Revisiting the need to combine educational and scientific-research processes in teaching CFD modelling to students

A I Fedyushkin1, A A Puntus2

1 Ishlinsky Institute for Problems in Mechanics of Russian Academy of Sciences, Prospekt Vernadskogo, 101-1, Moscow, 119526, Russia
2 Moscow Aviation Institute, Volokolamsk highway, 4, Moscow, 125993, Russia,

E-mails: fai@ipmnet.ru, artpuntus@yandex.ru

Abstract. Using the example of many years of experience in cooperation between Institute No. 8 "Information Technologies and Applied Mathematics" of the Moscow Aviation Institute and Ishlinsky Institute for Problems in Mechanics of RAS points out the need for cooperation between the university and specialists of academic institutions in the preparation of highly qualified specialists in the field of CFD, stages of training, examples of qualification work and the use of software CFD products for training are presented. The difficulties of teaching CFD modeling are discussed, achievements and examples of solving the problems of hydrodynamics and heat and mass transfer by students of the Moscow Aviation Institute are given.

1. Introduction
Computational Fluid Dynamics (CFD) is an important tool for solving and studying the problems of aero-hydrodynamics and heat and mass transfer. The increased interest in CFD in the last twenty years is associated with the development of computer technology and the emergence of new effective numerical methods that have allowed solving new problems. The relevance of training highly qualified CFD specialists is prompted by the need to carry out a multiple of fundamental scientific research and the necessary to solve a wide range of applied problems.

The task of the improvement of the training of highly qualified specialists in a university is both a traditionally urgent task and a particularly urgent task at the present time - the time of active development of scientific and technological progress. The solution of this problem is facilitated by the development and improvement of various forms of training of highly qualified specialists based on a conjunction of educational and scientific-research processes of teaching students. The important fundamental role in this is to both determine the content of this interaction and to determine its ultimate goal. There is no doubt that if the goal of this cooperation is set to educate the vast majority of students into qualified engineers, or technical and scientific staff, this goal may not be fully realized. However, on the other hand, even the doubt of needing to attract students to various types of independent creative research projects can certainly reduce the quality of training of future specialists, and in particular in CFD.

1 Dr. Alexey Fedyushkin, fai@ipmnet.ru.
2 Prof. Artur Puntus, artpuntus@yandex.ru.
At the present time of development of science, the researching encompasses many forms and methods, and even the word research is now an umbrella term. It includes the most diverse aspects of the educational, scientific, educational and organizational activities of the university, providing:
- requirements for successful mastery of students in their specialty;
- preparing students for independent creative activity;
- development of skills to use the acquired knowledge in practical work;
- formatting desire and the skills to constantly accumulate and improve knowledge;
- expansion of scientific and technical horizons;
- developing a well-rounded personality.

In order to implement these provisions, it is necessary to constantly increase the complexity and volume of knowledge as well as skills acquired by students during academic and extracurricular time, to ensure the continuity of methods and forms of training of specialists in the transition from one knowledge to another, from course to course. It is possible to solve the problems of improving the creative training of students only on the basis of an ever-increasing connection between student scientific research work (SSRW) and the educational process, when SSRW becomes its full-fledged form, and the educational process, in turn, helps to solve the scientific, technical, industrial, and social and educational tasks of the university.

2. Strategies and methods of teaching CFD modeling

Currently, training CFD specialists is relevant, since highly qualified CFD specialists are in demand not only in traditional fields of science and technology (such as mechanics, physics, chemistry, aviation, astronautics, nuclear and thermal energy, mechanical engineering, meteorology, metallurgy, etc.), but also in related areas that are not traditional for hydrodynamics, such as, for example, biology, medicine, sports, construction, light and food industries, etc. Therefore, in Russia, along with teaching students of technical universities basic subjects, such as physics, chemistry, mechanics, mathematics, there is an urgent need for students to get education in the field of CFD modeling. Learning the mathematical modeling of hydrodynamic processes requires significant time and material costs. Therefore, in many Western countries, the basics of CFD begin to be taught in colleges, using special educational software. Thus, at universities, students during their studies can gain more knowledge and modeling experience, that affect on their qualification. Cooperation experience of the Ishlinsky Institute for Problems in Mechanics of Russian Academy of Sciences (IPMech RAS) and MAI in teaching students to numerical simulation the processes of hydrodynamics and heat-mass transfer also showed that at least two years are necessary for the quality training of specialists. In addition to research papers, IPMech RAS workers have also published educational papers and books on CFD that can be necessary for students and postgraduates, for example, [3,4], some others are available on the Institute’s website: www.ipmnet.ru/.

The training of undergraduate and graduate students in computational fluid dynamics and heat and mass transfer, in addition to training in modeling using existing programs, also involves skills acquisition by students to the creation of new CFD software. The development of full-fledged software CFD products and training exercises is a job requiring time and material large costs, because this requires the cooperation of highly qualified CFD specialists from scientific institutes, university professors and programmers [1, 2]. The problem of finding effective models and the competent use of CFD programs is relevant, since the processes of hydrodynamics and heat-mass transfer in real scientific, technical and industrial problems are non-linear, multi-parameter and multi-scale. To become highly qualified CFD specialists, students must participate in fundamental scientific research and solve a wide range of applied problems.

Over the past decades, effective professional numerical modeling programs have been developed based on the solution of the Navier-Stokes equations of general and special purpose, including open, commercial and industrial complexes of programs. These complexes at best have training aids, in the form of user manuals, which are just instructions. But user guides in commercial or open CFD packages can not provide students with the necessary knowledge for competent formulation, the
optimal solution method and analysis of the problem being solved. Therefore, students need in-depth knowledge of CFD (fluid and gas mechanics, heat and mass transfer and numerical methods). In addition, often in solving applied problems CFD specialists require knowledge of related disciplines, which should also be taken into account when teaching CFD modeling. These problems and the stages of CFD training were discussed in [1,2].

The educational process for students to master modern CFD methods and tools should contain basic knowledge of fluid and gas mechanics, heat and mass transfer, numerical methods, and interdisciplinary computer systems. One of the first steps in teaching students can be based on the use of a one-dimensional approach or an approach such as a boundary layer focused on engineering education using the Mathcad system, as well as using exact solutions of the Navier-Stokes equations for special cases of flows. The next step in CFD training can be a workshop on modeling elementary flows based on the Navier-Stokes equations, for example, using computer systems COMGA (COvection in MicroGravity and Applications) [3], MASONA (MAtrix SOlution of the NAvier-Stokes equations) [5] and ASTRA (Automated System of Theoretical Research and Analysis) [6] developed at IPMech RAS and 3D code AliceFlow [7], written by K. A. Ivanov, a former student at the MAI, who completed an internship at the IPMech RAS.

Such type of independent student work - based on scientific research, as laboratory and term papers - greatly facilitates an active interaction of the educational and scientific processes. This is the most convenient form of training that allows including elements of research activity in these works. In addition, these works should combine the research part with a computational part, associated, for example, with the reasonable choice of a computational algorithm for a given task and with the subsequent execution of its computational part. It is desirable that the relevant coursework and laboratory work are based on research of the department staff in order to borrow from their expertise. Thus, as a result of the laboratory and term papers, not only theoretical knowledge is consolidated, but also the skills of conducting independent scientific and practical research are acquired. The experience of such work has shown that it’s best when the individual relevant work is carried out in a logical sequence and combined into a common educational and methodical workshop around a single educational research task. Thus, students find themselves involved in the holy of holies of science - the "kitchen" of scientific research. At the same time, opportunities open up for attracting interested students to scientific and applied research, for preparing reports and speeches at conferences, and for writing scientific papers.

It is always useful that special seminars are held for students, at which both students and teachers give scientific talks. These reports can be either a summary plan or talks around ongoing research work. As a result of mutual enrichment with ideas and tasks, the content of joint scientific research expands; students become more interested in participating in interdisciplinary research.

After completion of the theoretical fundamentals, students' computation and research projects play an important role in the curriculum. Students are assigned projects to help them solve applied problems in their research area. To solve them, students need to carry out mathematical modeling, then, in the case of computational practice, choose the necessary numerical method, develop a computational algorithm, create a block diagram of the program, write code, analyze the results and draw the necessary conclusions. The task of research practice helps the student gain a deeper understanding of the mathematical models associated with their applied problem. This requires not only its software implementation, but also the analysis of its physical and mathematical properties of this model, such as uniqueness, smoothness and stability of solutions, convergence and stability of the applied computational algorithm, the accuracy of the obtained result, etc.

During pre-diploma practice, the student studies literature, mathematical methods necessary to solve the posed problem; gets acquainted with mathematical tools that implement the methods of design and engineering calculations, with programs for graphical constructions; gets acquainted with the functioning systems of mathematical support, with the means of analyzing these systems and their possible modernization; acquires practical skills and abilities determined by the goals of the practice and qualification characteristics of the specialty of training; develops flowcharts of mathematical
software, compiles and debugs utility programs and software modules included in the software package for the task; compiles programs for solving the model problem, which allow working out the algorithm of the selected method, debugs them and performs calculations using computer technology; conducts preliminary calculations on computer technology, which allow choosing the best method for solving the problem; implements with the use of computer technology the solution of an auxiliary problem preceding the main task of the thesis; creatively selects materials that are later used in the thesis; shows and develops research abilities in solving the task.

Studying or choosing a method to solve an applied problem, students get acquainted with both domestic and foreign literature on this issue, while they must analyze the advantages and disadvantages of the method chosen to solve the problem, comparing it with other possible methods for solving the problem. Performing the necessary construction or formation of software for the implementation of the task, students need to realize the modern capabilities and principles of creating software in similar situations. In addition, the students are considering various options for constructing the necessary software, from which the best one should be chosen and the given choice justified. It is mandatory to build during practice a certain software module for solving the problem and implement it using modern computer technology.

The completion of the entire period of study is the completion of the thesis, the basis of which is, as a rule, the real subject of the institute, which also includes the completion of scientific research performed by students in the learning process. In most cases they present a complete research work and a practical result, which forms the basis of some real finished scientific and technical research, a scientific article, a competitive student research work, and deem the student a graduate of the institute, as an established qualified specialist capable of independent scientific and practical creative activity. The replenishment of the ranks of graduate students, and, subsequently, teachers and staff of the department’s staff is almost completely ensured by its graduates.

3. CFD experience and challenges

During the collaboration of the IPMech RAS and MAI, several dozens of students graduated. Almost all students who completed term papers, dissertations and dissertations at the MAI on the basis of the IPMech RAS successfully combined their academics with active scientific research work. Based on the results of such work, they participated in lectures at conferences and successfully prepared scientific publications. The works of these students at the student work contests took first places. Here are a few examples of such works, written by students of the MAI on the basis of the IPMech RAS [7-11].

Student MAI Korolkov A.Yu. began to cooperate with IPMech RAS from the 3rd year of study, completed a large scientific work and defended his excellent thesis on the topic “Modeling of convective processes in single and multiphase immiscible liquids under constant and vibrational influences”. Korolkov A.Yu. within three years, he numerically solved more than seven different problems of heat and mass transfer of single and multiphase fluids in areas with constant and changing geometries using dynamic grids [8].

Final qualifying paper of Podshipov P.M. “The influence of the heating area on heat and mass transfer during film boiling” was devoted to numerical modeling of convection of a two-phase incompressible liquid. The problem of boiling and the dynamics of a heated gas film in a liquid are considered. The simulation results showed that Marangoni convection accelerates the process of separation of the bubble from the heated surface, and also increases the value of the Nusselt number.

In the diploma work of Ivanov K. A., numerical modeling of the hydrodynamics of the melt flow under vibration action on the melt for crystal growth by the Chokhralsky method was carried out. The effect of vibrations on the temperature boundary layer for liquids with different Prandtl numbers was shown [9]. After graduating from MAI, Ivanov K. A. entered graduate school and wrote himself program AliceFlow [7] for calculating heat transfer based on solving 3D Navier-Stokes equations by the control volume method with solving a system of algebraic equations by the conjugate gradient method.
Final qualification work Volkov E.V. is devoted to the study of transitions between different flow regimes in a plane diffuser / confuser with a small opening angle for complex liquids that satisfy the Ostwald-de-Waele power law by numerically solving the Navier-Stokes equations. The result of the scientific work of E. V. Volkova is the establishment of ranges of Reynolds numbers for the existence of stationary asymmetric flows in the flow of complex liquids in the diffuser and confuser [10]. Currently, Volkov E.V. is studying in graduate school of MAI.

Yaremchuk V.P. passed the entire training cycle from a student to a graduate student at IPMech RAS and successfully defended his thesis on "Numerical modeling of spatial convective processes in space flight." In the work, unsteady Rayleigh – Benard convection was studied in the problem of heating from below, the boundaries and times of heat transfer regimes were determined [1,11].

Pivovarov D.E. passed through the IPMech RAS the entire training cycle from a 2nd year student of the MAI to a postgraduate student and researcher at IPMech RAS. He successfully defended his thesis on the topic “The stability threshold and three-dimensional convection structures in closed oblique rectangular volumes”. Currently Pivovarov D.E. works as a senior researcher at the Institute of Mechanics of Moscow State University and teaches CFD at Moscow State University, has many scientific papers on CFD https://istina.msu.ru/profile/brewer/.

The given examples show how the practical implementation of the combination of educational and scientific processes at a university actively contributes to identifying the most talented and creatively gifted students and attracting them to research, helps to increase their cognitive and creative abilities, and helps educating them become professional specialists for life. Such an individual form of preparation allows attracting students to this form of training both from the first steps of studying at the institute, and from any of the subsequent courses. Each of these students joins the research work at the institute’s department, achieves notable successes in studies and scientific activities, takes an active part in various competitions, contests, performs creative scientific work under the guidance of a teacher or scientific researcher of the department, participates with reports at various conferences and prepares scientific publications. At the MAI in recent years, the majority of graduates who entered graduate school as students successfully combined study with scientific work. Qualified research specialists and graduate students are in many respects the outstanding graduates of MAI.

It is necessary to say about the difficulties and problems in teaching CFD in Russian universities due to the overall reduction in student learning time. Currently, the restructuring of secondary and higher education with a reduction in the curriculum and training time for students of technical universities has made it problematic to train highly qualified specialists in the field of CFD modeling. President of the RAS Sergeyev A.M. At a meeting of the working group on assessing the creativity of schoolchildren, he said the following about education at universities: “There is a degradation in university education, graduates are less and less suitable to become scientists” [12]. Vice-President of the Russian Academy of Sciences Khokhlov A.R. proposed to introduce an external exam to test the quality of education in Russian universities, since there is an obvious tendency to reduce the level of university education [13].

4. Conclusions

To train highly qualified specialists in the field of CFD, cooperation between the university and specialists of academic institutes is necessary, using the accumulated methodological experience of university teachers and the scientific experience of scientists and developers of software tools for CFD. In teaching CFD modeling, it is necessary to go from specific tasks and in stages, moving from model statements to modeling actual processes and tasks. It should be borne in mind that learning CFD modeling is the work of teachers, scientists and students, requiring large time and material costs. Training highly qualified CFD specialists, teaching students the basics of CFD for only one semester and only within the university is an almost impossible task.

5. Acknowledgements

The study was supported by the Government program (contract # AAAA-A20-120011690131-7).
6. References

[1] Fedyushkin A I, Polezhaev V I, Yaremchuk V P 2005 Education & tutorials in modeling in computation heat transfer: From Elementary Processes on the Basis of Computer Laboratory to the Industrial Complexes CD ROM Proceedings of 4th ICCHMT May 17-20 2005 (France: Paris-Cachan No 97)

[2] Puntus A A 2016 On the forms of combining educational and scientific processes in a technical university Proceedings of the conference "Mathematics, Physics, Informatics and Their Applications in Science and Education" Moscow December 12-15 2016 (Moscow: MIREA) [in Russian]

[3] Polezhaev V I, Bune A V and et al 1987 Mathematical modeling of convective heat and mass transfer based on Navier-Stokes equations (Moscow: Nauka) p 272 [In Russian]

[4] Polezhaev V I, Bello M S and et al 1991 Convective Processes in Weightlessness (Moscow: Nauka) p 240 [in Russian].

[5] Fedyushkin A I 1990 Research of a matrix method for solving convection equations. Complex of programs "MASONA" (Moscow: IPM of the USSR Academy of Sciences Preprint No 471) p 32 [In Russian]

[6] Burago N G ASTRA program for solving one-, two- and three-dimensional non-stationary nonlinear problems of continuum mechanics on moving Lagrangian-Euler unstructured grids by the finite element method (http://www.ipmnet.ru/~burago/astra.htm)

[7] Ivanov K A 3D code AliceFlow simulation of hydrodynamics and heat and mass transfer. https://github.com/kirill7785/AliceFlow The AMG1r5 program designed to solve large sparse linear systems of equations by the algebraic multigrid method https://ru.wikipedia.org/wiki/Amg1r5.

[8] Korolkov A Yu, Fedyushkin A I, Puntus A A 2007 Modeling of convective processes in single and multiphase immiscible liquids under constant and vibrational influences. In the book: "Through thorns to the stars" (Moscow: Publishing House MAI) pp 376-383

[9] Fedyushkin A I, Ivanov K A 2014 Hydrodynamics and heat transfer during vibrational influences on the melt in the processes of growing single crystals (Moscow: IPMech RAS Preprint No 1085) p 107

[10] Fedyushkin A I, Puntus A A, Volkov E V 2019 Symmetry of the flows of Newtonian and non-newtonian fluids in the diverging and converging plane channels AIP Conference Proceedings 2181 No 1 pp 020016–1–020016–8. DOI:10.1063/1.5135676

[11] Polezhaev V I, Yaremchuk V P, Nikitin N V 2004 Three-dimensional convection in realistic microgravity environment & analysis of microgravity requirements AIAA Paper 42nd AIAA Aerospace Sciences Meeting and Exhibit (Reno: NV AIAA) pp 10864–70.

[12] Sergeev A M 2019 (Moscow: RIA NEWS May 17 2019) Access mode: https://ria.ru/20190517/1553587090.html

[13] Khokhlov A R 2019 (Moscow: TASS May 17 2019) Access mode: https://tass.ru/obschestvo/6442902?keepThis=true&TB_iframe=true&height=500&width=1100&caption=%D0%A2%D0%90%D0%A1%D0%A1%2Famp