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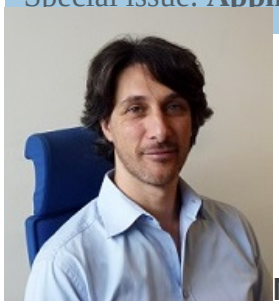
News

Fundamental Research

Engineering sciences | Solid mechanics

Special issue: **Applied Mechanics**



Managing the energy transition requires the industrial roll-out of new technologies to harness **renewable, low-carbon resources**. For instance, **offshore floating platforms for wind turbines** raise new scientific and technical challenges, due to extreme operating conditions.

The **sustainable exploitation of these energy resources**, in a highly competitive environment, requires the combined implementation of expertise and innovative solutions founded on high-quality scientific research. This requirement is also relevant to IFPEN's long-standing fields, which have to address cost and environmental impact issues.

With this in mind, **Applied Mechanics** researchers are working to build on their knowledge —

particularly in **offshore oil and gas production** — through scientific challenges whose resolution combines experimentation (including large-scale), modeling and numerical simulation in a number of fields: **complex flows, hydrodynamics, aerodynamics, fluid structure couplings, non-linear behavior of materials and structures.**

In this issue, we look at examples of progress made in the field of **computational mechanics** serving new energy technologies.

We hope that you enjoy this issue.

Laurent Cangémi, Deputy Scientific Director, Applied Physical Chemistry and Mechanics Division

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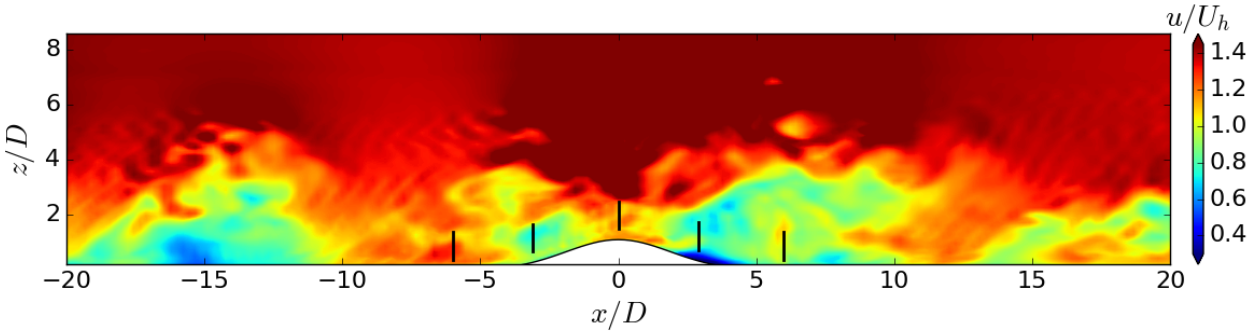
LES BRÈVES

The **development of wind farms requires the optimal placement of wind turbines** in relation to each other in order to maximize overall production. If the turbines are too close to each other, wake effects prevent maximum power output and can lead to **mechanical fatigue issues** caused by turbulence. Conversely, it they are too far apart, wind resources are not fully exploited.

Currently, **offshore wake-related power** loss can be as high as 40%. Consequently, optimizing the placement of wind turbines has become a major challenge, which can be addressed by precisely simulating wind flows through the farm. This is achieved by **modeling the wake effects of the turbines** in representative weather conditions, particularly from the point of view of the **atmospheric boundary layer**[a].

Such a model, created by IFPEN, was implemented in **Meso-NH**(1), the fine mesh weather model designed by the CNRM (French National Center for Meteorological Research, Météo France) and the Laboratoire d'aérologie (French Aerology Laboratory). In it, wind turbines are represented by the aerodynamic forces they generate (drag, lift), determined by simplified models. Hence, turbine wakes are defined thanks to the interaction of the **aerodynamic forces** with the wind, itself influenced by meteorological phenomena.



Wind fields calculated by Meso-NH on a configuration tested in a wind tunnel

Validation studies were conducted using wind tunnel tests (model representing five wind turbines on a hill). The **calculation/experience comparison** was conducted by studying the **vertical profiles of wind speed and turbulence intensity**, downstream of each of the wind turbines(1). It has thus been demonstrated that consideration of meteorological conditions offers a more accurate prediction of the wake generated by a wind farm.

This new tool will be employed to study the influence of atmospheric conditions specific to the offshore environment, in order to optimize the layout and productivity of wind farms and to study their potential environmental impact on local meteorology.

[a] *- The part of the atmosphere directly influenced by the presence of the earth's surface (continental or oceanic).*

(1) *P-A. Joulin et al., EWEA PhD Seminar, 2018.*

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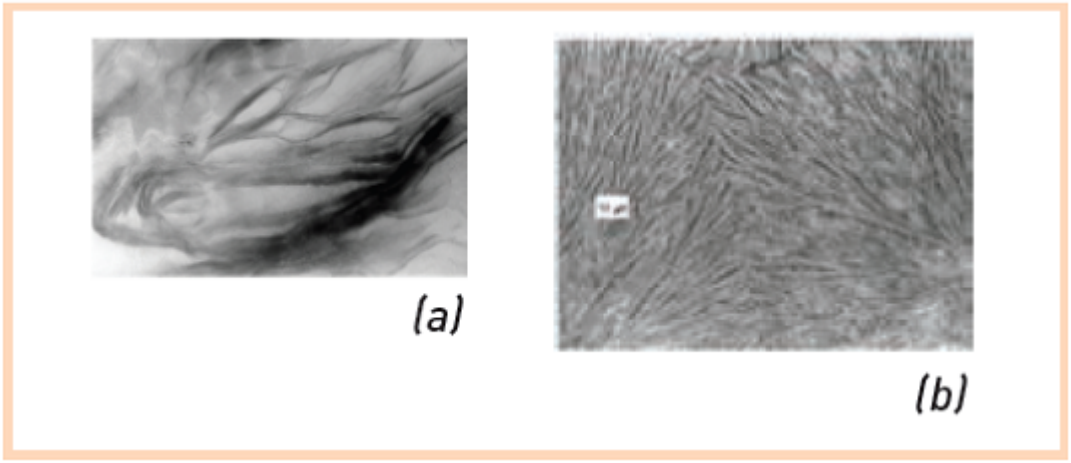
Wind farms – a more effective layout using modeling

In the energy sector, **semi-crystalline polymers**[a] are primarily used **within structures located in aggressive environments, to form coatings (waterproofing, thermal or electric barriers)**. These materials possess an **intrinsic flexibility** exploited in some offshore applications, such as oil production pipelines, but they are also found in **electric cables for the offshore wind energy sector**.

Through these various applications, the polymers can be exposed to a **variety of extreme stresses**: pressure (>1,000 bar), **swell, high voltage**, **temperatures** (from -20°C to 150°C), **liquid and gas diffusion**. In the latter case, the penetration of chemical species within the polymers can affect their mechanical behavior via multiphysical mechanisms that can cause damage: from the **creation of microcavities to the appearance of cracks** potentially leading to fracture.



Microstructure of a clay (a) and a polymer (b).

Towards a poro-chemical-mechanical model

In order to describe the **integrity of semi-crystalline polymers in harsh environments**, a model inspired by **natural porous and non-permeable materials**, such as **clays**, was developed by IFPEN. The model makes it possible to consider **multi-physical couplings** from both a theoretical and numerical point of view. The analogy with clays is based on the **microstructural arrangement** (figure) and **viscoplastic mechanical behavior**. But beyond this comparison, it is a phenomenological model capable of introducing couplings between deformation and diffusion of species that was introduced.

Hence, the parallel with natural porous media, combined with a rigorous theoretical framework, recently made it possible to treat **complex phenomena, such as pressure-diffusion cavitation, hydrolytic weakening and competition between fracture mechanisms (brittle or with plasticity)**[(1)]. One potential avenue for enhancing this model is to describe damage by the **diffusion of electric arcs**,
within coatings for immersed electric cables.

a - Comprising a crystalline phase and an amorphous phase.

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(1) *S. Maiza, X. Lefebvre, N. Brusselle, M-H. Klopffer, L. Cangémi, S. Castagnet, J.C. Grandidier. Submitted to Journal of Applied Polymer Science.*

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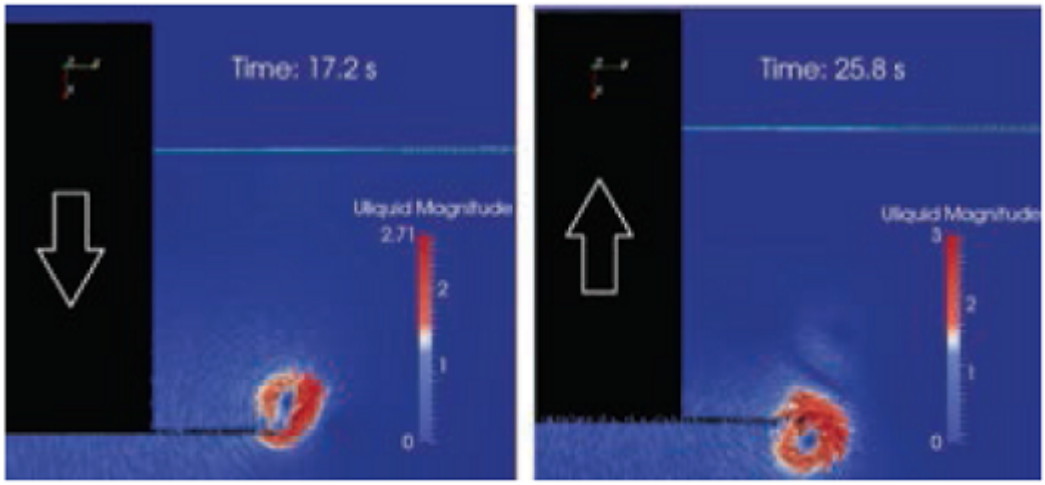
Semi-crystalline polymers: clays that are ignored?

The **development of floating platforms for offshore wind turbines**, to replace fixed foundations, paves the way for the harnessing of **wind reserves in ultra-deep offshore zones**. The potential is promising, estimated to represent **16 GW in France** by 2040[a].

The design and dimensioning of these new structures are dependent on the **calculation of the forces generated by swell and movements induced on the floater**. These calculations are currently carried out using dedicated software, from the offshore oil industry[b], based on simplified hydrodynamic models. Moreover, the **behavior of a floating wind turbine** is relatively far-removed from that of an oil platform and both the economic stakes and the industrial risks also differ. With this in mind, IFPEN is re-evaluating current dimensioning methods and tools.

The methodology consists in comparing **CFD[c] simulations** of a moving floating wind turbine, conducted using **open source[d] software** with results obtained from **conventional simplified models** . The objective is to evaluate the relevance of the latter and improve them where necessary, either by revising their formulation or by recalibrating them. This approach was firstly employed on simple cases involving — a **fixed floater with swell**, on the one hand, and a **moving floater without swell**, on the other — thereby enabling comparison with experimental results. Deployed to evaluate movement damping systems (figure), it produced satisfactory results [1-2].



Visualization of the velocity field surrounding a damping plate, during vertical movement of the floater.

The same approach, implemented for a floater developed jointly with SBM Offshore, delivered first promising results concerning the improvement of the hydrodynamic models used in **IFPEN's design tools**.

a - Les Echos 02/19/2018
*b - **DeepLines Wind software** developed with Principia*
*c - **Computational Fluid Dynamics***
*d - **OpenFOAM software***

(1) *P. Bozonnet, A. Emery, CFD Simulations for the Design of Offshore Floating Wind Platforms Encompassing Heave Plates, 25th International Ocean and Polar Engineering Conference, 21-26 June, Kona, Hawaii, USA. https://www.onepetro.org/conference-paper/ISOPE-I-15-382*

(2) *A. Emery, P. Bozonnet, Heave plate damping and added mass evaluation based on CFD simulations for floating wind turbine platforms. Submitted to Applied Ocean Research.*

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Improvement of hydrodynamic models for floating wind turbines

Energy storage, one of the major challenges within the context of the energy transition, can take a variety of forms. For **heat storage**, one of the solutions developed at IFPEN is based on a **fixed particle bed**. A fluid flows through the bed to store the heat in the particles or to recover it[(1)].

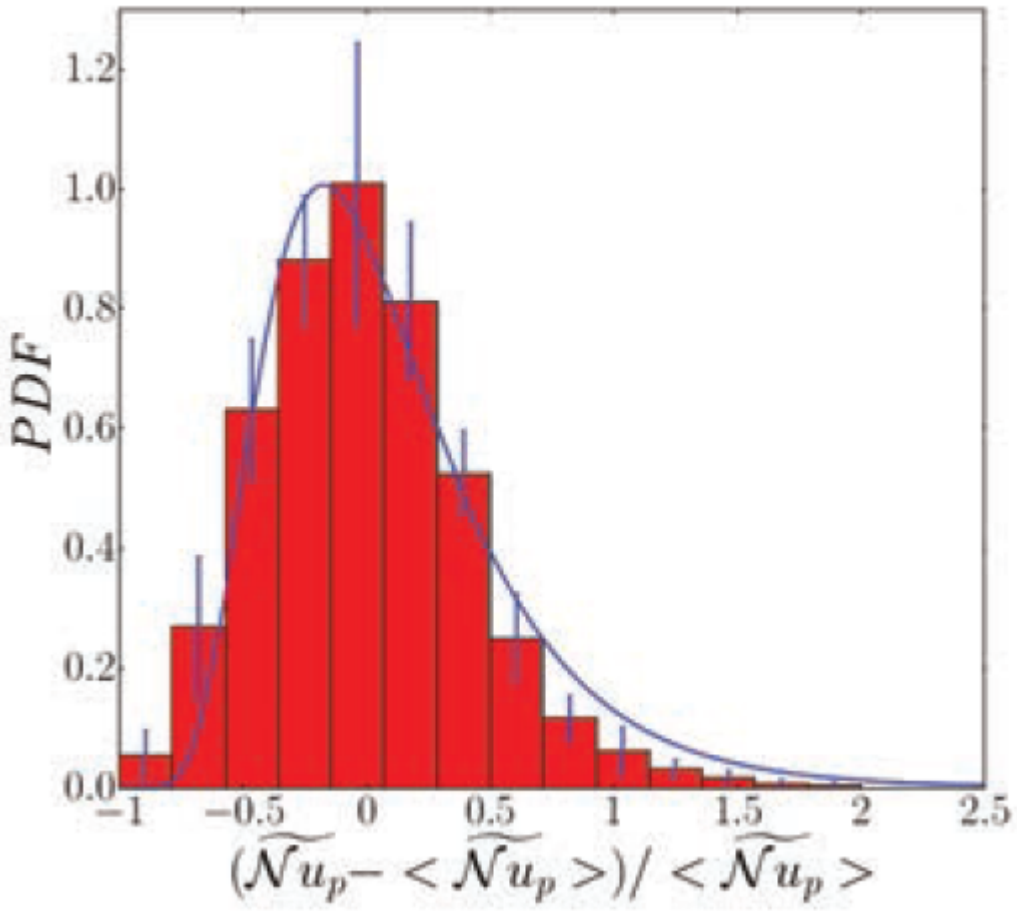
Due to the complexity of these storage systems (**large number of particles and non-linearity of the regimes studied**), the use of **numerical calculation** is essential for dimensioning purposes.

To this end, a large number of calculations were performed to assess the **impact of the variability of the different parameters (material, particle size and form, fluid type)** on the overall performance of the solution.

This work highlighted two fundamental results:

• **heat transfers within the bed vary locally** in quite a significant way (figure). Hence, conventional approaches based on average volume methods, need to be enhanced to take into account these local fluctuations;

• the **definition of the fluid reference temperature**, necessary for assessment of **fluid-particle heat transfers**, is far from simple, due to the existence of a temperature distribution in the bed. Nevertheless, simulations confirmed its relevance when considered “ad infinitum”, i.e. far from the location of the bed where the calculation is performed.



Distribution of the Nusselt(a) number within a fixed bed, calculated using the local approach.

The prospects for this research are numerous: in particular, the development of **heat transfer laws**, taking into account the **effects of local heterogeneities**, would pave the way for significant advances in the **dimensioning of industrial beds**.

a - A dimensionless number describing the intensity of heat exchange.

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(1) *M. Bélot, T. Phan, F. Euzénat, J-L. Pierson, D. Teixeira G. Vinay, Q. Falcoz, A. Toutant, A. Wachs. Turbulence, Heat and Mass Transfer 9. Brésil, 2018.*

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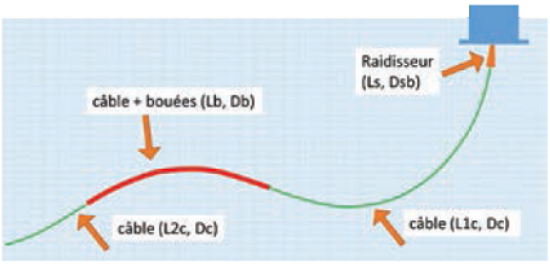
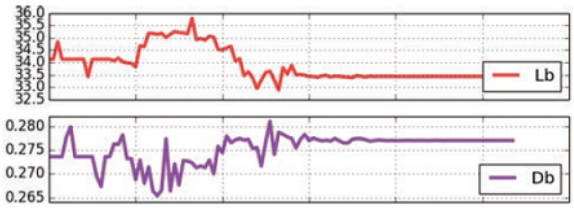
Stored heat

Floating wind turbine technologies, such as those co-developed by SBM and IFPEN[a] , are designed to **optimize the recovery of offshore wind energy**. Optimization solutions are currently being sought to **minimize the costs of transporting the electricity produced**, by **adapting the configuration[b] of cables**, which are exposed to currents and movements of the floating platform (figure 1).

Calculating the response of a floating wind turbine to these **aerodynamic and hydrodynamic loadings** requires the use of **complex numerical simulators** but ones that do not provide the gradient of this response with respect to model input parameters. Similarly, publications on the subject refer to non-gradient optimization algorithms that may converge slowly or are difficult to configure.

IFPEN's Atout[c] platform proposes the **SQA[d] algorithm**, which is particularly effective in this contexte(1). From a starting point, this algorithm rapidly finds the **optimal configuration for an electric cable** (figure 2) respecting force and displacement limits, for extreme loads(2).





Cable parameters (lengths, diameters).
Evolution of two parameters during optimization with the SQA4 algorithm.

This original approach will form the basis of more **effective research leading to the optimized configuration of electric cables**, dimensioned for a variety of load conditions.

a - SBM offshore - Floating wind turbine concept development
b - Various sections, each being characterized by its length, its diameter and its buoyancy (figure)
*c - **Advanced Tools for Optimization and Uncertainty Treatment**, the word "Atout" translates as "Asset"*
*d - **Sequential Quadratic Approximation***
*e - With **"black box"** type simulators (only the result is known)*

***(1)** H. Langouët, (2011), Optimisation sans dérivées sous contraintes : deux applications industrielles en ingénierie de réservoir et en calibration des moteurs, thèse Univ. Nice-Sophia Antipolis. HAL Id : tel-00671987, version 1*

***(2)** Y. Poirette, M. Guiton, G. Huwart, D. Sinoquet, J-M. Leroy (2017), An Optimization Method for the Configuration of Inter Array Cables for Floating Offshore Wind Farm, OMAE 2017 61655. Doi: 10.1115/OMAE2017-61655.*

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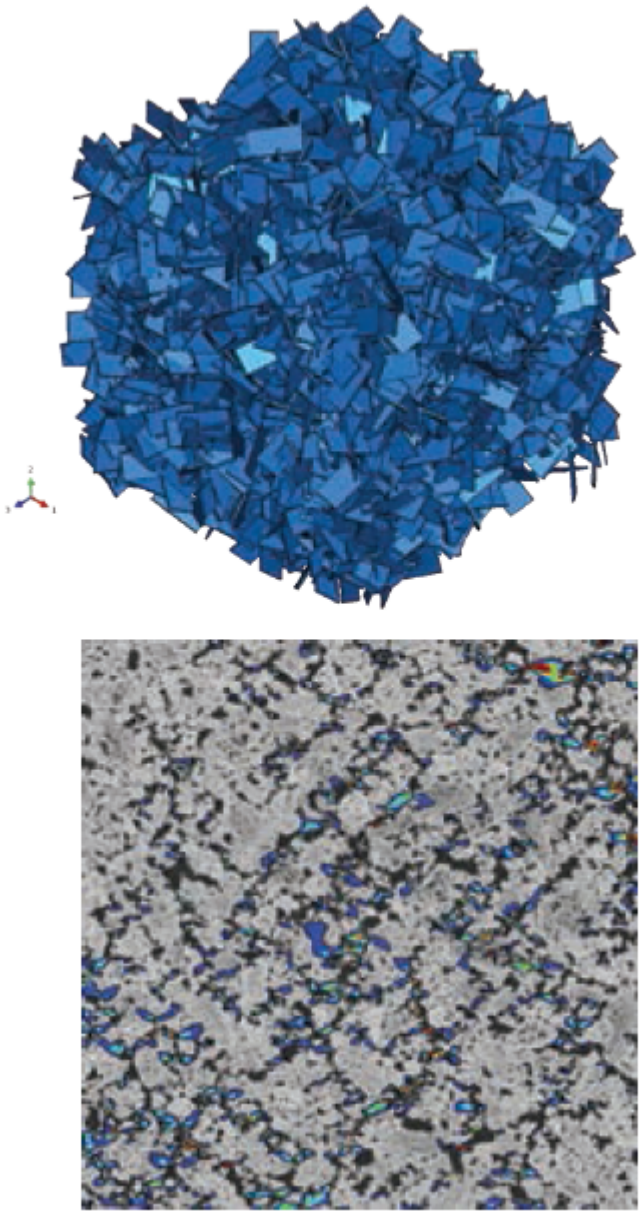
Optimizing the electric cable of a floating wind turbine

Proposing innovative technological products often requires recourse to simulation approaches in order to boost our capacity to evaluate original concepts. This is particularly true in the field of **mechanics of materials**, where one of the key challenges is to **understand and exploit the relationship between a material's microstructure and its usage properties**.

Research on this theme was initiated by IFPEN concerning the **mechanical behavior of lamellar porous materials**, such as some **catalyst supports (and some polymers)**. The objective is to have a calculation tool ultimately making it possible to dimension and develop such materials, structured on several scales (**from a nanometer to a tenth of a millimeter**) and capable of withstanding mechanical stresses.

The approach was based on current structural calculation capacities, which were adapted to the **calculation of microstructures with lamellar or granular stacking**(1). A **multi-scale workflow** was established based on two tools: **IFPEN's plug im!**[a] platform for microstructure generation, and the **Abaqus™ commercial calculation code**, capable of effectively dealing with non-linear mechanical behavior for large systems. The atomic scale properties forming the basis for the model were themselves estimated using molecular dynamics calculations.

A sequence of numerical methods enables the various scales of the material's structure to be crossed. This **In Silico[b] approach** was validated for the **prediction of the linear behavior (elastic properties) of alumina supports**.



Modeling of a catalyst support at mesoporous and macroporous scale.

Research is now focusing on plasticity and fracture, which governs the characteristics of interest concerning these materials in service. Within this context, a new milestone was recently reached for plasticity simulation using the finite element method, thanks to the improvement of local meshing methods. The next step will be to introduce **cohesion/fracture properties in the form of a local cohesive zone-based approach**[c], coupled with **molecular modeling techniques**.

a - https://www.plugim.fr/
b - Using complex computer-based calculations.
c - Method based on the mechanics of fracture by cracking and damage mechanics.

(1) *V. Le Corre, N. Brusselle-Dupend, M. Moreaud, Numerical modeling of the effective ductile damage of macroporous alumina, Mechanics of Materials 114 (2017) 161–171. DOI: 10.1016/j.mechmat.2017.08.002*

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In silico design: digital materials here we come!

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