Strategy documents

Physics research communities
Round table Physics
2020

Physics of Fluids and Soft Matter

NWO

1. Scope of 'Physics of Fluids & Soft Matter'

Research in the Physics of Fluids and Soft Matter (FSM) community is centered on the understanding, manipulation, and creation of soft materials and complex flow phenomena. A crucial aspect is the interplay of the spatial structure of (complex and reactive) fluids and soft matter with their emergent properties. Often, the collective properties of these materials emerge from the organization of simple building blocks into complex structures and phases. Hence, understanding and controlling the rich equilibrium and non-equilibrium phases of fluids and soft matter, as well as structure-property relations, play a key role.

The FSM community includes well-established sub-fields such as the dynamics of "simple" atomic or low-molecular weight fluids (e.g., turbulence, micro-fluidics, electrolytes, acoustics, phase change, and multiphase flows), the dynamics of fluid-solid systems (e.g., porous materials, granular flows, elastocapillarity), physics of plasmas (e.g., magnetohydrodynamics, gyrokinetic turbulence, non-equilibrium plasmas at atmospheric pressure, dusty plasmas), the dynamics and rheology of colloids, polymers, liquid crystals, and gels including phase behavior and self-assembly, and the dynamics and properties of bio(inspired) soft matter. These highly active fields within FSM have also seen many novel recent developments including, for instance but not limited to active fluids, (soft) robotic matter, 3D printing, nanofluidics, nanobubbles, plasma jets, and mechanical metamaterials, with many more new topics expected to emerge in the near future.

2. Vision for the next ten years

The Dutch scientific community has made significant contributions to the fundamental understanding of dynamics and multiscale processes in complex fluids, flows, plasmas, and (soft) condensed matter, including the understanding of structure-property relations, fluid-solid rheology and phase transitions. These contributions are aided substantially by close collaborations between experimental investigations, theoretical approaches and numerical (multiscale) modelling studies. Additionally, FSM is naturally cross-disciplinary, with strong connections to materials science, computational science, atmospheric and ocean science, chemistry and biology, as well as a variety of technology fields, such as (ubiquitous, low cost) sensing. This provides an excellent position for the FSM community to address new 'big questions' in the coming decade. Examples are (but not limited to):

- What are the fundamental physical principles underlying flow, deformation and transport in viscous, elastic and visco-elastic materials?
- How do ionization reactions, electromagnetism, plasma-chemistry, heating and flow interact to create a huge variety of plasmas in nature and technology?
- How can we understand complex interfaces (biologi cal membranes, bilayers, engineering micro-fabricated membranes) based on soft matter and fluid mechanics principles?
- What is the relation between molecular structure, in teractions and dynamics and rheological properties?
- How to bridge the gap between microscopic (atomis tic, colloidal, particulate) and the macroscopic world of continuum mechanics?
- How can the behavior and performance of fluids and soft materials in applied settings be broadened, improved, controlled or enhanced to make break through steps in clean energy, food, environment and health?
- What disruptive fundamental concepts and techniques will revolutionize turbulence research, materials science and soft robotics in the future?

3. Scientific challenges / themes

Multiphase and multicomponent fluid flows

Turbulence is one of the outstanding problems in the physics of fluids community. Even though major steps forward have been made with regard to turbulent single-phase flows, additional key challenges include the extension of our knowledge in the direction of multiphase and multicomponent turbulent flows, including particle- and droplet-laden turbulent flows, bubbly turbulent flows, active turbulence. Additional challenges arise when droplets or particles in a gas become electrically charged and respond to electric fields or even change them, as in thunderclouds, many granular media, and cleaning of exhaust gases. Another challenge is to apply smart and/or active particles to affect turbulence dynamics at its core. Understanding of such systems is crucial for progress in several application areas like marine applications, chemical process technology, food processing and catalysis. Another exciting challenge is the understanding of multiphase flow systems subject to mass/heat transfer, chemical conversions, and soft matter related multiphase flows such as found in polymer processing and emulsions. This is of particular interest for applications in chemical process engineering, food processing and development of new energy solutions, and significant for, e.g., biofuel reactors, synthetic biology, and tissue engineering. A related challenge concerns dry and wet granular matter, including their fluid- and solid-like behavior and phase transitions, with industrially relevant problems like segregation and mixing.

Fluid mechanics for planet, climate and sustainability

Understanding the multiscale Earth System requires a multidisciplinary effort where fluid and plasma mechanics and transport processes are an essential component. For example, fluid mechanics is key for improving our understanding of the global climate, atmosphere and ocean dynamics, estuarine flows, environmental disasters like land-slides/avalanches, and transport in the atmospheric boundary layer. It is also important for technological applications like renewable energy (hydro and wind power, energy conversion and storage), maritime hydrodynamics, etc. Understanding plasma stability and turbulence impacts the feasibility of fusion as a sustainable baseload energy source. The plasma physics of thunderstorms plays a particular role in generating substantial amounts of green-house gases (nitrous oxides, ozone) in the atmosphere. In these fields several of the current-day challenges come together such as flows with (charged) particles, droplets and bubbles, effects of buoyancy and rotation on (large-scale) flows, free surface flows, multiscale phenomena and computational modeling tools, and the role of big data and machine learning in solving such large scale problems.

Complexity in Plasmas

In most plasmas – ranging from low temperature non-equilibrium plasmas (in gases at low and atmospheric pressure) to high-temperature plasmas (in fusion) - there is a multitude of physical and chemical effects at play, combining to form inherently multiscale systems. These include ionization and recombination, interaction of the plasma with external and self-generated electromagnetic fields, turbulent flows,
collisional and radiative transport, interaction with neutral gas and surfaces, Ohmic heating, and plasma-chemical reactions. This variety of processes evolve on largely different spatiotemporal scales, are typically in non-equilibrium, and create complex structures in space and time. Advances in scientific computing, model reduction, data analysis, machine learning and plasma diagnostics will boost our understanding and control of a variety of plasmas.

Designer Soft Matter & Fluids

The unprecedented toolbox available to structure and create soft matter from scratch – colloidal synthesis, self-assembly, lithography, 3D printing – paired with an explosive growth in our understanding of how complex properties emerge, is increasingly allowing us to dream of, investigate, and create entirely novel types of fluids and soft matter with exciting new properties that cannot be found in nature. The next scientific revolution will be to attack the inverse problem and create on-demand designer materials and complex fluids. Striking examples include metamaterials with properties set by their spatial architecture and surpassing those of their constituent materials, complex fluids with designed rheology, programmable and controllable smart materials, foods designed with desirable structure, and artificial life.

Self-Assembly

The autonomous assembly of building blocks into complex phases and materials is a key (bio-inspired) principle of soft matter. It offers the unique opportunity to create highly ordered and well-controlled structures on length scales where direct manipulation is impossible. The Netherlands has a strong track record in the phase behaviour and structure in bulk and confinement (e.g., colloidal crystals, liquid crystals, micelles,
wetting, capillarity, flocculation, nucleation), with self-assembly often assisted by external fields or flow. The fluidic, photonic and catalytic properties of the resulting nanostructured materials couple this research field directly with a variety of topics within the wider FSM community.

Active Matter

Strong developments are taking place in active matter, which are composed of interacting self-propelled entities (e.g. colloidal particles half-coated with a catalyst, bacteria) that move autonomously while consuming fuel/food. In addition, active (soft) solids such as photosensitive polymers, hydrogels, chiral or magnetic particles, partly inspired on the physics of biological tissues or particles, are appearing. Understanding the physical mechanisms that govern the propulsion, self-organisation and collective behaviour in these systems is the key to the design and control of these new functional and self-driven fluids. Infusing soft matter and complex flows with (externally controllable) activity allows to probe novel questions in non-equilibrium physics, opens up new avenues for advanced functionality, and has a clear link to biology, granular matter and processing.

Advanced Functional Soft Matter

The low binding energies that make soft matter 'soft', allows to create highly sophisticated, dynamic materials, which bring responsive, switchable, adaptive, self-healing, extremely deformable, programmable, and highly recyclable materials within reach. These materials of the future are able to selectively and autonomously respond to external triggers, dynamically adapt their function, and seamlessly interface with biological systems. Functional surfaces and interfaces are, next to bulk materials, key in wetting, friction and coatings, and of decisive importance for advanced materials where physical and chemical cues are communicated through the interface, and where living/non-living interfaces play a role. These materials may find their way into nanomedicine devices, self-healing prosthetics, medical adhesives, flexible electronics, and soft robotics with deep links to engineering and applied sciences.

Fluid Mechanics for Biology and Health

A surge of activities in fluid mechanics and plasma physics with a strong focus on biological systems and health applications occurred during the last few decades. These activities will expand and become increasingly important as its societal impact is large, in particular for health and security applications. It covers topics like active biological fluids (bacteria, schools of fish, flocks of birds, human crowds), flows in biological systems as plants, animals, cells and tissue, but also relates to spread of infectious diseases and ecological systems. Non-equilibrium pulsed plasmas in atmospheric pressure gases are already used for disinfection and for air and water cleaning, and they are currently being developed as plasma-medical tools. As another example, cardiovascular fluid mechanics and mechanotransduction are relevant for diseases like atherosclerosis and aneurysms. Biomechanics (tissues, fluid-structure interaction) clearly connects this field with soft matter. An important field is also the area of (model-aided) medical diagnostics and predictive medicine.

Nanoscale transport and fluidics

The fluidic transport of mass, (nano)bubbles, charge, and solutes through micro- and nanofluidic devices, membranes, porous solid-state electrodes, or at solid-liquid interfaces involves many concepts of complex flows, fluid-substrate interactions, soft-matter and liquid-state physics. It may even imply in some cases the continuum breakdown, thus going beyond Navier-Stokes. The huge surface-to-volume ratio of the nanoscale allows for qualitatively new transport mechanisms and new fluidic circuitry elements (diodes, mechanical transistors), with impact on areas as diverse as electrochemistry, heat storage, osmotic energy production, catalysis, battery development, organ-on-chip, and water treatment, and control of slip in nano/microfluidic devices.

Emergence and complexity

Uncovering how complex properties, such as self-organization, complex rheology, structure formation, and memory emerge from the multiscale interactions of simple constituents remains a key challenge. An increasingly important theme is the non-equilibrium physics of soft matter, complex flows and plasmas. This includes externally driven systems (e.g., rheology of complex fluids, pulsed electric discharges in gases), internally driven systems (active matter – see above) as well as out of equilibrium glasses, complex ionized media, complex active flows, and jammed systems. An important perspective is to look at biology as a template for new manufacturing processes of engineering living materials (biofilms for coatings, textiles, living materials, etc.). Future progress on the principles of non-equilibrium systems will have wide impact.

Big data & Machine learning

Experiments and simulations in soft matter, turbulence and plasma research have a long history of dealing with extremely large data sets (e.g., confocal microscopy, video and magnetic resonance imaging, optical measurements, and computational fluid and plasma dynamics data) to understand complex (dynamical) behavior characterizing these fields. Machine learning is presenting new opportunities to interpret, classify, and process big data. Moreover, machine learning opens up new pathways for the design of advanced soft materials, understanding complex flows and plasma processes, and the novel strategies where machine learning controls and interacts with experimental protocols. In parallel, data science techniques offer new breakthroughs in the acceleration of powerful multiscale and multiphysics simulations across FSM, by circumventing computational bottlenecks through the development of accurate surrogate models using physics-informed machine learning algorithms.

4. Application perspective (including societal challenges)

The large variety of topics in FSM is of relevance for many application areas, e.g. chemical process engineering (reactors, catalysis, electrolysis, fluid transport), agro & food technology (crop spraying, plasma-agriculture), renewable energy solutions (solar fuels, blue energy, energy conversion and storage, fuel transport, hydro and wind power, fusion), biological and medical applications (synthetic biology, tissue engineering, nanomedicine devices, self-healing prosthetics, medical adhesives, plasma treatments), maritime and groundwater hydrodynamics, waste water management, and for several innovations in the high-tech sector (plasma deposition, lithography, printing, purification, desalination, anti-fouling, soft robotics, flexible electronics).

The astonishing variety of unusual and complex behavior of complex flows, plasmas and soft matter allows to impact key societal challenges in, for example, health (medical applications), agrofood, materials (designer/meta, soft and biomaterials, processing), smart industry (HTSM), the energy transition and the green and circular economy.

5 Strengths and infrastructure in NL & international perspective

The Netherlands has a vibrant community and strong international standing in fluid mechanics, plasma physics and soft matter research, which also includes a strong experimental and computational infrastructure (provided by SURFsara), at most Dutch universities (LU, RUG, TUD, TU/e, UvA, UT, UU, VU, WUR) and several NWO Institutes AMOLF, ARCNL, CWI, and DIFFER. On the national level knowledge exchange is fostered by, for example, the JM Burgers Center, the NNV section for Plasma and Gas Discharge Physics, Softmatter.nl with annual or biannual meetings. Strong relations between the FSM community and industry exists such as in HTSM (ABB, ASML, Océ/Canon, Signify, VDL), agrofood (Unilever, Friesland-Campina), medical (Philips), chemistry (AkzoNobel, DSM, Dow, Shell, Nouryon, Sabic, Tatasteel), and also with TO2s like Deltares, Marin, NLR, TNO and Wetsus.

6. Research portfolio

Organization	**# PTI members**
AMOLF	6
ARCNL	1
ASML Netherlands B.V.	1
CWI	4
DIFFER	8
NIOZ	1
Océ Technologies BV	1
Philips Lighting BV	1
Rijksuniversiteit Groningen	5
Technische Universiteit Delft	23
Technische Universiteit Eindhoven	40
Unilever R&D	1
Universiteit Leiden	3
Universiteit Twente	28
Universiteit Utrecht	13
Universiteit van Amsterdam	5
Wageningen University & Research	7
Young Wadden Academy	1
Total	**149**

Composition advisory committee Physics of Fluids and Soft Matter

Herman Clercx	TU/e
Martin van Hecke	UL
Michel Versluis	UT
Herman Wijshoff	OCE
René van Roij	UU
Jo Jansen	Unilever
Ute Ebert	CWI
Liesbeth Janssen	TU/e
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