A E R O N A U T I C S / A E R O S P A C E

Project Subjects for Graduation Theses 2014-2015

The AERONAUTICS/AEROSPACE Department is involved in a variety of research projects with both experimental and numerical aspects. Experimental facilities cover the entire speed range of aerial vehicles from low to hypersonic speed and are equipped with modern instrumentation and data acquisition systems. Numerical projects are concerned with the development of new physical models (e.g. for reacting flows, turbulence, plasma's) and advanced numerical algorithms for solving fluid flow (higher order schemes, solvers, grid generation).
Graduation projects are proposed in the following areas:

1. AEROTHERMODYNAMICS OF RENTRY VEHICLES IN PERFECT GAS TEST FACILITIES

Development of hypersonic vehicles for future access to space or civil transport applications requires improved knowledge of shock-wave boundary layer interactions and transition to turbulence in the hypersonic regime. Experimental and numerical investigations of these phenomena are currently being conducted in the framework of ESA programmes (e.g. EXPERT program for in-flight testing and validation with simulation and ground testing). For the experiments, two VKI facilities are being used : Longshot, which is a free-piston tunnel that produces high Reynolds and Mach number flows of short duration and H3, which produces Mach 6 flow for a range of Reynolds numbers. Topics of current interest include : control surface simulation, heat flux and pressure distribution measurements, instrumentation development, aerodynamic coefficients determination, and facility flow characterization.

1.1 Simulation of Mach 14 Longshot facility

The Longshot is a facility designed to produce a flow for a very short time but at high Mach number and high Reynolds number. This facility can be operated with nitrogen or carbon dioxide.

The purpose of this project is to study the behavior of the piston during all the phase of compression. When the piston is released, it reaches very high speed and a shock appears in front of it. This shock is reflected at the end of the tube before to impact the piston. After several reflections, the pressure can reach up to 4000 bar and the piston stops at the end of the tube.
Tools are now available for 1D modelisation of the behavior of the piston. This new program has first to be adapted to the Longshot configuration. The final objective is to be able to define new conditions with nitrogen, carbon dioxide or other gases. A correct modelisation can also be used to improve the capability of the tunnel by increasing the Reynolds number or the enthalpy. This new tool gives the possibility to investigate the use of the tunnel with air in order to obtain more real gas effects…
The project consists mainly in programming the new code. Existing experimental data will be used for comparison. Participation to new measurements can eventually be included.

This project requires capabilities in numerical modelling, aerodynamics and thermodynamics.

1.2 Unsteady computation on oscillating capsule in supersonic regime

The stability of reentry vehicles can be critical in low supersonic and transonic regime. Experiments were performed in this range of condition in order to deduce the stability criteria. Several methods were already tested in these conditions and give results.

This project is proposed in the field of a general study on the dynamic stability of space vehicle during the atmospheric reentry. In order to better understand the relation between the dynamic stability and the flow topology, it is propose in this project to study the flow when the capsule is oscillating. Different experimental approaches have been investigated like unsteady pressure measurement on the capsule or in the wake.

It is propose in this project to simulate the flow around a reentry vehicle. The first step consists in static computation in order to assess the effect of the support and how it can affect the flow. Then, unsteady computation should be done on a static model. Comparison with existing experimental results should help in a better understanding. The final objective is to perform unsteady CFD on an oscillating capsule.

The results will be analyzed to better understand the relation between the flow topology and the behavior of the vehicle.

Models tested will be the BLAST capsule because this model was recently tested in the transonic/supersonic wind tunnel.

1.3 Validation of the experimental methods used on oscillating capsule in supersonic regime to find the aerodynamic derivatives

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This project is proposed in the field of a general study on the dynamic stability of space vehicle during the atmospheric reentry. The experimental method used to compute the damping of a space vehicle was never validated properly.

A special set-up to impose a force proportional to the angular speed will be designed and manufactured. The solution can be electric, mechanic, hydraulic … .
Instrumentation associated to the set-up should be installed in order to measure accurately the applied forces. This set-up will be used with a real vehicle and a deep error analysis will be done on the results: the model under investigated for this study will be the BLAST capsule which was recently tested in the transonic/supersonic wind tunnel.

1.4 Design of a new experimental set-up to study the aerodynamic derivatives thank to the forced oscillation capsule

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Up to now, the study of the stability of capsule by experimental tools was limited to the pitch damping. Only 1 degree of freedom was considered.
The purpose of this project is to design the new generation of experimental set-up. The new equipment will allow deducing the pitch damping of course, but also the other derivatives.
Two or more degree of freedom can be considered in order to study the coupling between the different movement
The different possibilities will be studied and special care will be taken to limit the support effect. Associated measurement techniques will be investigated.

This project required a good mechanical engineer with solid knowledge in aerodynamics.
Numerical simulation can be used during this project in order to validate some choices.

Models under consideration in this project will be the BLAST capsule and the IXV vehicle. These models represent the two main configuration or a reentry vehicle.

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2. AEROTHERMODYNAMICS OF SPACE REENTRY VEHICLES

2.1 Experimental investigations on aerothermodynamics

Spaceships entering a planetary atmosphere are exposed to very high temperature flows. To study the thermal resistance of their heat shields, two wind tunnels generating a high temperature (up to 10 000 °K) plasma jet are available at the VKI. Also a large number of computational models of high temperature flows have been developed over the past decade.
A number of projects are available in this area and they include accurate simulation of re-entry conditions, characterization of plasma flows, thermal protection system (TPS) tests and use and development of numerical tools to investigate aero-thermodynamic phenomena:

2.1.1 Simulation of re-entry conditions

This research activity focuses on the duplication of the aero-heating environment on the critical components of spacecraft for different planetary re-entry conditions in a ground-test facility. Current projects include:

- Simulation of Mars aerocapture
- Thermal history of the heat shield during the entry phase
- Entry condition in dusty atmosphere and CO_2 atmosphere

2.1.2 Characterization of plasma flows and TPS tests

This research activity is concerned with the development of specific measurement techniques for high enthalpy flows. It includes adaptation of classical intrusive measurement techniques in severe environments, combined instrument measurements and plasma diagnostics by emission or absorption spectroscopy.

Specific topics are:

- Unsteady pressure and temperature measurement
- Catalycity determination
- Hemispherical and multispectral emissivity determination
- Reacting boundary layer characterization by spectroscopy measurements

2.1.3 Development of hypersonic flight extrapolation methodology for supersonic plasma wind tunnels

In the context of space vehicle design for ESA missions, the project will deal with an investigation of the duplication of the aerothermodynamics features for a hypersonic flight in high-enthalpy wind tunnels. Hypersonic similarity laws, local duplication of real flight, reactive boundary layer, wall chemistry will be considered.

2.1.4 Development of a new probe for intrusive radiative heat flux measurements in high enthalpy flows

(theory/experiments)

The aim of this project is to extend to radiative heat flux measurement the set of intrusive diagnostic capabilities available at the VKI for high enthalpy facilities. Starting from available material, the student will be involved in designing, building, and qualifying a new and challenging probe for in situ measurements of radiation in the UV and visible spectral ranges for air plasmas representative of Earth entry conditions. An extensive experimental campaign will be carried out by means of the new diagnostic probe for different test and operating conditions.

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2.1.5 Boundary layer control using DBD plasma actuator

(theory/experiments)

The control of the boundary layer separation is a challenging topic regarding potential active control using Dielectric Barrier Discharge (DBD) plasma. The aim of the project is to provide a phenomenological performance map of the DBD plasma actuator applied to a simple configuration (flat plate, step) for subsonic flow separation control. The student will be involved in the experimental bench design and implementation. For a wide range of operating conditions, he will characterize the effect induced by the plasma on the flow by means of simple visualization techniques and analyze the experimental data.

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2.1.6 Enthalpy Measurement in plasma flow
(theory/experimental)
To increase the accuracy of the free stream characterization at Plasmatron facility, a direct enthalpy measurement probe for Plasma flows is being developed at VKI. Starting from available material, the student will be involved in improving the current design, building and qualifying a new and challenging probe. A number of experiments in VKI Plasmatron facility will be carried out to build a database for a large pressure range and preferably at high heat flux rates. This subject also includes using other available tools at VKI to validate the probe design.
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2.2 Numerical investigation on aerothermodynamics

2.2.1 Study of non equilibrium phenomena in compression and expansion flows

In the frame of atmospheric re-entry conditions, investigations are made using 1D codes (like Shock tube code and Nozzle code) to study non equilibrium phenomena in expansion and compression situations. The starting point is the classical thermal non equilibrium approach developed by Park at NASA and can proceed with the implementation of vibrational specific model (STS).

2.2.2 Heat flux modelling for hypersonic experiment instrumentation

The VKI is actively involved in hypersonic flight experiments. In the framework of an ESA flight experiments project, we intend to perform inflight temperature measurements on the surface. It is known that several aspects influence the quality of the results. The VKI proposes that a detailed model of the Flight Instrumentation will be developed with a focus on the thermal behaviour. The heat flux into the surface and body shall be determined from the temperature measurements. Critical points shall be analysed.

2.2.3 *Catalysis in hypersonic flows*

The heat flux into the body of a hypersonic vehicle is one of the limiting parameters in its design. It is strongly dependent on the chemical gas-surface interaction. The VKI proposes to review existing models, implement them into a CFD code, and compare the obtained results. Optionally, a further model shall be developed based on the findings that represent correctly the phenomenological behaviour of the interaction.

2.2.4 Energy accommodation in gas surface interactions

It is known that exothermic reactions close to the wall contribute only partially their reaction heat to the wall. A non negligeable part serves to excite the recombined molecules leading to a non-Boltzmann distribution of internal energies. The VKI proposes to review recent techniques to determine this ratio of heat contributions and develop a methodology applicable in the VKI Plasma Facilities and to implement it into a CFD code.

2.2.5 Transition in supersonic/hypersonic flow

This subject will start by an update of the state of the art bibliography on the transition models/experiments in very high speed flow. The configuration under interest is a cubical or cylindrical roughness inducing transition in its wake. The subject will is containing benchmark exercises of existing transition models. These exercises will involve the use of the CFD framework CoolFluid or results obtained with this frame work by VKI researchers. Finally, new models or variation of previous models will be proposed, implemented and tested. The different part of the subject may be tackled independently.

2.2.6 Turbulence models for supersonic/hypersonic flow

This subject will start by an update of the state of the art bibliography on the turbulence models/experiments in very high speed flow. The subject will continue with the validation of previous VKI implementation of turbulence models by developers on the CFD framework CoolFluid. Finally, new models or variation of previous models will be proposed, implemented and tested. The different part of the subject may be tackled independently.

2.2.7 Computation of full Re-entry Trajectory

This subject involves the development of a simple and fast code allowing the computation of orbital trajectories of nano satellites once released by the launcher. The code will take into account all the physics allowing to tracks the Cubesat from its original altitude in the Mesosphere Thermosphere layer till its re-entry up to 80 km. The subject is part of a larger Cubesat project.

2.2.8 Development of a hypersonic flight extrapolation methodology for supersonic plasma wind tunnels

(theory /numerics/experiments)

In the context of space vehicle design for the space exploration program of ESA, this project deals with the duplication of the aerothermodynamics features of hypersonic flight into supersonic plasma wind tunnels.

Keywords: hypersonic similarity laws, flight extrapolation, parabolic equations, reactive boundary layer, wall chemistry.

2.2.9 Development of advanced nonequilibrium models for compressing and expanding flow simulations

(theory/numerics)

Understanding thermo-chemical nonequilibrium effects is important for an accurate prediction of the radiative heat flux to the surface of hypersonic vehicles and for a correct interpretation of experimental measurements in wind tunnels. We propose an innovative work, at the interface between computational chemistry and CFD, in collaboration with NASA Ames Research Center. Rate coefficients and cross-sections computed from first principles, for rovibrational excitation and dissociation of molecular nitrogen, will be used to study the dynamics of the excitation / dissociation mechanism in compressing and expanding flows. Then, kinetic theory will allow for the macroscopic conservation equations to be derived, together with the expressions for the transport fluxes and chemical production rates.

2.2.10 Study of detailed chemistry / radiation coupling in atmospheric entry flows

(theory/numerics/experiments)

During atmospheric entries, the gas heated in the shock layer emits radiation that contributes to the incident heat-flux to the vehicle surface. Radiation modeling involves determination of the population distributions over the internal energy levels and of the radiative contribution of each of these levels. At the early reentry stages for lunar and Martian missions, the electronic energy populations depart from equilibrium. We propose to develop a reduced collisional-radiative model that will be used for the first time in 3D CFD simulations. The metastable electronic excited states of the nitrogen and oxygen atoms will be considered as separate species. The high-lying excited states, that produce radiation, will be grouped in a limited number of electronic levels.

2.2.11 Pre- and post-flight data analysis for the EXPERT mission
(numerics/experiments)
The VKI is currently the primary investigator for two payloads for the EXPERT mission of ESA, dealing with: 1) gas-surface interaction over a thermal protection material junction, 2) characterization of an isolated roughness induced transition. These payloads have been designed and qualified to be integrated into the vehicle, which is expected to fly in early 2011. Physico-chemical models and computational tools developed in the Aeronautics and Aerospace Department at the VKI will be used for pre- and post-flight data analysis for this flight demonstrator.

2.2.12 Development of physico-chemical models for ablative materials
(theory/numerics/experiments)
The choice of the heat shield material is a critical problem for engineers. A new class of ablative materials, low density carbon / resin composites, is considered for numerous forthcoming missions. We propose to calculate the kinetic data for carbon-phenolic resin decomposition and transport of gaseous species for these materials. These data will be implemented in a high-fidelity model for ablation developed in collaboration with the Space Technology Division of NASA Ames Research Center. The model developed will be used for simulation of ablation experiments carried out in the VKI plasma facilities, for carbon / resin composites.

2.2.13 Uncertainty Quantification for the space exploration program
(theory/numerics/experiments)
To avoid mission failure and ensure safety of the astronauts and payload, engineers resort to safety factors to determine the heat shield thickness, at the expense of a reduced mass for the embarked payload. Determination of safety factors relies on Uncertainty Quantification (UQ) that aims at developing rigorous methods to characterize the impact of "limited knowledge" on (here) the heat flux. We propose to address the issue of stochastic aerothermodynamics in collaboration with Stanford University and the University of Texas at Austin. Their state-of-the-art tools for UQ will be adapted to quantify the influence of uncertain parameters related to the advanced physico-chemical models developed at the VKI. Experimental data will be used for validation (plasmatron and shock-tube facilities, as well as several ESA flight demonstrators, such as Expert).

2.2.14 Stability of hypersonic flows in the transition regime from laminar to turbulent
(theory/numerics)
The transition from laminar to turbulent is currently not well understood in hypersonic flows. This phenomenon is associated with an undesirable rise of the heat transfer on the thermal protection material for atmospheric entry vehicles. A conventional linear stability approach cannot be used to study hypersonic flows. We propose to derive a general Parabolized Stability Equation (PSE) accounting for generally curved surfaces, three dimensional disturbances, and thermo-chemical nonequilibrium effects, based on specialized software such as SAGE. The general PSE derived will be compared to partial equations available in the literature and will be implemented in code starting from an existing VKI solver. Strong interactions with VKI researchers studying hypersonic transition by means of a broad spectrum of tools (experimental and numerical models) will be crucial for the success of this project.

2.2.15 Development of an approximate Riemann solver for plasmas in thermal nonequilibrium
(theory/numerics)

Developing shock-capturing numerical schemes for plasmas in thermal nonequilibrium is a challenge due to the nonconservative mathematical structure of the system of macroscopic equations. For nonconserva
tive systems, the jump relations for discontinuous solutions depend on diffusion. We propose to develop an approximate Riemann solver for a new set of equations, for plasmas in thermal nonequilibrium, derived from kinetic theory. This problem is related to important applications such as plasma control of hypersonic cruise vehicles for the US Air Force, influence of precursor electrons in reentry flows for ESA and NASA missions, and supernova radiation.

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2.2.16 Plasma (ICP) Simulations for a Re-Entry CubeSat
(theory/numerics)

In the framework of the QB50 project, VKI's reentry CubeSat will carry a number of in-flight experiment payloads on board. The in-flight experiments will be designed according to the scientific questions associated with the re-entry physics. This project deals with preparing and making ICP (Inductively Coupled Plasma) simulations on the full CubeSat, also developing post processing tools. The outcome of this work will eventually provide suggestions for scientific payload design such as TPS recession sensors, heat flux gages, spectrometers etc.
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2.2.17 CFD of a CubeSat during Re-Entry
(numerics)

Development of a reentry CubeSat requires significant computational work based on the re-entry trajectory. In the framework of QB50, computations have to be done in order to provide input not only to the stability mechanism development to achieve the desired atmospheric re-entry but also to the in-flight experiment design in case of side panels (i.e skin friction measurements) and base flow (i.e fast response pressure transducers) investigations. The entire vehicle and the regions of interest should carefully be studied to contribute instrumentation decision process. Based on previous work done at VKI, the optimum nose shape design can be further developed.
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2.2.18 Rarefied flow simulations for the stability of a CubeSat in orbit
(numerics)

The QB50 Project aims at realizing a network of CubeSats in very low Earth Orbits (altitude less than 320 km) and this results in the opportunity to develop aerodynamic stability tools for CubeSats. Aerodynamic attitude control mechanisms would have significant mass, power and volume budget reductions compared to traditional attitude control subsystems with reaction wheels. For this purpose, rarefied flow simulations of various innovative aerodynamic control mechanisms (fins, tethers, flower or badminton style panels, parachute, etc) and aerodynamic drag augmentation systems need to be performed by Direct Simulation Monte Carlo (DSMC) and 6-DoF trajectory simulators.
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3. Model form uncertainty quantification for RANS turbulence and mixing models

Turbulence and turbulent mixing are fundamental processes in the vast majority of aerospace applications. While large-eddy simulations can provide accurate solutions for turbulent flow problems, they impose a significant increase in computational cost, and Reynolds-averaged Navier-Stokes simulations remain the most commonly used tool within the engineering community because of the affordable computational cost. The drawback of RANS turbulence and turbulent mixing models is the introduction of uncertainties in the solutions, and a tool to quantify these uncertainties could significantly improve the predictive capabilities of the approach. The following projects all aim to contribute to the development of such a tool.

3.1 Evaluating RANS turbulence model performance

This project will consider different flow configurations (channel flow, wavy wall with separation, jet in crossflow) for which DNS or LES datasets are available to evaluate turbulence model performance. The model errors will be evaluated by comparing the Reynolds stresses obtained from different RANS models to the DNS or LES results. The effect of the coupling to the mean flow will be eliminated by freezing the flow to the time-averaged DNS flow field and only solving the transport equations for the turbulence quantities. Special focus will be on investigating the role of turbulence production and dissipation terms in the prediction of the turbulence kinetic energy.

3.2 Implementing a turbulence model uncertainty quantification framework in OpenFOAM

This goal of this project is to implement an existing model form uncertainty quantification framework in the opensource code Openfoam. The framework consists of:

1. Computing a marker that identifies in which regions of the flow the model is not trusted.
2. Performing an eigenvalue decomposition of the anisotropy tensor obtained with the original Reynolds stress model.
3. Introducing perturbations in the magnitude, eigenvalues and eigenvectors in the previously identified regions.
4. Recompose the perturbed Reynolds stresses.
5. Compute the divergence of the perturbed Reynolds stresses and impose the modified source term in the momentum equations.

The framework will be tested for flow fields of different complexity (channel flow, wavy wall with separation, jet in crossflow)

3.3 Evaluating RANS turbulent mixing model performance

This project will consider different flow configurations (channel flow, wavy wall with separation, jet in crossflow) for which DNS or LES datasets of the flow and scalar fields are available to evaluate turbulent mixing model performance. The focus will be on mixing models based on the generalized gradient diffusion hypothesis. The model errors will be evaluated by comparing the scalar field and the turbulent scalar fluxes obtained from different mixing models to the DNS or LES results. The effect of the coupling to the flow and turbulence equations will be eliminated by freezing the mean and turbulent flow quantities to the time-averaged DNS or LES result, hence only solving the transport equations for the scalar. The validity of the generalized gradient diffusion models and the importance of correctly predicting the different terms in the tensorial diffusion coefficient will be investigated

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