%, hands-on exercises 30%.

Learning Outcomes: By the end of the course, students will be able to derive and interpret the governing equations of fluid motion, apply simplified flow models and scaling arguments, and analyze key fluid phenomena such as boundary layers, compressibility effects, stability and vorticity. They will also develop the ability to assess the validity and applicability of different models in research and engineering contexts.

Course notes and Literature

- Course Slides provided by the Lecturers.
- A Review of the Differential Equations of Fluid Dynamics, J.M. Buchlin, VKI-CN 195.
- P. Kundu, I. Cohen, D. R. Dowling, *Fluid Mechanics*, Sixth Edition, Elsevier, 2012.
- Bird R., Stewart, W., Lightfoot, E.N., *Transport Phenomena*, Wiley, 2005.
- F. White, *Fluid Mechanics*, 8th Edition, McGraw Hill, 2015.

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.

4.2 INTRODUCTION TO MEASUREMENT TECHNIQUES (IMT – 2.0 ECTS)

Lecturers: F. Fontaneto & D. Laboureur (coordinators), M. Mendez, O. Chazot, C. Schram, J. van Beeck, G. Grossir

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. The course content is framed such that it will provide students a good knowledge of the different experimental techniques available for fluid dynamic research, but also to enable them to select the appropriate measurement technique (Pressure probes and transducers, temperature measurements including infrared thermography, laser velocimetry and optical density measurement techniques, hot wire anemometry, flow visualization) to solve a given experimental problem. For each technique, details about its implementation, its accuracy, and the potential correction methods will be provided.

Learning outcomes:

On successful completion of this course, students will be able to:

- Construct the measurement chain for a given fluid dynamics quantity and quantify the associated measurement uncertainty.
- Select the most appropriate measurement technique to address a given fluid dynamics experimental problem
- Analyze the dynamic response of a measurement system to a time-varying input
- Apply correction methods to unsteady pressure measurements affected by the dynamic response of the measurement system.
- Explain the principles of signal processing techniques used to extract quantitative information from raw measurement signals.
- Implement direct measurement techniques for mass flow and temperature, and two of the following specialized measurement techniques (hot-wire anemometry, image processing, PIV, laser Doppler/LIDAR velocimetry), critically evaluate their application limit, and/or estimate their accuracy.

Teaching Approaches: 21 hours in formal lectures and 8 hours in lab sessions.

Course notes and Literature Measurement Techniques in Fluid Dynamics – An Introduction, Third revised edition, VKI, 1991, 383 pgs. Introduction to Measurement Techniques, VKI, 2025, 106 pp.

Evaluation. The objectives are verified by a single open book exam organized by the course coordinators based upon the questions they receive from the other lecturers.

The 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.

4.3 INTRODUCTION TO NUMERICAL METHODS (INM – 1.5 ECTS)

Lecturers: P. Schrooyen (coordinator)

This course is the counterpart of "Introduction to Computational Fluid Dynamics", focusing more on theoretical aspects of discretization methods and solution techniques. It is mandatory for all students. The course aims to give the broad mathematical view that prepares for making good choices in numerical simulation of PDE problems

Learning outcomes: The student will know classification methods for PDE. They understand principles of well-posedness of PDE problems, and how this notion is related to proper problem formulation (e.g. boundary conditions). The student will have a good overview of the principles of discretization methods (Finite Difference, Finite Element, Finite Volume). They will understand the conceptual commonalities and differences between these methods, such as derivation from strong form (finite differences) or weak form and integral conservation laws (finite elements and finite volume). At the end of this course, the student will understand how the principles of consistency, stability, and convergence are related through the Lax-Equivalence Theorem. They will be acquainted with quantitative methods to establish stability of numerical schemes. They will know the fundamental differences between convection/propagation and diffusion in their numerical treatment and understand dispersive and diffusive error modes. The student will be familiar with basic time integration methods used with the Method of Lines approach, as well as with classic iterative solution methods for linear systems (Gauss-Seidel, SOR).

Teaching forms: Formal lectures 18h

Literature

- Course Slides and references provided by the Lecturers.

Evaluation The evaluation is done based on several individual homeworks during the course.

4.4 SIGNAL PROCESSING (SP – 1.5 ECTS)

Lecturers: C. Schram (coordinator), M. A. Mendez.

This course presents a complete overview of tools for processing and learning from data. The course covers the fundamentals of signal analysis and statistics, uncertainty quantification and time-frequency analysis, as well as filter design and multi-resolution analysis.

Learning outcomes: The student will become familiar with the main methods for data analysis, including statistical tools, time-frequency processing, uncertainty quantification and FIR/IIR filters. They will learn how to effectively use these techniques to analyze signals, understanding the requirements and the constraints that each of these methods sets on a measurement chain. The course will be supported by a set of hands-on sessions on Python, providing a complete toolbox and a practical starting point to further develop computational proficiency in data analysis. At the end of the course, the student will be able to identify the best processing strategy for a given problem and thus capable of efficiently extracting knowledge from data.

Teaching forms: Formal lectures 70%, hands-on exercises 30%.

Literature

- Course Slides provided by the Lecturers.
- Random Data Analysis and Measurement Procedures, J. S. Bendat and A.G.Piersol, Wiley and Sons, 2001.

Evaluation The evaluation is based on a homework consisting in analyzing a set of data provided to the student, in order to characterize phenomena of interest for a given physical problem (e.g. velocity fluctuations measured in a free circular jet or wall pressure fluctuations under a turbulent boundary). The homework can be conducted by groups of 2-3 students. The grade is based on the report quality (50%), and on individual interviews addressing both the theoretical concepts explained in the course and the results obtained during the homework (50%).

4.5 PRESENTING, REPORTING AND RESEARCH MANAGEMENT (PRM – 4.0 ECTS)

Lecturers: D. Laboureur, C. Schram (coordinators), M. Mendez, O. Chazot. Course work can be complemented by experts from Industry and Organizations (for example the European Patent Office or the European Commission).

Complementary to the technical course work and to the multi-faceted learning environment given by the unique diversity of nationalities and cultures at VKI, the PRM course is devoted to help students advance personal and leadership skills recognized as success-factors for making an impact in Research or Industry. In scope of the PRM course are methodologies and practices for developing Presenting, Reporting and Managing skills. The course will support the students into developing expertise in international, multicultural collaboration and teamwork, proficient project management and effective communication in writing and in presenting, embracing diversity, innovative, inclusive, and critical thinking.

Further to support the career development of the RM student, a VKI career-round table will be conducted in the middle of the second trimester jointly with invited speakers from Research and Industry organizations. The PRM course may further be complemented by seminars with external speakers on selected topics such as Leadership, Intellectual Property management, and research ethics.

- The student will learn the basics of project management: defining, planning, conducting, and risk managing research projects in an international environment.
- The course will help to strengthen communication and presentation skills for international recognition and collaboration with expert and non-expert audiences and to acquire techniques for writing high-quality scientific reports and journal articles.
- The student will further learn the basics of structured and efficient Data Management, aimed at optimizing the exploitation and future re-usability of data generated experimentally or numerically applying principles of data documentation, curation, mining, archival and long-term backup.
- Through the practice of changing role from author or presenter to reviewer in a peer-to-peer process, the student will train feedback delivery, self-reflection, and constructive criticism for mutual team-based learning.

Learning outcomes: On successful completion of this course, students will be able to:

- Formulate a research proposal that identifies a research gap based on a bibliographic survey.
- Plan a research project in an international environment, including its scientific methodology (e.g. work breakdown structure, PERT diagram) and schedule (Gantt chart).
- Assess the risks associated with a research project and develop a mitigation plan.
- Apply scientific writing conventions to produce a clear, well-structured research proposal.
- Deliver an effective oral presentation of a research plan to both expert and non-expert audiences.
- Critically review a peer's research proposal and provide constructive, actionable feedback.

Teaching forms: Class lectures, assignments and peer review exercises.

Evaluation: Each student will be asked to provide a Research Proposal prior to the December PET meeting. With a maximum length of 6 pages (following a template

that will be provided by the Faculty), this Research Proposal will include the following elements:

- bibliographic survey and identification of the research gap,
- scientific methodology (Work Breakdown Structure, Pert diagram, ...),
- Gantt chart,
- risk assessment and mitigation plan.

Guidelines on how to prepare these elements of the Research Proposal will be explained beforehand during PRM classes.

The grade on the Research Proposal will combine a grading by the Faculty members who are part of the PET. Peer evaluation by the cohort of RM students is an important component of this PRM evaluation. A student peer review session will be organized in January where all students will be asked to review the research proposal of a fellow student, during a limited time in the conference room. Guidelines on how to perform this peer-review will be provided beforehand. This peer-review will allow the student to improve his proposal, before being graded by the Faculty.

The final grade for the PRM course (4.0 ECTS) will be established as an average of the Research Proposal grade (3.0 ECTS) and the mid-term presentation grade (1.0 ECTS).

Literature

- PowerPoint slides by all teachers. Students are highly encouraged to be active in taking notes during classes and seminars.
- Project Management, Duration-Driven Planning and Control, PM Alliance, 2024
- A Guide to Presenting Technical Information Effective Graphic Communication, Matthews, Clifford, John Wiley & Sons, June 2000.
- Websites indicated on the PowerPoint slides.

CHAPTER 5

Summary tables of all specializations

This chapter provides the full list of courses for all specializations within the three departments. Details of each course are provided in the following chapters.

5.1 Aeronautics/Aerospace (AR) Department

Students specializing in Aeronautics/Aerospace take both general and optional courses. Depending on their focus, they can choose experimental or numerical paths.

General Courses in Aeronautics/Aerospace

Course Title	Acronym	ECTS
Two Dimensional Boundary Layers	2DBL	2.5
Case Study & Seminars in Aerospace	CSSA	2.0
Experimental Laboratory	ELAB-1	2.0
Numerical Laboratory 1	NLAB-1	1.5
Introduction to Ground Testing Facilities	IGT	1.0
Introduction to Machine Learning for Fluid Dynamics-1	MLFD-1	1.0

Courses Experimental Specialization

Course Title	Acronym	ECTS
Experimental Laboratory-2	ELAB-2	2.0

Courses Numerical Specialization

Course Title	Acronym	ECTS
Advanced Numerical Methods	ANM	2.0

Optional Courses in Aeronautics/Aerospace

Course Title	Acronym	ECTS
Aircraft Performance, Stability and Aerodynamics	APSA	2.0
Physics of Compressible Flows	PCF	2.0
Hypersonic Aerothermodynamics	HYP	2.0
Physico-Chemical Models for Atmospheric Entry Flow	PCMAF	2.0
Boundary Layers and Flow Separation in 3D	3DBL	1.0

Introduction to Aeroacoustics	ACOUS	2.0
Numerical Laboratory-2	NLAB-2	2.0
Icing Physics and Ice Accretion Simulation	ICING	2.0
Introduction to Turbulence	TURB	2.0
Machine Learning for Fluid Dynamics-2	MLFD-2	2.0

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. They 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.

The attendees of the Aeronautics/Aerospace program will specialize in one of the following subgroups: experimental (section 6.6), or numerical (section 6.7).

Students should take an equivalent of minimum 4 ECTS of the following optional courses, depending on the project.

Table 5.1: AR Department – Curriculum Summary

Code	Course Title	Lecturers / Coordinator	EXP	NUM
COMMON COURSES (MANDATORY)				
FFD	Fundamentals of Fluid Dynamics	Faculty (M. A. Mendez coordinator)	3.00	3.00
IMT	Intro to Measurement Techniques in Fluid Dynamics LS	Faculty (F. Fontaneto & D. Laboureur coordinators)	2.00	2.00
INM	Introduction to Numerical Methods	P. Schrooyen	1.5	1.5
SP	Signal Processing	C. Schram / M. Mendez	1.5	1.5
PRM	Presenting, Reporting and Research Management	Faculty (C. Schram & D. Laboureur coordinators)	4.00	4.00
SUBTOTAL			**12.00**	**12.00**

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Code	Course Title	Lecturers / Coordinator	EXP	NUM
SPECIALIZED COURSES – AR (MANDATORY)				
ELAB-1	Experimental Laboratory-1	Faculty (D. Laboureur coordinator)	2.00	2.00
NLAB-1	Numerical Laboratory-1	T. Magin / P. Schrooyen	1.50	1.50
2DBL	Two-Dimensional Boundary Layers	G. Degrez	2.50	2.50
CSSA	Case Study and Seminars in Aerospace	AR Faculty	2.00	2.00
ELAB-2	Experimental Laboratory-2	Faculty (D. Laboureur coordinator)	2.00	
ANM	Advanced Numerical Methods	K. Hillewaert		2.00
IGT	Introduction to Ground Testing Facilities LS	Faculty (O. Chazot coordinator)	1.00	1.00
MLFD-1	Introduction to Machine Learning for Fluid Dynamics-1	M. Mendez	1.00	1.00
SUBTOTAL			**12.00**	**12.00**
OPTIONAL COURSES – AR (minimum 6 ECTS to be selected)				
APSA	Aircraft Performance, Stability and Aerodynamics	C. Schram / B. Bottin	2.00	2.00
PCF	Physics of Compressible Flows	O. Chazot	2.00	2.00
HYP	Hypersonic Aerothermodynamics	O. Chazot / G. Grossir	2.00	2.00
PCMAF	Physico-Chemical Models for Atmospheric Entry Flow	T. Magin	2.00	2.00
NLAB-2	Numerical Lab-2	T. Magin / P. Schrooyen	2.00	2.00
3DBL	Boundary Layers and Flow Separation in 3D	G. Degrez	1.00	1.00
ACOUS	Introduction to Aeroacoustics	C. Schram	2.00	2.00
TURB	Introduction to Turbulence	W. Munters / J. van Beeck	2.00	2.00
ICING	Icing Physics and Ice Accretion Simulation	S. Ozgen / N. Coudou / J.v.Beeck (coordinator)	2.00	2.00

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Code	Course Title	Lecturers / Coordinator	EXP	NUM
MLFD-2	Machine Learning for Fluid Dynamics-2	M. Mendez	2.00	2.00
MINIMUM SUBTOTAL			**6.00**	**6.00**
GRAND TOTAL			**30.00**	**30.00**
OPTIONAL COURSES – All Departments				
AELAST	Intro to Aeroelasticity across Engrg. Applications	S. Stapelfeldt / G. Dimitriadis	2.00	2.00
ANM	Advanced Numerical Methods	K. Hillewaert	2.00	
ATMOS	Introduction to Atmospheric Flows	N. Coudou / G. Glabeke / W. Munters (coordinator)	2.00	2.00
ATP-1	Aero-Thermodynamics of Turbomachinery & Propulsion 1	TU Faculty	3.50	3.50
DDMA	Data Driven Modal Analysis	M. Mendez	1.00	1.00
DTAC	Digital Twinning, Assimilation and Control	M. Mendez	2.00	2.00
ELAB-2	Experimental Laboratory-2	Faculty (D. Laboureur coordinator)		2.00
ELAB-3	Experimental Laboratory-3	Faculty (D. Laboureur coordinator)	2.00	
MDO	Multidisciplinary Design Optimization	T. Verstraete	2.00	2.00
PRP	Introduction to Propulsion	B. Saracoglu	2.00	2.00
TSC	Tools for Scientific Computing	M. Mendez	1.00	1.00

5.2 Environmental and Applied Fluid Dynamics (EA) Department

The specialization within the Environmental and Applied Fluid Dynamics (EA) equips students with the theoretical foundations and practical tools needed to tackle complex flow problems in both natural and industrial settings. The program is strongly research-oriented and closely aligned with the cutting-edge work conducted within the department's laboratories. EA Students follow a mandatory common set of core courses before choosing one of three specializations—in experimental techniques, numerical modeling, or machine learning applications such as digital twinning and flow control. The program is closely tied to the department's research activities, providing a strong link between theory and practice.

Mandatory Courses in Environmental & Applied Fluid Dynamics

Course Title	Acronym	ECTS
Methodology of Applied Fluid Dynamics	MAFD	3.0
Industrial Design Exercise	IDE	2.0
Introduction to Turbulence	TURB	2.0
Numerical Simulation of Industrial Problems I	NSIP-1	2.0
Experimental Laboratories–1	ELAB-1	2.0

Courses - Experimental Specialization

Course Title	Acronym	ECTS
Experimental Laboratory-2	ELAB-2	2.0

Courses - Numerical Specialization

Course Title	Acronym	ECTS
Numerical Simulation of Industrial Problems 2	NSIP-2	2.0

Courses – Machine Learning Specialization

Course Title	Acronym	ECTS
Machine Learning for Fluid Dynamics-1	MLFD-1	1.0
Machine Learning for Fluid Dynamics-2	MLFD-2	2.0

Digital Twinning, Assimilation and Control	DTAC	2.0

Optional Courses in EA

Course Title	**Acronym**	**ECTS**
Introduction to Atmospheric Flows	ATMOS	2.0
Tools for Scientific Computing	TSC	1.0
Experimental Laboratory 2	ELAB-2	2.0
Experimental Laboratory 3	ELAB-3	2.0
2D boundary layers	2DBL	2.5
3D boundary layers	3DBL	1.0
Introduction to Aeroacoustics	ACOUS	2.0
Icing Physics and Ice Accretion Simulation	ICING	2.0
Digital Twinning, Assimilation and Control	DTAC	2.0
Data Driven Modal Analysis	DDMA	1.0
Machine Learning for Fluid Dynamics 1	MLFD-1	2.0
Machine Learning for Fluid Dynamics 2	MLFD-2	2.0
Advanced Numerical Methods	ANM	2.0
Introduction to Ground Testing Facilities	IGT	1.0
Introduction to Aeroelasticity	AELAST	2.0
Multidisciplinary Design Optimization	MDO	2.0

Students choosing the experimental fluid mechanics specialization gain more hands-on experience in advanced measurement techniques and flow diagnostics. As part of the specialization, they are required to take at least one additional laboratory course beyond the mandatory one, though enrolling in two more is strongly recommended to build a well-rounded experimental skillset, i.e. ELAB-1, ELAB-2, ELAB-3, each lab focussing on a different measurement technique.

The numerical fluid mechanics specialization focuses on the simulation and modeling of complex flow problems using computational methods. Students in this track are required to take the course Numerical Simulation of Industrial Problems – 2 (NSIP-2), which builds on the core numerical course and provides deeper insight into advanced simulation strategies relevant to industrial and environmental applications.

The machine learning for fluid dynamics specialization focuses on data-driven modeling and digital twinning for the modeling and control of fluid systems. Students in this track are required to take both Digital Twinning, Assimilation and Control (DTAC) and Machine Learning for Fluid Dynamics 2 (MLFD-2). The optional course "Data-Driven Modal Analysis (DDMA)" is strongly recommended, along side "Tools for Scientific Computing (TSC)" for students that do not have a solid background on Python programming. Together, these courses provide a solid foundation for applying modern AI tools to complex fluid dynamics problems.

Table 5.2: EA Department – Curriculum Summary

Code	Course Title	Lecturers / Coordinator	EXP	ML	NUM
COMMON COURSES (MANDATORY)					
FFD	Fundamentals of Fluid Dynamics	Faculty (M. A. Mendez coordinator)	3.0	3.0	3.0
IMT	Intro to Measurement Techniques in Fluid Dynamics LS	Faculty (F. Fontaneto & D. Laboureur coordinators)	2.0	2.0	2.0
INM	Introduction to Numerical Methods	P. Schrooyen	1.5	1.5	1.5
SP	Signal Processing	C. Schram / M. Mendez	1.5	1.5	1.5
PRM	Presenting, Reporting and Research Management	Faculty (C. Schram & D. Laboureur coordinators)	4.0	4.0	4.0
SUBTOTAL			**12.0**	**12.0**	**12.0**

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Code	Course Title	Lecturers / Coordinator	EXP	ML	NUM
SPECIALIZED COURSES – EA (MANDATORY)					
MAFD	Methodology of Applied Fluid Dynamics	EA Faculty	3.0	3.0	3.0
IDE	Industrial Design Exercise	EA Faculty	2.0	2.0	2.0
TURB	Introduction to Turbulence	W. Munters / J. van Beeck	2.0	2.0	2.0
MLFD-1	Machine Learning for Fluid Dynamics-1	M. Mendez		1.0	
MLFD-2	Machine Learning for Fluid Dynamics-2	M. Mendez		2.0	
NSIP-1	Numerical Simulation of Industrial Problems 1	J. van Beeck / S. Lopes / M. Faruoli	2.0	2.0	2.0
DTAC	Digital Twinning, Assimilation and Control	M. Mendez		2.0	
NSIP-2	Numerical Simulation of Industrial Problems 2	W. Munters / S. Lopes			2.0
ELAB-1	Experimental Laboratory-1	Faculty (D. Laboureur coordinator)	2.0	2.0	2.0
ELAB-2	Experimental Laboratory-2	Faculty (D. Laboureur coordinator)	2.0		
SUBTOTAL			**13.0**	**16.0**	**13.0**
OPTIONAL COURSES (min. 5, 2 for ML option)					
ATMOS	Introduction to Atmospheric Flows	N. Coudou / G. Glabeke / W. Munters	2.0	2.0	2.0
ICING	Icing Physics and Ice Accretion Simulation	S. Ozgen / N. Coudou / J.v.Beeck (coordinator)	2.0	2.0	2.0
AELAST	Intro to Aeroelasticity across Engrg. Applications	S. Stapelfeldt / G. Dimitriadis	2.0	2.0	2.0
ELAB-2	Experimental Laboratory-2	Faculty (D. Laboureur coordinator)		2.0	2.0

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Code	Course Title	Lecturers / Coordinator	EXP	ML	NUM
ELAB-3	Experimental Laboratory-3	Faculty (D. Laboureur coordinator)	2.0	2.0	
IGT	Introduction to Ground Testing Facilities	Faculty (O. Chazot coordinator)	1.0	1.0	1.0
ANM	Advanced Numerical Methods	K. Hillewaert		2.0	2.0
ACOUS	Introduction to Aeroacoustics	C. Schram	2.0	2.0	2.0
MLFD-2	Machine Learning for Fluid Dynamics-2	M. Mendez	2.0		2.0
DDMA	Data Driven Modal Analysis	M. Mendez	1.0	1.0	1.0
DTAC	Digital Twinning, Assimilation and Control	M. Mendez	2.0		2.0
TSC	Tools for Scientific Computing	M. Mendez	1.0	1.0	1.0
2DBL	Two-Dimensional Boundary Layers	G. Degrez	2.5	2.5	2.5
3DBL	Boundary Layers and Flow Separation in 3D	G. Degrez	1.0	1.0	1.0
MDO	Multidisciplinary Design Optimization	T. Verstraete	2.0	2.0	2.0
MINIMUM SUBTOTAL			**4.0**	**2.0**	**4.0**
GRAND TOTAL			**30.0**	**30.0**	**30.0**

5.3 Turbomachinery and Propulsion (TU) Department

Most of the world-wide energy conversion is realized in power plants that employ turbomachinery either as a core engine or as an auxiliary subsystem. Applications span gas turbines for aircraft propulsion, auxiliary subsystems for spacecraft and rockets, gas turbines and steam turbines for power generation, steam turbines for nuclear power, gas turbines or turbochargers for transportation on land and sea, compressors and gas turbines for pressurizing pipelines, and gas turbines, compressors, steam turbines, and expanders for processing in refineries and the wider chemical process industry, from olefin and terephthalic acid production to steel production. The Turbomachinery and Propulsion course work is designed to build a profound understanding of the underlying physics of compressible flows in turbomachinery and propulsion systems, together with the state-of-the-art experimental and numerical methods, and concurrent research directed toward a climate-neutral and sustainable future in aviation, aerospace, power generation and the chemical industry. Recently, the Innovation Lab has been added to the curriculum for pursuing technical-economic exploration of emerging energy conversion systems and disruptive technologies. The specialization in Turbomachinery and Propulsion prepares the student for a position in research and technology in academia, government or industry across the broad field of Aviation, Aerospace, Power Generation, Oil & Gas, Renewable Energy and the emerging industry of Climate-Neutral technologies.

SPECIALIZED COURSES IN TURBOMACHINERY AND PROPULSION (MANDATORY)

Course Title	Acronym	ECTS
Aero-Thermodynamics of Turbomachinery & Propulsion 1	ATP-1	3.5
Aero-Thermodynamics of Turbomachinery & Propulsion 2	ATP-2	2.5
Turbomachinery Experimental Laboratory	TULAB	3.0
Turbomachinery Numerical Laboratory	TUCFD	3.0

OPTIONAL COURSES IN TURBOMACHINERY & PROPULSION

Course Title	Acronym	ECTS
Advanced Course on Axial Compressors	AC-AC	2.0
Advanced Course on Radial Compressors	AC-RC	2.0
Advanced Course on Axial Turbine Aerodynamics	AC-AT	2.0
Introd. to Aeroelasticity across Engineering Applications	AELAST	2.0
Multidisciplinary Design Optimization	MDO	2.0
TP Tutorial: Design Exercise, CFD, or Innovation Lab	TPTUT	2.0
Introduction to Propulsion	PRP	2.0
Introduction to Aeroacoustics	ACOUS	2.0
Machine Learning for Fluid Dynamics-1	MLFD-1	1.0
Machine Learning for Fluid Dynamics-2	MLFD-2	2.0
Experimental Laboratory-1	ELAB-1	2.0

The general courses will provide for a thorough understanding of the fundamentals of turbomachinery and propulsion relating to thermodynamics, compressible flow physics, experimental and computational techniques. These courses are mandatory to all TU students.

The student will undertake a research project that is dominated by experimental research work.

The student will undertake a research project that is dominated by numerical research work. If the optional tutorial is selected, the student will select either the INNOVATION or the CFD LAB.

Table 5.3: TU Department – Curriculum Summary

Course Code	**Course Title**	**Lecturer / Coordinator**	**EXP/NUM (ECTS)**
COMMON COURSES (MANDATORY)			
FFD	Fundamentals of Fluid Dynamics	Faculty (M.A. Mendez coordinator)	3.0
IMT	Intro to Measurement Techniques in Fluid Dynamics LS	Faculty (F. Fontaneto & D. Laboureur coordinators)	2.0
INM	Introduction to Numerical Methods	P. Schrooyen	1.5
SP	Signal Processing	C. Schram / M. Mendez	1.5
PRM	Presenting, Reporting and Research Management	Faculty (C. Schram & D. Laboureur coordinators)	4.0
	SUBTOTAL		**12.0**
SPECIALIZED COURSES TU (MANDATORY)			
ATP-1	Aero-Thermodynamics of Turbomachinery & Propulsion 1	TU Faculty	3.5
ATP-2	Aero-Thermodynamics of Turbomachinery & Propulsion 2	TU Faculty	2.5
TULAB	Turbomachinery Experimental Laboratory Exercise	S. Lavagnoli, F. Fontaneto	3.0
TUCFD	Turbomachinery Numerical Lab	T. Verstraete	3.0
	SUBTOTAL		**12.0**

Course Code	Course Title	Lecturer / Coordinator	EXP/NUM (ECTS)
OPTIONAL COURSES TU (minimum 6 ECTS to be selected)			
AELAST	Intro to Aeroelasticity across Engrg. Applications	G. Dimitriadis, S. Stapelfeldt	2.0
MDO	Multidisciplinary Design Optimization	T. Verstraete	2.0
AC-AT	Advanced Course on Axial Turbine Aerodynamics	S. Lavagnoli	2.0
AC-RC	Advanced Course on Radial Compressors	T. Verstraete	2.0
AC-AC	Advanced Course on Axial Compressors	F. Fontaneto	2.0
PRP	Introduction to Propulsion	B. Saracoglu	2.0
ELAB-1	Experimental Laboratory	Faculty (D. Laboureur coordinator)	2.0
TPTUT	TP Tutorial: Design Exercise, CFD, or Innovation Lab	TU Faculty	2.0
ACOUS	Introduction to Aeroacoustics	C. Schram	2.0
MLFD-1	Machine Learning for Fluid Dynamics I	M. Mendez	1.0
MLFD-2	Machine Learning for Fluid Dynamics II	M. Mendez	2.0
	MINIMUM SUBTOTAL		**6.00**
	GRAND TOTAL		**30.00**
OPTIONAL COURSES - other departments			
ATMOS	Introduction to Atmospheric Flows	N. Coudou / G. Glabeke / W. Munters	2.0
ICING	Icing Physics and Ice Accretion Simulation	S. Ozgen / N. Coudou	2.0
IGT	Introd. to Ground Testing Facilities LS	Faculty (O. Chazot coordinator)	1.0

Course Code	Course Title	Lecturer / Coordinator	EXP/NUM (ECTS)
TURB	Introduction to Turbulence	W. Munters / J. van Beeck	2.0
TSC	Tools for Scientific Computing	M. Mendez	1.0
DDMA	Data Driven Modal Analysis	M. Mendez	1.0
DTAC	Digital Twinning, Assimilation and Control	M. Mendez	2.0
ANM	Advanced Numerical Methods	K. Hillewaert	2.0
2DBL	Two-Dimensional Boundary Layers	G. Degrez	2.5
3DBL	Boundary Layers and Flow Separation in 3 Dimensions	G. Degrez	1.0

CHAPTER 6

Description of Departmental Courses

This chapter lists, one after another and at the same level, every department-specific specialized course and every optional course of the Research Master program, covering the Aeronautics/Aerospace (AR), Environmental and Applied Fluid Dynamics (EA), and Turbomachinery and Propulsion (TU) departments, followed by the courses that are optional for all specializations. An overview of which courses belong to which department, together with the introductory text for each department, is given in chapter 5. For every course below, a short paragraph indicates the course type and whether the course is mandatory or optional, and for which department(s).

6.1 INTRODUCTION TO GROUND TESTING FACILITIES (IGT – 1.0 ECTS)

Lecturers: O. Chazot (coordinator), Ch. Schram, J.v. Beeck, T. Arts, B. Bottin, G. Grossir

Course type and status: This course is a lecture-and-laboratory course (VKI Lecture Series). It is a mandatory course for AR department students, and an optional elective for EA, TU department students.

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 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. They should be able to select the appropriate ground testing environment to study a given experimental problem. They 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: 15 hours of formal lecture and 3 hours of lab sessions

Literature

- Lecture series folder with courses notes and slides.
- References in the course notes.

Evaluation The evaluation is done by an oral closed book exam.

6.2 TWO DIMENSIONAL BOUNDARY LAYERS (2DBL – 2.5 ECTS)

Lecturer: G. Degrez

Course type and status: This course is a lecture course. It is a mandatory course for AR department students, and an optional elective for EA, TU department students.

This is the basic boundary layer course for AR students open for students from other departments.

Learning outcomes: 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 they 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 flow viscous/inviscid interaction.

Teaching Forms: Formal lectures 30 %, Coding tutorials in Python 70%

Course Notes:

1. Laminar Boundary Layers, G. Degrez, VKI-CN 143
2. 2D Boundary layers – Transition and turbulent Flows, G. Degrez, VKI-CN 143 Part II, (Draft)

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

6.3 CASE STUDIES AND SEMINARS IN AEROSPACE (CSSA – 2.0 ECTS)

Lecturers: AR faculty and research engineers

Course type and status: This course is a project-based seminar course. It is a mandatory course for AR department students.

The objective of the Case Studies in Aerospace course (CSA) is to expose students to a small project representative of the preliminary phases of large aerospace projects. To this end, the faculty will play the role of an external customer and will formulate a practical engineering problem that must be analyzed within a relatively short timeframe. Drawing on the practical and theoretical knowledge acquired throughout the aerospace curriculum, students are expected to develop a preliminary response to the customer's request. The objective is not to provide a fully detailed solution, but rather to present a detailed and convincing scientific proposal that demonstrates a sound and credible approach to addressing the problem.

The CSA topic is chosen by the student from a list of aerospace engineering topics encompassing different problems including pre-flight analysis, ground testing methodology, design of experiment, flight extrapolation or any aerospace application. As far as practicable, students will be grouped into teams of two based on their individually stated project preferences. An introductory meeting will be organized between the students and the point of contact for the selected topic in order to further clarify the project and scope.

Each CSA is designed to require approximately one week of full-time work (about 40 hours), which students may distribute over a period of roughly one month. An informal review meeting will be held midway between the project launch and final evaluation, providing an opportunity for students to verify that their proposed approach aligns with the customer's expectations.

Learning outcomes: Upon completion of the course, the student will be able to draw upon a broad range of aerospace engineering tools, including modeling, numerical methods, and experimental strategies, to critically assess a customer-defined problem. The student will be capable of developing a rigorous research methodology and proposing a credible and technically sound approach to address the challenge.

At the end of the case study, the students should:

- be able to combine all the engineering resources for aerospace research: theory, modeling, numerical approach, and/or experimental strategy,
- be able to discuss a given problem and define a preliminary solution,
- be able to develop a research methodology to convince a potential customer.

Literature

- All relevant references from the AR curriculum.
- An introductory presentation by the faculty describing further the goals of the selected CSA topic.

Evaluation The student will give a 10-minutes oral presentation (with an adequate number of slides) in front of a jury composed of AR faculty members and AR research engineers. This will be followed by a 20 minutes Q&A session with the AR faculty. A formal written report is not required. However, students must document their work and provide all necessary support documents for proper archival and further use, within 2 days following the oral presentation. This includes:

- PDFs of reference literature used for the CSA,
- presentation slides,
- commented source files and compiled versions of the codes developed/modified through the CSA,
- commented input files & scripts (Matlab/Python/Bash...) used to run existing codes (all scripts should run by themselves without requiring any further modification, enabling to reproduced the results discussed during the CSA evaluation)
- structured read-me file describing the material being archived,
- and anything else allowing research groups to capitalize on the student's work.

The evaluation criteria will include:

- Presentation quality and organization,
- Research methodology,
- Relevance of solutions,
- Discussion of the results,
- Definition of the limits of the study and estimation of results uncertainty (when applicable),
- Conclusion and proposed perspectives,
- Availability and quality of support documents.

The final grade will be given by the jury after a deliberation taking all given criteria into account.

In support of the Case Study in Aerospace, Seminars In Aerospace (SIA) are organized throughout the academic year and address various subjects in aeronautics and aerospace, from basic and fundamental knowledge to advanced studies focusing on current research investigations. They are organized to fulfill multiple objectives:

- Some seminars intend to discuss fundamental principles already covered in previous educational curricula, focusing on a more accurate understanding brought by reexamining the topic considering the increased knowledge that the students have gained through their education outside and inside VKI.

- Some seminars are dedicated to consolidating the background in aeronautics and aerospace.
- Some seminars address more specific and advanced subjects in applied mathematics, physical modeling or ground testing for aerospace research. They will serve to give an expert profile in some particular subjects relevant for aerospace applications.

Each seminar is designed to be self-contained in a two-period lecture (100 minutes).

A list of available seminars is distributed each year by the faculty POC, Prof. B.Bottin. Students choose which seminars to attend from the available options, following these rules:

- Total Seminars: Each student must select five (5) seminars.
- Mandatory Seminars: All students are required to select the seminars marked as mandatory.
- Consolidation Seminars: During course selection interviews, the faculty will determine whether a student is required to attend consolidation seminars. Students who are assigned consolidation seminars must select at least 2 seminars from the consolidation seminar list.
- Backup Seminars: Each student must select at least two (2) backup seminars, in case some seminars are canceled due to insufficient enrollment.

Evaluation Since seminars are intended to improve the student's knowledge, examinations would be impractical. Also, many advanced seminars are designed to provide support for solving Case Studies in Aerospace (CSA), and for the individual RM project.

6.4 EXPERIMENTAL LABORATORIES (ELAB-1, ELAB-2, ELAB-3 – 2.0 ECTS per lab)

Lecturers: D. Laboureur (coordinator), J. van Beeck, Ch. Schram, O. Chazot, G. Grossir.

Course type and status: This course is a hands-on experimental-laboratory course. ELAB-1 is a mandatory course for AR and EA department students and an optional elective for TU department students; ELAB-2 is mandatory for the AR and EA experimental-option students and optional for EA otherwise; ELAB-3 is an optional elective for AR and EA department students.

This course intends to provide in-depth knowledge of typical measurement techniques to students who plan to use them in their project. 3 laboratory sessions, ELAB-1, ELAB-2, ELAB-3 are selected from the following list of experimental techniques.Each laboratory session is worth 2.0 ECTS.

1. Boundary layer laboratory with pressure probes, CTA, Lidar-Doppler Velocimetry
2. Particle Image Velocimetry laboratory
3. Jet dynamics and data processing laboratory
4. Compressible flows visualization laboratory
5. Aerodynamic balance laboratory
6. Heat transfer laboratory (Infrared Thermography)

Learning outcomes: Regardless of which three laboratories are selected, on successful completion of this course students will be able to:

1. Perform the calibration or select the proper parameters associated with a given measurement technique.
2. Apply data-reduction procedures to convert raw measurements into physical quantities.
3. Conduct an uncertainty analysis to estimate the accuracy of the measured physical quantities.
4. Critically evaluate experimental results through comparison with theoretical models, numerical simulations, or literature data.
5. Communicate experimental methodology, results, and critical analysis in a written laboratory report.

Content covered (student selects 3 of the following 6 techniques, as ELAB-1, ELAB-2, ELAB-3):

1. Boundary Layer laboratory: Measurement of boundary layer flow with three different techniques: pressure probes, hot-wire, and Laser Doppler Velocimetry, and comparison of the three techniques against theoretical relations
2. Heat transfer Laboratory: Measurement of heat transfer by natural and forced convection between solid surfaces and gases using two measurement techniques: thermocouples and infra-red imaging
3. Particle Image Velocimetry laboratory: Measurement of a low speed water jet with Particle Image Velocimetry and Particle Tracking Velocimetry, with parametric analysis on the key parameters of both techniques.
4. Jet dynamics and data processing laboratory: Measurement of a turbulent jet using hot wire anemometry and data acquisition and processing principles
5. Aerodynamic balance laboratory: Measurement of the forces acting on a model traveling a supersonic velocity using a model equipped with an aerodynamic balance

6. Compressible flow visualization laboratory: Visualization of the flow topology around a model traveling a supersonic velocity using oil flow, Schlieren, and Background Oriented Schlieren (BOS).

Teaching Forms: For each laboratory session, the teaching forms will consist in:

- 1h Introductory session to the whole laboratory schedule and methodology
- 1h Introductory class to understand the objectives of the laboratory as well as the principles of the instrumentation that will be used
- 1 week of measurements in the laboratory in groups of 2 to 4 consisting of a min. of 6 afternoons. Each group will be supervised by a PhD student qualified in the technique.

Course Notes: Guidelines for the Measurement Techniques laboratories, VKI Faculty and PhD candidates, VKI-CN 191, Oct. 2020

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 Laboratory supervisor as well as the PhD students who followed the group to this report. Emphasis is put on accurate description of the performed measurements as well as 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 and PhD supervisors. Criteria are the understanding of the techniques, calibration and 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).

6.5 NUMERICAL METHODS LABORATORY 1 (NLAB-1 – 1.5 ECTS)

Lecturers: Th. Magin / P. Schrooyen

Course type and status: This course is a hands-on numerical-laboratory course. It is a mandatory course for AR department students.

This course complements "Introduction to CFD" (**??**) and "Introduction to Numerical Methods" (4.3) with a more practical outlook. Students work on exercises and projects, accompanying the content of the above-mentioned courses. Example codes for model problems will be investigated. The students will also work on small projects using third-party CFD tools.

Learning outcomes: The student should be able to confirm theoretical knowledge about discretization methods with numerical experiments. They will be able to understand and modify computer code written in either high-level programming language (C, FORTRAN) or script language (MATLAB, Python). Furthermore, the

student should be able to set up and compute a simple flow (e.g. one of the flows investigated experimentally in the experimental labs) using either an in-house or a commercial CFD package. Issues to become familiar with include: Practical gridding guidelines and grid sensitivity, boundary conditions, stability and iterative convergence.

Teaching forms:
Formal lectures (25%), exercises 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

6.6 EXPERIMENTAL LABORATORIES (ELAB-2 – 2.0 ECTS)

Course type and status: This course is a hands-on experimental-laboratory course, mandatory for AR experimental-option students. The full description is given in section 6.4. Students following the experimental option have to choose 2 labs, ELAB-1 & ELAB-2, with an option for a third experimental laboratory (ELAB-3) out of a portfolio of 6 labs.

6.7 ADVANCED NUMERICAL METHODS (ANM – 2.0 ECTS)

Lecturers: K. Hillewaert

Course type and status: This course is a numerical-methods lecture and tutorial course. It is a mandatory course for AR department students in the Numerical specialization option, and an optional elective for EA department students (Numerical and Machine Learning specialization options).

This course is a logical continuation of "Introduction to Numerical Methods" (4.3) but goes much deeper into the details. Course topics include both PDE theory and numerical methods with relevance to applications in flow simulation. The construction and analysis of high-resolution and high-order schemes, as well as advanced stabilization methods, are discussed.

Learning outcomes: Upon completion of this course students master the theory of characteristics, with emphasis on hyperbolic conservation laws including weak solutions, jump relations, concept of mathematical entropy condition, and boundary conditions. Compared to the introductory course, the student will acquire a deeper theoretical understanding of the main discretization techniques (finite difference, finite volume, finite element, and spectral methods). This includes extension of approximation methods to higher order, emphasis on nonlinear problems, and non-trivial analysis regarding convergence (e.g., Lax-Wendroff theorem). The student will master non-trivial stabilisation methods required in the context of convection-diffusion problems. In particular, the student will master the principles of mono-

tone schemes for hyperbolic conservation laws based of TVD and positivity (LED) conditions, as well as stabilized finite element schemes (SUPG, GLS). The student will have a good understanding of advanced iterative methods for solving linear systems, (e.g., Krylov subspace) methods and multigrid methods.

Teaching forms: Formal lectures (24hours)

Course notes:

- Typed-up Course notes, G. May Partial Differential Equations and their Numerical Solution (Parts 1/2), H. Deconinck, VKI-CN 142
- Numerical Methods for Fluid Dynamics 2, H. Deconinck, VKI-CN 227
- Numerical Methods for Fluid Dynamics 2, Exercises, H. Deconinck, VKI-CN 182
- Numerical Methods for Fluid Dynamics 2, Solutions to Exercises, H. Deconinck, VKI-CN 183

Literature:

- References in the course notes.

Evaluation:

- The evaluation is done based on homework and an oral exam discussing the homeworks.

6.8 AIRCRAFT PERFORMANCE, STABILITY, AND AERODYNAMICS (APSA – 2.0 ECTS)

Lecturers: B. Bottin and Ch. Schram

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR department students.

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

Learning outcomes: At the end of this course students should have a good knowledge of the fundamental background of inviscid incompressible and compressible aerodynamics leading to basic concepts of flight mechanics such as lift and drag characteristics of aircraft including their dependencies with Reynolds and Mach numbers, altitude, etc. The students should also comprehend 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 take-off and landing performance requirements related to safety will be addressed as well. The student should finally 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.

Course notes:

- Introduction to Aircraft Performance, Stability and Aerodynamics, B. Bottin and Ch. Schram, (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 questions covering all the course subjects (weight is 50% for each).

6.9 PHYSICS OF COMPRESSIBLE FLOWS (PCF – 2.0 ECTS)

Lecturers: O. Chazot and T. Magin

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR department students.

This course is oriented toward physical approach of compressible flows appropriated for an introduction of aerothermodynamics research. It presents the typical features of transonic/supersonic flows and it is organized to cover compressible regime phenomenology where the specific aspects of transonic and supersonic 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 and the extension to hyper-velocity flows. At the end of these courses the student should be capable of using this understanding and these theories in the interpretation of wind tunnel experiments or CFD simulations. It intends to be a complement to the elements of compressible flow theory given in FFD. Some more basic

aspects of incompressible and compressible flows are given during the Seminar in Aerospace (SIA) for students who need to reinforce their background in those fields.

Learning outcomes: 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). They 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.

Students should also 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 and supersonic regimes with their particular features. They should gain basic knowledge on high-speed testing.

Course notes:

- Inviscid Compressible Aerodynamics, G. Degrez, IVK-CN 145.
- Elements of Transonic Aerodynamics G. Degrez, VKI-CN 194
- Handwritten notes by O. Chazot

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.
- Elements of Gasdynamics, H.W. Liepmann and A. Roshko, GALCIT Aeronautical series, John Wiley, 1957.
- Bibliography of VKI-CN 194

Evaluation: Evaluation consists of two parts:

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

- 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 (1.3.0 ECTS) and 1/3 for the exercise (0.7 ECTS) giving in total 2.0 ECTS.
- or, a written exam, closed book, at the end of the course period, focusing on typical transonic/supersonic flows problems. The evaluation criteria are based on the understanding of basic compressible regime phenomenology, by reading Schlieren pictures, and theoretical results together with classical applications.

6.10 HYPERSONIC AEROTHERMODYNAMICS (HYP – 2.0 ECTS)

Lecturers: O. Chazot and G. Grossir

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR department students.

This course offers an in-depth study of hypersonic aerothermodynamics, addressing the complex physical and chemical phenomena that arise during high-speed atmospheric flight at large Mach numbers. It is organized in coordination with PCF and PCMAF courses.

Learning outcomes: The objective of this course is to ensure that the student has a good understanding of the specificities of the hypersonic flow regime. The characteristic features of the hypersonic flow regime are first described. The student will be introduced to the asymptotic trends for flows properties across normal and oblique shock waves at large Mach numbers, and will be guidede through the definition of the Mach number independence principle, and of the hypersonic similarity parameter. Approximate methods for hypersonic aerodynamics will be exposed (Newtonian methods, shock expansion, tangent-wedge and tangent-cone approaches, blast wave theory...) providing the student with a detailed practical insight on how to estimate hypersonic aerodynamic performances. Design methodologies for high-performances hypersonic waveriders (caret and osculating-cone based) will be introduced. The student will also be introduced to the influence of viscous effects on hypersonic flows, with emphasis placed on strong and weak viscous effects, along with the general features of reacting hypersonic boundary layers, and gas-surface interactions. Theoretical approaches are developed to provide the student with practical methods to estimate hypersonic heat transfer both for on- and off-stagnation point regions. The physical mechanisms responsible for laminar-to-turbulent boundary layer transition are presented, along with different modeling and experimental approaches towards their experimental characterization and numerical prediction. Overall, the student will acquire a good insight into the hypersonic flow physics, including the hypersonic boundary layers and the consequences of high temperature (i.e. dissociation, non-equilibrium, etc.). They should also 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 (20h)

Course Notes:

- Hypersonic Aerodynamics, R. Korkegi VKI-CN 9
- Fundamentals of Hypersonic Flow – Aerothermodynamics, D. Fletcher, VKI CN 190
- Handwritten notes by O. Chazot
- Slides by G. Grossir

Literature:

- Hypersonic and High temperature gasdynamics, Anderson J.D., MCGraw-Hill, 1989.
- Hypersonic Aerothermodynamics, Bertin J.J., AIAA, 1994.
- Introduction to physical Gasdynamics, W.G. Vincenti & C.H. Kruger, John Wiley and sons, 1965.

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.

6.11 PHYSICO-CHEMICAL MODELS FOR ATMOSPHERIC ENTRY FLOW (PCMAF – 2.0 ECTS)

Lecturers: T. Magin

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR department students.

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 outcomes: 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.

Teaching methods: Course: 16h theory + 4h exercises (take-home assignment)

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

Evaluation: Evaluation 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.

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 Longshot gun tunnel, studying the ablation phenomenon of a carbon phenolic ablators tested in the Plasmatron facility.

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.

6.12 BOUNDARY LAYERS AND FLOW SEPARATION IN THREE DIMENSIONS (3DBL – 1.0 ECTS)

Lecturers: G. Degrez

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR, EA, TU department students.

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 outcomes: 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. They 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. The student 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).

6.13 INTRODUCTION TO AEROACOUSTICS (ACOUS – 2.0 ECTS)

Lecturers: Ch. Schram

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR, EA, TU department students.

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 outcomes: 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 bearing on the theoretical aspects taught during the course, complemented by a homework in which the student has to apply those concepts to a practical case of industrial relevance.

6.14 METHODOLOGY OF APPLIED FLUID DYNAMICS (MAFD – 3.0 ECTS)

Lecturers: EA FACULTY

Course type and status: This course is a lecture course. It is a mandatory course for EA department students.

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: On successful completion of this course, students will be able to:

- Identify the fluid dynamic aspects of an industrial problem.
- Select the most appropriate investigation methodology for a given problem.
- Estimate the resources, in terms of manpower and technical facilities, required to carry out the investigation.
- Establish a research program, including a time schedule and cost estimate.
- Produce a contract proposal for a research investigation, justifying the technical feasibility of the proposed approach.
- Defend the proposed methodology and technical choices in an oral examination.

Teaching forms: Formal lectures on methodology in applied fluid dynamics illustrated by examples (20%) and Exercises (40%). Tutorial, Courses and Seminars (TCS) relevant for learning the methodology of applied fluid dynamics on specific problems in Fluid Dynamics. These are called MAFD-TCS in the course schedule (40%). The topics vary regularly depending on the research carried out in the Department.

Some TCS are given by VKI-alumni:

- Pollutant dispersal in the atmosphere
- Introduction to heat exchangers
- Introduction to two-phase Flows
- Non-Newtonian Fluids
- Cryogenic flows
- Transport phenomena in liquid sprays
- Wind turbine and wind farm wake modeling
- Introduction to aeroelasticity
- Bluff-body aerodynamics
- Applied research in coating processes

Literature

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

- MAFD-TCS slides.

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 or a research engineer. 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 their choices and explain their approach to the problem.

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

6.15 INDUSTRIAL DESIGN EXERCISE (IDE – 2.0 ECTS)

Lecturers: EA FACULTY

Course type and status: This course is a design-exercise course. It is a mandatory course for EA department students.

The objective of the industrial design exercise is to solve, individually, 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; this time you should not make a research proposal but find a solution to the given problem. The subject of the industrial design exercise is selected in relation to the options and the research project in which the students are already involved.

Learning outcomes: On successful completion of this exercise, students will be able to:

- Select the most appropriate solution approach (e.g. a handbook solution, a reduced-order model, or available data) for a given industrial fluid dynamics problem, given the constraints of the allocated time.
- Apply the selected approach to produce a complete solution to the problem, taking into account the context of a complex industrial engineering system.
- Define the limits of application of the proposed solution and estimate the associated uncertainty.

- Propose directions for future work that could improve the solution if more time or resources were available.
- Defend the proposed solution and its underlying technical choices in an oral examination.

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.

6.16 INTRODUCTION TO TURBULENCE (TURB – 2.0 ECTS)

Lecturers: W. Munters and J. van Beeck

Course type and status: This course is a lecture course. It is a mandatory course for EA department students, and an optional elective for AR, TU department students.

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.

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. They should understand 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: 100% formal course

Course Notes:

- Concepts of Turbulence modeling, C. Benocci and D. Olivari, VKI-CN 158, slides compendium L. Koloszar
- 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.

6.17 NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS - 1 (NSIP-1 – 2.0 ECTS)

Lecturers:W. Munters (Coordinator), S. Lopes, J.van Beeck, L. Koloszar

Course type and status: This course is a hands-on laboratory course. It is a mandatory course for EA department students.

The objective of this laboratory 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 them to acquire the critical sense and physical feeling necessary to evaluate the relevant numerical results. The course is composed of a laboratory where the capabilities and the limitations of numerical simulation in industrial environmental problems are practiced.

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 their numerical results to their own corresponding experimental results, obtained during the MT labs prior to the NSIP1 course.

Teaching Forms: Formal lectures 30%, Exercises 60%, Seminar 10%

Course Notes:

- Numerical simulation of industrial flows – slides compendium L. Koloszar & S. Lopes
- Numerical simulation of industrial flows – slides, C. Benocci, VKI-CN 181

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.

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

6.18 Experimental Laboratory 1 (ELAB-1 – 2.0 ECTS)

Course type and status: This course is a hands-on experimental-laboratory course, mandatory for EA department students. See "Experimental Laboratories" in section 6.4 for the full description.

6.19 MACHINE LEARNING FOR FLUID DYNAMICS 1 (MLFD-1 – 1.0 ECTS)

Coordinator: M. A. Mendez
Lecturers: J. van Den Berghe and M. A. Mendez

Course type and status: This course is a lecture and tutorial course with hands-on Python computing exercises. It is a mandatory course for AR, EA department students, and an optional elective for TU department students.

This course provides a foundational introduction to machine learning with a focus on the mathematical tools essential for understanding and applying ML techniques in fluid dynamics. The emphasis is on developing a solid grasp of core concepts, including probability theory, multivariate calculus, linear algebra, and optimization. These topics are presented in the context of supervised learning, with linear regression as a guiding example. The course prepares students to engage with more advanced machine learning methods by building the mathematical intuition required for data-driven modeling and analysis in fluid systems.

Pre-requisites:
A good background knowledge of Python programming is assumed. For those who need a review, following the course 'Tools for Scientific Computing' is strongly encouraged.

Learning outcomes: By the end of the course, students will understand the key mathematical foundations of machine learning, including probability, multivariate calculus, and optimization. They will be able to formulate and solve linear regression problems, apply uncertainty quantification techniques to assess model confidence and reliability, and develop the skills needed to critically assess and implement supervised learning methods in fluid dynamics contexts.

Teaching Forms: 60% formal course 40% exercises in Python

Course Notes:

- Hands on Machine Learning for Fluid Dynamics; Course Slides - M. A. Mendez
- Data Driven Fluid Mechanics: Combining First Principles and Machine Learning, M. Mendez, A. Ianiro, B. Noack and S. Brunton, Cambridge University Press, 2023
- Machine Learning for Fluid Mechanics, Edited by M. A. Mendez and A. Parente, Published by VKI.

Evaluation The evaluation is based on a tutorial exercise, ideally linked to the student's project. Several template problems will be provided (regression, classification, compression, or assimilation) presented in the course. The exercise should be presented in a short presentation at the interview. The grade is based on the report quality (50%), and on an interview addressing both the theoretical and the practical challenges faced during the homework (50%).

6.20 Experimental Laboratory - 2 (ELAB-2 – 2.0 ECTS)

Course type and status: This course is a hands-on experimental-laboratory course, mandatory for EA experimental-option students and optional otherwise. See "Experimental Laboratories" in section 6.4 for the full description.

6.21 NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS - 2 (NSIP-2 – 2.0 ECTS)

Lecturers: W. Munters, S. Lopes, L. Koloszar, Ph. Planquart, J. Christophe, M. Faruoli

Course type and status: This course is a numerical-simulation, project-oriented course. It is a mandatory course for EA department students in the Numerical specialization option.

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 open source flow solver OpenFOAM, 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 literature. The main objective is the understanding of the models and the approximations, which are a necessary part of this class of simulation.

Teaching Forms: Introduction to OpenFOAM 50% + Individual exercise 50%

Course Notes:

- Numerical simulation of industrial flows – slides, C. Benocci, VKI-CN 181
- User manual for OpenFOAM.

Literature: Same as Numerical Simulation of Industrial Problems - 1 (NSIP-1).

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 or similar 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 modeling. The mark is 100% based on the report.

6.22 MACHINE LEARNING FOR FLUID DYNAMICS 2 (MLFD-2 – 2.0 ECTS)

Coordinator: M. A. Mendez
Lecturers: R. Poletti, S. Ahizi, L. Schena, M. Ratz, M. Fiore, M. A. Mendez

Course type and status: This course is a lecture course. It is a mandatory course for EA (machine-learning option) department students, and an optional elective for AR, EA, TU department students.

This course builds on MLFD-1 by introducing more advanced topics in machine learning. It covers nonlinear regression methods and artificial neural networks, including advanced training strategies such as physics-informed and physics-constrained learning. The course also explores both linear and nonlinear dimensionality reduction techniques, as well as kernel-based methods, Bayesian inference and evolutionary algorithms for optimization.

Pre-requisites: Students are expected to have first followed MLFD-1.

Learning outcomes: By the end of the course, students will understand and be able to apply advanced machine-learning methods for the analysis and modeling of fluid-dynamics problems. They will be able to design and train deep neural networks, develop physics-informed neural networks that incorporate governing equations and physical constraints, and use kernel methods for surrogate modeling, regression, and statistical inference. Students will also be able to apply nonlinear dimensionality-reduction techniques, including autoencoders and manifold-learning methods, to identify low-dimensional representations of complex data. More broadly, they will develop the skills required to critically assess, implement, and compare advanced data-driven and physics-informed approaches in fluid-dynamics applications.

Teaching Forms: 60% formal course 40% exercises in Python

Course Notes:

- Hands on Machine Learning for Fluid Dynamics; Course Slides - M. A. Mendez
- Data Driven Fluid Mechanics: Combining First Principles and Machine Learning, M. Mendez, A. Ianiro, B. Noack and S. Brunton, Cambridge University Press, 2023
- Machine Learning for Fluid Mechanics, Edited by M. A. Mendez and A. Parente, Published by VKI.

Evaluation The evaluation is based on a tutorial exercise, ideally linked to the student's project. Several template problems will be provided (regression, classification, compression, or assimilation) presented in the course. The exercise should be presented in a short presentation at the interview. The grade is based on the report quality (50%), and on an interview addressing both the theoretical and the practical challenges faced during the homework (50%).

6.23 DIGITAL TWINNING, ASSIMILATION AND CONTROL (DTAC – 2.0 ECTS)

Coordinator: M. A. Mendez
Lecturers: S. Randino, F. Monteiro, S. Discetti, M. A. Mendez

Course type and status: This course is a lecture course. It is a mandatory course for EA (machine-learning option) department students, and an optional elective for EA, TU department students.

The concept of digital twins promises to revolutionize engineering by offering new avenues for optimization, control and predictive maintenance. Digital twins seek to virtually replicate systems using models that continuously "learn" from data, automatizing data collection, validation and refinement to achieve the "self-learning" status. This course presents an overview of methods and tools to combine ideas from machine learning, data assimilation and physics-based models to develop digital twins. The course is divided in three parts. The first part gives a review of microcontrollers and real time data processing. Tutorials using Arduino and Raspberry Pi will be provided. The second part goes into the details of data assimilation for real time system identification, covering both variational (adjoint-based) methods and statistical (Kalman filter) methods including linear and nonlinear systems. Finally, the last part provides an overview of optimal control theory and reinforcement learning, and an introduction to a new paradigm, under development at the von Karman Institute, called Reinforcement Twinning.

Pre-requisites: A good background knowledge of Python programming is assumed. For those who need a review, following the course 'Tools for Scientific Computing' is strongly encouraged. It is also strongly recommended to follow MLFD-1 first.

Learning outcomes: Students should be able to tackle system identification and control problems, blending machine learning techniques and physics-based modeling and using real time data processing and advanced data assimilation tools.

Teaching Forms: Formal lectures 70 %, Coding tutorials in Python 30%

Course Notes: Course slides together with a collection of codes and exercises.

Literature

- Course Notes and Slides by the Lecturers.
- Reinforcement Twinning: from digital twins to model-based reinforcement learning, by L. Schena, P. Marques, R. Poletti, S. Ahizi, J. van den Berghe, M.A. Mendez, Journal of Computational Science (available at https://arxiv.org/abs/2311.03628) 2023
- Fundamentals of Physics-Constrained Regression, M. A. Mendez, Chapter 2 in "Machine Learning for Fluid Dynamics", edited by M. A. Mendez and A. Parente, , published by VKI, 2024.
- Tutorials in Physics-Constrained Regression, M. A. Mendez, J. van Den Berghe, M. Ratz, M. Fiore, L. Schena, Chapter 3 in "Machine Learning for Fluid Dynamics", edited by M. A. Mendez and A. Parente, published by VKI, 2024

- "Raspberry Pi Cookbook": Software and Hardware Problems and Solutions, by Simon Monk, O'Reilly, 2023.
- "Arduino Workshop, 2nd Edition: A Hands-on Introduction with 65 Projects", No Starch Press, 2021.

Evaluation Same as MLFD: the evaluation is based on a tutorial exercise, ideally linked to the student's project. If no overlapping with the main student's project is found, the exam will be based on the lab session on twinning and system identification. The grade is based on the report quality (50%), and on an interview addressing both the theoretical and the practical challenges faced during the homework (50%).

6.24 TOOLS FOR SCIENTIFIC COMPUTING (TSC – 1.0 ECTS)

Coordinator: M. A. Mendez
Lecturers: L. Schena, M. A. Mendez

Course type and status: This course is a hands-on tutorial course. It is not mandatory in any department; it can be selected as an optional elective course by AR, EA, TU department students.

This is an optional course which shows how to use powerful and opensource tools to solve the practical problems that the student will encounter in their work. The aim is to provide a well-equipped and general-purpose toolbox that serves as a solid starting point to move forward in their specific area of interest, whether in the experimental or numerical specialization. The amount of theoretical material is kept to a minimum, and almost all the lectures are linked to topics from classical VKI courses such as Measurement Techniques, Data Acquisition and Processing, Turbulence and Numerical Methods.

Learning outcomes: Students should master the use of the open-source language Python to solve practical problems in their work and to convert their ideas into functioning algorithms. At the end of the course, the student will be able to efficiently handle, manipulate and visualize large amounts of data, perform frequency and time-frequency analysis, solve nonlinear systems of equations, perform data-driven model order reduction, study simple dynamical systems and efficiently use modern machine learning libraries.

Teaching Forms: Formal lectures 30 %, Coding tutorials in Python 70%

Course Notes: Course slides together with a collection of codes and exercises.

Literature

- Foundations of Applied Mathematics, by Jeffrey Humpherys, Tyler J. Jarvis, Emily J. Evans (https://foundations-of-applied-mathematics.github.io/)

- A primer on Scientific Programming with Python, by S. Linge- H-P Langtanger, SpringerOpen 2009, Oxford University Press 2013.
- Scipy Lectures https://scipy-lectures.org/intro/language/python_language.html

Evaluation The learning outcome is verified by a coding (open book and with access to the internet) exam. The student must be able to solve an assigned coding problem involving vast portions of the material presented (e.g., post-processing of a given dataset). Criteria for the evaluation are the understanding of the problem set and the correct and efficient implementation of the provided tools.

6.25 DATA DRIVEN MODAL ANALYSIS (DDMA – 1.0 ECTS)

Coordinator: M. A. Mendez
Lecturers: R. Poletti and M. A. Mendez

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR, EA, TU department students.

This is an optional course dedicated to linear dimensionality reduction techniques such as Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD). Originally developed for identifying coherent structures in turbulent flows, these decompositions have nowadays become a fundamental tool in many data processing problems. The course aims at providing the mathematical background of these decomposition and an overview of their applications to pattern identification, filtering, data compression and reduced order modeling of Partial Differential Equations.

Learning outcomes: Students should master the use of the data driven decomposition of numerical and experimental data. They will be able to effectively use POD and DMD to identify coherent pattern and to filter/compress datasets. The student should be able to derive a POD-Galerkin projection reduced order model of a simple PDEs.

Teaching Forms: Formal lectures 30 %, Coding tutorials in Python 70%

Course Notes: Course slides together with a collection of codes and exercises.

Literature

- Generalized and Multiscale Modal Analysis, M. A. Mendez, Chapter 8 in 'Data Driven Fluid Mechanics', edited by M.A. Mendez, A. Ianiro, B.R. Noack and S. Brunton, Cambridge University Press 2022.
- Multiscale Proper Orthogonal Decomposition of complex fluid flows, by M.A. Mendez, M. Balabane and J.-M. Buchlin

- Model Order Reduction, Volume 2: Snapshot-Based Methods and Algorithms, Edited by P. Benner; De Gruyter 2021

Evaluation Same as MLFD: the evaluation is based on a tutorial exercise, ideally linked to the student's project. The template includes problems on filtering, pattern identification or ROM of a PDE. The grade is based on the report quality (50%), and on an interview addressing both the theoretical and the practical challenges faced during the homework (50%).

6.26 AERO-THERMODYNAMICS OF TURBOMACHINERY & PROPULSION -1 (ATP-1 – 3.5 ECTS)

Lecturers: TU FACULTY

Course type and status: This course is a lecture course. It is a mandatory course for TU department students.

This basic course is mandatory for all turbomachinery students. The course starts with an overview of the development history of turbomachinery and the major applications. Then the course provides insights into the flow behavior laying the foundation for the detailed design of turbomachines and future research work. Different thermodynamic cycles are introduced with a detailed analysis. The turbomachinery components used in such cycle are then discussed in more detail by an overview of the overall characteristics and one-dimensional flow analysis. Subsequently, the conservation laws for fluid dynamics are derived in a rotating frame of reference, leading to the definition of rothalpy. The Euler momentum equation is derived and the velocity triangles in turbomachinery are discussed with typical parameters such as flow coefficient, work coefficient and degree of reaction for axial and radial turbines and compressors. An essential insight into the flow in axial turbomachinery will be created by using the S1/S2 model for the general description of the flow, 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. The flow in the S1 blade-to-blade plane is detailed by looking into cascade flows. The aim is to obtain a profound understanding of the influence of blade loading on the design of axial compressor and turbine profiles. Additionally, the tools that allow for the numerical optimization of such profiles are explained. Concepts of optimal incidence and deviation are thoroughly discussed. In the S2 meridional plane, the radial equilibrium is expressed and analyzed for typical design choices. The impact of these choices on various aspects such as degree of reaction, blade twist etc is highlighted. The impact of streamline curvature is also detailed. Finally, a coupling methodology is presented for simultaneously solving the flow in S1 and S2 planes. Typical secondary flows due to the presence of end wall boundary layers are discussed. The Buckingham-Pi theorem is used to select non-dimensional groups for similitude analysis. The course completes an overview of the typical technology and product development processes as well as component design process.

Learning outcomes: At the end of this course the student should have acquired a good understanding of the thermodynamic cycles and the fundamentals of propulsion in addition to a good knowledge of turbo-propulsion elements, the laws of similitude and the prediction correlations. They 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 turbines. 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 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 main objective of the study of the flow in a S1 blade-to-blade plane is to get 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 (deviation, optimal incidence, secondary flows, impact of Reynolds- and Mach number on operating range, etc.) and be available to implement them in a design strategy. The student should also have acquired the basic knowledge and competences for the design of axial gas turbines and their turbomachinery components. 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 among the objectives of the course. The aim is to get a physical understanding of the theoretical relations on which the axisymmetric 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 student should be able to make a first lay-out of a multistage compressor or turbine, choose a vortex distribution and predict the performance based on the S1-S2 model.

Teaching forms: Formal lectures 100%.

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

- Flow in turbomachines and turbomachinery component characteristics, F. Breugelmans, VKI-CN 83 Blade to Blade flow in Turbomachinery, R.A. Van den Braembussche, VKI CN 172
- Compressor Cascade Flow and Losses, T. Verstraete, PowerPoint slides
- Inverse Design Methods for Axial and Radial Turbomachines, R.A. Van den Braembussche, VKI Preprint 1994-35
- Aerodynamic design of a gas turbine, McDonald, P.W., VKI-CN 95
- Radial equilibrium in Turbomachines, T. Arts, (handwritten notes)

Literature

- Viscous Fluid Flow, Frank White, McGraw-Hill Science/Engineering/Math, 3rd Revised edition, 1 April 2005
- 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.
- Aerothermodynamics and Flow in Turbomachines, M.H. Vavra, R.E. Krieger Publishing Co.

Evaluation The evaluation is done by an open-book, oral exam with written preparation. The aim of the evaluation is not to verify the ability of the student to reproduce derivations etc., but rather to measure the student's understanding of the different topics introduced in the course, such as for instance the Joule cycle, the fundamentals of propulsion, velocity triangles, the S1/S2 superposition of two 2D flows, optimal incidence, deviation, secondary flows, non-dimensional groups,... The aim of the course is to develop a profound understanding of the working principles of turbomachinery. The evaluation therefore consists with an open-book, written preparation part where the questions probe the level of understanding the students have gathered during studying the course content. After the written preparation, the students' answers will be verified by the faculty in a dialogue where further questions will be asked to probe further the level of understanding.

6.27 AERO-THERMODYNAMICS OF TURBOMACHINERY & PROPULSION -2 (ATP-2 – 2.5 ECTS)

Lecturers: TU FACULTY

Course type and status: This course is a lecture course. It is a mandatory course for TU department students.

This course is the natural follow-up of ATP-I and aims at specializing in the basic thermodynamics and fluid dynamics notions provided in ATP-I, on single turbomachinery components such as compressors and turbines. Attention is also devoted to applied boundary layer flow phenomena and their integration at engine level while the peculiarities of the different components (e.g. stall and surge for compressors) will also be discussed. ATP-II is thought to provide the basis for the advanced courses. The course is structured upon five different modules:

- Boundary-layer flows and phenomena in turbomachinery components
- Axial compressors
- Axial turbines
- Radial Compressors
- System and Engine Integration

Learning outcomes: Critical to the aerodynamic, aero-thermal and aero-mechanical performance of turbomachinery components is the behaviour of the flow in the boundary-layer. Starting with a brief review of boundary-layer theory of relevance for compressible turbomachinery flows including integral parameters of velocity and thermal boundary layers, the module discusses boundary layer development under adverse and favorable pressure gradient, effects of suction and blowing, laminar-turbulent transition phenomena, boundary-layer separation, and key notions on heat transfer and film cooling. In the domain of axial compressors, the students will be firstly exposed to the typical applications of such component and, hence, to the related nomenclature. In a second part, the characteristic map will be introduced, with the accent posed on its physical interpretation and its use within some phases of the design process (e.g. matching and scaling). Following from the previous topic, stall and surge will be described from a phenomenological point of view and in terms of impact on the performance and integrity of the machine. Choking flow in compressors will be then treated, clarifying the link with supersonic compressors and their special features (i.e. unique incidence). The final part of the module is devoted to the description of blade families for transonic compressors, examples of blade load distribution and its physical interpretation and 3D design features impact. The characteristics of future axial compressor design trends will be discussed all along the module. The axial compressor module is foreseen to be delivered in 9 hours of frontal teaching. For the axial turbine section, the course will review turbine architectures and applications. We present the turbine characteristic map. We introduce the velocity triangles for a turbine stage, the link with relevant design parameters and turbine thermodynamics and energy exchange. The last part of the module will introduce concepts for the one-dimensional design of axial turbines for different turbine applications. In the radial compressors section, a down selection of topics from the advanced radial compressor course is provided. A major difference with axial machines is the strong participation of the Coriolis force in the energy transfer, which will be discussed in detail. The flow in the various components of a radial compressor will be discussed, such as the inducer, impeller, vaneless or vaned diffuser and volute. In the section engine and system integration,

an overview of the secondary air systems and other higher-level system integrations aspects will be discussed. The turbo components turbine and compressor are part of the overall gas turbine system. The secondary air system connects compressor extractions with the sealing and purge flows of the engine as well as cooling air for parts of the hot-gas path section for the combustor and the turbine. The student will gain an appreciation of research and development on different system levels, such as the sub-component, component, or sub-system and develop initial understand of the linkage between the various system levels for the architecture of the entire engine or power-plant. The capability to understand bottom-up and top-down relationships is becoming of growing importance in the pursuit of development for climate-neutral technologies.

Teaching forms: Formal lectures 100%.

Course Notes:

- Hands-out of classes
- Off-design Performance of Axial Compressors, J. Chauvin VKI-CN 100
- Transonic Compressor Cascades, H. Griepentrog, VKI-CN 73.

Literature

- Viscous Fluid Flow, Frank White, McGraw-Hill Science/Engineering/Math, 3rd Revised edition, 1 April 2005
- 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, NASA Lewis Research Center.

Evaluation The evaluation is done similar to ATP-I by an open-book, oral exam with written preparation. The aim is to test the student's profound understanding of the flows in the three most common types of turbomachines and of the limitations of applicability of experimental and numerical methods, the design and optimization of compressors and turbines. The oral part is preceded by a written preparation where students can make use of the material provided during the lectures. During the oral part, the evaluators review the written preparation and will ask for clarifications with further detailed questions aiming to check if the students master the course content. The oral part is closed-book but on the basis of the written preparation.

6.28 TURBOMACHINERY EXPERIMENTAL LAB (TULAB – 3.0 ECTS)

Lecturers: F. Fontaneto, S. Lavagnoli

Course type and status: This course is a hands-on laboratory course. It is a mandatory course for TU department students. Students work in small teams on a representative turbomachinery test facility and gain practical experience in the planning, execution, data reduction and assessment of an experimental campaign.

The Turbomachinery Experimental Laboratory provides hands-on experience with the planning, execution, processing and interpretation of an experimental campaign on a turbomachinery test facility. Students work in small teams and are exposed to the complete experimental workflow, from the preparation of the experiment and selection of the measurement approach to data acquisition, reduction and critical assessment of the results. Depending on the assigned activity, students are either requested to design, build and operate a measurement device, such as a pressure probe, or to conduct a measurement campaign for the characterization of a turbomachinery component, such as a compressor or turbine cascade, or an isolated airfoil tested in a low-speed wind tunnel. Particular attention is given to the practical selection and use of instrumentation, including operating range, accuracy, spatial and temporal resolution, uncertainty, installation constraints and suitability for the intended measurements. Students work from raw acquired signals through calibration, corrections and data reduction to obtain relevant aerodynamic and performance quantities. Measurement uncertainty is quantified and propagated through the data-reduction chain. The laboratory also emphasizes the critical assessment of experimental data through repeatability, consistency, uncertainty and physical plausibility. The processed results are interpreted to identify relevant trends, anomalies and limitations and to formulate technically supported conclusions. Short preparatory and analysis activities complement the experimental work and provide practical insight into the decisions, compromises and difficulties involved in planning and conducting a turbomachinery experiment.

Learning outcomes: At the end of the course, the student should be able to:

- **Plan** a turbomachinery experimental campaign, defining the main experimental steps, measurement requirements and resources needed to obtain meaningful results.
- **Evaluate** the selection of measurement techniques and instrumentation considering the measurement objectives, operating conditions, uncertainty, practical limitations and alternative approaches.
- **Process** raw experimental measurements into relevant aerodynamic and turbomachinery performance quantities using appropriate calibration, corrections and data-reduction procedures.
- **Quantify** measurement uncertainty and propagate it through the data-reduction process to derived quantities and performance parameters.
- **Validate** experimental results by assessing repeatability, consistency, uncertainty, physical plausibility and potential sources of measurement or experimental error.

- **Interpret** experimental results to identify relevant trends, anomalies and limitations and draw technically supported conclusions.

Teaching forms: The course is organized around hands-on experimental work in small teams, complemented by introductory lectures, technical briefings and supervised analysis sessions. Students plan and prepare the assigned experiment, operate the test facility and instrumentation, acquire and process experimental data, quantify measurement uncertainty, and critically interpret the results. Short preparatory and off-class activities support the experimental work and final analysis. The course combines introductory preparation, intensive hands-on laboratory work and post-processing activities. Students receive approximately 4-8 hours of preparatory classes and technical briefings covering the assigned experiment, facility, instrumentation and experimental procedures. The experimental activity is then carried out over 3-4 full laboratory days, corresponding to approximately 25-30 hours of hands-on work. A further 16-20 hours are dedicated to data processing, uncertainty analysis, interpretation of the results and preparation of the final report.

Course Notes: Laboratory instructions, technical documentation, experimental procedures, data-processing material and selected references are provided by the instructors for each assigned experimental activity.

Evaluation: The evaluation is based on the laboratory report (70%) and a collective interview with each student group (30%). The assessment considers the quality and completeness of the experimental work and report; the selection and justification of instrumentation, experimental setup and data-acquisition parameters; the quality of the data reduction and uncertainty analysis; and the critical interpretation and validation of the experimental results. During the interview, students are also assessed on their understanding of the measurement campaign and experimental methods, and on their ability to apply the acquired experimental knowledge and judgment to other test cases.

6.29 TURBOMACHINERY NUMERICAL LAB (TUCFD – 3.0 ECTS)

Lecturers: T. Verstraete

Course type and status: This course is a hands-on numerical-laboratory course. It is a mandatory course for TU department students.

The intention of this course is to provide a basic knowledge of the numerical methods employed in a CFD solver, such that students can select the right numerical scheme for the problem to be analysed and should allow the student to troubleshoot when the CFD solver diverges or does not provide consistent results. The course uses simplified model equations such as the advection and diffusion equations as a simpler substitute for the Reynolds Averaged Navier Stokes equations to explain basic ingredients such as consistency, stability, and convergence. The von Neumann stability analysis will be applied to standard numerical schemes to demonstrate the

CFL condition. A distinction between explicit and implicit schemes will be investigated. The concept of artificial viscosity will be introduced through the Lax scheme and the Lax-Wendroff scheme. Different type of boundary conditions will be explained with some application of the ghost cell approach. Finally, characteristic lines for hyperbolic partial differential equations will be studied, demonstrating that the numerical domain of influence needs to include the physical domain of influence. The course then considers the Euler equations and particular solution techniques are discussed ranging from central schemes to upwind schemes. The students will then be provided with a coding task where a 1D Euler solver will need to be developed. This will serve as an exercise where various concepts that are introduced in the course can be experimented with and verified. With the basic notions of numerical discretization established for model equations, the course will proceed with the discussion of critical aspects of numerical modeling relating to the influence of meshing and especially turbulence and transition modeling for steady-state simulations and time-resolved unsteady flow simulations.

Learning outcomes: The student should master following basic concepts and practical aspects of turbomachinery CFD:

- Consistency
- Stability through a von Neumann analysis
- Convergence
- Artificial viscosity
- Mesh metrics and their effects on numerical stability and the numerical results
- Turbulence models and their influence on numerical stability and the numerical results
- Quality requirements of a structured CFD study

The student should be able to perform the following tasks:

- Apply a standard discretizations approach to an ordinary differential equation and analyze the stability, consistency, and convergence of this choice.
- Run a 2D CFD study and apply the learned concepts of numerical modeling for interpretation of the numerical results for application to a compressor and a

Teaching forms: Lectures and exercises.

Course Notes:

- Powerpoint slides by lecturers

Evaluation The evaluation is based on the following three exercises: i) stability analysis of a discretization scheme, ii) development of a 1D Euler solver testing various concepts discussed during the course iii) 2D CFD study of a compressor or turbine profile

6.30 INTRODUCTION TO AEROELASTICITY (AELAST – 2.0 ECTS)

Lecturers: G. Dimitriadis, S. Stapelfeldt

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR, EA, TU department students.

This course provides an overview of aeroelasticity in aerospace and turbomachinery. It is designed to provide a theoretical introduction to aeroelasticity followed by insights into the state of the art of aeroelastic research and practice. The course starts by introducing basic aeroelastic behaviour and different aeroelastic models. The core of the course covers static and dynamic aeroelasticity in more depth, including control reversal and coupled bending-torsion instability. Aerodynamic and structural modeling techniques are introduced. In the last part of the course, high fidelity computational methods are described and aeroelasticity of turbomachines is introduced. The course gives participants an opportunity to expand their interdisciplinary knowledge, real engineering examples will demonstrate the importance of aeroelastic analysis for cutting edge technologies.

Learning outcomes: At the end of the course, participants will have a solid understanding of aeroelastic principles and phenomena to support root cause analyses and engineering design processes. This course is offered to RM and Ph.D. students of all departments interested in gaining a first introduction into aeroelasticity and fluid-structure interaction. This course is also offered to external participants from industry and research centers.

Teaching forms: Formal lectures (50%) and practical sessions (50%)

Course Notes:

- VKI LS 2022-08

Evaluation The evaluation consists of an oral exam where the student's understanding of key elements is tested.

6.31 ADVANCED AXIAL COMPRESSOR COURSE (AC-AC – 2.0 ECTS)

Lecturers: F. Fontaneto

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by TU department students.

This advanced course builds upon the common turbomachinery courses and is followed by students who have selected the axial compressor option. The course is structured similarly to the compressor module of ATP-II, with additional lectures dedicated to secondary flows and supersonic compressors, as well as a symposium on compressor design. In addition to classical course notes and handouts, the course

makes extensive use of conference articles and journal papers. The course focuses on the physical understanding of the phenomena governing the performance and stability of state-of-the-art axial compressors. Emphasis is placed on the modelling of these phenomena and on the effective use of such models within the design process. In the final part of the course, an outlook on forthcoming technologies is provided, together with a critical assessment of their potential in terms of efficiency, operability, and feasibility.

Learning outcomes: At the end of this course, students should have a clear understanding of the specificities of multistage, low-speed, transonic, and supersonic axial compressors and of how different operating conditions influence their design. They should understand the impact of flow unsteadiness, secondary flows, casing treatments, inlet distortion, and erosion on compressor stability, including surge and rotating stall, as well as the advantages and limitations of variable geometry and bleeding. Students should master design methodologies specific to high-speed applications, including stage-matching techniques. They should also be aware of the differences between aeronautical and industrial applications, understand the impact of gas composition, and recognize the different design philosophies associated with these applications.

Teaching forms: Formal lectures (80%) and exercises in class (20%). The practical application of the course material is addressed in the Design Exercise and may also be included in a compressor-related CFD LAB or INNOVATION LAB.

Course notes:

- 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.
- Pre-prepared handouts for each class.
- Extensive bibliography in CN 192 and CN 218.
- 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.
- 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, FF. 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° Cambered DCA Airfoil.
- Comparison with 2D Flow Calculations in the Compressible Flow Regime, F. Breugelmans, VKI-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 Advanced 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, J. Lepine, VKI-LS 2003-06 (slides, part of).
- LP Compressor Design, J. Lepine, VKI-LS 2003-06 (slides, 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 A2I8b Mean Lines, P.T. Bernot & M. Savage, NACA RM L57H08.
- 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.

Evaluation The learning objectives are assessed by a closed-book written examination covering the entire content of the course, followed by an oral examination. The written examination lasts approximately two hours and consists of short exercises and open questions. The oral examination lasts approximately 30 minutes. The evaluation approach is designed to assess the student's effective understanding and comprehension of the physical phenomena, modelling approaches, and design methodologies discussed during the course.

6.32 ADVANCED COURSE ON AXIAL TURBINE AERODYNAMICS (AC-AT – 2.0 ECTS)

Lecturers: S. Lavagnoli

Course type and status: This course is a lecture course. It is not mandatory in any department and can be selected as an optional elective course by TU department students.

This advanced course follows the turbomachinery courses ATP-I and ATP-II and provides an advanced introduction to the aerodynamic design, analysis and operation of axial turbines. The emphasis is on developing the physical understanding and engineering judgement required to analyse realistic turbine flows, identify the dominant aerodynamic and loss mechanisms, and assess possible design improvements. The course first places axial-turbine design in the context of different engine architectures and applications, including aero-engines, power-generation turbines and compact high-performance turbines. The relation between engine requirements, preliminary turbine design, operating range, turbine characteristics, off-design operation and engine matching/control is introduced. Basic one-dimensional turbine design is briefly revisited and applied through a preliminary design exercise. The course then addresses two- and three-dimensional blade and stage aerodynamics, with particular attention to the application of compressible-flow concepts to staggered turbine passages. Subsonic, transonic and supersonic blade flows, shock systems and shock–boundary-layer interactions, trailing-edge flows, transition and separation are discussed in relation to aerodynamic design and performance. The current course already gives substantial attention to transonic cascade physics and trailing-edge phenomena, which provides the basis for this part of the revised course. Three-dimensional turbine aerodynamics covers secondary and endwall flows and their interaction with blade loading and spanwise design, together with the principles and limitations of three-dimensional blade-design techniques. Tip-leakage, cavity, rim-seal and purge flows are introduced as important sources of aerodynamic interaction and loss in real turbine stages. Additional topics include cooled-turbine aerodynamics and coolant-mainstream interaction, as well as an introduction to rotor–stator interaction and other relevant unsteady-flow phenomena. Turbine loss mechanisms and performance-prediction approaches are discussed with emphasis on their physical basis, assumptions, range of validity and limitations. Throughout the course, experimental and computational results are used to connect aerodynamic theory with realistic turbine flows and to discuss the level of modelling or experimental evidence required to analyse different phenomena reliably. Short exercises and engineering thought problems are used to apply the concepts to representative turbine design and analysis challenges, including the effects of aerodynamic, thermal, mechanical and manufacturing constraints.

Learning outcomes At the end of the course, the student should be able to:

- **Relate** axial-turbine architectures and aerodynamic design choices to engine requirements, application, operating range and off-design operation.
- **Analyse** subsonic, transonic and supersonic flows in turbine blade pas-

sages using the relevant compressible-flow physics, including shock systems, trailing-edge flows, transition and separation.

- **Diagnose** the principal two- and three-dimensional aerodynamic and loss mechanisms in axial turbines, including profile, secondary/endwall, tip-leakage, rim-seal/purge and cooling-related flows.

- **Evaluate** the influence of blade and stage design choices, including loading, reaction, blade geometry and three-dimensional design features, on turbine flow behaviour and aerodynamic performance.

- **Assess** the applicability and limitations of aerodynamic models, loss correlations, CFD predictions and experimental evidence when analysing turbine performance and complex flow phenomena.

- **Critique** an existing axial-turbine aerodynamic design or flow field and propose technically justified design modifications under realistic operating and design constraints.

Teaching forms: Formal lectures complemented by short in-class exercises, engineering thought problems and selected off-class exercises. Exercises combine qualitative flow analysis, interpretation of experimental and CFD results, and short quantitative design/analysis problems. Computational tools may be used where appropriate to support the aerodynamic analysis rather than as a learning objective. The estimated workload is 25-30 hours of frontal classes and approximately 25 hours of individual study and exercises.

Course Notes:

- *Advanced Course on Axial Turbine Aerodynamics*, C. Sieverding, VKI-CN221.

- Slides, notes, selected technical material and exercises provided by the instructor throughout the course.

Evaluation The evaluation consists of a written closed-book examination of approximately 3 hours, comprising short quantitative exercises, interpretation and analysis questions, and open engineering questions based on the principles and physical models discussed during the course. The examination assesses the student's ability to apply turbine aerodynamic concepts rather than reproduce empirical correlations or detailed formulae from memory. Where required, specialized correlations, equations, charts or data are provided. Part of the examination may consist of the analysis of a representative turbine design or flow field, requiring the student to identify the dominant aerodynamic mechanisms, assess design limitations and propose technically justified improvements.

6.33 ADVANCED RADIAL COMPRESSOR COURSE (AC-RC – 2.0 ECTS)

Lecturers: T. Verstraete

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by TU department students.

This advanced course is the follow-up of the basic turbomachinery course ATP-1-2 and is followed only by students who have selected the radial 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.

Learning outcomes: The learning objective 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. They 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). They 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 course is also offered to external participants from industry and research centers and PhD students preparing a thesis related to radial compressors.

Teaching forms: Formal lectures (90%) and exercises in class (10%).

Course Notes:

- Design and Analysis of Centrifugal Compressors, Rene Van den Braembussche, Wiley 2019, ISBN: 978-1-119-42409-3

Evaluation The evaluation consists of the detailed analysis of a paper in the field of radial compressor design methodology. The exam is designed to assess the understanding of key concepts of radial compressor design as well as to probe the understanding of the flow physics in radial machines.

6.34 MULTIDISCIPLINARY DESIGN OPTIMIZATION (MDO – 2.0 ECTS)

Lecturers: T. Verstraete

Course type and status: This course is a design-exercise course. It is not mandatory in any department; it can be selected as an optional elective course by EA, TU department students.

This course introduces the concept of shape optimization applied to aerodynamic design problems. The course aims to give a non-exhaustive overview of different methods that can be applied to shape optimization problems. A formulation of optimization problems is introduced through some exemplary shape optimization studies, while the concept of a Pareto front is explained. Different methodologies are then introduced to solve optimization problems, such as genetic algorithms, particle swarm optimization, metamodel assisted optimization techniques and gradient based methods. The latter also discusses methods to compute the gradient efficiently, i.e. by using the adjoint method. The different techniques are then illustrated by a large number of examples.

Learning outcomes: The learning objective is to introduce the student to the different optimization techniques that can be used for shape optimization problems. While very expensive CFD simulations are generally needed for aerodynamic design improvement, the focus is to find computationally cheap methods that reach optimal designs with a minimum of CFD simulations. Students should be aware of the advantages and disadvantages of various optimization methods and understand the underlying mechanisms that allow reaching for improved designs. This course is also offered biennially to external participants from industry and research centers and PhD students preparing a thesis

Teaching forms: Formal lectures (100%)

Course Notes:

- Introduction to Multidisciplinary Design Optimization of Turbomachinery Components, T. Verstraete, VKI LS 2020 (part of)
- Introduction to Multidisciplinary Design Optimization, slides, T. Verstraete

Evaluation The evaluation consists of an oral exam where the student's knowledge of different optimization techniques is tested.

6.35 INTRODUCTION TO PROPULSION (PRP – 2.0 ECTS)

Lecturers: B.H. Saracoglu, T. Verstraete

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by TU department students.

High-speed propulsion systems remain as the main enabler component for the future military and civilian aerial platforms and space access vehicles. The course aims at covering the fundamental aspects of the critical components and overall

propulsion system for various flight missions including the supersonic and hypersonic trajectories. The content includes the foundational physics of the compressible flows observed in the ram/scramjet flow path, detonation engines as well as through the components of the turbo-jet/fan engines specifically used for supersonic flight. Quantification of the performance parameters of these engines as well as how to maximize the output of the overall propulsion systems is one of the focus areas to be covered.

Learning outcomes: The learning objectives of the course are to gain fundamental understanding on principles of propulsion relevant to high-speed aircraft technologies, to acquire knowledge on state-of-the-art supersonic and hypersonic propulsion systems and their critical components as well as the flow physics involved in these engine components.

Teaching forms: Formal lectures (10h), course project assignment for the students to prepare individually (20h), student self-study for the course material (20h).

Course Notes:

- Course notes are being prepared ahead of this course's first offering this academic year.
- Lecture slides SARACOGLU, BH (2024), "ATP-2 Propulsion Lectures" and additional material to be updated.

Evaluation The evaluation consists of a presentation of a course project assignment (of a given topic (50%)) and an oral exam (50%).

6.36 TP Tutorial (TPTUT – 2.0 ECTS)

Lecturers: T. Verstraete, S. Lavagnoli, F. Fontaneto

Course type and status: This course is a design-exercise / laboratory course. It is an optional course for TU department students.

The objective of the tutorial is to offer the students the possibility to apply the theory and concepts acquired in the introductory and advanced courses to practical applications and problems in the field of turbomachinery and propulsion. Based on interest and fit with selected course work and the Research project, the student **can choose between three types of tutorials** in consultation with the faculty:

- DESIGN LAB
- CFD LAB
- INNOVATION LAB

Through close interaction and exchanges with the instructors, the student will perform the design of a turbomachinery component (either a compressor or a turbine) in the DESIGN LAB, conduct a detailed numerical analysis of a component

(CFD LAB), or propose a technical and financial proposal for a hypothetical research program that answers a specific challenge in energy conversion/propulsion systems (INNOVATION LAB). The different LAB types are further described as follows.

6.36.1 DESIGN LAB **Fontaneto, Lavagnoli**

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 (ATP-I & ATP-II, advanced courses on turbines or compressors). The design object will be defined in agreement with the choices of the student's specialization courses

Learning outcomes: 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 must 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.

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.

Teaching forms: Exercise 100%.

Course Notes:

- All Turbomachinery course notes used in the courses ATP-I & -II,
- Course notes provided in AC-AT/RC/AC courses

Evaluation The evaluation is based on a written report that documents the design strategy, methodology and the final design. The grade is based on the report quality (30%), and on the quality of the design or modeling choices assessed during an individual interview addressing both the theoretical and the practical challenges faced during the exercise (70%).

6.36.2 CFD LAB — Verstraete

The purpose of the Turbomachinery and Propulsion CFD tutorial is to advance CFD application skills necessary to conduct meaningful analysis for purpose of Research or Industry R&D. In focus of the CFD LAB is to explore the interdependent triangle of the flow physics, the modeling assumptions and the numerical methodology in a tension field of limited time and resources. Each student will work on a specific assignment, either individually or with another colleague. For the assignment, students are encouraged to come up with their own proposals but can also pick a subject in discussion with faculty. There will be weekly to bi-weekly seminars, where each student presents own advancements and engages in the review and support of the other participants. The seminars thus provide an opportunity to learn on a broader range of CFD applications and perspectives in rather short time by changing the role from presenter (of own work) to peer reviewer (of other work). The student will practice the set up and execution of a CFD analysis or optimization task, starting from defining an optimized solution strategy for a problem at hand, then performing one or more of the main work steps – which can well require iteration – such as mesh generation, the choice and formulation of boundary conditions, the setting of parameters for the numerical scheme applied and the chosen turbulence or transition modeling. In the seminar, the student will practice giving regular progress reports on slides according to defined structure, receiving and giving supportive feedback from / to their peers.

Teaching forms: Lectures 10%, seminars 25%, exercise 65%.

Course Notes:

- All Turbomachinery course notes used in the courses ATP-I & -II,
- Course notes provided in AC-AT/RC/AC courses
- Course notes provided in courses oriented to numerical methods and CFD simulations

Evaluation Regular engagement in the seminars and a brief report will be required that documents the CFD project conducted with a project plan, the solution strategy, the methodology and the final results. The grade is based on the weighted grade average of the seminar engagement grade (35%) and at the end with the closure presentation (30%) and the evaluation of the report (35%).

6.36.3 INNOVATION LAB Verstraete, Lavagnoli

Recently, the innovation tutorial has been added to the curriculum for pursuing technical-economic exploration of new energy conversion systems and disruptive technologies for climate-neutral transportation, power generation and processing technologies. The tutorial will provide guidance for a structured approach in exploring new fields starting from brainstorming techniques, assessing technical feasibility with reduced-order models or textbook formulas to eventually draft a venture capital pitch or a scientific project proposal in a limited time to achieve a TRL-1 at least (Technology-Readiness-Level). The student will be assigned the task to solve a specific technical question for the improvement of an existing or entirely new turbomachinery or energy system technology. Students are also encouraged to present their own ideas to define the subject of their innovation lab in consultation with faculty. The lab work consists of the preparation of a research proposal that describes the technical work and activities required to answer the project assignment, including demonstrations of the technical feasibility and scientific soundness of the proposed research methods. The technical proposal will be supported by a planning and a budget estimation for the implementation of the project proposal. The subject of the lab, constraints, and other boundary conditions relevant to the lab assignment will be provided and discussed with the instructors at the start of the innovation lab. The lab assignment will be preferably performed by groups of two students.

Teaching forms: Guided project work 100%.

Literature: Specific publications, books and other notes may be suggested by the lecturers depending on the lab subject.

Evaluation The evaluation is based on a brief technical report and an individual interview with the lab instructors aimed at achieving a successful TRL-1 level. Thus, the following aspects will be assessed: a technical description with the expected benefits supported by initial analysis, an identification of potential risks, a potential implementation roadmap with an outline of the next steps leading to a TRL-2 and a TRL-3 level. The grade is based on the student's engagement during the tutorial (25%), the originality and correctness of the proposed technical work (50%) and the feasibility of the roadmap (25%).

6.37 Introduction to Atmospheric Flows (ATMOS – 2.0 ECTS)

Lecturers: W. Munters (Coordinator), G. Glabeke, N. Coudou, S. Gremmo

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR, EA, TU department students.

This course serves as an introduction to basic principles of the physics of atmospheres, and is optional for all students. Emphasis is put on the relation between flow physics and modeling. Topics include the general structure of the atmosphere,

atmospheric dynamics, boundary layer meteorology, field and lab scale testing, and numerical modeling. This course is continuously updated following the research activities at VKI.

Learning outcomes: At the end of the course the student should understand the basic vocabulary and philosophy of the physics of atmospheres:

- Energy balances in the atmosphere
- Driving forces and general circulation structure in atmospheric dynamics
- Concepts of atmospheric stability and its role in the atmospheric boundary layer
- Working principles of instruments used for atmospheric measurements, including their strengths, weaknesses, uncertainties and cost
- Scaling rules applied to model the atmospheric boundary layer experimentally in a wind tunnel
- Strategies for modeling atmospheric flows on a range of scales and fidelity
- How to set up and run a weather model

Teaching Forms: Formal lectures 12 h, Hands-on weather modeling session 2 h

Course Notes: VKI Lecture slides compiled by lecturers.

Literature References in the course notes **Evaluation** The evaluation is done by a closed book exam. A 1 page handwritten formula sheet can be used.

6.38 ICING PHYSICS AND ICE ACCRETION SIMULATION (ICING – 2.0 ECTS)

Lecturers: S. Özgen, N. Coudou, J. van Beeck (VKI coordinator)

Course type and status: This course is a lecture course. It is not mandatory in any department; it can be selected as an optional elective course by AR, EA, TU department students.

This course serves as an introduction to basic principles of icing physics and ice accretion simulation and is optional for all students. Emphasis is put on the relation between icing physics, meteorological aspects, important factors affecting icing and icing conditions defined in airworthiness certification requirements. This course is continuously updated following the research activities at the VKI.

Learning outcomes: At the end of the course the student should understand the basic vocabulary and philosophy of icing physics:

1. Aerodynamic effects of icing
2. Factors affecting icing and their definitions: Liquid water content, temperature, median volumetric diameter, airspeed, temperature, water catch rate, relative humidity
3. Icing clouds: stratiform clouds, cumuliform clouds
4. Kinds of ice: rime ice, glaze ice, mixed ice, beak ice, runback water
5. Icing conditions defined in airworthiness certification requirements
6. Steps of ice accretion simulation:
   - flow field solution,
   - droplet trajectory and collection efficiency solution,
   - convective heat transfer coefficient calculation,
   - ice growth rate calculation; Messinger Model and Extended Messinger Model

Teaching Forms: Formal lectures 12 hours.

Course Notes: VKI Lecture Notes and Slide compendium.

Literature References in the Lecture Notes.

Evaluation The evaluation is done by a closed book exam.

6.39 NUMERICAL LABORATORY 2 (NLAB-2 – 2.0 ECTS)

Lecturers: P. Schrooyen, O. Chazot

Course type and status: This course is a hands-on numerical-laboratory course. It can be selected as an optional course by AR Department students.

This course builds on the introductory Numerical Laboratories but has more emphasis on nontrivial computational projects. These projects implement finite volume and finite element methods, as well as Krylov subspace methods for the solution of linear systems.

Learning Outcomes: Students should be able to implement and validate numerical methods for nontrivial problems. They will be able to organise the workflow required to do this, from understanding of the theory to choosing algorithms, and writing complex codes, written in either high-level programming languages (C, C++, FORTRAN) or script languages (Python, MATLAB).

Teaching forms: Formal lectures (25%), exercises on computer (75%) **Course Notes**:

INM / ANM Course Notes and various selected papers.

CHAPTER 7

Lecture Series

See VKI website www.vki.ac.be for list of Lecture Series running during the current academic year.

Part IV

Appendix

CHAPTER 8

Extended descriptions of VKI facilities and instrumentation

8.1 VKI 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%.

- 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 investi-

gation on the consequences of liquid sloshing due to seismic activity on the different internal structures of the MYRRHA reactor.

- 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. It can also inject droplets for ice accretion research, thus operating as an ICING wind tunnel.

- 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. 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 x 106/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 schlieren/shadowgraph imaging system, and PIV capability. Reynolds number to 1×10^8/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 numbers 5 and 6 in a 120mm diameter free jet, with a schlieren/shadowgraph imaging system, and infrared measurements capability. Reynolds number from 3×10^6/m to 30×10^6/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. Free-flight measurement technique for non-intrusive aerodynamic measurements. Reynolds number 3×10^7/m at Mach 15. Operation with nitrogen or CO_2, 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 (CO2) can be used. Particles addition for simulation of dusty Mars atmosphere, and model pre-cooling to simulate Mars entry initial conditions. Capability of simulation of Titan atmosphere radiation for the Huygens entry was added.

- The "Plasmatron": A high enthalpy facility generating an argon, air or CO2 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 8000 K, test chamber pressure from 1 to 200 mbar.

- 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.

- 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.

- 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 5x104 to 8x105.

- High Speed Cascade Tunnel C-3: 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.

- Jet Calibration facility C-4: 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.

- Shock Tube ST-2: 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.

- Compression Tube CT-2: 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.

- Compression Tube Turbine Facility CT-3: 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.

- High Speed Compressor Facility R-4: 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.

- 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 (2.5m^2 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.

8.2 Instrumentation available at VKI

- 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 visualizations, 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 additional Nd-YAG lasers with energy of 150 to 400 mJ are also available.

- Particle Image Velocimetry: A large number of developments in this domain have been made at the VKI over the years. 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 1280 × 1024, 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 4-channel hot wire anemometry system is also available.

- Microcomputers/Acquisition: More than 20 PCs 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 TP department.

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

- Emission Spectrometer System: The optical system consists of a 750 mm focal length Acton Series SP-2750 Czerny-Turner spectrograph, a 100 mm focal length lens with variable aperture and a removable spectral filter to avoid contamination by second order dispersion at wavelengths greater than 500 nm. The spectrometer is equipped with a triple grating turret with 150, 1200, and 3600 grooves/mm respectively. The central wavelength of the dispersion can be changed by a software-controlled rotation mechanism, allowing high resolution spectral scans in the UV-Vis-NIR spectral range. An intensified CCD detector (Princeton Instruments PI-MAX3) with a resolution of 1024x1024 pixels

and a pixel size of 12.8 micron is connected to the exit slit of the spectrograph. Complementary fast-sample spectrometers that cover the spectral range from 200 to 900 nm provide straightforward 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.

CHAPTER 9

VKI Faculty

The name, country of origin, most recent university degree, academic position, and departmental affiliation of each member of the faculty are listed below.

- **BEECK J., van (The Netherlands)**
  Dr.ir. Technische Natuurkunde, Technische Universiteit Eindhoven, The Netherlands, 1997
  Head of Department, Dean of Faculty, Professor, Environmental and Applied Fluid Dynamics

- **CHAZOT O. (France)**
  Docteur en Génie des Procédés, Institut National Polytechnique de Grenoble, France, 1997
  Head of Department, Professor, Aeronautics and Aerospace

- **FONTANETO F. (Italy)**
  Dr. Sca., Università degli Studi di Bergamo, Italy, 2014
  Associate Professor, Turbomachinery and Propulsion

- **GROSSIR G. (France)**
  Docteur en Sciences de l'Ingénieur, Université Libre de Bruxelles, Belgium, 2015
  Assistant Professor, Aeronautics and Aerospace

- **LABOUREUR D. (Belgium)**
  Docteur en Sciences de l'Ingénieur, Université Libre de Bruxelles, Belgium, 2012
  Associate Professor, Environmental and Applied Fluid Dynamics

- **LAVAGNOLI S. (Italy)**
  Dr. Sca., Universidad Politécnica de Valencia, Spain, 2012
  Associate Professor, Turbomachinery and Propulsion

- **MAGIN Th. (Belgium)**
  Docteur en Sciences Appliquées, Université Libre de Bruxelles, Belgium, 2004
  Professor, Aeronautics and Aerospace

- **MENDEZ M.A. (Italy)**
  Docteur en Sciences de l'Ingénieur, Université Libre de Bruxelles, Belgium, 2018
  Associate Professor, Environmental and Applied Fluid Dynamics

- **MUNTERS W. (Belgium)**
  Ph.D., KU Leuven, Belgium, 2017
  Assistant Professor, Computational Fluid Dynamics, Environmental and Applied Fluid Dynamics

- **SCHRAM C. (Belgium)**
  Docteur en Sciences Appliquées, Université Libre de Bruxelles, Belgium, 1997
  Professor, Environmental and Applied Fluid Dynamics and Aeronautics and Aerospace

- **SCHROOYEN P. (Belgium)**
  Docteur en Sciences Appliquées, Université Catholique de Louvain, Belgium, 2015
  Assistant Professor, Aeronautics and Aerospace

- **VERSTRAETE T. (Belgium)**
  Dr. Toegepaste Wetenschappen, Universiteit Gent, Belgium, 2008
  Head of Department, Professor, Turbomachinery and Propulsion

Honorary Professors

- **ARTS T. (Belgium)**
  Docteur en Sciences Appliquées, Université Catholique de Louvain, Belgium, 1982
  Honorary Professor, Turbomachinery and Propulsion

- **BUCHLIN J-M. (France)**
  Docteur en Sciences Appliquées, Université Libre de Bruxelles, Belgium, 1978
  Honorary Professor, Environmental and Applied Fluid Dynamics

- **CARBONARO M. (Italy)**
  Laurea in Ingegneria Aeronautica, Politecnico di Torino, Italy, 1967
  Honorary Professor, Aeronautics and Aerospace
  Honorary Director, VKI

- **DECONINCK H. (Belgium)**
  Dr. Toegepaste Wetenschappen, Vrije Universiteit Brussel, Belgium, 1983
  Honorary Professor, Aeronautics and Aerospace

- **VAN DEN BRAEMBUSSCHE R. (Belgium)**
  Burgerlijk Electro-Werktuigkundig Ingenieur, Katholieke Universiteit Leuven, Belgium, 1968
  Honorary Professor, Turbomachinery

Adjunct Professors

- **BOTTIN B. (Belgium), Institut Supérieur Industriel de Bruxelles (ISIB)**
  Dr. Sca., Université de Liège, Belgium, 1999
  Adjunct Professor, Aeronautics and Aerospace

- **DEGREZ G. (Belgium), Université Libre de Bruxelles**
  Dr. Sca., Université Libre de Bruxelles, Belgium, 1985
  Adjunct Professor, Aeronautics and Aerospace

- **DIMITRIADIS G. (Greece), Université de Liège**
  Doctor of Philosophy, Ph.D., University of Manchester, 1999
  Adjunct Professor, Aeroelasticity

- **HILLEWAERT K. (Belgium), Université de Liège**
  Doctor of Philosophy, Ph.D., Université Catholique de Louvain, 2013
  Adjunct Professor, Computational Fluid Dynamics (CFD)

- **STAPELFELDT S. (UK), Imperial College London**
  Doctor of Philosophy, Ph.D., Imperial College London, 2014
  Adjunct Professor, Aeroelasticity