International Conference on Engineering Education and Research "Progress Through Partnership"

A Masters Program in Computational and Experimental Turbulence

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KEYWORDS: *turbulence, fluids, engineering, international, students*

ABSTRACT: *The advent and wide-spread utilization of modern computational and measurement capabilities has greatly expanded the need for highly trained engineers who can interpret the results. Unfortunately, although most engineering flows are turbulent, turbulence remains the foster child of engineering education, since traditional undergraduate engineering programs do little to prepare students for the realities of industrial expectations, or even for Ph.D. studies in most disciplines involving transport processes. Several years ago we began under the auspices of the International Masters Programs at Chalmers, an innovative program to prepare students for study in the wide variety of engineering problems which involve turbulent flows.*

Because of its omnipresence, turbulence presents one of the greatest challenges to the advancement of both science and engineering. Whether the primary interest is the environment, energy, industrial processes, or aero/hydrodynamic design, turbulence often dominates. In the absence of a complete theoretical understanding or even of general turbulence models, the practice of turbulence design is as much an art as science or engineering. Unfortunately because of its difficulty, the study of turbulence is often postponed until a very late point in graduate study, and sometimes ignored entirely. Thus though most flows of practical importance are turbulent, even most Ph.D. students learn little to nothing about turbulence. As a consequence, though modern computer codes contain turbulence models (usually many different ones), engineers are poorly prepared to use them, since most lack the tools to decide which to use or even whether they should use them at all. The same is true with modern experimental techniques which can be used successfully only in conjunction with an understanding of the turbulence phenomenon being investigated -- an understanding which is often completely absent.

The Chalmers program reverses the usual trend in engineering education toward a broad-based approach to the final undergraduate years. Instead it encourages the students to gain an in-depth understanding of turbulent flow before moving into the wide variety of applications where the knowledge can be applied. This innovative program introduces both the science and the art of turbulence to students during their fourth year of undergraduate studies, or at the very beginning of graduate studies, so this knowledge can be immediately employed. The fundamental concepts of turbulence are taught together with advanced computational and experimental methodologies, so the student not only has an understanding of all three, but can learn how they can be used together. The goal is to prepare students to directly apply the skills and knowledge learned to a wide variety of scientific and engineering disciplines wherever turbulence occurs.

Students are then encouraged to chose electives and master projects to apply this knowledge to a wide range of disciplines. These have ranged so far from combustion to air-sea interaction, from automotive technology to wind power generation, most in industry or abroad. As we hoped, about 2/3 of the graduates have moved to other disciplines for further study or employment, and about 1/3 continue in the study of turbulence itself.

This paper will report on our progress in the past two years with the more than 40 students who will have completed the program by June, the response of employers, and our plans to modify the international program to accommodate the more general goals of the Bologna agreement.

1 INTRODUCTION

The flow of liquids and gases is very common in industrial processes and apparatus, and also in everyday practice. We need only think of the many pumps and fans we find in the heating and ventilation systems of our houses to realize the truth of this. Other examples are found in the weather system, airplane wings and car engines, etc. In many cases the character of the flow field determines how well a certain apparatus or system works, like the flow induced force on an airplane wing. The design engineer needs to understand how he can influence the character of the flow field to improve on the performance properties of the apparatus. In other cases the flow acts to a disadvantage, like drag on automobiles, and the engineer needs to understand what is possible to do to counteract the negative influence of the fluid flow on the performance of the apparatus. In either case it is necessary for engineers developing these systems to have a proper understanding of all the phenomena governing fluid flows.

A particular problem is at hand in most fluid problems in industrial practice as well as in everyday life: the flow is turbulent. We all have experienced this as for example gust winds or the fluctuating force on a hand stretched out of a car window. Because most flow fields are turbulent the engineer must develop the skills necessary to deal with this phenomenon to be able to design apparatus and processes that work well. Yet, this phenomenon is not understood, and the engineer must learn how to deal with it in the absence of a proper understanding. Turbulence is one of very few problems in classical physics that is not yet understood, and it poses a real challenge to its practitioners.

Our fundamental lack of understanding of turbulence as a phenomenon, and the simultaneous necessity to be able to deal with it in engineering design, poses a particular problem on teaching the subject. Should we first teach all that is known about the mechanics of fluids, and then introduce our limited understanding of turbulence, or should we integrate turbulence at an early stage in the teaching of fluid mechanics and introduce the added complexities it causes in the various flow fields without being able to offer a complete understanding?

The first alternative is probably the most common choice. It has the advantage that the subject may be presented efficiently and in a very orderly fashion. On the other hand, turbulence is not introduced until the end of the program, typically at the doctoral level, and before that the students are left with only some empirical correlations for example of the drag on certain bodies. They have no real chance to be able to understand what design changes could possibly lead to an improvement in the functioning of a device or a reduction of negative influences, like drag, without negatively affecting other properties. This latter ability is precisely what marks a successful engineer. Another effect of this approach is that interpretation of experimental results is largely dependent on a proper understanding of at least the basic statistical nature of turbulence, and, with a lack of such an understanding, the engineer cannot even take advantage of the outcome of experiments, which would otherwise provide evidence of the functioning of the real world.

The second alternative is that explored here, and has the advantage that the students are made aware of the full complexity of fluid flow from the very beginning. Already after a first elementary course on the statistical properties of turbulent flow fields they will be able to understand how to set up an experiment, and how to interpret the results. They will be able to understand the way the turbulent fluctuations affect the gross properties of the mean flow field. They will be able to use commercial codes to compute flow fields, and to judge whether a realistic result is produced or not. Yet, of course, a deeper study is required to understand the mechanisms how turbulence actually alters the mean flow field, and to understand how it should be properly modelled. The drawback of this approach to teaching fluid mechanics and turbulence is that, given a limited time frame to teach the subject, the subject may appear less rational to the student, and some other important aspects of fluid flows, like compressibility, chemical reactions, multi-phase flows, and rheology may have to be sacrificed until later.

The purpose of this paper is to describe a course package set up to teach turbulence as an integral part of a fluid mechanics program at the master's level, and to report on the outcome of this program. The program was designed to fit into the framework of international master's programs at Chalmers University of Technology, Sweden. It recruits students from all over the world, and is taught entirely in English.

2 THE TURBULENCE PROGRAM

2.1 International master's programs at Chalmers

The international master's programs at Chalmers were created more than a decade ago to provide a mechanism to create an international exchange of students. At that time quite a number of student at

Chalmers went abroad for their final year of study, but foreign students were reluctant to come to Sweden due to the language barrier. To bring about a balance in the exchange of students study programs were created, which:

a) should be taught entirely in English, and
b) should be offered in areas where Chalmers was particularly strong.

These international master's programs turned out to be a success. As time went on more programs were added, and today the number of students coming to Chalmers from abroad far outnumbers the students from Chalmers doing their final year at other universities.

The international master's program in Turbulence is one of these programs, and is now running for its second academic year.

2.2 Unique features and overall view of the Turbulence program

The Turbulence program is designed in such a way that all relevant aspects of turbulence are taught parallel to general fluid mechanics. The turbulence courses introduce the basic statistical description, the theoretical understanding presently at hand, a thorough basis of computational and experimental techniques, and the modelling of turbulence. The instruction emphasises that all our knowledge should be considered tentative in the absence of a complete theory of turbulence. Students are encouraged to accept all ideas as 'working hypotheses', not as facts. The basic supporting argument is that one should not be rigid in thinking or instruction in a field about which we know so little – like turbulence.

The fluid mechanical package gives a series of courses covering the basic equations, their fundamental solutions and the most important phenomenon encountered, like boundary layers and potential flow fields, both compressible and incompressible, separation and transition to turbulence. The course package spans from the intermediate level to the doctoral level, and can thus offer students with quite widely varying backgrounds a sound improvement in knowledge. This basic set of courses is supplemented by a number of electives in a variety of related subjects like combustion and combustion engines, turbo-machinery, heat transfer and mathematics. The aim of these supplementary courses is to offer the student a possibility to go into other fields of specialization where a proper knowledge of turbulence is a necessity for productive and successful work. The theoretical part of the program is done in one full year of study. The program completes with a project work of duration of one semester. When finished with the program the student should be well prepared to go to any fluid mechanics related position in industry or to carry on as a Ph. D. student at Chalmers or any other university in Sweden or abroad.

The program recruits students from Chalmers undergraduate program and from all over the world, the international group of students forming the majority. Typically ten different nationalities are represented in each class. Chalmers rules prohibit more than twenty international students in each program on the average.

Each course is taught during one quarter of the academic year (8 weeks), i.e., at a very intense rate. Typically the number of contact hours per week is 6-8. In addition to this most courses have shorter project tasks to be handed in for grading or, for the experimental course an extensive laboratory project.

Table 1. The complete course package

Quarter	Compulsory courses	Primary electives	Selection of secondary electives
1	Introduction to Turbulence	Advanced Fluid Mechanics	Fourier Analysis
2	Experimental Fluid Dynamics	Applied Fluid Dynamics	Road vehicle aerodynamic design, Partial Differential equations
3	Turbulence Theory	Computational Fluid Dynamics	Gas Turbine Technology
4	Turbulence Modelling	Convective Heat Transfer	Internal Combustion Engines, Functional Analysis

Four courses on the program are compulsory: Introduction to Turbulence, Turbulence Theory, Experimental Fluid Dynamics, and Turbulence Modelling. Unless the student in his/her undergraduate studies already has not taken courses corresponding to the following primary electives they should be taken concurrently: Advanced Fluid Mechanics, Applied Fluid Dynamics, and Computational Fluid Dynamics. These courses are organized according to Table 1. Note that only a selection of secondary electives is presented. All courses comprise 7.5 ECTS credit points.

In this table it is clear how the turbulence courses and the fluid mechanical courses parallel each other. The secondary electives contain courses in specialized sub-fields in fluid mechanics and related applied fields, as well as a set of courses in mathematics at different levels of difficulty that may be chosen depending on the students' background and interests.

2.3 The four compulsory courses

The compulsory courses are designed to provide a comprehensive knowledge base in turbulence, especially for students who have not had a graduate fluids course and know virtually nothing about turbulence.

2.3.1 Introduction to Turbulence. In the first course, Introduction to Turbulence, the focus is on understanding the averaged equations of motion and the underlying physics they contain. The goal is to provide the student with the tools necessary to continue the study of turbulence, whether in the university or industrial setting, beginning with the basic statistical description of turbulent flow fields. Topics covered include: what is turbulence, the Reynolds-averaged equations, instability and transition; simple closure models, the Reynolds stress equations, simple decaying turbulence, homogeneous shear flow turbulence, free turbulent shear flows, and wall-bounded turbulent flows. Of particular interest are the Reynolds stresses and how they are related to the production, diffusion, pressure-strain and dissipation terms in the transport equations for the Reynolds stresses. A particular feature of this course is that the basic statistical measures needed to properly set up an experiment and evaluate the statistical uncertainty are covered, and illustrated with lab experiments and data.

2.3.2 Turbulence Theory. The course on Turbulence Theory focuses on the advanced methodologies of turbulent flow, with particular attention to those processes which control the production and dissipation of turbulence energy. The concept of "scale" is explored in detail using probabilistic, and multipoint techniques like proper orthogonal decomposition (POD) and spectral methods. These techniques are used to examine how energy is transferred from the mean flow to the turbulence, from one turbulence scale to another, and how energy is dissipated. Similarity ideas are introduced as appropriate to illustrate how the various parts of the flow fit together, and how they are affected by the Reynolds number. The ideas and concepts discussed form the bulk of our understanding of turbulence, and as well the current tools for advancing the state of our knowledge about it. Throughout, the emphasis is on showing how these ideas affect engineering practice, experimental design and computer model development. The goal is to not only learn about current understanding, but to learn about where the problems are so the student is prepared to continue to learn as new ideas and models develop.

In the course one laboratory experiment (grid turbulence) and two computer exercises are carried out to reinforce the students' skills in understanding and analysing turbulent flow fields. Examples of such exercises are decaying turbulence downstream a grid including computation of various spectra, and cross-spectral measurement in a jet used as the kernel for a proper orthogonal decomposition

2.3.3 Experimental Fluid Dynamics. The principal objective of the course in Experimental Fluid Dynamics is to introduce the students to modern experimental techniques and instrumentation used in fluid mechanics, and particularly in turbulence. The student acquires a working knowledge of the interaction of the sensing bodies and flow fields in order to understand both how the flow field is altered by the measurement and how the flow field induces an observable change in the properties of the sensor. A large variety of instruments for a broad range of flow field properties are thoroughly studied and a working knowledge of their use is acquired in laboratory exercises. The course deals with: wind tunnels and other standard equipment, design issues and their use, signal processing with special emphasis on the statistical properties of turbulent flow fields, instrumentation, their use in different circumstances, their advantages and limitations and, in particular, how the sensors interact with the flow field. This includes equipment for visualization, instrumentation for the measurement of for example volume and mass flow, velocity, pressure, wall shear stress, temperature and heat transfer.

An additional aim of the course is that the students afterwards shall be able to design, plan, execute and report an experiment. They shall also have acquired the ability to choose which tool that is right for a specific problem and to be able to critique experiments found in literature. The course consists of a number of lectures and a project that runs throughout the course. The project consists of the design and implementation of a specific experiment. The project results are presented in a written report as well as in individual oral presentations by each group member. This particular course and the way it is presented to the students is the subject of another presentation at this conference, Johansson (2004).

2.3.4 Turbulence Modelling. The object of the course in Turbulence Modelling is to give the students a thorough knowledge and understanding of modern, advanced turbulence models including Large Eddy Simulation (LES). Reynolds stress models (both transport models and algebraic ones) are discussed in some detail. The pressure-strain term is an important part in these models that must be modelled. Different approaches for modelling this term are discussed. Non-linear eddy-viscosity models are also discussed, especially from the perspective of a compromise between modelling accuracy and numerical stability.

Approximately half the course is devoted to Large Eddy Simulations (LES), not because of their present use in applications, but because they represent the foreseeable future. In LES the Navier-Stokes equations are filtered over a small volume. Thereby the dependent variables are split into one subgrid part (turbulent fluctuations smaller than the cell) and one resolved part (turbulent scales which are resolved by our numerical method). The big advantage of LES is that only a small part of the turbulence is modelled (the subgrid scales) and thus dependence of the turbulence modelling is hopefully weak and the accuracy of LES is hopefully high. The disadvantage with LES is that since a large part of the turbulence is resolved, we must solve the unsteady equations, which is one of the main reason why LES is very expensive.

Two projects are carried out by the students. First fully developed flow in a plane channel is considered. The students use and implement a Reynolds stress transport model. All six transport equations are solved. In the second task the students are given DNS data. From this data various exact terms in the transport equations of turbulent quantities (turbulent kinetic energy or shear stresses, for example) are to be compared to the corresponding modelled terms. Different filtered quantities relevant for LES are also computed.

2.4 Primary electives

The primary electives form a more conventional set of advanced fluid mechanical courses. This program differs from the classical approach in that these courses are taught *in parallel* with the turbulence courses, not before. Together with the turbulence courses they provide a fairly comprehensive education in the most relevant aspects of fluid mechanics and turbulence, both from an industrial and an academic viewpoint. The primary electives consist of a set of four courses, and cover a broad spectrum, from the fundamental to various applied fields.

2.4.1 Advanced Fluid Mechanics. The course Advanced Fluid Mechanics aims at providing a deepening of the knowledge in the field assumed to have been studied in basic courses. Emphasis is on the basic equations, vorticity-theory and stability. Focus is on the interpretation and understanding of various physical phenomena through a study of the basic equations. The course should widen the basis for continued studies in both fluid mechanics and heat and mass transfer. The course starts with a careful derivation of the basic equations, the Navier-Stokes, continuity and energy equations. Some of the few available analytical solutions are treated. Vorticity dynamics is introduced and applied to both viscous and frictionless flow fields. The course concludes with an introduction to stability theory.

Throughout the course Cartesian tensor notation is used (as in the parallel turbulence course). A number of tutorial sessions are provided to make sure that the students actually get a thorough understanding of the basic equations and their implications. One special project task is also included.

2.4.2 Applied Fluid Dynamics. The detailed content of the course Applied Fluid Dynamics may vary from one year to another. Independent of the particular topics covered the aim of the course is to develop the students' skills in using the governing equations of fluid mechanics and to gain insight into some of the complicated flows encountered in nature and engineering applications. During 2002/2003, the course focused on aerodynamic flows, while during the academic year 2003/2004 flows involving surfaces, rotation and buoyancy were considered, especially as they relate to the atmosphere and oceans. This was in part in response to the demand of the students for courses related to the environment. The course started with the fundamentals of the atmospheric system including a discussion of the basic equations and the special features encountered in atmospheric systems, like rotation and buoyancy. The theory was applied to some fundamental cases such as the famous "tea-cup problem", Ekman layers in the ocean and atmosphere, and their relation to secondary flows in general. Effects of natural convection in the environment as well as stability problems and waves were also included.

2.4.3 Computational Fluid Dynamics. The basic aim of the course in Computational Fluid Dynamics is to give a thorough knowledge and understanding of the finite volume method for computational fluid dynamics (CFD). A large part of the course is devoted to the implementation of turbulence models in the computational schemes. The course starts by carrying out a detailed derivation of the finite volume method and it is first exemplified by the diffusion equation in one and two dimensions, and after that by convection-diffusion problems. For the convective part, different discretization schemes are discussed where the delicate balance between numerical accuracy and numerical stability must be considered.

Turbulence models based on single-point closures are first introduced. The use of wall functions is introduced, but the more modern approach using low Reynolds number models form the kernel of the treatise. A significant part of the course is devoted to the more elaborate Large Eddy Simulation techniques. The course includes three exercises in which the students write their own finite volume solver. The cases considered are the diffusion equation, the convection-diffusion equation in two dimensions and the fully developed turbulent flow in a channel including different turbulence models.

2.4.4 Convective Heat Transfer. The aim of the course in Convective Heat transfer is to improve on the student's knowledge and physical understanding of convective heat transfer. Simultaneously he/she will gain skills in using the Fluent commercial CFD software. The course is project-oriented, so the emphasis is on three computer tasks, covering the basics of convective heat transfer and the necessary computational skills, and laminar as well as turbulent flow cases. One of the tasks is chosen individually by the students and may involve almost any sub-field of heat transfer such as forced/natural convection, conduction and radiation.

2.5 Secondary electives

Most secondary electives are oriented towards practical engineering applications, like internal combustion engines, gas turbines and the like. This gives the students a chance to find out how the knowledge and skills they have developed in the more theoretically oriented courses fit into the problem solving encountered in practical engineering tasks. Another objective is to allow them to study areas of special interest to prepare for their master's project (see below). In addition to the application oriented courses a number of courses in mathematics and physics can also be chosen.

3 THE MASTER'S PROJECT

The program demands that the students carry out a one semester thesis project. This can be done in university or in industry, in Sweden or abroad. About half of the students chose to carry out their thesis work within the Thermo and Fluid Dynamics Division at Chalmers. The larger fraction of those remaining at Chalmers did their projects with research groups other than our turbulence group, which points to the fact that we have managed to produce students with skills that are much more general and useful than the name of the program might imply. Some of the students went to research institutes and academic institutes in different places in the world, including the USA and Canada. The remaining part went to industry. We experienced little difficulty finding suitable positions for them, and in fact had more opportunities than students.

The student tasks were of a very varying character, with projects ranging from fuel and air injection in furnaces to the flow of cement in rock cracks, from wind engineering to the study of cooling air flows in car breaks. All of the industrial projects offered a modest living stipend (approximately 3000 Euros), generally paid upon completion of the project. In all cases the students work was highly appreciated, and all employers/supervisors expressed a willingness to accept more such students in the future. In most cases the students were offered (and usually accepted) either full-time employment or the opportunity for continued studies toward their Ph.D. degree. We actively encouraged these arrangements, since the goal of the program was never to simply provide highly trained Ph.D. students solely for Chalmers.

4 RECRUITMENT

The program has attracted students from all over the world; all continents except Australia have been and are represented. More than half of the students come from Europe, the largest number of students, not surprisingly, from Sweden. But almost as many students come from India, France and Iran. The number of applicants for each position on the program is slightly larger than 3 (program starting fall 2004) and more than doubles if second choices for other programs are considered. In addition to the students formally admitted to the program, a number of other students follow one or more of the courses offered within the program. These are primarily Erasmus students and students from Chalmers, but also students from other universities in Sweden.

5 SOCIAL ACTIVITIES

The program has attracted students from all over the world. Many of them have little previous experience of travelling and many of them have had no exposure to the Swedish culture and way of life. They arrive in Sweden without knowing anyone, and they need to get to know both their fellow students on the program and the Swedish students. Most have a strong desire to learn about Sweden, to get acquainted with and to absorb part of the culture.

To help the students in their efforts to adapt to Swedish society and to get a smooth start on their studies the International Office at Chalmers and the student union together arrange a set of activities. These include not only practical matters like finding accommodation, to find their way around Chalmers, a comprehensive introduction to the way courses are run at Chalmers and where to find food they recognize from their home countries, but also visits to places of particular interest, introduction to the specifics of the Swedish social and traditional culture patterns, and get together parties. The last one of these activities is probably of particular importance since there they meet with Swedish students.

In addition to this some activities are arranged also by the turbulence program. We consider it of importance to reinforce the identification of a special turbulence group. We do this in a couple of ways. The students are given a special room of their own to help develop a certain feeling of belonging to the group. Here the students can study or relax, chat with each other, make coffee and phone calls. They also have computer access. We also make it a point to incorporate small project tasks in the courses where the students work together to further promote their social interaction. This has helped creating strong friendships that have persisted throughout the program.

A special event is the ‘turbulence parties’. Such parties are arranged at the beginning of their first semester and at regular intervals thereafter. At the first party all the students are asked to bring some food typical of their home country, and also to perform a traditional song or dance. In this way the students’ varying backgrounds are made evident to each one of them, and they quickly develop an awareness and respect for their different cultures and social patterns.

We also try to introduce the students to some of the special features of Swedish cultural traditions. An example is the habit in the Nordic countries to celebrate the Festival of Saint Lucia shortly before Christmas, a festival recognizable around the world by the candles worn atop the head of the girl chosen to be St. Lucia. The presence of 30 to 40 multi-cultural, multi-racial students at a large cathedral is truly a highlight of the year for the staff, and particularly the interest and reactions as the students watch the Swedes (and vice versa).

An activity that has been particularly appreciated is a return to Chalmers and reunion after the students have finished their thesis projects, since most of the students have done so outside Chalmers, in many cases far away. They are brought together to present their thesis work and to get a last chance to meet each other before they depart and go on to the next phase in their professional development.

6 OUTPUT

6.1 Course output and evaluation

It is evident that the outcome of a study program to a large extent depends on the background and abilities of the students. The turbulence program has been fortunate in that the admitted students largely have turned out to be quite talented, in some cases very talented. Needless to say these students have also performed extremely well on the program. However, due to the widely varying curricula and grading systems around the world it is very difficult to carry out an entirely objective screening of the applicants, and as a consequence, a few less talented students were also admitted to the program. One might expect that these students would have failed badly, but this turned out not to be the case. An early screening of the students and active teacher support in combination with a willingness on the students' hand to work very hard turned out to compensate for the lesser abilities of these students. With only a very few exceptions all the students in the first program graduated on time. The few remaining ones are presently finishing off their thesis reports and will be done soon.

Early in the program and at repeated occasions evaluation questionnaires are handed out to the students. Here they are requested to state their opinion on the courses, the way they are conducted and the performance of the teachers. In this way we have been able to catch at an early stage shortcomings in the courses and have been able to adjust and counteract negative consequences. These questionnaires have been widely appreciated by the students.

6.2 Professional success

It's difficult to access the success of the program in terms of the appreciation its students will receive in their future professional careers, especially given the limited time the program has been in operation. The first students on the program graduated only a few months ago. However, some evidence is available based on the experienced demand of the students.

It is quite natural that the students on the program will fit well into the doctoral program offered by us, and four of them have accepted such positions. More important though is that other groups at Chalmers also have found them highly qualified and accepted some of them. Moreover, two of the students are accepted as Ph. D. students abroad and several others are presently negotiating positions. This must be considered a rather high output of research grade students.

A significant fraction of the students have also found positions in industry either within Sweden or abroad. They cover a wide variety of professions, including wind engineering, hydraulic power engineering and the car industry to mention a few.

7 THE FUTURE AND THE BOLOGNA AGREEMENT

At present the masters program in turbulence is organized as one year of full time study followed by one semester during which the students carry out a thesis project. Quite soon Chalmers plans to switch over to offer an education following the Bologna agreement with a three years basic education followed by a two-year masters and subsequent Ph. D. level studies. It is most likely that the masters programs offered will be very similar in type to the already present ones; the main difference being that an additional set of courses filling one more semester will be required.

It appears that the present masters programs at Chalmers, and especially the Turbulence program, can quite easily be adapted to this new system. The present set of courses will form the kernel of the new system, and a few new courses will be developed along the same lines as the present ones. We have already started the development of these new courses. During the last year two fluid mechanics courses at the doctoral level were introduced for the first time, and it is expected that they will be the natural extension of the general fluid mechanical part of the program. The turbulence program will be extended by a course entitled Advanced Topics in Turbulence. The content of this course will vary from one year to another, covering different advanced aspects of turbulence. As the theory of turbulence is improved this will be directly reflected in this course. The remainder of the course package will be an elective course of the student's choice, preferably in an applied engineering area.

After finishing the masters program in turbulence the students are expected to have acquired all basic training required to start on a doctoral project or to go directly into productive work in industry.

8 CONCLUSIONS

A new and innovative program has been described to teach turbulence and fluid mechanics in the last year of diploma level mechanical engineering programs. This program teaches both subjects in parallel and manages thereby to accomplish both a thorough understanding of fluid mechanics and a sound knowledge of turbulence simultaneously. This is of extreme importance in practical engineering, since most engineering flow fields are turbulent.

The approach has also turned out to produce very good candidates for doctoral studies. Contrary to the expectations of some, however, the program has proven *not* to narrow students in their choices of future studies or a career, but in fact to broaden those opportunities. We believe this has happened for two reasons: First turbulence underlies most transport phenomena, so a solid foundation in turbulence moves the students abilities to a different level by imparting essential skills before they begin the study of those areas. Second, the intellectual discipline required to study a subject like turbulence about which so little is known for sure provides an excellent platform for further learning in any subject.

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