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The European GO-VIKING Project on Flow-Induced Vibrations: Overview and Current Status

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ABSTRACT

The interaction between cooling fluid and solid structures (rods, tubes) in nuclear power plants may lead to flow-induced vibrations (FIV), causing material fatigue, fretting wear, and eventually loss of component integrity. This can cause further safety issues as well as substantial standstill costs due to longer or unplanned outages. With the growing computational power, the application of modern 3D numerical simulation tools for the accurate prediction of FIV phenomena is rapidly increasing. In 2022, the GO-VIKING (**G**athering expertise **O**n **V**ibration **I**mpa**K**t **I**n **N**uclear power **G**eneration) project received a grant within the Horizon Europe research and innovation funding program. Sixteen European and two US partners already started their collaboration in the field of FIV experiments and analysis. Over four years, the GO-VIKING project investigates FIV phenomena occurring in nuclear reactor cores and steam generators under single- and two-phase flow conditions. The project's main objectives are to expand the expertise in the field of FIV through generation of new experimental data; development, improvement, and validation of fluid-structure interaction (FSI) methods for FIV evaluation; training stakeholders in the application of these methods; and synthesizing guidelines for the prediction and assessment of FIV phenomena in nuclear reactors. This paper provides an overview of the GO-VIKING objectives, scientific program, as well as of the main scientific achievements in the first project year.

KEYWORDS

Flow-induced vibration, fluid-structure interaction, GO-VIKING, CFD, CSM

1. INTRODUCTION

The integrity of the nuclear steam supply system (NSSS) of a nuclear power plant (NPP) is essential for the plant's safety and operability. In a pressurized water reactor, this contains the primary circuit of the NPP with all major components such as reactor pressure vessel (RPV), main coolant pumps, hot and cold legs, pressurizer, as well as the steam generators. Key NSSS components such as fuel assemblies (FA) or steam generator (SG) tubes are subject to several ageing challenges like corrosion mechanisms, neutron flux embrittlement, and vibratory loads. Vibrations induced by coolant flow are particularly important challenges, as they lead to increased wear and tear and/or material fatigue, so that they have been and remain important contributors to key components' failures. Such failures can degrade NPP safety features and even lead to a breach of confinement barriers (rod cladding, steam generator tube walls), thus generating not only operational, but also safety issues.

Over 70% of all fuel rod leakages in US pressurized water reactors (PWR) are due to flow-induced vibrations (FIV), according to EPRI (2008). According to IAEA, grid-to-rod-fretting wear (GTRFW), resulting from such vibrations, is the cause of 58% of fuel failures in PWRs worldwide (IAEA 2019). The highly turbulent coolant flow in FA during normal operation results in asymmetric and fluctuating pressure forces on the fuel rods' surfaces. The pressure fluctuations are random, and oscillate over a broad band of frequencies and amplitudes over the entire rod surface. This leads to dynamic spacer grid-to-rod contacts and frictions, resulting in material wear in the contact region between the rod and its support in the FA construction (springs and dimples).

FIV cause damage also in SG. In 2012, a SG tube rupture (SGTR) accident occurred in the US NPP San Onofre. An extensive wear of more than 3000 SG tubes was found in its units 2 and 3, leading to primary-to-secondary circuit coolant leaks. The SG in these units were put in operation one year earlier. The principal reason for the extensive wear and the tube damage was found to be related to FIV (NRC

2015). Since then, these units are in a shut-down condition pending decommissioning. SGTR as a result of FIV has also been observed in many other NPPs in the past (Kotthoff 1984; MacDonald et al. 1996).

The recent trend, set by vendors, to further increase the thermal efficiency of heat exchangers, SG, and other thermal equipment led to component designs with higher thermal efficiency. This is mainly achieved with higher temperatures, increased fluxes and mass flow rates, as well as thinner tube walls (Fischer 2001). The enhancement of the heat transfer in the heat exchangers through increased flow velocities and thinner tube walls automatically leads to increased susceptibility of the tubes to FIV. Further, ageing mechanisms have a negative impact on the structural behavior concerning FIV. With time, the material fatigues and wear increases, the gaps between the structural components increase, while at the same time the mechanical contacts between the structures degrade. This is even more important for long-term operation (LTO). All this makes the nuclear components more prone to vibrations, induced by the working fluid (coolant). Therefore, it is important to properly calculate the vibratory loads, induced by the flow already in the component design phase. Later, these loads have to be addressed in the NPP operational surveillance and maintenance programs.

In the last decade, many NPPs underwent extensive power uprate programs, some of them even more than one. Such uprates are often realized including, but not limited to, increased thermal power, temperatures and flow velocities, especially in the steam lines. These led to increased vibrations in some of the plant components, leading to plant operation at a dramatically reduced power (down to 30% of the nominal one) for longer periods (months). Therefore, FIV have to be carefully considered, when a plant power uprate is planned.

As tests and measurements under operational conditions are often costly or not feasible, prediction of FIV loads by numerical simulation could be a practical solution. The GO-VIKING Horizon Europe project (<https://go-ving.eu/>) gathers expertise from academia and research organizations, industry, and technical safety organizations (TSO) to synthesize and improve good practices, as well as to generate experimental data and to develop accurate numerical simulation methods (Papukchiev et al. 2023). These will support the prediction and evaluation of FIV by EU stakeholders, as well as their decision making on FIV countermeasures in the NPPs.

The current paper gives an overview of the GO-VIKING project with its specific objectives (SO) and work package (WP) structure. Further, some first results achieved in the project's first year are presented.

2. THE EUROPEAN GO-VIKING PROJECT ON FLOW-INDUCED VIBRATIONS

The GO-VIKING project (Grant Agreement No. 101060826) builds upon the VIKING (Vibration **ImpaKt** **In** Nuclear power **Generation**) initiative that started in 2020 as an in-kind collaborative effort under the SNETP umbrella (label from 09.2021) to improve the understanding and the prediction of FIV phenomena relevant to NPPs (Zwijssen et al. 2022). VIKING delivered important results on the simulation of FIV in FA and SG relevant geometries, and thus paved the way for the GO-VIKING project. GO-VIKING started in June 2022 and will run for four years, coordinated by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany and the Nuclear Research and consultancy Group (NRG), The Netherlands.

2.1. GO-VIKING Partners

The following 18 partners have joined forces in the GO-VIKING collaboration:

- Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH, Germany (GRS)
- Nuclear Research and consultancy Group, The Netherlands (NRG)

- Universiteit Gent, Belgium (UGENT)
- LGI Sustainable Innovation, France (LGI)
- Electricité De France, France (EDF)
- Technische Universiteit Delft, The Netherlands (TUD)
- Teknologian tutkimuskeskus VTT Oy, Finland (VTT)
- Framatome GmbH, Germany (FRA-G)
- Institut de Radioprotection et de Sûreté Nucléaire, France (IRSN)
- Institut von Karman de dynamique des fluides, Belgium (VKI)
- IPP Centre LLC, Ukraine (IPP)
- EDF Energy, United Kingdom (EDF-E)
- European Nuclear Education Network, Belgium (ENEN)
- University of Manchester, United Kingdom (UoM)
- Forsmarks Kraftgrupp AB, Sweden (FK)
- Commissariat à l'énergie atomique et aux énergies alternatives, France (CEA)
- Pennsylvania State University, USA (PSU)
- Virginia Commonwealth University, USA (VCU).

This mix of research institutes, technical support/safety organizations, universities, power generation industry, vendors, and utilities implies not only a solid knowledge fundament for the common work in GO-VIKING, but it also ensures that the outcome of the project will reflect the interests/needs of the different partner groups in the nuclear business. The project results will be disseminated through the different group networks to find their way into the nuclear legislation, NPP component design, plant operation, and nuclear research.

2.2. GO-VIKING Specific Objectives

The main objective of the GO-VIKING project is to increase the knowledge of reactor-relevant FIV, to develop, improve and validate FSI methods for FIV evaluation, and to provide guidelines for the prediction and assessment of FIV phenomena in nuclear facilities. Building on that, it aims to bring them into application at European nuclear stakeholders for improving the design, operation, and maintenance of key NPP components, and thereby, enhance both safety and availability of existing and future NPP in Europe. The following GO-VIKING specific objectives (SO) were defined:

SO1: Generation of new experimental and high-resolution numerical data, relevant for nuclear FA and SG. The further development and validation of FSI methods to evaluate FIV for these key NSSS components is inhibited by the limited number of FIV experiments publicly available. Most of

these are focused on single phase flow problems and mainly involve structural vibration measurements (time-dependent displacements or accelerations). The lack of information on the flow field, responsible for the vibrations, limits the possibility to fully understand and in-depth analyse the complex formation of the vibration excitation mechanisms in FA and SG. Furthermore, such data is of great importance for the validation of the numerical tools and the assessment of their predictive capabilities.

SO2: Expanded knowledge on efficiency, accuracy and reliability of FSI methods. The available FSI methods for the evaluation of FIV phenomena can be based on turbulence modelling resolution, one- or two-way data transfer, explicit or implicit coupling, moving or fixed fluid grids, etc. Some of the FSI methods provide sufficient accuracy for a certain type of FIV, but can lead to inadequate results when used for other FIV types. Therefore, knowledge on the advantages and disadvantages of the different methods, as well as the range of their applicability have to be developed.

SO3: Provision of validated fast-running FSI tools with uncertainty quantification methods. Within GO-VIKING, high- and medium-resolution FSI methods will be developed, validated and provided to the European nuclear stakeholders. Since the industry is also in need of fast-running approaches, development, validation and application of practical and efficient FSI methods, based on reduced-order models (ROM), are included in the work program of the project. Such methods will enhance the development and application of uncertainty quantification (UQ) techniques, needed for best-estimate calculations when used as evidence to support safety cases.

SO4: Highly increased expertise of and awareness on FIV phenomena in NPPs. The performed experiments together with the numerical analysis of FIV with high-resolution 3D computational fluid dynamics (CFD) and computational structural mechanics (CSM) tools will allow deeper insights in the FIV formation mechanisms as well as improved understanding of the interplay between fluids and structures. This will lead to a highly increased expertise in the different FIV phenomena that take place in the NSSS key components such as FA and SG. The result will be increased knowledge and awareness of the operators and regulators concerning FIV in NPPs.

SO5: Synthesis of best practices and training of stakeholders and graduates in numerical FIV analysis. The expertise, generated within GO-VIKING on the evaluation of FIV in nuclear reactors with the help of validated FSI simulation tools, will be synthesized in Best Practice Guidelines (BPG) on the use of FSI methods for FIV evaluation. The document will guide NPP utilities, stakeholders and practitioners in the FIV evaluation, starting from the correct classification of the identified issue, through the selection of the appropriate numerical tool and modelling approach, till the evaluation of the achieved results. This will ensure an efficient and reliable analysis of the complex multi-physics FIV phenomena that will enhance the identification of efficient FIV countermeasures in the plants.

2.3. Concept of the GO-VIKING Project

The advances in CFD and CSM simulation tools, coupling techniques, and computing resources have set the preconditions for the establishment of FSI methods in the EU nuclear industry. The GO-VIKING project gathers partners from industry, research, TSO and academia with a strong background in the CFD, CSM, experiments, and FSI-related research and development with the purpose to further increase the knowledge on FIV phenomena in key NSSS components such as FAs and SG, as well as to develop FSI techniques and tools and bring these into practical application. To reach the aforementioned SO, the GO-VIKING project follows a systematic approach. The project is focused on stakeholder needs, as represented by the institutional diversity of the GO-VIKING partners. But going beyond that circle, GO-VIKING actively and repeatedly engages with further stakeholders from EU nuclear industry and safety authorities to appropriately address their needs, encourage the transition to FSI techniques developed and demonstrated in the project, as well as train and educate EU experts in these matters. To reach the GO-

VIKING SO, a project concept was developed. It is based on the project’s global targets, activities, resources, and the expected outcome. Figure 1 presents this concept.

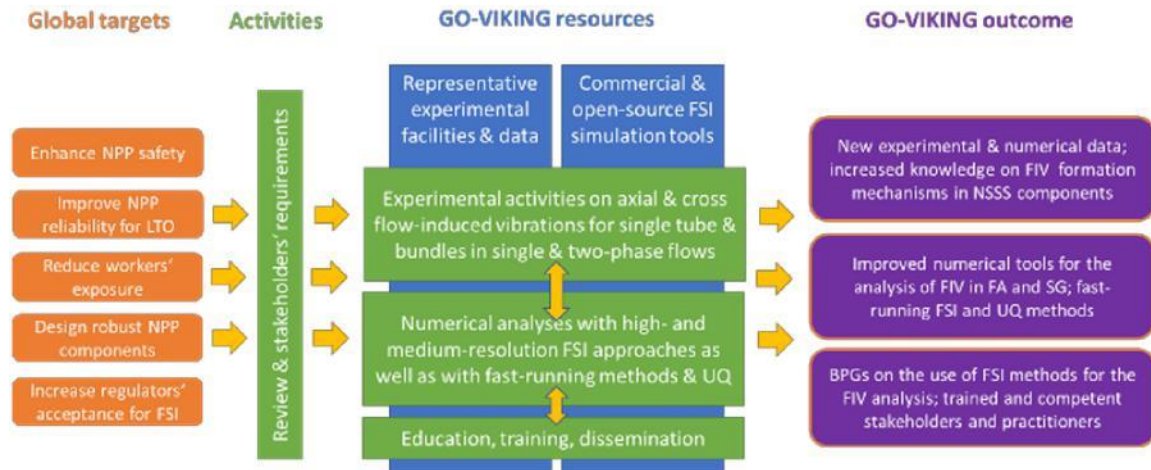


Figure 1. GO-VIKING concept, showing project’s global targets as well as the available activities and resources to generate the expected project outcome.

Many of the existing single-phase FIV experiments focus primarily on the structure vibration characteristics and do not measure the flow structure in detail with modern measurement techniques like Particle Image Velocimetry (PIV) or Laser Doppler Velocimetry (LDV), which allow to acquire more detailed information on the flow field needed for validation of CFD based methods (Cardolaccia and Baj 2015). The existing experimental database for vibration phenomena in two-phase flows is very limited and not sufficient to understand the ongoing FSI mechanisms. With respect to **SO1**, GO-VIKING aims to perform single and two-phase FIV experiments that strive to go beyond the current state-of-the art with setups consisting of large numbers of rods/tubes, fine geometry details (spacer grids, springs, dimples, real life tube diameters, pitches, lattices), more realistic boundary conditions (higher Re numbers), and the use of advanced instrumentation. Further, high-resolution numerical data, based on either Direct Numerical Simulation (DNS) or wall-resolved Large Eddy Simulation (LES) approaches, will be generated to support the validation of the lower resolution FSI methods or fast-running models. Such numerical data will complement the experiments by providing extra information for the flow field and the acting forces.

With the large variety of FSI methods and the lack of knowledge and expert consensus on which FSI method is adequate and efficient for the analysis of a particular FIV phenomenon, the choice of an appropriate analysis approach is not simple. With respect to **SO2**, GO-VIKING aims to perform cross-validation using high- and medium-resolution FSI methods with modern CFD-CSM codes on a range of recent and completely new experiments for FIV relevant to SG and FA. Results from high-resolution and full-order 3D coupled simulations, based either on DNS or wall-resolved LES, will be compared to medium-resolution methods that rely on the Unsteady Reynolds-Averaged Navier-Stokes (URANS) approach or on less refined scale-resolving simulations (SRS), for example, based on hybrid turbulence models (Menter 2015). Further, methods, built on moving computational fluid meshes such as Arbitrary Lagrangian Eulerian (ALE) will be compared to fixed fluid grid approaches (Immersed Boundary (IB)) on different cases to evaluate the performance and the applicability of these FSI methods. The results of all comparative analyses will help expanding the knowledge on efficiency, accuracy and reliability of the FSI methods.

Since the required computational resources for an FIV analysis are very high, there is a strong interest in the development and implementation of fast-running simulation tools. One approach is the utilization of

reduced-order model (ROM) techniques that might represent either the structural or the fluid domain. Currently, there is a lack of knowledge on effective strategies for ROMs and other fast-running simulation approaches for the simulation of FIV in SG and FA. With respect to **SO3**, the GO-VIKING project will address this by developing and validating fast-running, low-resolution FSI methods for the solid and fluid domains. Further, efficient uncertainty and sensitivity quantification methods for FSI will be developed, since such methods are required as part of the safety demonstration according to, e.g., IAEA SSG-2 (IAEA 2010).

With respect to objective **SO4**, the increased awareness of and knowledge on FIV will eventually assure the safe operation of the existing plants even in case of power uprate and LTO programs. This will be achieved through more in-depth understanding of FIV formation mechanisms as well as their accurate and reliable prediction for FA and SG, as vibrations are one of the major causes of failures of these components. GO-VIKING aims at developing expertise on different phenomenological levels: FIV in axial and cross-flows (turbulence and vortex shedding mechanisms); FIV in single and two-phase flow environments; FIV in single rod/tube and rod/tube arrays. This multilevel experimental and numerical scientific program aims at addressing FIV in PWR and boiling water reactor (BWR) FA as well as in PWR SGs, thus generating valuable expertise on the FIV phenomena occurring in these key NSSS components.

The lack of guidelines limits the application of FSI methods for the analysis of FIV and the level of acceptance of FSI methods by the regulatory bodies, as well as their expectations on such programs for safety demonstrations of current and new nuclear facilities are unclear. With regard to **SO5**, the experience gained throughout the whole GO-VIKING project on the analysis of FIV phenomena in key NSSS components with modern 3D programs will be synthesized in BPG. These guidelines will help vendors, regulators, TSOs, and industry to obtain a deeper understanding on the FIV nature and their impact on the safety of nuclear reactors, and to provide them with knowledge and confidence in their analysis in this very challenging interdisciplinary field.

GO-VIKING will maximize the return from the gained experience and disseminate the generated know-how, while at the same time strengthening the human capital in research and innovation. The scientific community will be the direct beneficiary here: 33 out of 34 deliverables will be publicly available. For the success of this large and ambitious collaborative project, possible critical risks were identified and mitigation measures were proposed within the GO-VIKING risk management strategy.

2.4. Structure of the GO-VIKING Project

The structure of the project is based on eight work packages, as shown in Fig. 2. In WP1, the relevant FIV phenomena in NPPs and the available FSI methods will be studied, while the needs and expectations of the stakeholders for FSI tools will be identified in a dedicated workshop. All important findings and conclusions will be provided to the experimental and numerical work packages (WP2-WP5), in which FSI methods and models are developed and validated. WP2 is dedicated to the analysis of single-phase FIV in FA, while WP3 deals with single-phase FIV in cross-flow, relevant to SG. The complex nature of the FIV in multiphase environment will be investigated in WP4, for both FA and SG relevant configurations. The data generated in WP2-WP4, together with conclusions and recommendations, will also be used as an input for the development of fast-running methods in WP5. Further, in WP5 UQ methods for FSI simulations will be developed, and the experience gained in all other technical WPs will be synthesized in *BPG on the Use of FSI Methods for the Evaluation of FIV in Nuclear Applications*. Within WP6, the project results will be disseminated, and practitioners from stakeholders, as well as students and postgraduates, will be educated and trained in the application of the developed methods and tools. The GO-VIKING project management activities are enclosed in WP7, while WP8 deals with ethics.

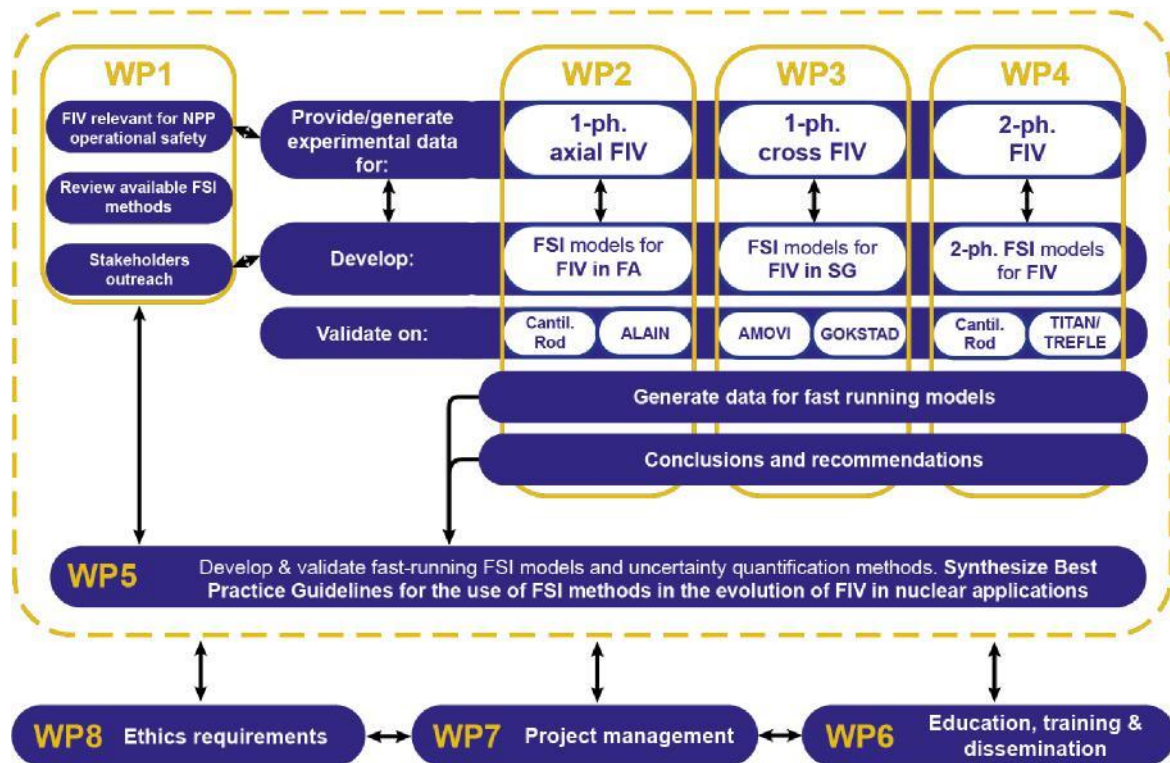


Figure 2. Structure of the GO-VIKING project: it consists of five technical work packages, dedicated to the analysis and understanding of flow-induced phenomena, as well as three work packages dealing with education, training, dissemination, project management and ethics.

3. GO-VIKING WP1: STATE-OF-THE-ART AND STAKEHOLDER OUTREACH

In WP1, the available nuclear power plant operational experience with FIV are investigated. The most relevant FIV phenomena are being summarized and in parallel, a literature review on the available FIV experiments is being carried out. The gaps in the experimental data are identified and will be considered in the design phase of the new experimental rigs to be built within GO-VIKING. Further, the currently available FSI methods are classified. Their advantages/drawbacks and their applicability for the objectives of the project will be evaluated as well.

3.1. GO-VIKING Stakeholders' Outreach Workshop

GO-VIKING strives to take into account the needs of the different stakeholders concerning FIV analysis in its research and outcome as much as possible. One of the two goals of WP1 is to identify industry needs and regulatory expectations in terms of tools and methods for the analysis of FIV phenomena in NPPs. To do that, a stakeholders' workshop was organized by EDF and IRSN. The workshop took place on the 16th of February 2023 at EDF Lab in Chatou: 14 stakeholders and institutions from Europe and North America attended the event and presented their relevant topics on FIV. The nuclear power generation industry was represented by EDF (France), EDF UK (UK), TVO (Finland), Vattenfall and Uniper Energy (Sweden, involving three NPPs), EPRI (USA). The vendors Framatome (France and Germany) and Westinghouse (USA) contributed to the workshop as well: Further presentations were given by nuclear safety authorities (NRC (USA), CNSC (Canada)) and TSOs (GRS (Germany), IRSN (France)).

During the workshop, a feedback was obtained from the stakeholders concerning the FIV problems they face and have to solve as well as the numerical tools they need for this. It was found that LES, when computationally feasible, would represent an ideal choice to estimate turbulence-induced forces on the

fuel rods of a FA, and there is a need for experimental measurements for the validation of the LES results. For SGs, several FIV modelling approaches were presented, ranging from component-scale porous media approaches up to CFD-scale simulations coupled to structural beam models. The consistency of the two-phase CFD simulations for the different two-phase flow-regimes and the flow regime transition inside a SG has to be assessed through CFD-grade experimental database, which is currently lacking. Safety authorities and TSOs presented their requirements in terms of quality plan, verification and validation and uncertainty quantification process for numerical tools, used for FIV analysis within the safety demonstration. The acceptance of CFD-CSM results by the regulators is therefore subjected to a rigorous preliminary validation phase, which should be considered by the stakeholders already at the beginning of the safety demonstration process. The outcomes of this outreach together with the corresponding solutions to be provided by the GO-VIKING project were documented in a deliverable that will be made public.

4. GO-VIKING WP2: FLOW-INDUCED VIBRATIONS IN FUEL ASSEMBLIES

The main focus of WP2 of the GO-VIKING project is on FIV under single phase axial flow conditions, particularly relevant for nuclear FA. In WP2, advanced simulation methods and tools will be developed, applied, and validated to facilitate the understanding of FIV and support the free-of-failure operation of FA and other components in NPPs that are exposed to an axial flow. Specific focus of WP2 is put on the development of efficient simulation tools, capable of providing reliable prediction of FIV in FA within acceptable times and with reasonable computational cost. The development of medium-resolution models for fluid flow analysis in combination with low-resolution structural models (beams) and efficient FSI coupling algorithms is of particular interest for the partners involved in this work package. In the following sections, a brief description of the experiments and the accompanying numerical simulations for each benchmark in WP2 is provided. Although the experiments below cannot match the exact reactor core geometry and operating conditions (5 m/s flow velocity, 155 bar pressure, 330 °C temperature in a generic PWR design), efforts were put to generate experimental data for code validation that is relevant to the vibration phenomena occurring in the core.

4.1. Cantilever Rod Experiment

The main aim in designing the Cantilever Rod experiment by The University of Manchester, (Fig. 3), was to generate benchmark experimental data in controlled conditions with non-invasive simultaneous resolution of structural vibration (via non-contact optical tracking) and fluid flow (via Particle Image Velocimetry (PIV)). The test section consists of a vertical confining tube, in which the rod is positioned (Cioncolini et al. 2018; Cioncolini et al. 2023;). The vibrating rod and the confining tube are made of stainless steel: the rod is filled with lead, whereas the confining tube accommodates a transparent section for optical access. This provides a simple configuration, with dimensions and linear mass density chosen to be representative of water-cooled nuclear reactor fuel rods. The length of the cantilever rod is 1 m and its diameter is 10 mm. Its upper end is clamped, while the bottom end vibrates freely. Experiments were performed for two different setups: flow directed from bottom to top and flow directed from top to bottom of the test section. Within GO-VIKING, new experiments with Reynolds number (based on the hydraulic diameter of the annulus formed by the rod and the confining tube) between 5,000 and 80,000 are performed. This Reynolds number range is significantly larger than the one of the existing data on axial-flow-induced vibration of free-clamped rods. Although simplified, the experimental configuration is representative for nuclear FA. The data is already available for the partners performing numerical analyses. Further, additional experiments with different rod tip forms (curved, blunt, conical) were performed. Measured time-averaged contours of the normalised axial velocity and vector field for bottom-top flow at a Reynolds number of 20k is shown in Fig. 4. High-resolution simulations of the Cantilever Rod experiment are already being conducted at EDF using wall-resolved LES with Code_Saturne. The numerical mesh consisted of 46 million cells. An in-house structural solver, based on Euler-Bernoulli beam theory is being coupled to the LES simulation via one-way coupling. The results show good agreement for the calculated

first frequency peak of 3.8 Hz, which is identical to the measured one. Currently, two-way approach is being investigated at EDF. Further high-resolution simulations will be performed by PSU using DNS with the Nek5000 CFD code. The results from these fine-resolution computations will be validated against experimental data, and used for further development and validation of medium-resolution simulation models, based on URANS approach, to be performed by NRG, EDF-E and IPP. In this respect, NRG also started its work on the Cantilever Rod experiment: simulations were performed with STAR CCM+ to assess the fundamental frequency of the rod as well as the damping in air and water. These agreed well with the data provided by the experimentalists from UoM.

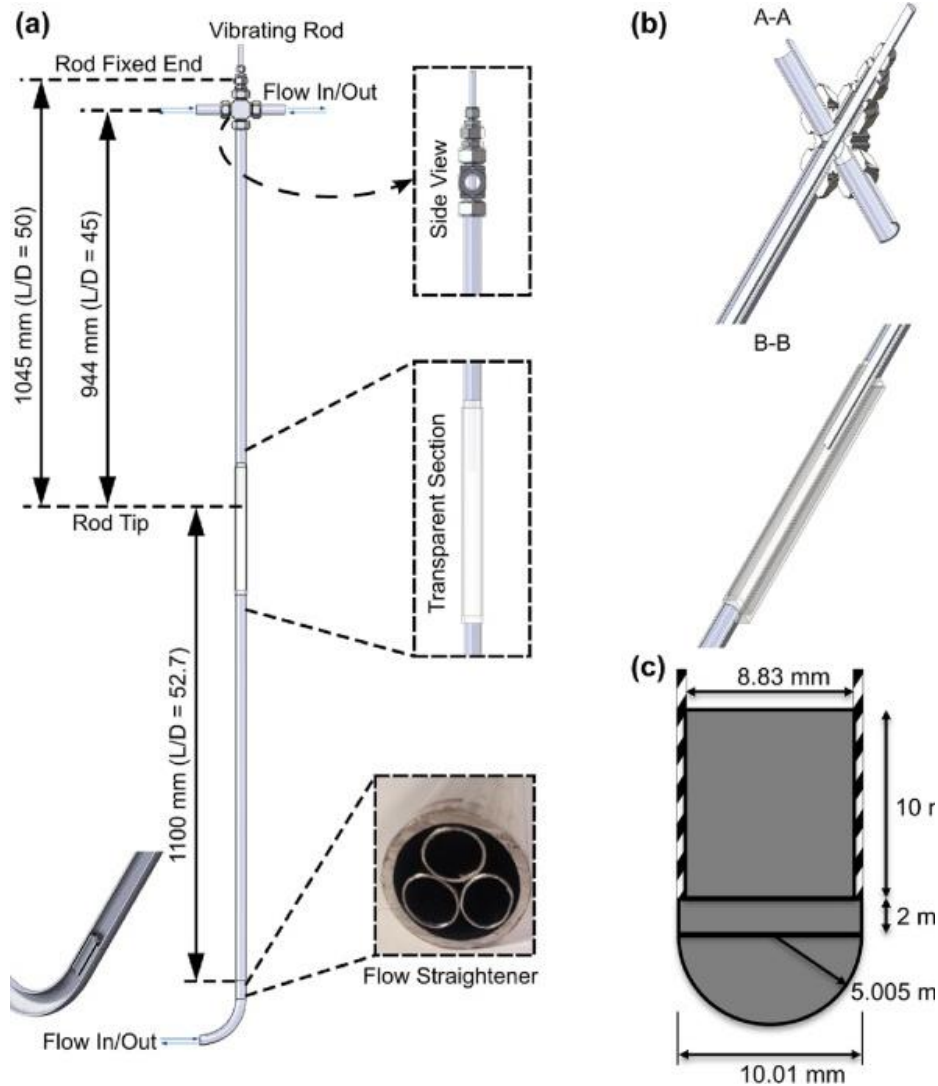


Figure 3. Cantilever Rod experiment by UoM: test section with vibrating rod, instrumentation and flow straightener upstream the tip of the rod. This figure shows the configuration with flow directed from the bottom to the top of the flow channel with: (a) the entire test section, (b) cut-through the union cross connection and cut-through of the transparent section, (c) form of the vibrating rod end (Cioncolini et al. 2023).

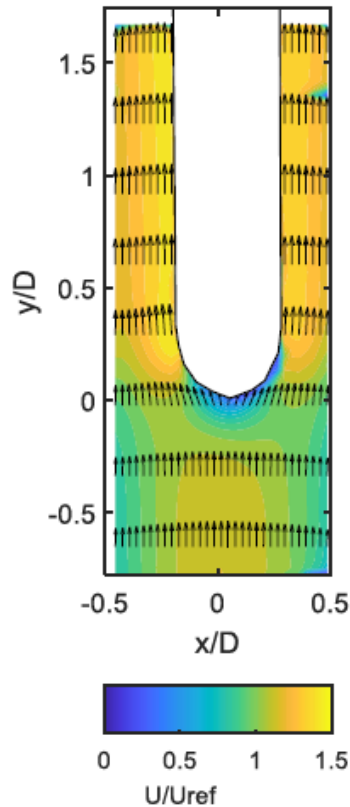


Figure 4. Measured by UoM time-averaged contours of the normalised axial velocity and vector field for bottom-top flow ($Re=20,000$) around the Cantilever Rod tip (Cioncolini et al. 2023).

4.2. ALAIN 5x5 PWR Rod Bundle Experiment

The ALAIN experiments had been performed by Framatome GmbH in Erlangen, Germany, with the aim to study complex FIV behavior of different FA designs. The experimental setup is illustrated in Fig. 5, right. It represents a reduced 5x5 PWR test FA that was placed in a channel with a square cross-section with a nominal lateral gap between the bundle and test channel of 1.5 mm. The vibration response of the FA was measured using lasers for a wide range of the flow rates (Reynolds number based on average axial velocity and hydraulic diameter within the bundle between 50,000 and 120,000). According to the project plan, the experimental results for the axial velocity corresponding to Reynolds number of 90,000 are provided by FRA-G. This data set was selected because the LDA flow measurements are also available for this condition. In addition to experimental results, the geometry and other relevant data of the fuel assembly and the test setup required for the simulations are also provided to the project partners. The simulations for this benchmark are performed for the axial flow velocity corresponding to Reynolds number of 90,000 (5.2 m/s flow velocity), for which LDA flow measurements were also carried out. The Reynolds number in a PWR at normal operation conditions is around 500,000. The ALAIN tests were carried out at nominal medium temperature of 40 °C and the nominal absolute pressure at the inlet to the test section of 4 bar.

The simulations for this benchmark are realized in two phases. First, stand-alone CFD simulations using an appropriate medium-resolution and high-resolution modelling approach, based on LES, are performed

by FRA-G and CEA. The purpose of these simulations is to evaluate the global flow field and the detailed unsteady flow characteristics within the fuel assembly, as well as to assess the requirements for the medium-resolution CFD approaches. Within VIKING collaboration, FRA-G already performed CFD analyses, based on wall-modelled LES approach, to calculate the fluid forces, acting on the fuel assembly. The time dependent forces from CFD simulation are then used as external excitation for the structural model within a decoupled simulation approach. Finite element model, consisting of linear Euler beam elements with additional rotational stiffness at spacer grid locations was implemented. The vibration response in the frequency domain was well reproduced, while the vibration amplitude was overestimated. This initial experience from VIKING collaboration provides the basis for further refined analyses within GO-VIKING project with the main objective to assess the requirements for the medium-resolution CFD approaches.

In the second step, coupled FSI simulations, based on medium-resolution modelling, are performed by FRA-G, IPP and GRS. For coupled FSI simulations, either integrated or user implemented FSI solutions in combination with commercial and open-source CFD codes (STAR-CCM+, ANSYS CFX, OpenFOAM) are utilized. The coupling between OpenFOAM and the structural mechanics code CalculiX was implemented at GRS. This was realized with the help of the preCICE coupling interface (preCICE 2024). The coupled code OpenFOAM-CalculiX was demonstrated on a simple test case, and currently, a numerical mesh is being generated, based on the provided CAD geometry by FRA-G.

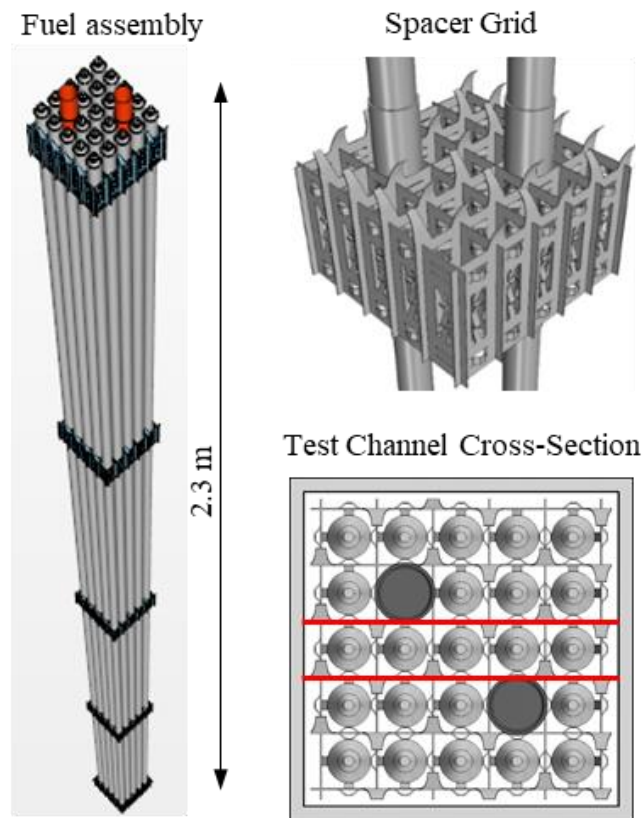


Figure 5. ALAIN 5x5 experiment by Framatome: reduced-length assembly with 23 rods, two guide tubes and several spacer grids. The red lines show the measurement positions for the flow field profiles, these measurements are taken at different elevations.

5. GO-VIKING WP3: FLOW-INDUCED VIBRATIONS IN STEAM GENERATORS

The focus of WP3 is put on the development, implementation and validation of beyond the state-of-the-art medium-resolution numerical tools to provide reliable assessment of structural vibrations, occurring in SG under single-phase, cross-flow conditions. Hereto, new experimental and high-resolution data is generated to allow the further development and validation of such tools. This experimental and high-resolution numerical data is obtained from two different experimental facilities: CEA's AMOVI and VKI's GOKSTAD. Although the experiments below cannot match the exact U-tube geometry and SG operating conditions (two-phase flow, 68 bar pressure, 286 °C temperature in a generic SG design), efforts were put to generate experimental data for code validation that is relevant to the vibration phenomena occurring in the SG. This is also valid for the experiments in WP4.

5.1. AMOVI Experiment

AMOVI (Cardolaccia and Baj 2015) is a small modular and easy-to-maneuver loop aimed at studying cross-flows in tube bundles, operated at CEA. It addresses low-turbulent regimes in a normal-square tube bundle of 3x5 tubes plus two columns of 5 semi-tubes. In the AMOVI test section, which is shown in Fig. 6, the flow is at low pressure ($p < 5$ bar) and low-temperature ($T < 40$ °C) conditions. The diameter of the tubes is 12.15 mm with a pitch-over-diameter (P/D) ratio of 1.44, values similar to those used in steam generators of NPPs (). The maximum volumetric flow rate in AMOVI is 4.2 l/s, which results in $Re \sim 23,000$ in the gap between the tubes (Panunzio et al. 2022). PIV, LDV and high-speed camera measurements are performed to provide data on the flow pattern inside the test section and the vibration characteristics of the central tube. Different types of experiments were performed, in which flow velocities, forces, and displacements were measured. First, tests were performed for a single tube in the flow channel (rigid and then flexible). Then, experiments with bundle in the test section were carried out with all tubes in the bundle being fixed. These were necessary to understand the flow field pattern inside the tube bundle and the acting forces on the tube surfaces. Lastly, experiments were carried out, in which the central tube was flexible, while all others in the bundle were fixed. Currently, four different experimental runs are under discussion for the numerical benchmarks. These have different mass flow rates and tube configurations. Figure 7 shows the PIV measurements of the averaged velocity field in the AMOVI tube bundle for one of the selected experimental test cases.

High-resolution computations with Code_Saturne are being prepared at EDF. The researchers gained simulation experience for similar bundle configurations exposed to a cross-flow (VISCACHE experiments). Since such high-resolution analyses are very expensive, EDF is currently identifying the modelling approach that will best fit to the AMOVI geometry and boundary conditions. GRS and IPP focus on medium resolution analyses, based on URANS and hybrid turbulence models. GRS generated two CAD and mesh models of the AMOVI test section: one with a single vibrating tube, and second, with a tube bundle in the flow channel. Figure 8 shows the numerical mesh generated for the bundle test case. It was decided to start the FSI simulations with the configuration with only one vibrating tube, exposed to a cross-flow. In these first analyses, rigid body motion model was activated in ANSYS CFX to account for the tube movement in the fluid domain. Additional structural analyses were performed to determine the spring stiffness as well as the mass moment of inertia. While this model is fast and robust, it still represents a simplification of the mechanical system. At a later stage, the FSI results generated with rigid body motion model will be compared with the results of the full coupling ANSYS CFX – Mechanical and conclusions will be drawn.

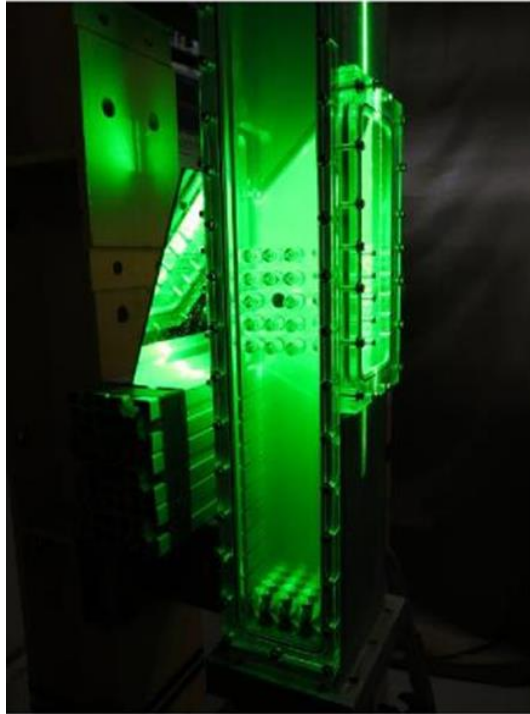


Figure 6. AMOVI experiment by CEA: the left picture shows the AMOVI test section with the bundle configuration with one moving tube in its center. The flow is directed from the bottom to the top of the experimental channel.

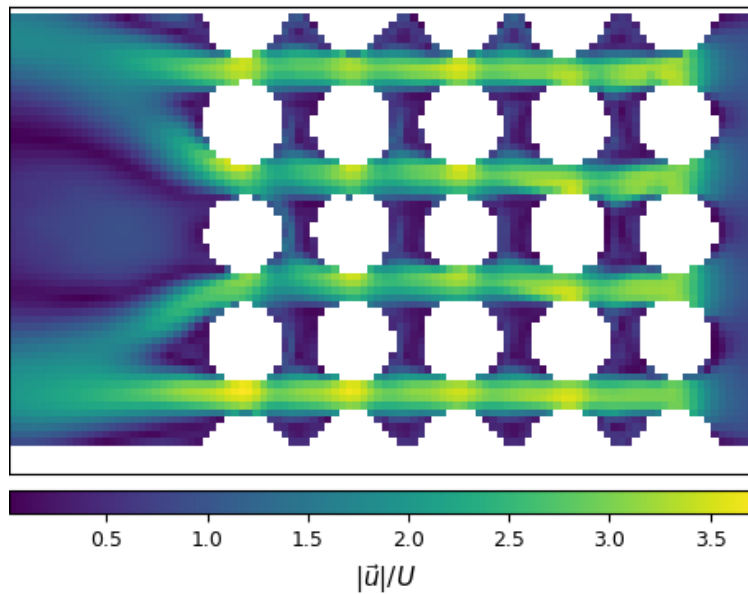


Figure 7. AMOVI flow measurement: average velocity field in the test section with bundle configuration for the experimental run with volumetric flow rate of 2.9 l/s (0.41 m/s inlet velocity), measured with PIV technique at CEA.

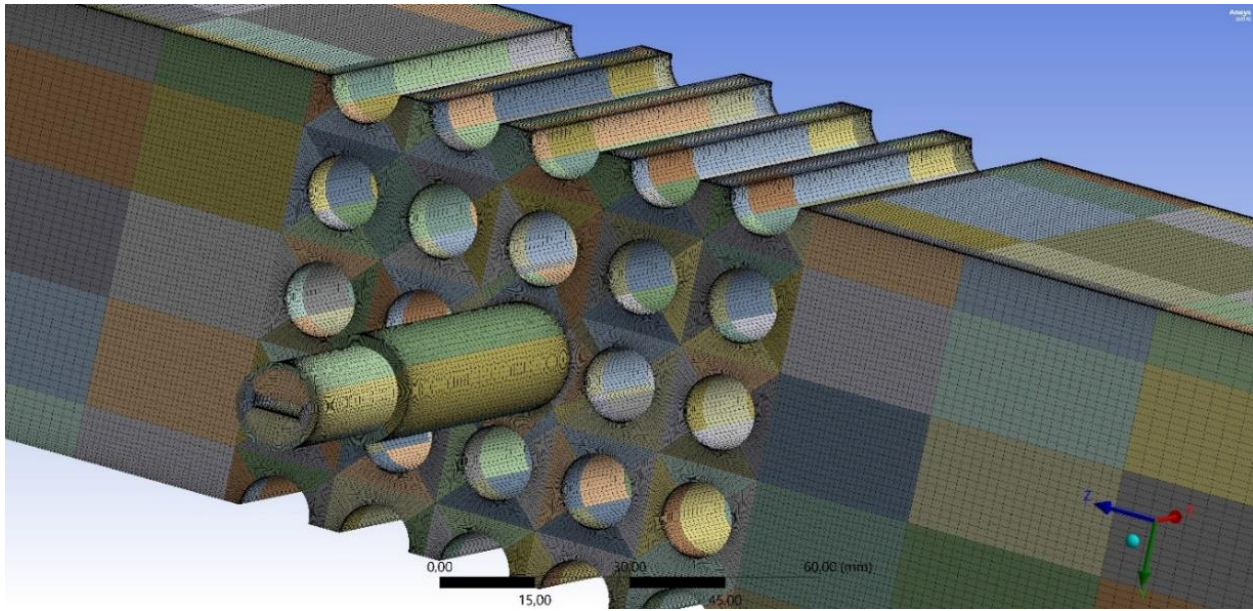


Figure 8. Numerical mesh of the AMOVI test section with bundle configuration and one central vibrating tube, generated by GRS for the first rigid body FSI analyses with ANSYS CFX.

5.2. GOKSTAD Experiment

At VKI, a new experiment named GOKSTAD is currently being designed to generate new high-resolution data for single-phase, cross-flow induced vibrations of flexible tubes within a tube bundle. It will be a square tube bundle of 7x7 tubes using water as medium, with the aim to perform experiments at a maximum Reynolds number $Re = 82,500$, higher than what is currently available in the literature. This value corresponds to a gap velocity in the tube bundle of 4.9 m/s, which is representative for a PWR. The Re number varies in the secondary SG side of a real reactor, because of the different U-tube sections' geometries (straight, arc) and void fractions. The design will be flexible allowing to vary the number and position of the flexible tubes. If possible, the GOKSTAD test section will be designed in a way that the tubes' movement can be switched to a single Degree-Of-Freedom, i.e., in either pure lift or drag direction. Time-Resolved Particle Image Velocimetry (TR-PIV) is used to measure the flow field (mean, fluctuating components, Reynolds stresses), essential for proper validation of the flow solver used in FIV models. Four strain gauges will be used to measure the fluid forces acting on the tube surface during the static tests with fixed tubes. These are very sensitive and can detect even very small surface deformations of the fixed tubes. Accelerometers will be installed to measure the displacements of the moving tubes in the dynamic tests. Data will be generated for a range of flow velocities, as well as for cases involving all fixed tubes, one central moving tube, as well as two moving tubes, placed next to each other. Figure 9 shows sketch of the GOKSTAD experiment to be built at VKI in Belgium.

Agreement has been reached by the partners on the geometrical design and dimensions of the facility. Furthermore, VKI has identified commercially available equipment for various crucial components, such as the pump, flow meter, sensors and piping. Procurement of these parts will start soon. VKI currently is working on the design of the moving tubes' fixation, ensuring their motion is as rigid as possible. Different mechanical tests are being performed for the different systems to check their viability. Additionally,

High-resolution simulations of GOKSTAD using Nek5000 coupled to Diablo (structural mechanics), based on an ALE approach, will be performed by VCU. Results hereof are to be compared with experimental data and also to be used for the further development and validation of medium-resolution models. For GOKSTAD, the latter work is done by both NRG and EDF. NRG will use STAR-CCM+ with a low Reynolds URANS and/or hybrid method in combination with the ALE approach, while EDF will employ a low and/or high Reynolds URANS method in Code_Saturne with the ALE approach and/or in NEPTUNE_CFD using an IB method.

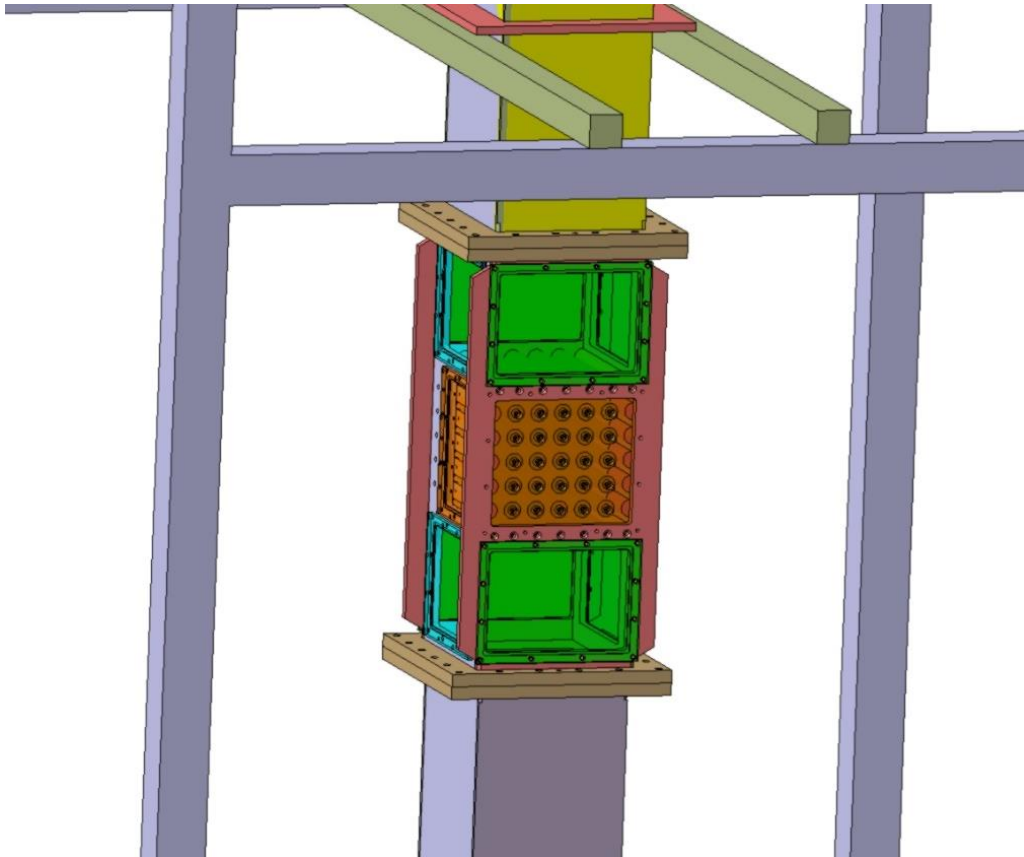


Figure 9. Sketch of the GOKSTAD experiment to be built at VKI in Belgium.

6. GO-VIKING WP4: FLOW-INDUCED VIBRATIONS IN MULTIPHASE FLOWS

From scientific point of view, the experimental and numerical work to be performed in this WP represents one of the major challenges in the project. These challenges are related not only to the simulation of the complex vibration phenomena in two-phase flow environment, but also to the very high computational costs. The selected experiments (both for axial- and cross-flow conditions) are relevant for PWR FA under abnormal conditions and BWR FA in normal operation, as well as for SG. The data generated is used for the development and validation of two-phase FSI tools for FIV analysis. With this database, numerical tools are developed and improved in order to obtain as accurate as possible predictions for different flow regimes. The developed tools are expected to provide the possibility for deeper understanding of FIV, resulting from the exposure of flexible structures to two-phase axial and cross flows. To achieve this, three experiments are considered within WP4: TREFLE, TITAN, and Cantilever Rod.

6.1. Cantilever Rod Experiment (Two-Phase)

The Cantilever Rod facility at The University of Manchester described in Chapter 4 was extended in order to perform similar experiments to the ones in WP2, though now for two-phase air-water mixtures. The test rig is an expanded version from the rig used by Cioncolini (2023) with an additional air flow injection system to the original flow loop. It provides capability for two-phase flow experiments using a mixture of air and water. The air injection system is connected to the main flow loop via a mixing section, located upstream of the test section. Within the mixing section, four air injection points, arranged circularly on the connection pipe, are used to inject air. The injection points are independently controlled by individual valves to allow modulation of the air-water mixture upstream of the test piece. In the experiments, the water temperature is expected to be close to the ambient temperature. The water mass flow rate is measured with a heavy-duty turbine flow meter and the facility is equipped with an extra device to measure the void fraction distribution. Figure 10 shows the design of the section for the mixing of air and water in the Cantilever Rod facility at UoM (Li et al. 2023).

Numerical simulation of these experiments will be computed by three partners based on various methods in terms of turbulent modeling, fluid-structure interface tracking method, and mechanical resolution, such as an URANS approach with the IB method of NEPTUNE_CFD (EDF), the internal FSI solver of ANSYS FLUENT using URANS or a hybrid method (VTT) and an URANS-based ALE method, implemented in the coupled code NEPTUNE_CFD-FEniCS (EDF-E).

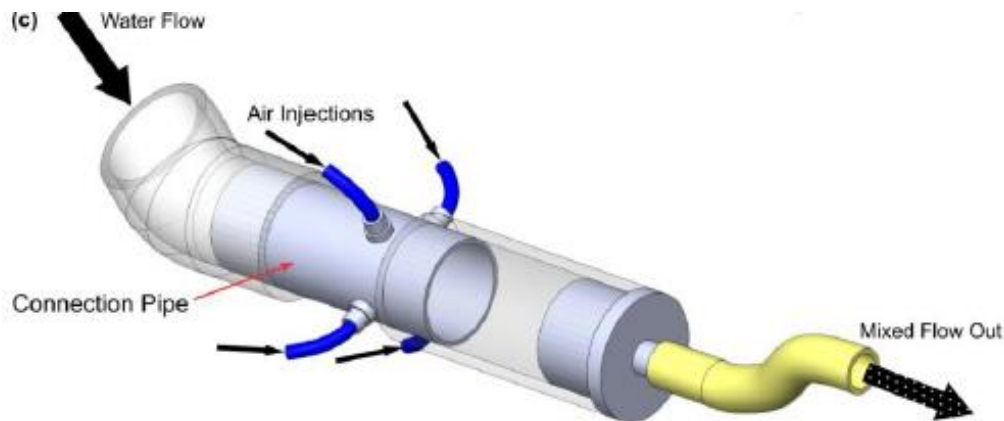


Figure 10. Design of the section for the mixing of air and water in the Cantilever Rod facility at UoM (Li et al. 2023).

6.2. TREFLE Experiment

The test section of the TREFLE experiment is shown in Fig. 11. TREFLE is a 5x5 square tube bundle in a square lattice to study two-phase FIV in an air-water mixture. The diameter of the tubes is 30 mm. One or two tubes in the central region of the tube bundle are free to vibrate, while the rest of the tubes are fixed. The objective of this experiment is to provide data for the investigation of FIV in two-phase cross-flow for the validation of CFD simulations. Both structure and fluid measurements are possible. Two-dimensional void fraction contours are captured with the help of a wire mesh sensor, while a high-speed camera is used for the recording of bubble dynamics. Bubble velocity, bubble size and void fraction evolution inside the tube bundle are obtained with optic probe measurement. The void fraction in TREFLE can range from very low to very high values. Detailed flow measurements are also performed at the air-water injection region, in order to provide CFD-grade data to be used for the definition of the numerical boundary conditions. The tube vibrations are measured with accelerometers.

Five partners will simulate this experiment with different tools. IRSN will use NEPTUNE_CFD with the Generalized Large Interface Model; EDF-E will apply STAR-CCM+ and an ALE method; NRG will perform calculations with OpenFOAM coupled to Deal.II with the preCICE coupling interface, based on the ALE method; VTT will use the intrinsic FSI solver of ANSYS FLUENT, though if deemed necessary, full coupling with ANSYS FLUENT Mechanical will be used; CEA will apply NEPTUNE_CFD with an IB method.



Figure 11. TREFLE test section with 5x5 tube array, exposed to a two-phase cross-flow at IRSN. The tubes are arranged in a square lattice, two of these vibrate, while the rest are rigid.

6.3. TITAN Experiment

CEA proposes experimental data for tube vibrations under two-phase flow conditions (water-air mixture) with increasing difficulty for codes and numerical methods testing (Panunzio et al. 2022; Piteau et al. 2022). These data have been obtained with the TITAN mock-up. In contrast to TREFLE, the TITAN bundle consists of 50 stainless steel tubes, positioned in a triangular lattice, with two columns of half-tubes at both lateral plates to minimize test section wall effects (see Fig. 12). A flow straightener is placed upstream the test section to regulate the inlet flow direction. Each experimental run has been performed with a constant void fraction. In some experiments the flow is increased until fluid-elastic instability (critical velocity) is reached. The maximum Reynolds number achieved is around 250,000. The RMS displacement amplitude over flow pitch velocity is available. For the simulation of TITAN, the two-phase flow, the triangular tube lattice, and the higher Re number are the main numerical challenges. Four partners will simulate this experiment: IRSN will use ANSYS FLUENT; EDF-E will perform simulations with STAR-CCM+ (ALE approach); NRG will apply OpenFOAM coupled to Deal.II via the preCICE coupling interface; EDF will utilize NEPTUNE_CFD with an IB method and the Generalized Large Interface model.



Figure 12. TITAN test section consisting of a tube array with a tringle lattice exposed to a two-phase cross-flow. This CEA experiment is performed at high flow velocities and also deals with fluid-elastic instability phenomenon.

7. GO-VIKING WP5: FAST-RUNNING METHODS, UNCERTAINTY QUANTIFICATION AND BEST PRACTICE GUIDELINES

Methods that can provide valuable information with similar accuracy to the one of the original, full-order model, but at significantly lower computational cost, are termed fast-running methods. Such methods often include reduced order models (either of the CFD, or of the CSM domain). Since the CFD simulation is typically orders of magnitude more costly than the CSM solution, efforts in this European project are dedicated to the generation of fast-running FSI methods with increased fluid flow calculation efficiency.

7.1. ROMs for the CFD Domain

Within GO-VIKING WP5, novel data-driven and projection-based ROMs for the fluid component is being developed with the aim to closely reproduce the physics of the full-order models. Such methods will be constructed by building a data-set of time-resolved fluid simulations with forced displacement of the domain walls, followed by system-identification techniques. Another fast-running approach will be based on building a ROM that predicts the turbulent pressure spectrum from significantly cheaper

RANS or URANS models. NRG already started with the further development of the NRG Pressure Fluctuation model (PFM) in combination with a URANS turbulence model that allows to predict the pressure fluctuations that drive the structural vibrations at a much more reasonable computational cost. The savings in terms of computational time result mainly from the coarser spatial discretization needed for the URANS simulation in comparison to LES. The Pressure Fluctuation Model aniPFM is extended to include turbulence anisotropy, convection and time correlation. The tests show that the new model is able to reproduce structural vibrations (Zwijssen et al. 2023). Within GO-VIKING, a third fast-running method for the CFD domain is in development. The proposed approach by IPP Centre is based on the generation of synthetic turbulent fluctuations in combination with standard URANS approach. Currently, the exact speed-up factors are unknown, but within the GO-VIKING project, the acceleration resulting from the utilization of all ROMs will be evaluated in detail.

7.2. ROMs for the CSM Domain

ROMs can be used not only for the CFD, but also for the CSM domain (Zwijssen et al. 2023). Beam models will be developed and implemented within other GO-VIKING work packages to speed up the calculation on the CSM side. These will substitute the detailed 3D modelling of the investigated rods/tubes. Further, in WP5, the ANSYS MOR (Model Order Reduction) (Einzinger and Frey 2014) is currently being implemented for the analysis of the AMOVI experiment. The approach is based on the mode-superposition method, which uses the natural frequencies and mode shapes. These are generated from a modal analysis in order to characterize the dynamic response of the structure of interest to transient or steady harmonic excitations. GRS used the CAD model of AMOVI tube and its blade, generated in WP3, to build a mathematical model in ANSYS Mechanical for the modal analysis. Fig. 13 shows first vibration mode shape. Fig. 14 shows the flow pattern around the vibrating tube in the AMOVI test section with a single tube, visualized with the turbulence kinetics energy. The formation of a von Kármán vortex street behind the vibrating tube is typical for cylinders exposed to a cross-flow. The modal analysis revealed that the first natural vibration frequency of the structure is 29.3 Hz, while the experimentalists from CEA report 27.5 Hz. The generated data for the vibration frequency and the nodal displacement for each of the calculated 8 modes will be used as an input for the MOR model that is currently being generated.

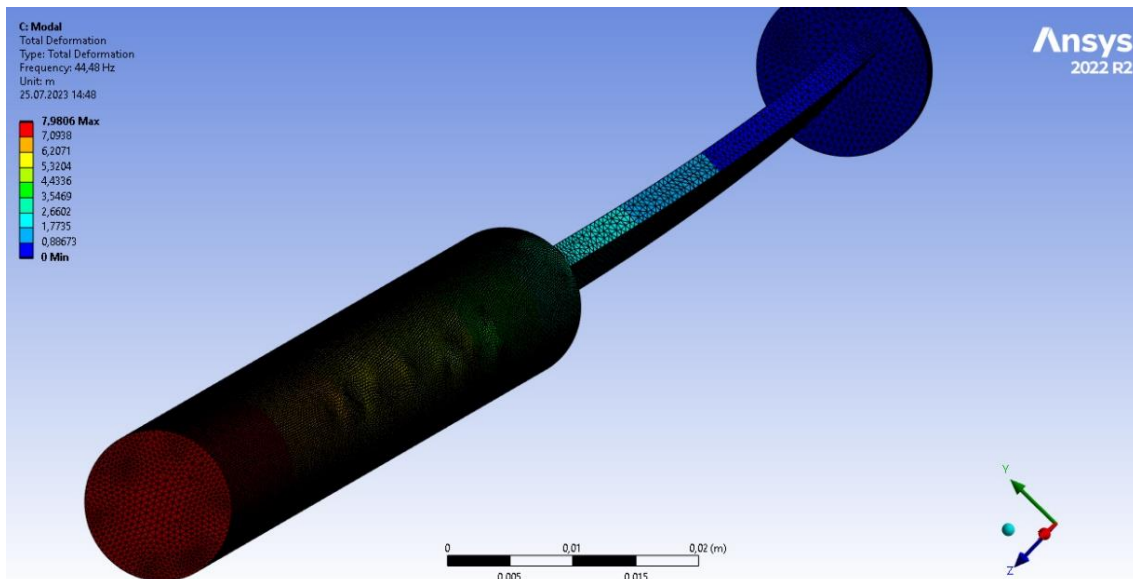


Figure 13. First mode shape of the AMOVI flexible tube and the attached blade.

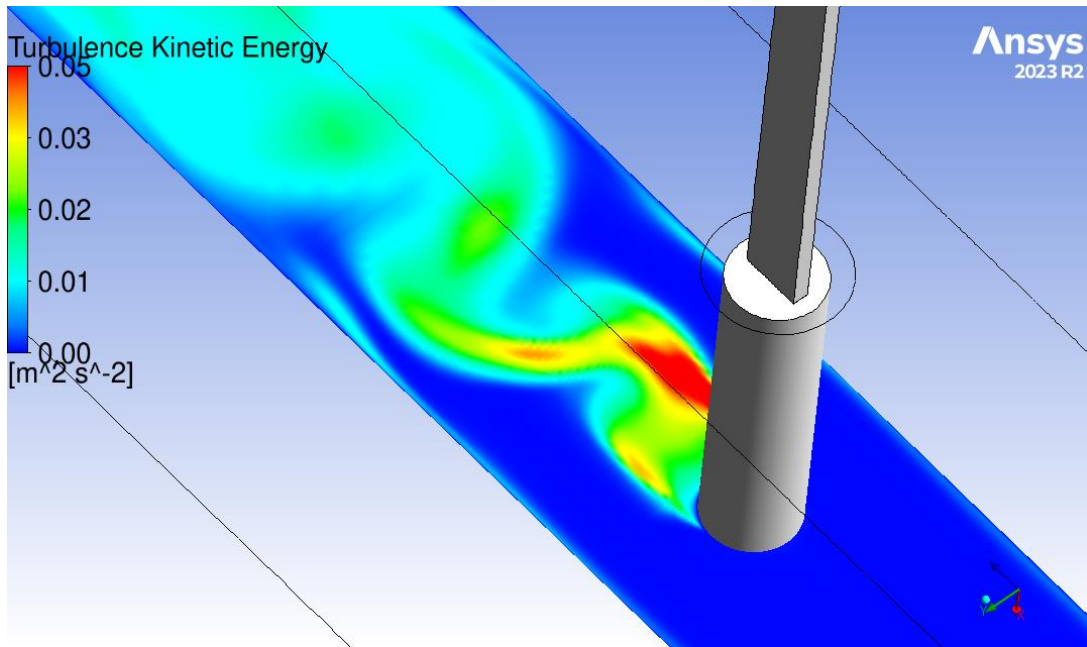


Figure 14. Formation of a von Kármán vortex street behind the vibrating tube in the AMOVI test section.

The need for UQ methods for FIV analyses became apparent in the Horizon 2020 MYRTE (MYRTE 2024) and SESAME (SESAME 2024) projects. In GO-VIKING, FSI simulations will be combined with different UQ techniques that will permit the calculation of the distribution of modal characteristics (eigenfrequency and damping ratio) for the model by performing a relatively limited number of FSI simulations. The developed UQ approaches will lead to a fast identification of high importance input parameters, needed for best-estimate calculations when used as evidence to support safety cases. In addition, global sensitivity analyses will be performed. These activities will be performed by UGENT and TUD. UGENT identified the non-intrusive UQ technique polynomial chaos expansion (PCE) as a promising method for the UQ in the time-demanding FSI analyses. One of the main advantages of this approach is the low number of computational runs that are needed in comparison to other methods such as Monte Carlo (MC). UGENT performed analyses with different expansion orders and also compared the results with a standard MC method, proving the benefits of the PCE (Dolfen et al. 2023). Currently, experimental cases are being identified for the application of PCE. Possible sources of uncertainties such as material properties, structural alignments, operational conditions are being discussed.

7.4. Best Practice Guidelines for FIV analysis

The main outcomes of the GO-VIKING will be evaluated, based on the results from the scientific work performed. The gained experience and knowledge throughout the whole project on the use of FSI methods for FIV will be used to synthesize Best Practice Guidelines on the use of FSI methods for FIV evaluation for vendors, operators and regulators. These will be discussed with stakeholders and international partners. Their feedback will be considered in the final version of the document.

8. GO-VIKING WP6: EDUCATION, TRAINING AND DISSEMINATION

Training of young scientists, master and Ph.D. students on FIV related to nuclear applications is a fundamental part of the of the project. GO-VIKING will prepare a new generation of scientists with dedicated code training and code benchmarking. Training sessions on FSI with OpenFOAM and TrioCFD based FSI tools will be carried out in the second half of GO-VIKING. These will be hosted by GRS and CEA. The educational material on FIV and the BPG for FIV analysis will be valuable for the young engineers, regulators, scientists. Open lectures on FIV will be given yearly, starting from the second project year. Further training material (videos, presentations, etc.) will be generated by the partners throughout the whole project, focusing on the experimental and numerical aspects of the FIV analysis. Communication and dissemination of the GO-VIKING results will take place during the whole project by combining events for the general public, and presentations of the results for experts in the field in conferences and journals. Finally, an international event with the key stakeholders will be organized at the end of the project to share the results obtained during these four exciting years.

9. CONCLUSION AND OUTLOOK

To improve the understanding and the prediction of FIV phenomena, relevant to nuclear power reactors, eighteen partners from Europe and USA, including vendors, operators, TSOs, universities and research organizations, started in June 2022 the Horizon Europe GO-VIKING project. Within this project, experimental and numerical activities are combined to: (i) increase the experimental database of FIV inside NPPs; and, (ii) improve the existing capabilities of the numerical tools to simulate and predict these phenomena. An overview of the GO-VIKING consortium was provided along with information about the project's structure, including the work packages and the planned tasks. Furthermore, details of all planned experimental and numerical work that will be performed were also presented. The project will run for a total of four years, with the final product of the project being BPG summarizing the gained experience and knowledge throughout these years on the use of FSI methods for FIV evaluation in NPPs. These will be disseminated to vendors, operators and regulators in order to support them in the design, evaluation and decision making in the field of FIV in nuclear power reactors.

One year after the beginning of GO-VIKING, the project enters its productive phase and is well on track with 20% of all deliverables already being delivered and 27% of all milestones being achieved. The existing experimental data was made available to the partners involved in the numerical simulations, allowing them to start the modelling efforts. On the other hand, the design of the new experimental facilities, which is often a bottleneck in such projects, is progressing as scheduled. It is obvious that matching the exact geometric and thermal-hydraulic conditions of the NSSS in the experimental facilities will not be possible. Building such installations that operate at high pressures and temperatures, as well as utilizing two-phase water-steam flow with phase change, occurring in a SG, is extremely costly. Still, the experiments performed within GO-VIKING strive to go beyond the current state-of-the-art and provide data at conditions (geometries, velocities), which are representative for the NSSS. The simulation of such conditions is challenging for the currently available numerical tools and methods. First project results were already presented in work package and progress meetings, some of these were published in deliverables, conference proceedings, and scientific journals. The commitment of all GO-VIKING partners is substantial for the good project progress and keeping this pace in the upcoming three years will guarantee its success.

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REFERENCES

- EPRI (2008). Fuel Reliability Guidelines: PWR grid-to-rod fretting. Technical report 1015452. <https://www.epri.com/research/products/1015452>.
- IAEA (2019). Review of fuel failures in water cooled reactors (2006-2015). IAEA No NFT-2.5, NE1864, Vienna, Austria.
- NRC (2015). <https://www.nrc.gov/docs/ML1501/ML15015A419.pdf>
- Kotthoff, K. (1984). Erkenntnisse aus dem Ablauf ausländischer Vorkommnisse mit Dampferzeuger-Heizrohrbruch, GRS, Technische Mitteilungen, Bd. 77, Nr. 1 (1984).
- MacDonald, P. E., Shah, V. N., Ward, L. W. and Ellison, P. G. (1996). Steam generator tube failures”, NUREG/CR-6365 INEL-95/0383 (1996).
- Fischer, M. (2001). Dreidimensionale numerische Simulation strömungsinduzierter Rohrbündel-schwingungen, Dissertation, Fakultät für Maschinenwesen, Technische Universität München (2001).
- Papukchiev, A., Zwijsen, K., Vivaldi, D., Hadžić, H., Benhamadouche, S., Benguigui, W. and Planquart, P. (2023). The European GO-VIKING project on flow-induced vibrations. In: Proc. of the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20) conference, August 20-25, Washington, USA.
- Zwijsen, K., Roelofs, F., Vivaldi, D., Iakovides, H., Cioncolini, A., Papukchiev, A., Benhamadouche, S., Deri, E., Uribe, J., Hadzic, H., Lascar, C., Chazot, B., Goreaud, N. (2022). VIKING: a joint industry project on fluid-structure interaction. In: Proc. of the 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19) conference, online, March 6-11 (2022).
- Cardolaccia, J. and Baj, F. (2015). An experimental study of fluid-structure interaction in basic in-line arrangements of cylinders. In: Proc. of the ASME 2015 Pressure Vessels and Piping Conference. Volume 4: Fluid-Structure Interaction. Boston, Massachusetts, USA. July 19–23, 2015. V004T04A030. ASME. <https://doi.org/10.1115/PVP2015-45311>
- Menter, F. (2015). Best practice: scale-resolving simulations in ANSYS CFD”, Version 2, ANSYS, 2015.
- IAEA (2010). Deterministic safety analysis for nuclear power plants”, IAEA Safety Standards Series No. SSG-2 Specific Safety Guides (2010).

Cioncolini, A., Silva-Leon, J., Cooper, D., Quinn, M. K. and Iacovides, H. (2018). Axial-flow-induced vibration experiments on cantilever rods for nuclear reactor applications, Nucl. Eng. and Des. 338, pp. 102-118.

Cioncolini, A., Zhang, S., Nabawy, M., Li, H., Cooper, D. and Iacovides, H. (2023). Experiments on Axial-Flow-Induced Vibration of a Free-Clamped/Clamped-Free Rod for Light-Water Nuclear Reactor Applications, Annals of Nuclear Energy, Volume 190, 2023,109900, <https://doi.org/10.1016/j.anucene.2023.109900>.

<https://precice.org/>

Li, H., Zhang, S., Cioncolini, A., Iacovides, H. and Nabawy, M. (2023). WP4 – Flow-induced vibrations in multiphase flows. In: Part 1 of Deliverable 4.1 of the GO-VIKING project (101060826) Multiphase cantilever rod experiment and benchmark setup.

Panunzio, D., Lagrange, R., Piteau, P., Delaune, X. and Antunes, J. (2022). Experimental investigation of cross-flow fluidelastic instability for rotated triangular tube bundles subjected to single-phase and two-phase transverse flows. In: 12th International Conference on Fluid-Induced Vibration, July 5-8, 2022, Paris-Saclay, France.

Piteau, P., Delaune X., Panunzio, D., Lagrange, R. and Antunes, J. (2022). Experimental investigation of in-flow fluidelastic instability for rotated triangular tube bundles subjected to single-phase and two-phase transverse flows. In: 12th International Conference on Fluid-Induced Vibration, July 5-8, 2022, Paris-Saclay, France.

Zwijnsen, K., Marreiros de Freitas, A., Tajfirooz, S., Frederix, E., Roelofs, F. and Van Zuijlen, A. (2023). Towards optimization of an anisotropic pressure fluctuation model for the simulation of turbulence induced vibrations of fuel rods. In: Proc. of the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20) conference, August 20-25, Washington, USA.

Papukchiev, A. (2022). FSI analysis of flow-induced vibrations in a BWR instrumentation tube experiment. In: Proc. of the 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19) conference, online, March 6-11 (2022).

Einzinger, J. and Frey, Ch. (2014). Bi-directional fluid-structure interaction with model order reduction. ANSYS Germany (2014).

MYRRHA Research and Transmutation Endeavour, <https://cordis.europa.eu/project/id/662186>

Thermal Hydraulics Simulations and Experiments for the Safety Assessment of Metal Cooled Reactors, <https://cordis.europa.eu/project/id/654935/de>

Dolfen, H., Vandewalle and S., Degroote, J. (2023). Effect of stochastic deformation on the vibration characteristics of a tube bundle in axial flow, Nuclear Engineering and Design, 411, 112412, <https://doi.org/10.1016/j.nucengdes.2023.112412>.

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