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Basic vs. applied doctoral theses in nuclear engineering – Case study of theses completed in Slovenia

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ABSTRACT

In view of many discussions on rethinking graduate education to better support the non-academic careers, we have reviewed the doctoral theses, completed within graduate studies of nuclear engineering at the Jozef Stefan Institute and the University of Ljubljana (Slovenia) between 1993 and 2019. The theses are divided (in the present paper) in three groups: "basic", "applied" and "application-oriented basic". The merits of each kind are discussed, including from the point of view of nuclear engineers intending to continue their careers in the nuclear industry. As a specific case, the topics studied were reactor thermal hydraulics, severe accidents, ageing and integrity of components, and probabilistic safety assessment. The review shows a strong preponderance of basic and application-oriented basic theses over applied ones. It also appears that the predominantly academic orientation of the doctoral theses enabled not only academic, but also industrial careers.

1. Introduction

One of the ultimate purposes of engineering is the application of physical laws in product development and industrial processes. However, similarly to other engineering fields, nuclear engineering has evolved in the past decades from a purely "technical" field into one within which advanced research is also being carried out. This development appears to be somewhat contradictory with the recent proposals to rethink the graduate education to better prepare the students for the non-academic or industrial careers (Leshner, 2015). In view of this, we have reviewed the doctoral theses, completed within graduate studies of nuclear engineering at the Jozef Stefan Institute and University of Ljubljana (Slovenia) between 1993 and 2019 to evaluate their potential impact on the subsequent careers of the students.

Research in nuclear engineering as such belongs to the topics of reactor physics, fluid mechanics, heat and mass transfer (usually included, in nuclear engineering conferences or journals, in topics called "thermal-hydraulics" or "severe accidents"), material science (usually included in the topic called "ageing and integrity of components"), probabilistic safety assessment (PSA), and other miscellaneous topics. The length scale of studied phenomena encompasses the range from the atomic level over the continuum scale up to the scale of components and systems.

As a logical consequence following the development of nuclear engineering as a research topic, doctoral theses in nuclear engineering also appeared and are nowadays an established part of research in this field. In their previous works (Kljenak and Mavko, 2011; Cizelj et al., 2013; Kljenak et al., 2012), the authors of the present paper have divided doctoral theses in two groups: "basic" and "applied-oriented". However, since then, the completion of new theses in the studied group has lengthened the list and offered a different perspective. Based on the research quadrants defined by Stokes (1997), which categorises research depending on the quest for fundamental understanding and the consideration of use, the following three categories are defined (Fig. 1): "basic", "applied" and "application-oriented basic". Theses are divided into these three categories using the following criteria:

- **Basic theses** deal essentially with universal physical phenomena (be it through experiments, or theoretical modelling and analysis), mostly on a local scale, or with abstract theories. The aim is to understand and model relationships between causes (such as forces or temperature differences) and effects (such as motion, heat transfer, displacement or crack propagation), or relationships between probabilistic quantities. Although basic physics on the macroscopic level are nowadays supposed to be understood, many phenomena still cannot be adequately and reliably predicted, which necessitates the performing of experiments to enable a better insight into the observed phenomena and the development of additional theoretical models that are linked with established physical laws. Likewise, research in the field of probabilistic mathematics are also pursued. Although the considered phenomena or theories are related to nuclear systems (be it during normal operation or during hypothetical accidents), they are not limited (within the theses) to "nuclear-specific" systems or conditions.

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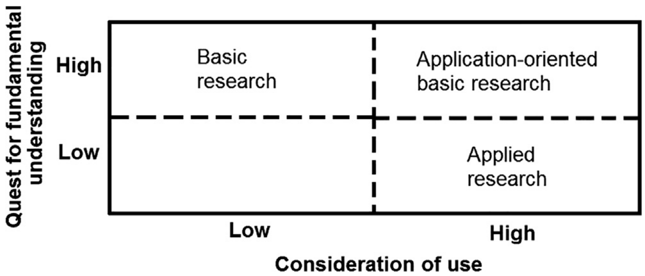

Fig. 1. Research quadrants (Stokes, 1997).

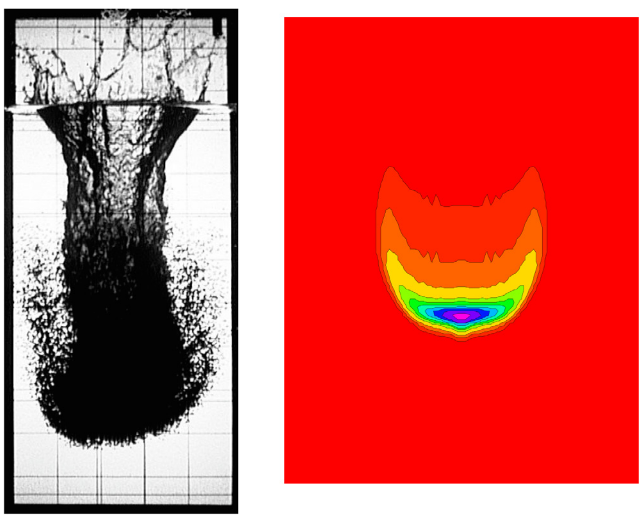

Fig. 2. Simulation of premixing phase of steam explosion.

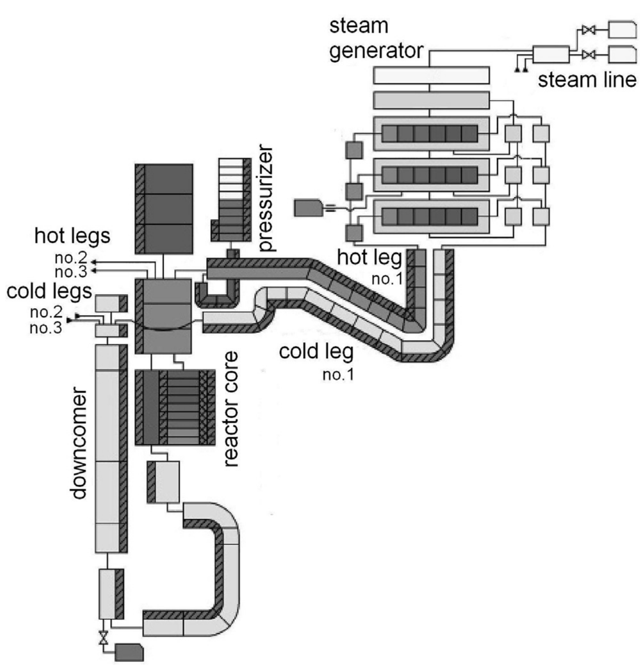

Fig. 3. RELAP5 input model for simulation of transient in PWR primary system (boiling in reactor core).

- **Application-oriented basic theses** are, in the sense of research, similar to basic ones. The difference is that the phenomena or theories are considered in "nuclear-specific" systems or conditions. However, the new knowledge gained from these theses is not yet meant to be applied to actual nuclear systems. The reasons for this are either that the knowledge has not been sufficiently validated yet or purely practical (such as long computation times or lack of specific data).
- **Applied theses** also deal with the issues of understanding and modelling cause and effect relationships, but provide new knowledge that can be readily applied to actual nuclear systems (that is, the knowledge may be considered to be sufficiently validated and there are no practical limitations).

Holders of doctoral degrees in nuclear engineering usually opt for one of the following career possibilities:

- to remain in the field of research (nuclear or non-nuclear), either by staying in the academic or research institution, where they have obtained their degree, or moving to some other one;
- to join a nuclear power plant (NPP), a nuclear utility company, a nuclear power plant vendor (these three entities will be referred collectively in the paper as "nuclear industry") or a nuclear regulatory body (within the state administration);
- to move to some other industrial field, where they eventually use some of the knowledge that they have acquired during their doctoral studies of nuclear engineering.

For the first possibility, a basic thesis is probably more appropriate, whereas an applied thesis seems more adequate for the second and third possibilities. As to application-oriented basic theses, they may, on one hand, form a basis for further research (thus, be suitable for the candidate to opt for the first possibility), but, on the other hand, also enable the candidate to acquire detailed knowledge on some nuclear system or phenomenon (thus, be suitable for the candidate to opt for the second or even the third possibility). Thus, it appears that the type of a thesis could be important for the subsequent career path of a doctoral candidate.

In the present paper, the issue of the choice of the thesis type and the merits of each type are discussed. Then, as a case study, doctoral theses completed in Slovenia at the Jozef Stefan Institute Reactor Engineering Division and the University of Ljubljana in the period 1993–2019 are reviewed. In the present paper, nuclear engineering studies dealing with thermal hydraulics, severe accidents, ageing and integrity of components, and probabilistic safety assessment (related to nuclear engineering) are considered.

To the best of the authors' knowledge, this is the first published study of this kind. The presented work may be used as guidance in the strategic development of higher nuclear education and research. The study might also be considered as an encouragement for other educational institutions to perform similar analyses. The ability to serve all nuclear stakeholders is explored as well.

2. Choice of thesis type

To obtain a doctoral degree in nuclear engineering, a graduate student has to be engaged in research that represents a novel contribution to the field. To ensure an adequate scientific level of the performed research, a usual requirement is that the results of the research be published in (at least) one paper in an international scientific journal. To achieve this, the thesis subjects often deal with basic research (in the general sense, that is, including "application-oriented basic" theses referred in the present work), which are connected to some field of nuclear engineering, but in which students that will move to the nuclear industry will in generally not be involved anymore (that is, with the basic research as such). Namely, results of applied theses, although in principle no less intellectually demanding, usually do not provide the same novelty and originality, which are the usual requirements set by faculties, and which are also among the prerequisites for acceptance of papers in scientific journals. As an example, an accurate prediction of the overall course of a small-break loss-of-coolant

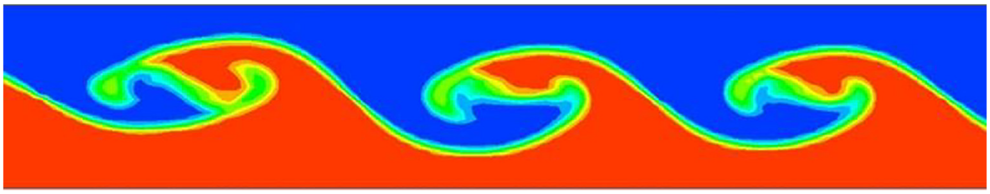

Fig. 4. Simulation of stratified gas–liquid flow (red field: liquid; dark blue field: gas; other fields: interface).

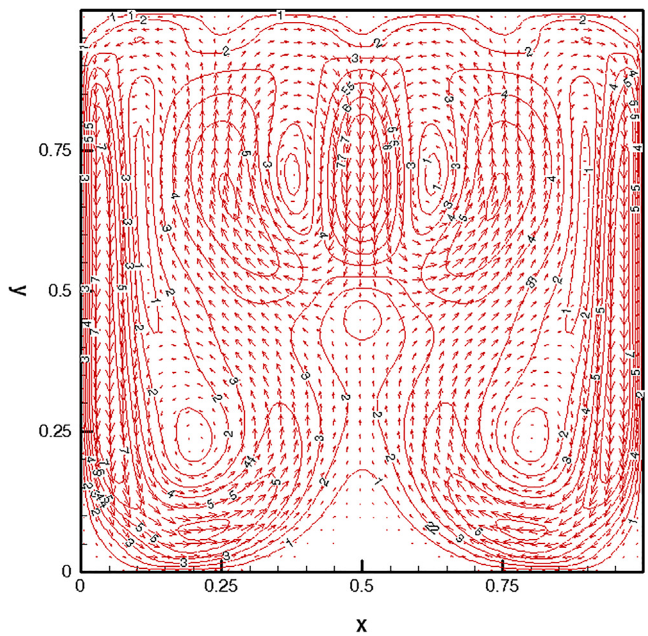

Fig. 5. Simulation of natural convection in fluid with internal heat generation (vertical cross-section of square cavity - instantaneous velocity field).

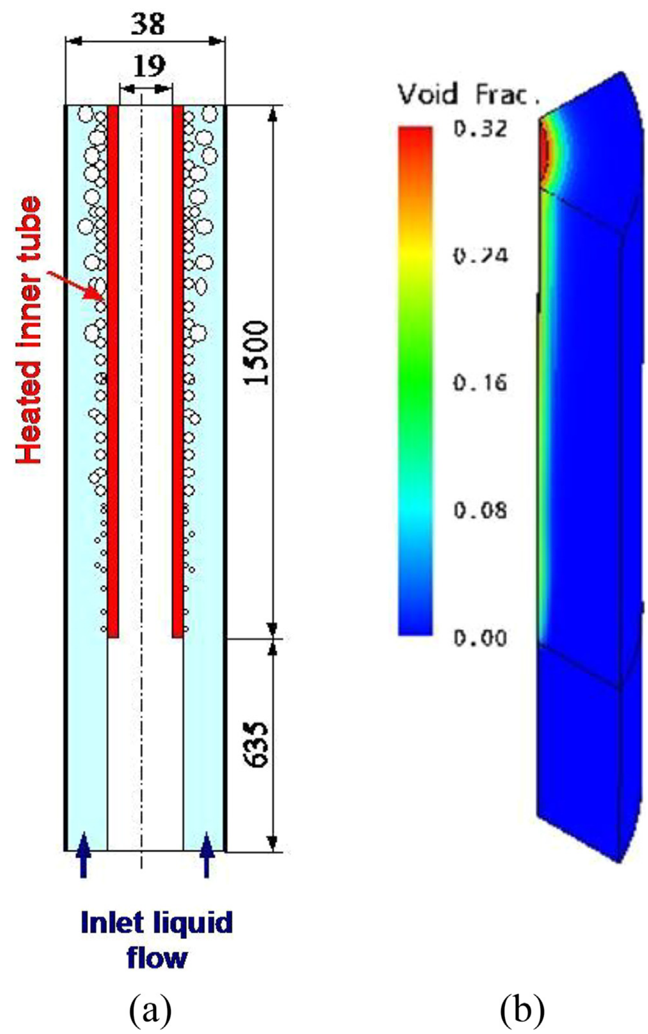

Fig. 6. Simulation of convective nucleate boiling (a) schematic of experiment (b) simulated local void fraction.

accident (SB LOCA) in a Pressurized Water Reactor (PWR) is no less demanding than a detailed prediction of the flow conditions in the cold leg during the same accident, even if boundary conditions are known. Nevertheless, research on stratified gas–liquid two-phase flow in a horizontal tube will be considered more appropriate for a thesis and a publication in a journal than a comprehensive simulation with a so-called system thermal–hydraulic code (such as RELAP5 or TRACE), even if some innovative approaches are used in the modelling. Thus, it appears at first glance that the education that students undergo while working on their doctoral theses are somehow disconnected from “real” nuclear engineering.

In general, the subject of a thesis is proposed to a candidate by the thesis supervisor, who takes into account the following factors:

1. Ongoing research programmes and projects, whether confined to the supervisor’s own team or within the larger unit (laboratory or department). This is related to the necessity to finance the research work of the doctoral student (candidate), with the financing guaranteed until the expected completion of the thesis.
2. Current research interests of the thesis supervisor. This is customary in the mentoring of doctoral students by supervisors. One aspect is that supervisors will have a broader and deeper knowledge on a subject, in which they are interested themselves. Another aspect is that they will be much more interested in the candidate’s work (and will thus spend more of their time on it and with the candidate), if the research brings answers also to their own curiosity.
3. Research interests of the doctoral candidate. This is also customary in doctoral studies. Although doctoral candidates have less choice in this respect than their supervisors, research within their (candidate’s) interests enhances the prospects of a successful completion of the thesis. Often, the interests of the candidate are not completely rational, but also the result of personal affinities. For instance, some candidates might be interested in nucleate boiling, whereas others might be interested in adiabatic gas–liquid two-phase flow.
4. Possibility to achieve results, which would deserve publication in a scientific journal within the time frame during which a thesis is expected to be completed (usually between three and five years). This is a kind of “pragmatic” condition, dictated by the common requirement, that the results of the thesis research be published.
5. Capabilities of the doctoral student, as estimated by the thesis supervisor. This condition does not mean, that the difficulty of the subject is adapted to the student’s intellectual capacities, but that the expected methods that will be used are in conformity with the student’s way of thinking (at least, according to the estimation of the supervisor). Thus, some students may be more inclined towards analytical solutions of equations describing the considered physical phenomenon, whereas others may be more inclined to numerical solutions (which implies developing computer programs).

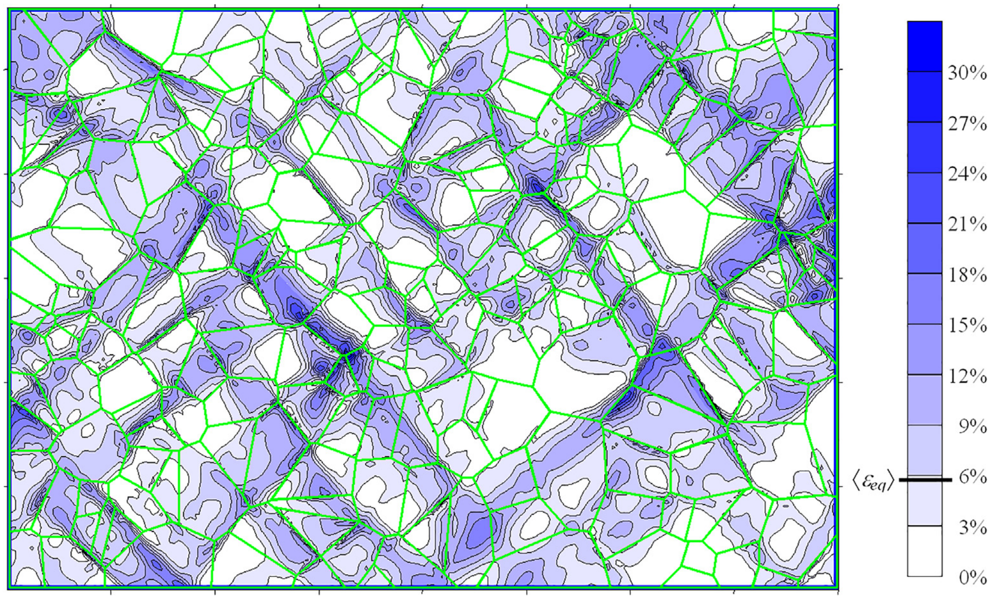

Fig. 7. Equivalent strain [%] for 212-grain polycrystalline aggregate with displacement boundary conditions.

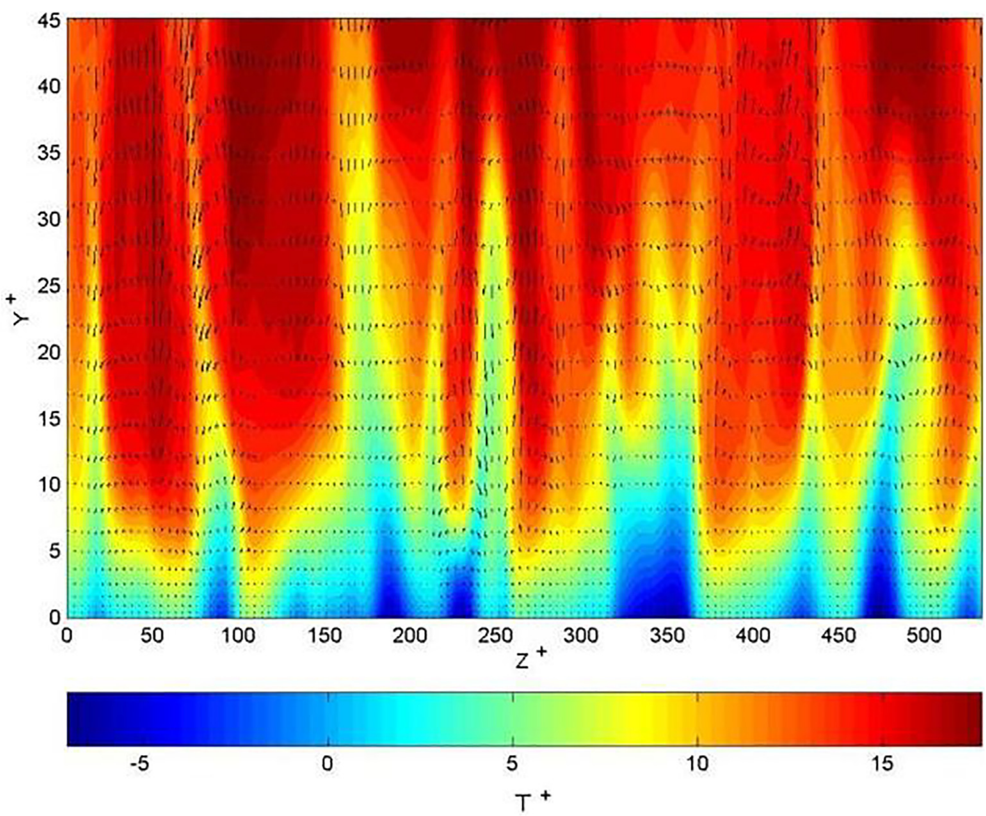

Fig. 8. Simulation of passive scalar transport in turbulent flow (dimensionless temperature field).

The determining criterion, which in fact influences most the preponderance of basic and application-oriented basic theses (as shown later for the presented case study), is the one listed under no. 4. Namely, many applied theses could usually just as well fulfil the first three criteria. Also, a student having the capability to complete a basic thesis (again, in the general sense) could also be expected to have sufficient capabilities to complete an applied one. However, as already stated in this section, results from applied research work are usually difficult to publish in scientific journals. Namely, the aim of most scientific journals is to publish novel fundamental contributions to a specific field. As the publication of a paper has become almost a standard necessary condition for completing a doctoral thesis, this definitely causes a bias towards basic topics.

3. Comparative merits of basic, application-oriented basic and applied doctoral theses

The discussion in the present section deals mainly with the issue of holders of doctoral degrees, which move to the nuclear industry. Namely, as this is where most of graduates are expected to pursue their

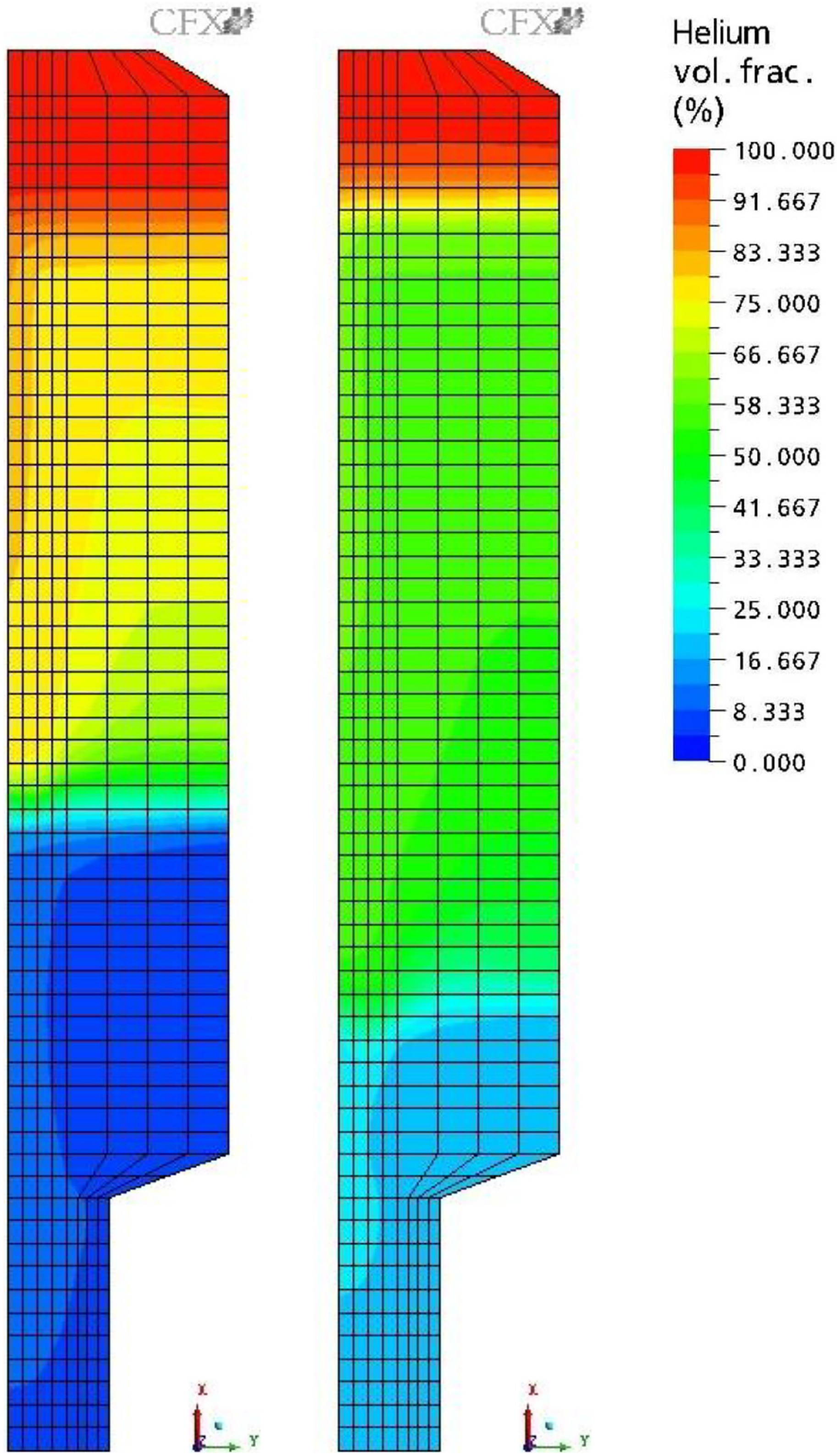

Fig. 9. Simulation of atmosphere mixing due to interaction with spray droplets (helium concentration evolution in a planar cross-section of cylindrical vessel).

careers, it is important to assess the suitability of each type of theses, as these reflect the type of education the candidates have received through their research work. Some of the arguments may of course also apply to doctors working in academic or research institutions or moving to different technical fields.

The main advantages of basic doctoral theses are:

- Students learn the details of a specific physical phenomenon. Apart from becoming knowledgeable in the studied phenomenon, they may use the acquired knowledge of basic physics (or mathematics) to understand and start working on other related phenomena, which may have to be considered within safety and/or design analyses of nuclear power plants. As an example, a candidate working on

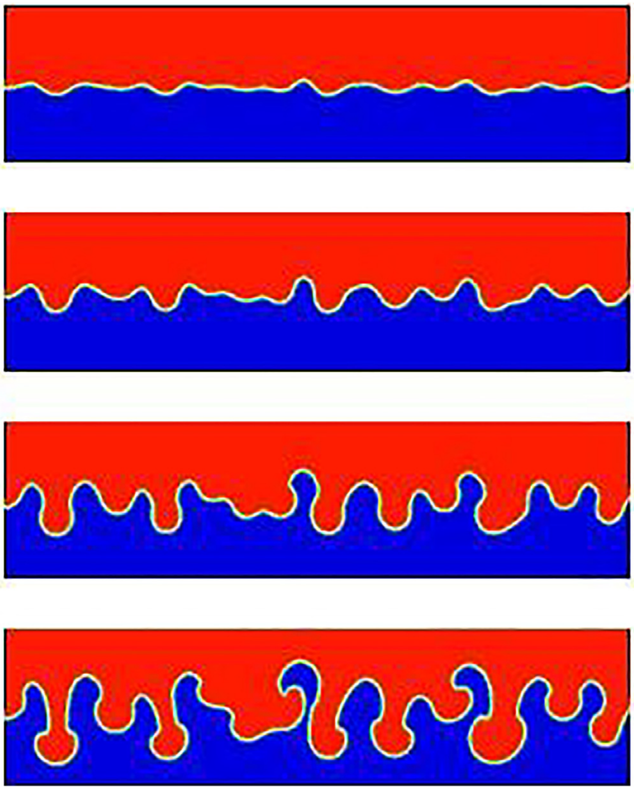

Fig. 10. Simulation of instabilities in stratified gas–liquid flow (blue field: liquid; red field: gas).

bubbly flow that may occur during boiling in the reactor core will get acquainted with interphase interaction in gas–liquid two-phase flow and will be able to understand better other two-phase flow patterns, such as stratified flow that may occur during a small-break loss-of-coolant accident (SB LOCA) in the cold leg or annular flow that may occur in steam generator tubes, also during a SB LOCA.
- Students learn to think about methods that are used in safety analyses of nuclear power plants (such as simulations with system codes) in terms of physics. Thus, they will be able to understand the physical background of technical analyses, which will make them more likely to detect eventual physical errors and inconsistencies. As an example, a knowledge of critical heat flux phenomena will enable the future doctor to evaluate if, at some conditions, departure from nucleate boiling might be expected.

Application-oriented basic doctoral theses have the same advantages as basic ones. In addition, candidates working on such theses become knowledgeable in the functioning of specific nuclear systems, in which the considered phenomena occurs. Thus, such candidates should in principle be more prepared to continue their professional path in the nuclear industry than candidates who have completed a basic thesis.

The main advantages of applied doctoral theses (in contrast to the previous two groups) are the following:

- Students get used to think about the functioning (or fault trees in PSA) of complex nuclear systems, including interactions and cause and effects between phenomena occurring in different components. As an example, they can observe the resulting integral behaviour of the system during thermal–hydraulic transients.
- Students acquire specific skills, necessary to perform technical analyses (including safety analyses) of nuclear power plants. As an example, they may get used to perform simulations of transients in reactor cooling systems with so-called system thermal–hydraulic codes such as RELAP5 or TRACE, or simulate different aspects of severe accidents with system codes such as MELCOR, ASTEC or MAAP. They may also learn to evaluate the probabilities of specific accidental events or failures.
- Students learn about specific components of nuclear power plants, such as, for example, reactor pressure vessels, steam generators, pumps, etc.

The last two cited advantages of applied theses are often cited by the nuclear industry as arguments that, by their emphasis on basic research, academic and research institutions do not provide adequate professionals for their needs (that is, professionals that could start using their knowledge fairly soon and not only after a lengthy period of acquaintance with specifics). However, this is a misinterpretation of the role of academic and research institutions: as educational institutions, their role is essentially to teach high-level knowledge, which will enable students to learn later a wide variety of technical skills, as well as to understand the characteristics and modes of functioning of different technical systems. It is true, that holders of doctoral degrees who were involved in basic research cannot start applying their knowledge immediately after completing their doctoral theses, and that the nuclear industry must first invest in them before benefiting from them. It is also true, that candidates having worked on a basic subject might lack the broad vision, necessary to oversee the functioning of a complex industrial system. However, in the long term, students having completed a doctoral thesis on basic subjects (i.e., basic and applied-oriented basic theses) are also professionals that could be expected to work on a much wider range of topics than the specific topic of their thesis.

4. Theses in nuclear engineering in Slovenia

4.1. Background and nuclear engineering studies

Nuclear energy in Slovenia plays a notable role. It provides about one third of the country's total electricity production and roughly 60% of zero carbon electricity. It therefore significantly contributes to the lowering of CO_2 emissions, which became a serious concern over the past three decades due to possible influence on climate. The sole Slovenian nuclear power plant (NPP) that is located in Krško has been in operation since 1983. The plant is a two-loop Westinghouse Pressurized Water Reactor (PWR) with 696 MW electric power and 1994 MW thermal power. The ownership of the plant is divided in two equal parts between the republics of Slovenia and Croatia through public utility companies.

The introduction of nuclear power in Slovenia prompted the development of corresponding studies at advanced levels. Studies in nuclear engineering might differ sensibly by countries. In Slovenia, the graduate studies program in nuclear engineering was established in 1986, jointly by the Jozef Stefan Institute (JSI) and the Faculty of Mathematics and Physics of the University of Ljubljana. Since 1993, 48 doctoral theses have been completed (Table 1).

4.2. Topics in research

Nuclear reactor thermal hydraulics deal essentially with flow phenomena and heat and mass transfer in the reactor primary and secondary systems. Basic research involves, in most cases, fluid mechanics and heat and mass transfer, with physical phenomena described on a local instantaneous scale. Sometimes, Computational Fluid Dynamics (CFD) codes are used to solve the transport equations of fluid mechanics. Application-oriented basic research in thermal hydraulics involves the same topics, but within specific nuclear or nuclear-like systems. On the other hand, applied research in thermal hydraulics involves simulations of integral reactor systems using so-called system computer codes (such as RELAP5 or TRACE). To be able to simulate transients (that typically last several hours) in large parts of a nuclear

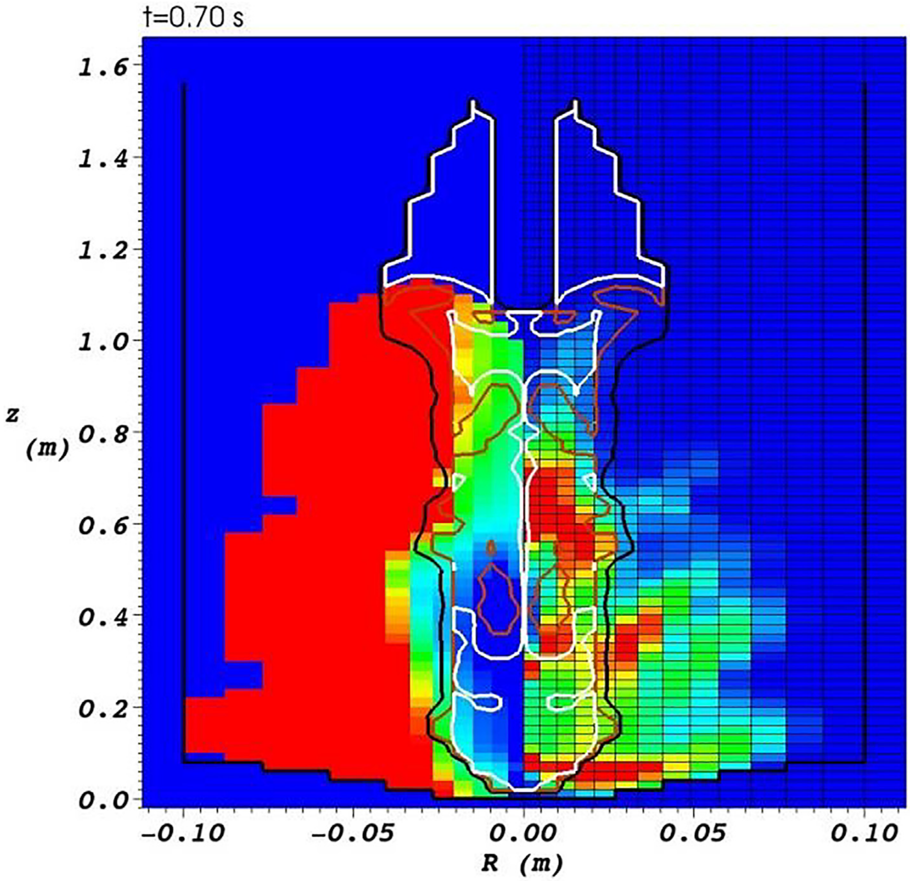

Fig. 11. Simulation of steam explosion experiment in KROTOS facility (experiment performed at Commissariat à l'Energie Atomique, France) Left: bulk temperature (lines) and crust thickness (field) Right: bulk temperature (lines) and melt droplet distribution (field).

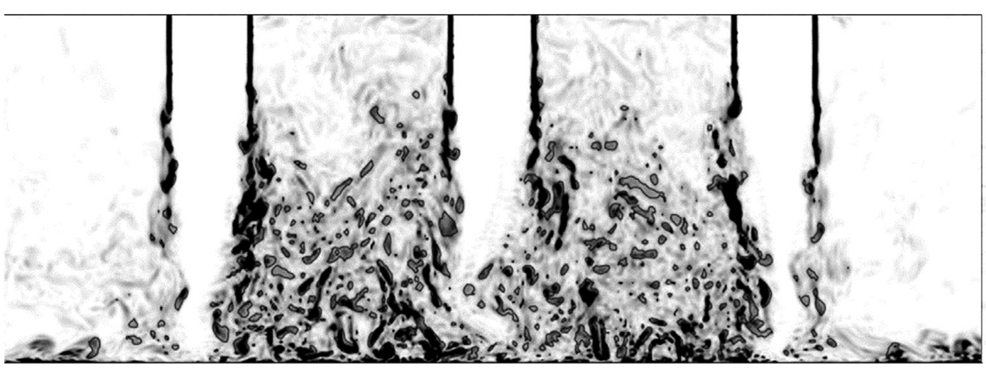

Fig. 12. Simulation of turbulent jets, impinging on hot surface.

plant, system codes use relatively simplified descriptions of physical phenomena (for instance, assumption of one-dimensional flow). Heat and mass transfer are usually modelled using empirical or semi-empirical correlations involving non-dimensional quantities; these correlations might be improved or updated in newer versions of the codes following new findings or validations.

Severe accidents consider phenomena that occur if cooling of the reactor core, following the start of an accident, has not been successful and core degradation and melting has started. As for thermal hydraulics, basic research in severe accidents also involves, in most cases, fluid mechanics and heat and mass transfer, with physical phenomena, specific for severe accident conditions, described on a local instantaneous scale with eventual use of CFD codes. Similarly to thermal hydraulics, application-oriented basic research in severe accidents involves the same topics, but occurring in nuclear or nuclear-like systems. Thus, for basic research (in the general sense), the distinction from the field of thermal hydraulics is somewhat artificial. However, this division has become customary in nuclear engineering and is used, for instance, in most conferences and technical journals. As to applied research in severe accidents, system codes (such as ASTEC or MELCOR) are being used to simulate phenomena in the reactor pressure vessel, reactor cavity, NPP containment or other relevant parts, but usually with even more simplified descriptions of physics than in thermal–hydraulic system codes (for instance, assumption of homogeneous conditions in large volumes). For this reason, such research is seldom suitable for doctoral theses.

Ageing and integrity of components deal mainly with structural and fracture mechanics of solids. Basic (including application-oriented) research involves micromechanics, whereas applied research involves application of probabilistic fracture mechanics techniques in the

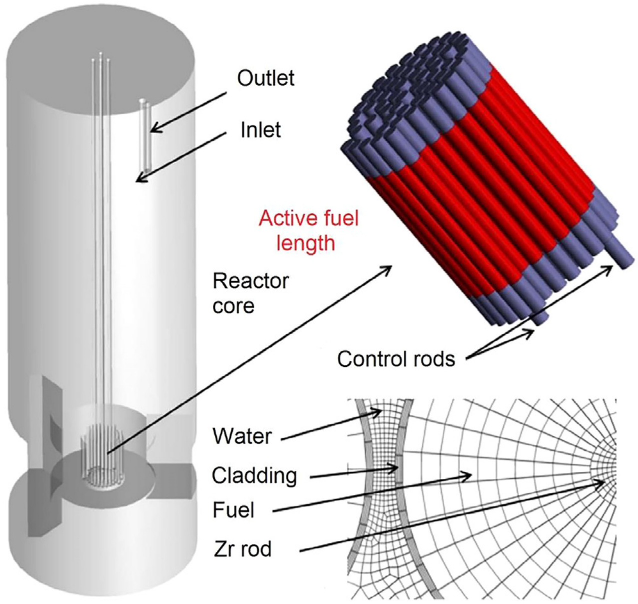

Fig. 13. Coupling of neutronics and computational fluid dynamics.

management of industrial cracking problems.

Probabilistic safety assessment deals mainly with the application of probability theory and statistics to the quantification of risk. Basic (including application-oriented) research involves new mathematical methods, whereas applied research involves the development of methodologies for specific complex industrial systems.

4.3. Topics of doctoral theses

Table 2 shows in detail the topics and specific subjects of 26 doctoral theses in the considered four fields (the remaining 22 theses were completed in other fields of nuclear engineering – see Table 1). As illustration and further information of the completed doctoral theses, the paper (or, if there was more than one, the most important paper) in which the research was published (the paper was typically published in the same or the following year after the thesis was completed) are refered in the table, along with corresponding illustrative figures for some of them. Although 26 theses is a relatively small sample, the tentative general conclusions that are drawn may be used as guidelines for similar analyses in educational organizations with a much larger number of doctoral students.

One may see, that only two (Nos. 4 and 6) out of 26 theses are

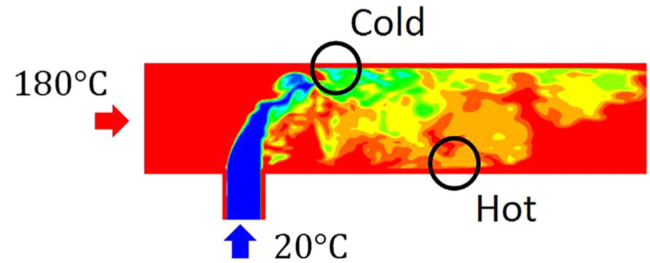

Fig. 15. Non-homogeneous temperature field, inducing thermal fatigue in tube wall, due to injection of cold liquid into hot liquid.

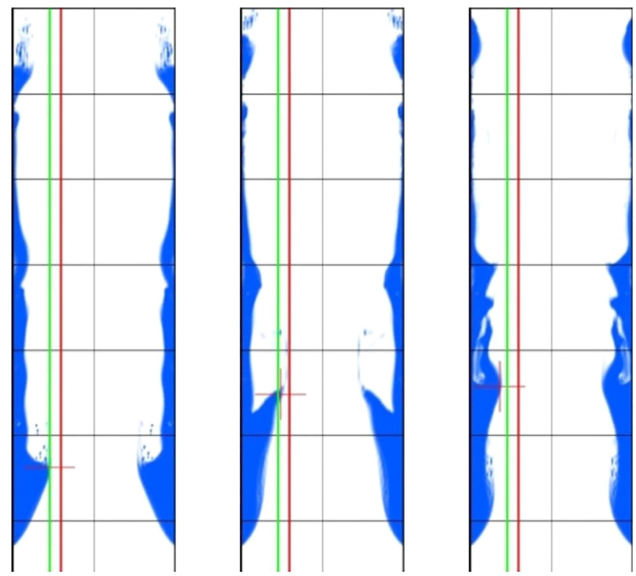

Fig. 16. Simulation of liquid waves in vertical upward gas–liquid churn flow.

categorized as “applied”: these theses dealt with simulations of transients in the PWR reactor primary system, using the well-known RELAP5 system code. From the remaining 24 theses, 13 were basic, whereas 11 were application-oriented basic (thus an even division between these two groups).

Basic and application-oriented basic theses in thermal hydraulics and severe accidents dealt with various subjects: gas–liquid two-phase flow, steam explosions, core melt in reactor pressure vessel lower plenum, convective boiling, liquid and gas turbulent flow, fluid–-structure interaction, droplet flow in atmosphere, hydrogen

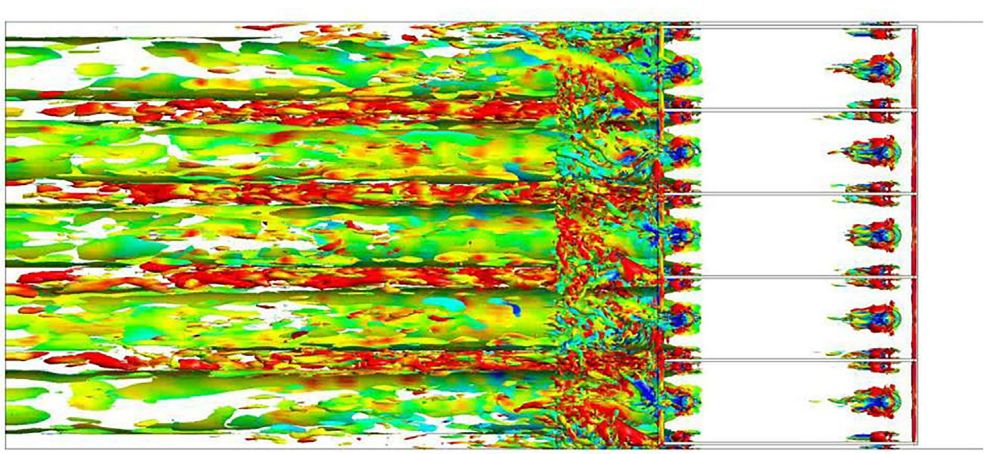

Fig. 14. Simulation of turbulent flow through horizontal rod bundle.

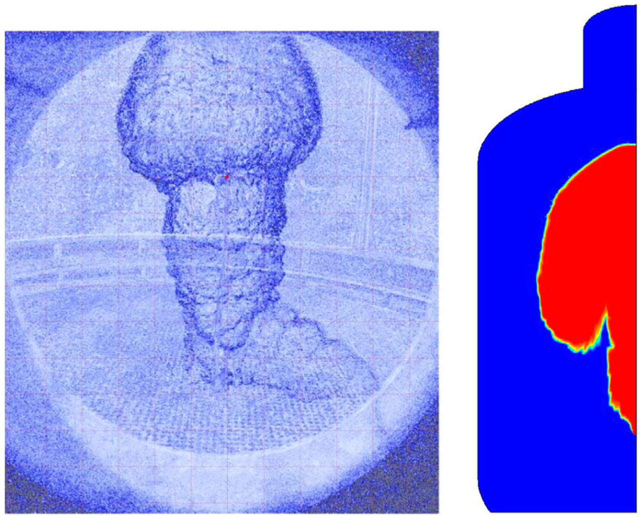

Fig. 17. Photograph and simulation of flame propagation in hydrogen combustion experiment (performed at Karlsruhe Institute of Technology, Germany).

combustion, without a strong preponderance of any subject. Such theses in ageing and integrity of components dealt with initiation and propagation of cracks, as well as with thermal fatigue. And in probabilistic safety assessment, such theses dealt with assessment and influences on reliability, influence of ageing and scheduling.

The knowledge acquired by the candidates during their basic research work in nuclear engineering may well be applied to a wider range of processes involving the basic disciplines of fluid mechanics, heat and mass transfer, structural mechanics and probabilistic safety assessment. This is an illustration of the merits of basic and application-oriented basic theses, described in Section 3.

The number of basic (including application-oriented basic) theses definitely dominates over the number of applied ones: the difference is not just a statistical uncertainty or a fluctuation, but a definite trend that seems likely to continue in the future. The most likely explanation for this trend is offered in the preceding section of this paper. So, due to the current criteria for obtaining a doctoral degree, a shift towards applied theses is not expected.

4.4. Subsequent professional careers of doctoral students

In categorizing the subsequent careers of students, the position some five years after the completion of the thesis was taken into account. As for more recent theses, the position in which candidates settled for a prolonged period following the completion was considered. That said, the subsequent career path of the considered candidates was the following:

Table 1
Number of doctoral theses in nuclear engineering by topics in Slovenia in the period 1993–2019.

Topic	Number of theses	Considered in present paper
Reactor physics	20	No
Thermal hydraulics	**14**	**Yes**
Severe accidents	**4**	**Yes**
Ageing and integrity of components	**3**	**Yes**
Probabilistic safety assessment	**5**	**Yes**
Other	2	No

- 14 stayed in the field of nuclear research (including those that have completed the two applied theses), which somehow contradicts the statement, that most graduates are expected to pursue their careers in the nuclear industry;
- 3 moved to the nuclear industry;
- 1 moved to a non-nuclear research organization;
- 5 moved to non-nuclear industrial companies, where they are mainly involved in modelling of systems and physical phenomena;
- 1 moved to a university as full-time member;
- 2 moved to completely different fields.

4.4.1. Further careers in nuclear/non-nuclear, research/non-research

The main issues of interest, when looking at the entire population of candidates, are:

- what proportion of candidates stayed in the nuclear field?
- what proportion of candidates stayed in research?

In principle, the higher the proportion of candidates that stay in the nuclear field, the more meaningful the nuclear engineering programme may be considered. The fact that 17 (out of 26) candidates stayed in the nuclear field confirms the adequacy of the considered nuclear engineering studies. However, only 3 candidates ended up in the nuclear industry. Although no candidate ended up in the nuclear regulatory authority, the graduates retained in nuclear research with the Jožef Stefan Institute significantly contribute to the scientific and technical support given to the regulator.

However, when considering the proportion of candidates that stay in research (be it nuclear or non-nuclear), what should be best is less

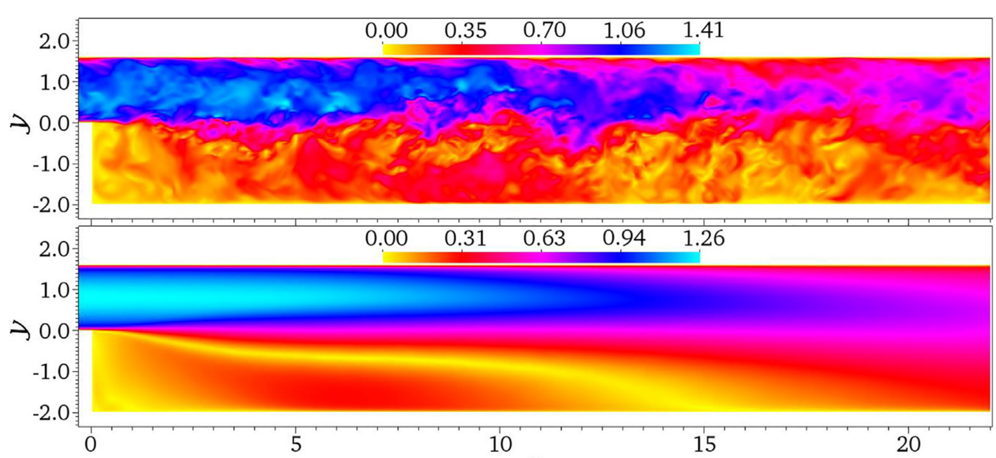

Fig. 18. Instantaneous (top) and average (bottom) velocity fields of turbulent flow over backward facing step. Inflow: left; outflow: right.

Table 2
Doctoral theses in Slovenia in the fields of thermal hydraulics, severe accidents, ageing and integrity of components, and probabilistic safety assessment, in the period 1993–2019 (B: basic, AB: application-oriented basic, A: applied).

No.	Year	General topic	Research subject and work	B/AB/A	Later position of candidate
1	1993	Ageing and integrity of components	Application of probabilistic fracture mechanics in steam generator problem management (Cizelj et al. 1996)	AB	Nuclear research
2	1997	Gas-liquid two-phase flow	Simulation of pressure transient in two-phase flow using own one-dimensional model and code (Tiselj and Petelin, 1997)	B	Nuclear research
3	1999	Probabilistic safety assessment	Improvement of computerised safety-related systems realiability in nuclear power plants (Čepin, 2002)	AB	University
4	1999	Transients in PWR primary system	Simulation of transient in PWR primary system using RELAP5 system code, with emphasis on evaluation of uncertainty of peak cladding temperature during uncovering of reactor core (Prošek and Mavko, 1999)	A	Nuclear research
5	2000	Steam explosions	Simulation of premixing phase of steam explosion (interaction between core melt and coolant) using own model and computer code (Fig. 2) (Leskovar et al., 2000)	B	Nuclear research
6	2001	Transients in PWR primary system	Simulation of transients in PWR primary system using RELAP5 system code, with emphasis on boiling in reactor core (Fig. 3) (Parzer et al.1995)	A	Nuclear research
7	2001	Gas-liquid two-phase flow	Simulation of stratified gas–liquid flow using own two-dimensional model and code (Fig. 4) (Černe et al., 2001)	B	Non-nuclear industry
8	2001	Core melt in reactor pressure vessel lower plenum	Simulation of natural convection in fluid with internal heat generation using own Large-Eddy Simulation two-dimensional model and code (Fig. 5) (Horvat et al., 2001)	B	Non-nuclear industry
9	2001	Probabilistic safety assessment	Component reliability assessment using probability theory and theory of fuzzy sets (Jordan et al., 2001)	B	Non-nuclear public service
10	2003	Convective boiling	Simulation of convective nucleate boiling at low-pressure conditions using CFD code and own models for inter-phase momentum, heat and mass transfer (Fig. 6) (Končar et al., 2004)	B	Nuclear research
11	2004	Ageing and integrity of components	Influence of microstructure of development of large deformations in reactor pressure vessel steel (Fig. 7) (Kovač and Cizelj, 2005)	B	Non-nuclear industry
12	2006	Turbulent flow	Simulation of passive scalar transport in turbulent flow using Direct Numerical Simulation (Fig. 8) (Bergant and Tiselj, 2007)	B	Nuclear industry
13	2008	Fluid-structure interaction	Coupled thermal–hydraulic simulation of 1D single or two-phase flow and structural simulation of 2D piping system modelled with beam approximation (Gale and Tiselj, 2008)	AB	Non-nuclear industry
14	2008	Droplet flow in atmosphere	Simulation of interaction between spray droplets and atmosphere, using CFD code and own models for heat, mass and momentum transfer between droplets and atmosphere (Fig. 9) (Babić et al., 2009)	AB	Business consulting
15	2008	Probabilistic safety assessment	Impact of offsite power system reliability on nuclear power plant safety (Volkanovski et al., 2009)	AB	Nuclear research
16	2009	Gas-liquid two-phase flow	Simulation of instabilities in stratified gas–liquid flow using own two-dimensional model and code (Fig. 10) (Štrubelj et al.2009)	B	Nuclear industry
17	2011	Steam explosions	Modelling of solidification effects in fuel–coolant interactions (Fig. 11) (Uršič et al., 2011)	B	Nuclear research
18	2012	Probabilistic safety assessment	Multi-objective optimization of testing and maintenance in nuclear power plants considering component ageing (Kančev et al., 2013)	AB	Nuclear industry
19	2013	Probabilistic safety assessment	Optimal generation schedule of nuclear and other power plants with application of genetic algorithms (Gjorgiev et al., 2013)	AB	Non-nuclear research
20	2015	Turbulent flow	Numerical simulations of turbulence and heat transfer of multiple jets impinging on a heated surface (Fig. 12) (Draksler et al., 2017)	B	Nuclear research
21	2016	Ageing and integrity of components	Simulation of random thermal loads and study of their influence on thermal fatigue of nuclear piping (Fig. 13) (Costa Garrido et al., 2016)	AB	Nuclear research
22	2016	Turbulent flow	Modelling of turbulent flow in a fuel assembly of pressurized water reactor (Fig. 14) (Mikuž and Tiselj, 2016)	AB	Nuclear research
23	2017	Reactor physics and heat transfer	Neutronic and thermal-hydraulics coupling for simulations of TRIGA Mark II research reactor (Fig. 15) (Henry et al. 2017)	AB	Nuclear research
24	2018	Gas-liquid two-phase flow	Modelling of isothermal separated gas–liquid flow in a vertical pipe: study of liquid waves in churn flow (Fig. 16) (Tekavčič et al., 2018)	B	Nuclear research
25	2019	Hydrogen combustion	Modelling of turbulent hydrogen combustion in large-scale experimental containment facilities (Fig. 17) (Holler et al., 2019)	AB	Non-nuclear industry
26	2019	Turbulent flow	Direct numerical simulation of flow separation with heat transfer (Fig. 18) (Oder et al., 2019)	B	Nuclear research

clear. On one hand, research organisations should receive regular influxes of new researchers. On the other hand, the society at large should also benefit directly from highly skilled individuals. The fact that the majority (15 out of 26 candidates) stayed in research indicates, that these benefits could be higher. Besides, only a single candidate went into non-nuclear research. This indicates that those who stay in research are not likely to move to different fields. However, among the candidates that did not continue in research, only 3 (out of 11) stayed in the nuclear field. Thus, the majority of those who did not continue in research also opted out of nuclear.

4.4.2. Correlations with thesis type

Due to the small sample, eventual correlations between the thesis category and the subsequent professional path of the doctoral candidate should be taken with caution. From the candidates who have completed a basic thesis, 9 (out of 13) stayed in the nuclear field. From the candidates who have completed an applied or an application-oriented basic thesis, 8 (out of 13) stayed in the nuclear field. Thus, the ratios are very close (considering the small sample).

Looking to the further occupations of candidates, from those who have completed a basic thesis, 7 (out of 13) stayed in research. From the other group, 8 (out of 13) stayed in research. Again, the ratios are very close. This indicates, that the type of thesis does not necessarily determine, whether a candidate will stay in research or not.

Looking the other way round, of the 8 candidates who went into the industry (nuclear or non-nuclear), 5 completed a basic thesis and 3 an application-oriented basic thesis. The presented evidence indicates, that work on basic theses (including application-oriented basic theses), at least within the considered topics of nuclear thermal hydraulics, severe accidents, ageing and integrity of components, and probabilistic safety assessment, may still be an adequate basis for future careers in the nuclear or other industries.

5. Conclusions

The current conditions for obtaining a doctoral degree engender, in the field of nuclear engineering, a predominance of basic (including application-oriented) doctoral theses over applied ones. This was confirmed by a review of doctoral theses completed at the Jozef Stefan Institute and the University of Ljubljana during the period 1993–2019. A survey of later positions of the considered holders of doctoral degrees shows that most of them (17 out of 26) continued their careers in the nuclear field. Out of 16 that stayed in academia and research, 14 remained active in nuclear research. These contribute notably to nuclear education, public outreach and to the scientific and technical support to the regulator. From the 8 that choose industrial careers, only 3 remained in the nuclear industry.

The lessons learned are that the work on a basic thesis has been an adequate basis for careers in the academia and nuclear or other industries. It also appears that the holders of nuclear doctorates are much more likely to start a career in nuclear academia and non-nuclear industries than in nuclear industries and especially nuclear regulators. This does not call for any immediate changes in the existing graduate curricula and procedures. At the same time, it clearly indicates a need for much stronger involvement of nuclear industry and regulators in the strategic planning of nuclear education.

Similar reviews from other institutions involved in nuclear engineering education would be beneficial to compare the statistics, confirm or refute the theses presented in the present paper, and to facilitate the further strategic development of the graduate nuclear engineering education in the future.

CRediT authorship contribution statement

Ivo Kljenak: Conceptualization, Formal analysis, Writing - original draft. **Leon Cizelj:** Formal analysis, Writing - review & editing. **Iztok Tiselj:** Writing - review & editing. **Borut Mavko:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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