Physics of Fluids

at University of Twente
1998-2018

28-31 October 2018

PHYSICS of FLUIDS at UNIVERSITY OF TWENTE 1998-2018

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Preface

On July 1st, 2018, the Physics of Fluids group at the University of Twente had its 20th birthday. On occasion of this anniversary, from October 28 to October 31, 2018, we organize the Symposium "Physics of Fluids for the 21st Century", with all present and former Physics of Fluids staff, postdocs, and PhD students being invited. The title points to the future and not to the past, as new challenges and opportunities in physics of fluids keep on popping up.

From my point of view we presently live in the golden age of fluid dynamics. The reasons are that (i) Moore's law is kept on being followed for the computational power, now making simulations possible of which even ten years ago we did not dare to dream of, and (ii) a similar revolution (for the same reason) in digital high-speed imaging, now being able to routinely resolve the millisecond time scale and even smaller scales, revealing new physics on these scales which up to now was inaccessible and producing a huge amount of data on the flow.

Also other advanced equipment like confocal microscopy, digital holographic microscopy and atomic force microscopy get more and more used in fluid dynamics. With all of these advances together, the gap between what can be measured and what can be ab-initio simulated is more quickly closing than we had anticipated at the end of the last century.

Also other gaps are closing. Fluid dynamics is bridging out to various neighboring disciplines such as chemistry and in particular colloidal science, catalysis, electrolysis, medicine, biology, computational science, and many others. Here the techniques, approaches and traditions from fluid dynamics can offer a lot to help to solve outstanding problems and vice versa, these fields can offer wonderful questions to fluid dynamics. Academic fluid dynamics is also bridging out not only to traditional applications on large scales such as in chemical engineering, in the food industry, or in geophysics, but also to various new high-tech applications, be it in inkjet printing, immersion and XUV lithography, chemical diagnostics, and lab-on-a-chip microfluidics. Many of these developments we will see in the talks at the symposium.

But with an age of 20, one is allowed to also look back. In the last 20 years, the group has achieved quite a lot, thanks to all the enthusiastic and driven young scientists and staff. We put this booklet together for all them. Next to an outline of the various research lines in the last 20 years, it contains photographs of all of us and in addition the PhD theses covers and as highlight various journal covers of the last 20 years. We also included some statistics of the group over the years.

I would like to thank Sander Huisman, Joanita Leferink, and Huub Eggen for the great help in putting this booklet together.

We hope you will enjoy both this booklet and the conference!

Detlef Lohse

Twente, September 2018

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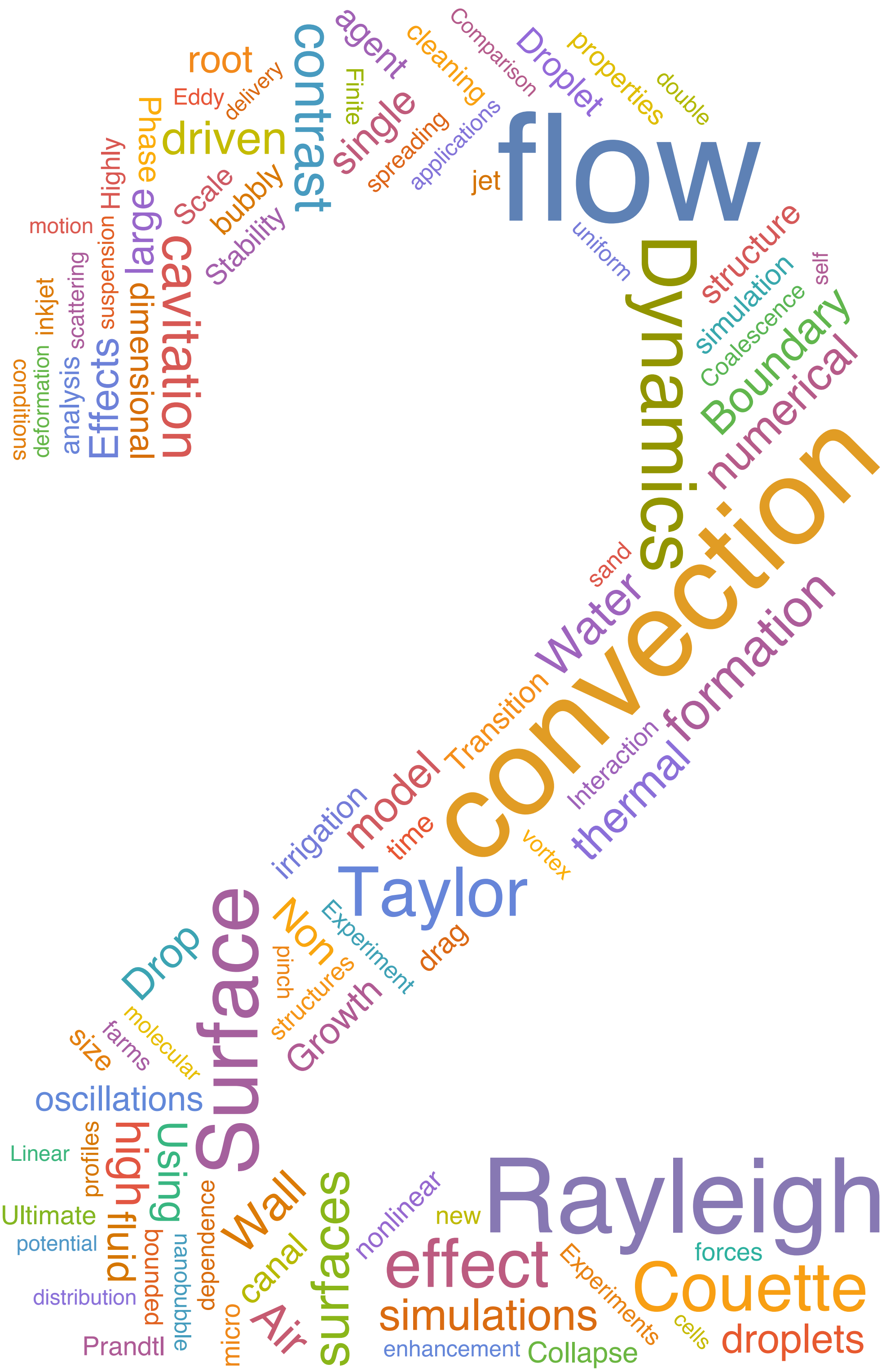
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Physics of Fluids: Research Lines 1998 - 2018

Detlef Lohse

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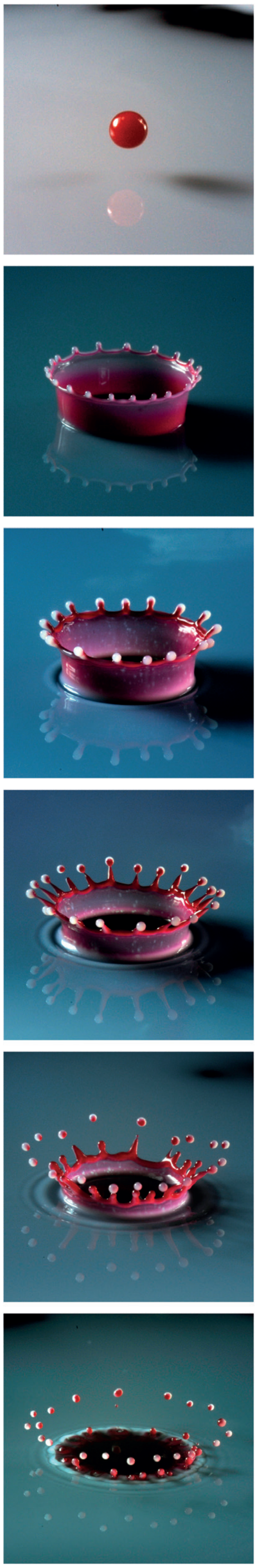
The Physics of Fluids group at the University of Twente officially started on July 1st, 1998, with my appointment at the university. By now, the research interests of the group cover fluid dynamics in a broad sense, with focus on turbulence and multiphase flow, micro- and nanofluidics, biomedical flow including ultrasound imaging, and granular flow. Both fundamental and more applied science is done and both experimental, theoretical, and numerical methods are used. The main characteristics of the work is the direct interaction between experiment, theory, and numerics. The covered length scales range from sub-nanometer to astrophysical scales. Various subjects have an application perspective and we closely collaborate with several companies, among them Océ, ASML, AkzoNobel, and Shell.

In this summary we outline what we have identified as the main 15 research lines of the group over the last 20 years, one often developing out of the other. All research lines have been driven and advanced by the PhD students and postdocs of the group, and it has been a great pleasure and privilege to work with so many young brilliant scientists. Up to now, 80 PhD students have finished their theses at Physics of Fluids and 40 PhD theses are ongoing, and the group cumulatively hosted about 60 postdocs. We briefly describe what they worked on or have been working on and how one subject developed out of the other. A chronological list of the theses, with pictures of the PhD students, is also given in this booklet. Full summaries of the theses are available at https://pof.tnw.utwente.nl/publications/phdtheses.

We greatfully acknowledge that our work has only been possible thanks to continuous financial support by the University of Twente, NWO via FOM, STW, CW, and the European Union via ERC and other programs, and various other funding organizations.



A splash of red, This crown is formed by the splash and droplets of a 2-mm drop of red dye impacting on a thin layer of milk. A single droplet of red dye was released from a height above a substrate and recorded with high-speed photography. The extremely fast sequence of events following the droplet impact strongly depends on the type of liquid, droplet size, impact velocity, and the substrate. For a substrate covered with a very thin layer of liquid the impact of a droplet results in an upward jet forming a crown splash. High-speed photography reveals crown formation with tips of entrained milk covering the rim of the coronet. The rim breaks up in a number of satellite droplets determined by the most unstable wavelength of the Rayleigh-Plateau instability. Such photographs led to the logo of the PoF group, very nicely representing the work done in our group. Image taken by Wim van Hoeve, Tim Segers, Hans Kroes, and Michel Versluis.

Introduction: Appointment and the first year

In 1997, after my habilitation at the University of Marburg, I was in the process of applying for a professorship and incidentally bumped into an advertisement in Physics Today, for a professorship in "Dispersed multiphase flow". I thought: Dispersed multiphase flow – this is turbulence with bubbles. And as in my PhD thesis I had worked on "Fully developed turbulence" and in my postdoctoral time in Chicago and later in Marburg on "Single bubble sonoluminescence", I thought that it would not do any harm to apply. After two separate visits in early 1998 and two separate application talks – the first one on single bubble sonoluminesce and the second one on probe effects in measurements of turbulent spectra – the appointment committee, headed by the Dean of Physics, Prof. Jan Greve, offered me the job, which I gratefully accepted.

When I arrived in Twente in July 1998, apart from me, the group consisted of ir. **Gerrit de Bruin**, the technician **Henni Scholten**, and the secretary **Marianne van der Linde**.

All helped me a lot in understanding the Dutch university system. The greatest treasure of the group was a vertical turbulent water channel with an active grid, built up in the group of my predecessor **Prof. Leen van Wijngaarden**, namely by his last PhD student Edwin Poorte and the technicians Henni Scholten and **Gert-Wim Bruggert**, who, though those days still part of the Engineering Department, also tremendously helped the group. After Henni's retirement in 2000, Gert-Wim formally joined the group and has ever since been one of its major pillars, carrying and developing a huge amount of technological knowledge and taking care of everybody in many ways.

In 1998, FOM – the Dutch National Foundation for Fundamental Research On Matter – had set up a scientific program on dispersed multiphase flow and so it was very natural to continue with this line of research. Out of this program, FOM generously sponsored one assistant professorship position, one postdoc position, and one PhD position, to work on the water channel, in which FOM had invested before. By 1st of January 1999, I could fill the PhD position with **Judith Rensen**, who had done her master thesis at the IMFT in Toulouse and had ample experience with experimental two-phase flow. I also wanted to continue with my line of research on single bubble sonoluminescence and my numerical and theoretical activities on turbulence. I had meanwhile acquired a FOM "projectruimte" grant on "Upscaling single bubble sonoluminescence" and also January 1st, 1999, I could fill the corresponding PhD position with **Rüdiger Tögel**, who had worked with me as master student in Marburg. Out of the startup funds from the university, I hired **Irene Mazzitelli** to work on the numerics of bubbles in turbulence, together with the first postdoc of the group,

Federico Toschi, and out of a German grant on the theory of anisotropic turbulence we still had, I could hire **Anna von der Heydt**, whom I knew as student from teaching Statistical Physics in Marburg. All three started in spring 1999.

I was lucky enough to be able to fill the assistant professorship position with **Michel Versluis**, who started in Twente on April 1st, 1999. As a theoretician, I knew that experimental expertise and skills were badly needed in the group, and Michel brought all this. It is crucial that a group has complementary skills on board and we have ever since followed that principle. Michel soon moved up the ranks and since 2013 is full professor.

Perhaps given my young age, the Dean Prof. Jan Greve had the idea to strengthen the group by the appointment of an experienced scientist as 0.2 fte part time professor and I loved the idea. There was by far no one suited better for this than **Andrea Prosperetti**, who highly appreciated Leen from his time as PhD student in Caltech in the early 1970s where Leen was visiting professor. I knew Andrea Prosperetti from several conferences and in particular from a two-week workshop on sonoluminescence in Leavenworth/Washington State in summer 1997. Andrea liked the experimental opportunities in Twente and joined as part-time professor by December 1, 1998 and I am very thankful that ever since he has kept that position. I have learnt tremendously from Andrea over these two decades and he has had a huge impact on the group. To realize his experimental program, he had negotiated a postdoc, and we were lucky to find **Claus-Dieter Ohl**, who joined us in spring 1999.

The early team is completed by **Bas Benschop**, who also joined in spring 1999, first to take care of the unix computers we had those days and later to be system manager and technician for electronic issues, making sure in his patient and skillful way that everything is running smoothly.

So this was the composition of the group in mid 1999: Gerrit de Bruin, Michel Versluis, and me as scientific staff, Andrea Prosperetti as part-time professor, Henni Scholten, Gert-Wim Bruggert and Bas Benschop as technical staff, Marianne van der Linde as secretary, the two postdocs Federico Toschi and Claus-Dieter Ohl, and the four PhD students Anna von der Heydt, Judith Rensen, Irene Mazzitelli, and Rüdiger Tögel. With this, an elementary matrix of methods and themes as shown in table I had already filled. We were then housed in the so-called "hal IV", which is now called "West-Horst", with the turbulent water channel as only major facility.

TABLE I: Elementary scheme of themes and methods at Physics of Fluids, 1999.

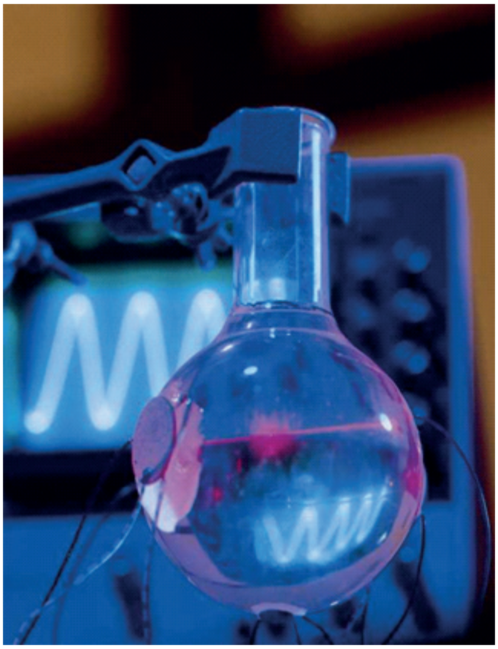
	experiment	theory & numerics
micro-scale	Tögel, Ohl	Tögel
macro-scale	Rensen	von der Heydt, Mazzitelli, Toschi

In this introduction, I also would like to already highlight and stress the role of our group manager **Joanita Leferink**, though she joined the group only in 2001 after Marianne's retirement. As everybody of us knows, she not only works for at least three and literally takes care of everything, from appointments to housing to finances and agendas, but is also the good soul of the group. Without her, Gert-Wim, Bas, **Martin Bos** (who joined us as technician in 2005), and **Dennis van Gils** (who re-joined us in 2016) the group could not have flourished and I am very thankful to them.

As one may have noticed, I have employed a color code for the names (on their first appearance), namely **boldface black** for staff, **boldface green** for PhD students who already graduated, **boldface light green** for ongoing PhD students, and **boldface blue** for postdocs or young visiting scientists. Obviously, in this article I cannot cite all papers of the young scientists. So I had to make a selection (based on my knowledge, my personal and subjective preferences, or often simply based on the story line), which hopefully will not offend anybody. I do have a deep appreciation of every single piece of new scientific insight and research output.

boldface black
boldface green
boldface light green
boldface blue

FIG. 1: Setup for single bubble sonoluminescence: Piezos are glued to a flask filled with water. They excite a standing acoustic wave in which the light-emitting bubble is trapped. This setup has its resonance frequency at about 20 kHz. Photo taken by Rüdiger Tögel, Physics of Fluids, Twente, 2000. I also chose this photo as cover page for the booklet with my inaugural speech.



1. Sonoluminescence and cavitation

In Marburg, as master student Rüdiger Tögel had already worked on single bubble sonoluminescence (SBSL) and had built a setup, to study the effect of alcohol surfactants on the strength of the light emission in single bubble sonoluminescence. He brought the setup (operating at 20 kHz) along, improved it (see figure 1), and this work led to my first real Twente publication [1] (though of course there were also publications in 1998 and 1999, but originating from my prior work). He also built a new single bubble sonoluminescence setup, operating at (a very painful!) 7 kHz. Fortunately, adults cannot hear the noise. Cats can, but Marianne was not willing to bring her cat for testing this. The flask is still used in our present bio-lab for degassing water. With this setup Rüdiger revealed the role of water vapor in single bubble sonoluminescence, showing that it prevents the (intuitively expected) upscaling of the light intensity [2]. He also studied SBSL at low temperatures around 4°C, namely with the windowed fridge which is now in the technician's office, serving other purposes. His main result was the full phase diagram of sonoluminescing bubbles, taking various chemical reactions into account [3]. With the collection of his work, he graduated as first PoF PhD student on December 11, 2002.

Around that time, I also wrote the Review of Modern Physics on SBSL [4], together with Michael Brenner and **Sascha Hilgenfeldt**, who had been my first PhD student (finishing in Marburg in 1998 and after that joining Howard Stone (then Harvard) as postdoc, working on

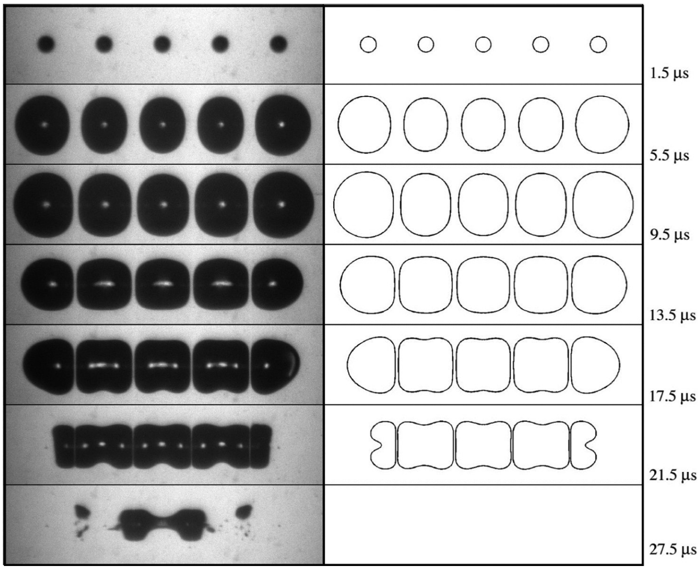


FIG. 2: Comparison between experiment and boundary integral simulation of the cavitation of 5 bubbles in microholes set on a line with a distance of d = 200 μm and a driving pressure of Pa = –1.4 MPa. One clearly sees the shielding effect for the inner bubble, collapsing later than the outer ones. Figure taken from ref. [9].

foams). Just as the other two RMPs I wrote, it took 15 months, but in all three cases these were very enjoyable months in which I learnt a lot. In 2000, Sascha had returned to Europe and joined us as scientific staff. He mainly worked on acoustically driven bubbles and, together with **Adrian Staicu**, continued to work on foams [5].

Sonoluminesence has brought a lot to me and many subjects which later developed in the group, both on the fundamental side and the application side, can be seen as spin-off from our work on single bubble sonoluminescene. I have decribed this in more detail in ref. [6]. One of these subjects is clearly the snapping shrimp, for which we showed that the sound emission is thanks to a cavitating bubble, thanks to wonderful high-speed imaging done by Michel, correlated with acoustic measurements [7]. Later Michel could even show that light got emitted at the shrimp-generated bubble collapse, a phenomenon that we termed shrimpoluminescence [8].

After having fully understood single bubble sonoluminescence [4], we moved to more complicated situations as coated bubbles, bubbles close to walls, interacting bubbles, and vapor bubbles. **Philippe Marmottant** developed a model for the radial dynamics of coated bubbles [10] and, together with Sascha Hilgenfeldt, studied acoustic streaming around oscillating bubbles and the resulting interaction with vesicles [11, 12]. **Nicolas Bremond** studied interacting surface bubbles [9, 13]. Later, extending this work, **Bram Borkent** studied the cavitation threshold for bubbles in a single nanoscopic micropit [14], next to various other cavitation studies. From the theoretical side, also **Marie-Caroline Jullien** worked on oscillating bubbles.

The regime of very violent cavitation was also intensively explored by Claus-Dieter Ohl, with his PhD student **Manish Arora**, in particular with respect to medical and biological applications [15]. Later, also the cleaning applications of cavitating bubbles were explored, namely by **Rory Dijkink** [16] and **Aaldert Zijlstra** [17], the latter in the context of cleaning of semiconductor surfaces, in collaboration with IMEC in Belgium. Later, Michel, together with his PhD student **Bram Verhaagen**, further extended this line of research towards acoustical cleaning of dental root canals [18]. **Christos Boutsioukis** collaborated on this dental project, performing CFD on fluid-structure interactions and on transport and mixing during the ultrasonic file cleaning process [19].

Combining our prior work on chemical reactions within cavitating bubbles [3] and on surface bubbles cavitating out of micropits [13], together with the group of Han Gardeniers and in particular his PhD student David Fernández Rivas, we explored the chemical reactions inside such bubbles [20]. The experiments were performed by David and Aaldert, and the theory by Aaldert and **Laura Stricker** [21]. Together with Andrea Prosperetti, who later also wrote a wonderful review on vapor bubbles [22], **Edip Can** performed a numerical study on cavitating vapor bubbles in confined geometries [23]; this work was continued by

Peter van Dijk and Laura Stricker. Also **Chao Sun**'s first Twente paper, then as a postdoc, was on collapsing vapor bubbles (together with Edip and Rory), more precisely on the growth and collapse of a vapour bubble in a microtube, exploring the role of thermal effects [24]. This line of research on vapor bubbles was further followed by **Oleksandr Shpak**, who, together with Michel, characterized acoustic droplet vaporization both acoustically and optically [25, 26], combining ultra-high-speed imaging and modeling.

Presently, **Mikhail Zaytsev** and **Yuliang Wang** are working along this research line, namely on laser-generated plasmonic bubbles, disentangling the effects of vapor and gas [27, 28].

'Sonoluminesence has brought a lot to me and many subjects which later developed in the group, both on the fundamental side and the application side, can be seen as spin-off from our work on single bubble sonoluminescene.'

2. Turbulence and turbulent Rayleigh-Bénard and Taylor-Couette flow: theory and numerics

As written in the introduction, as PhD student and as postdoc, I had worked on fully developed turbulence. Given that the community is far from "solving" this problem (whatever this means), it was natural to continue with this line of research. Anna von der Heydt theoretically and numerically explored "non-ideal turbulence", where the non-ideality consisted of anisotropy and on non-continuous forcing. This work was in close collaboration with my PhD advisor Professor Siegfried Grossmann, who those days often visited in Twente, where we jointly discussed the physics on the whiteboard. We took up the theme of non-ideal turbulence in the context of thermal convection with **Francisco Fontenele Araujo**, who studied, next to wind-reversals, non-Oberbeck-Boussinesq effects in strongly turbulent Rayleigh-Bénard (RB) convection [29]. We approached both problems also numerically [30, 31], namely **Kazuyasu Sugiyama** and **Enrico Calzavarini**. Here we could also closely collaborate with the experimentalists, namely with Guenter Ahlers in Santa Barbara and with Ke-Qing Xia in Hongkong. This also led to two reviews on Rayleigh-Bénard convection, one Rev. Mod. Phys. focusing on the global flow properties [32] and an Annu. Rev. Fluid Mech. focusing on the local flow properties [33].

In the RMP, we have also extensively covered our unifying theory of thermal convection [35–38] on the dependences of the Nusselt number and the Reynolds number on the Rayleigh number and the Prandtl number. But after all the controversial experiments on that subject, we thought that it would get time to do serious numerics. This is what **Richard Stevens** did, achieving $Ra = 10^{12}$, see figure 3. He also performed numerical simulations on rotating RB. This work was followed up by

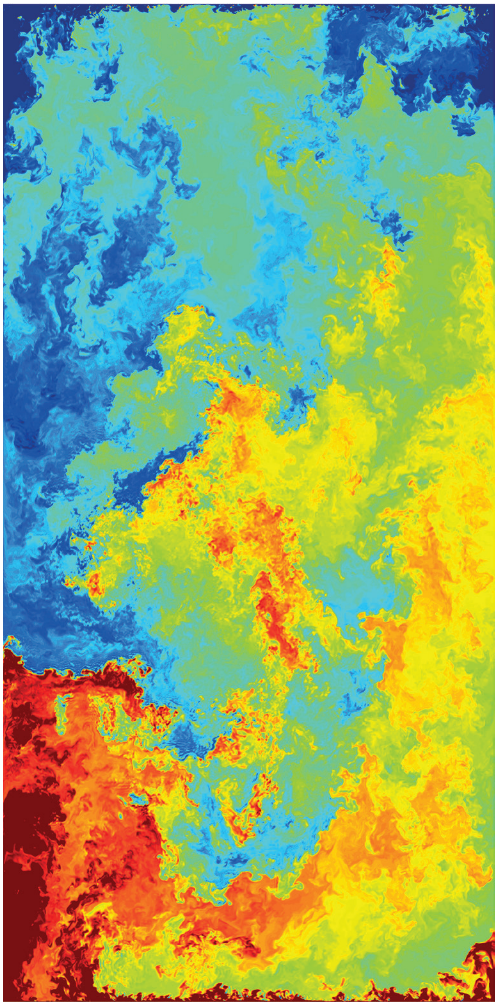


FIG. 3: Temperature field in 3D numerical simulations of thermal convection at $Ra = 2 \cdot 10^{12}$, $Pr = 0.7$, and $\Gamma = 1/2$. Figure taken from ref. [34].

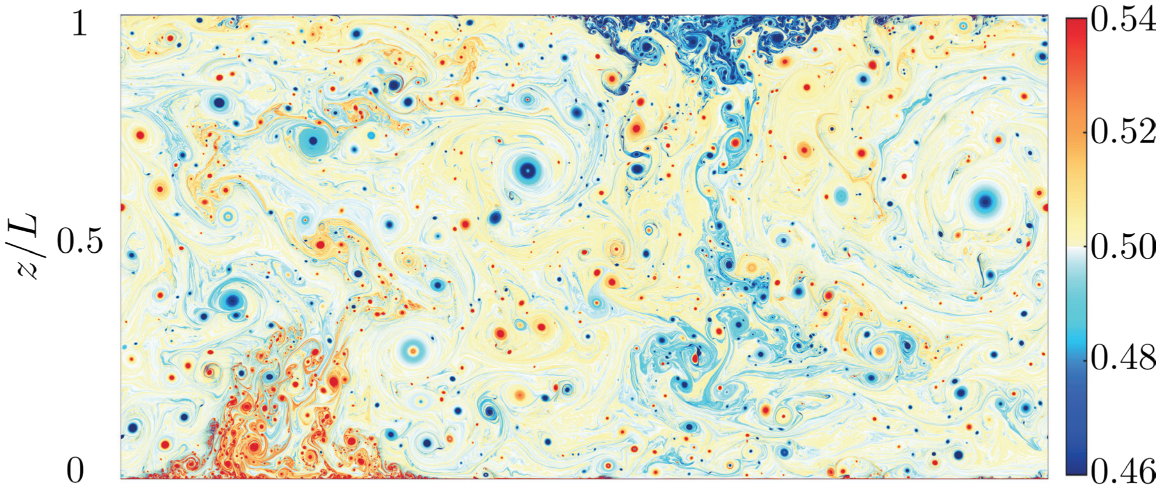


FIG. 4: Temperature field of our numerical simulation of 2D Rayleigh-Bénard at Ra = 10^{14} and P r = 1, close to the onset of ultimate turbulence. Figure taken from ref. [42].

Erwin van der Poel [39], who improved the parallelization of the numerical code considerably and made it open-access [40], together with **Rodolfo Ostilla Mónico**, who also extended the code to the Taylor-Couette (TC) geometry and numerically explored the phase diagram of fully turbulent TC flow [41].

The numerical work has been led by **Roberto Verzicco**, who had joined us in 2010 as part-time professor and who has had tremendous impact on the group. The code was also extended to a multiple-resolution version [43] so that large Prandtl and Schmidt numbers could be treated, and in particular double diffusive convection in the oceanographic context, a sub-line of research pushed ahead by **Yantao Yang** [44, 45]. He numerically simulated double diffusive convection, namely thermohaline convection, with the salt concentration field driving the flow and the temperature field stabilizing it, which can lead to staircase formation, as seen in figure 5.

Further major progress, both on highly turbulent TC and RB, was achieved by **Xiaojue Zhu**, who was the first in our group to include wall structure and roughness into numerical TC and RB flow [46, 47] and in 2D RB even achieved the onset of the ultimate regime [42]. An impression of the flow structure close to the onset is given in figure 4.

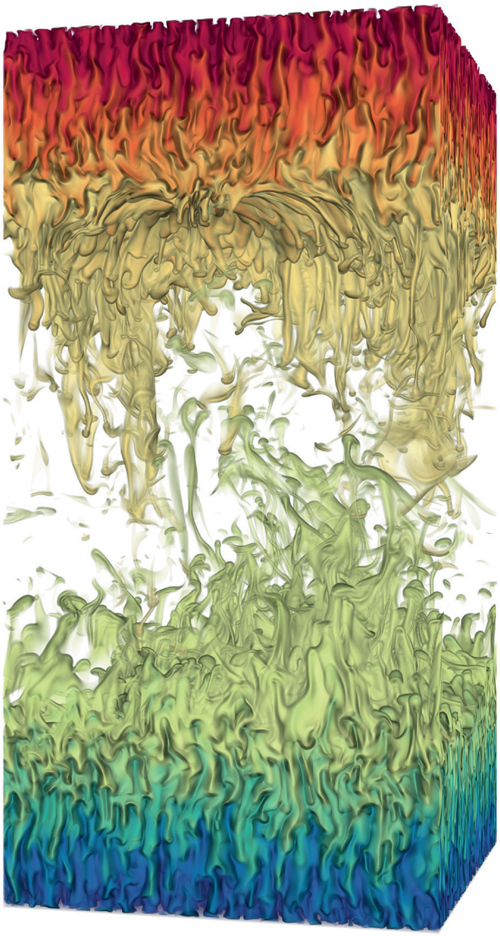
The present PhD students in this line of research are **Alexander Blass**, who is numerically exploring the effect of shear on strongly turbulent RB, and **Pieter Berghout**, who puts in realistic roughness in turbulent TC flow.

3. Bubbly flow in the Twente water channel: experiments

As written in the introduction, the Chair was intended for research in turbulent bubbly flow, with the turbulent water channel as key facility, constructed by Leen van Wijngaarden's group from the mid 1990s on. We wanted to continue with this line of research, and Judith Rensen was the first PoF PhD on that subject. Her main result was to measure the spectra of turbulent bubbly flow, finding them to be less steep than the classical −5/3 Kolmogorov scaling for homogeneous isotropic turbulence, thanks to the local energy input of the bubbles [48]. In the lab, Judith was directly supervised by **Stefan Luther**, who helped tremendously with bubble detection through hot-wire anemometry and optical probes. Judith was succeeded by **Ramon van den Berg**, who, with the water channel, studied the effect of microbubbles on turbulence [49]. Unfortunately, during his PhD the water channel was not available for about two years, as the group was then temporarily housed in "Gebouw A", next to what now is The Gallery. During that time, Ramon entertained himself and us with measurements on Dan Lathrop's TC setup in Maryland [50, 51], finding and exploring bubbly drag reduction. In that period the Twente water channel was stored – and unfortunately stolen. Presumably the expensive metal parts, including the elaborate active grid, had simply been illegally sold to a second-hand metal dealer.

Fortunately, it was insured, and so in our new Meander building, in which we moved in in 2008, we could build a completely new Twente turbulent water channel, overcoming all children's diseases of it predecessor, see figure 6. Gert-Wim did a great job in redesigning and improving it. In fact, the Meander building was built around the water channel, which was put into the ground first. Ramon's successor was **Julián Martínez-Mercado**, who studied microbubble clustering and energy spectra in pseudo-turbulence and turbulence [52], together with **Daniel Chehata Gómez** and in particular **Chao Sun**, and also the Lagrangian statistics of bubble and light particles in turbulence [53]. Chao had entered the group as a postdoc, but soon it was clear

FIG. 5: Staircase formation in double diffusive convection. Shown is the salt concentration field. Adopted from the numerical simulations of Yantao Yang. This image also served as logo for our Max Planck Center Twente.



that he was indispensable and he thus quickly moved up the ranks to finally become full professor. He soon led the experimental turbulence activity.

Julian was succeeded by **Vivek Prakash**, who also studied the dynamics of much larger light particles [54] and the energy spectra in bubbly turbulence with much larger bubbles [55]. Next to Chao, the daily supervision was done by **Yoshi Tagawa**. Vivek was then succeeded by **Varghese Mathai**, who focused on the dynamics of large light particles in turbulence, in particular revealing the effect of the wake [56], of gravity [57], and that of the moment of rotation [58]. Varghese, together with **Elise Alméras**, also worked on an experimental investigation of the turbulence induced by a bubble swarm rising within turbulence [59].

The present PhD student on the Twente water channel, shown in its present form in figure 6, is **Jelle Will**, who is studying the dynamics of oddly shaped particles in fully developed turbulence. He is co-

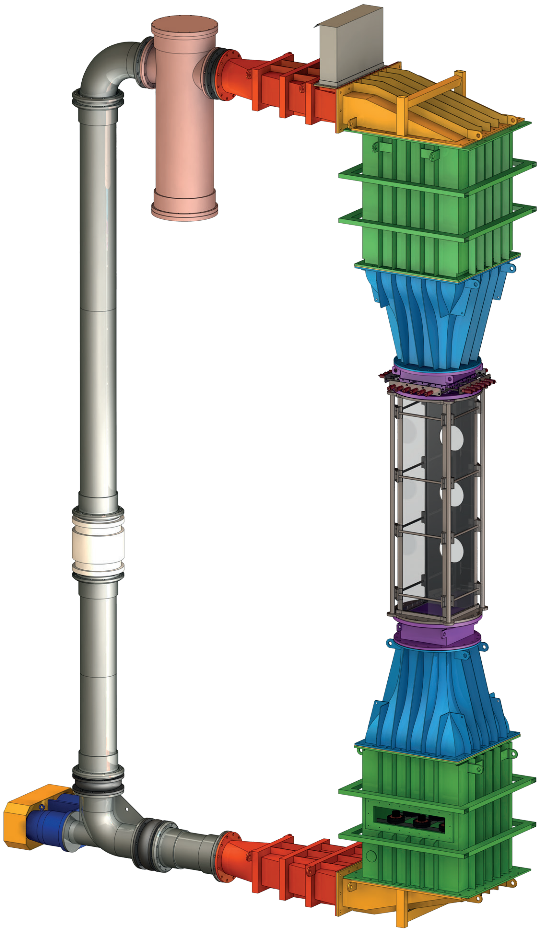


FIG. 6: Sketch and photograph (at right) of the Twente water channel.

supervised by **Dominik Krug**, who this year joined us as scientific staff within our Max-Planck Center Twente on Complex Fluid Dynamics, and will work on flotation and sound propagation in bubbly liquids, among other subjects.

Around 2017, the Twente water channel got a little off-spring, the Twente Heat and Mass Transfer water channel, designed by Gert-Wim Bruggert, Dennis van Gils, **Sander Huisman** (who meanwhile had rejoined us as scientific staff on our MCEC project), and Chao Sun, and the PhD students **Biljana Gvozdić** and **Peter Dung**. With this channel we will study heat and mass transfer in bubbly flow.

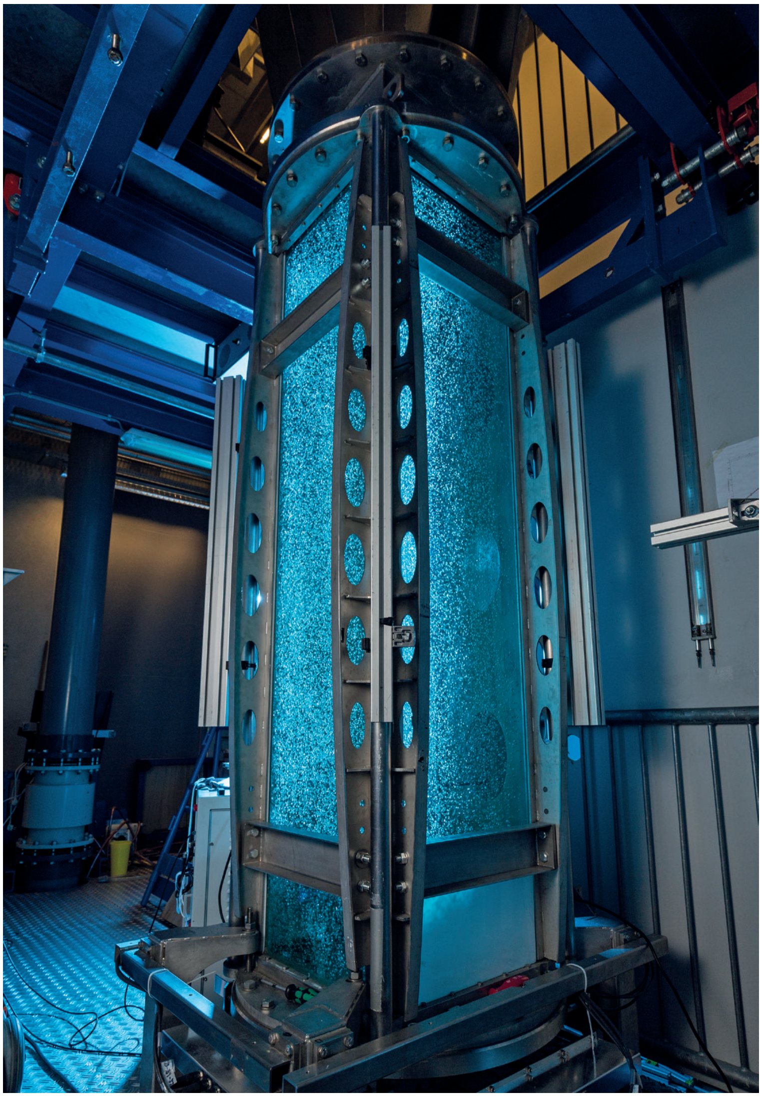


PHOTO RIKKERT HARINK

4. Numerical simulations on bubbly turbulence

From the very first moment, the experimental work on the Twente water channel was accompanied by numerical simulations. In the first years, we used the point-force model in the spirit of Maxey and Riley [60], but then for bubbles. I have discussed this line of research in detail in chapter 9 of [6]. As already elaborated in the introduction, the first PhD student along that line was Irene Mazzitelli, co-supervised by Federico Toschi. She could reveal the relevance of the lift force for the experimentally observed spectra [61, 62] and was also the first to obtain the very intermittent Lagrangian statistics of light particles in turbulence [63]. This line of research was continued with Enrico Calzavarini, who calculated and characterized the clustering properties of point bubbles and point particles in turbulent flow [64, 65], see figure 7.

With **Paolo Oresta**, we extended the point particle approach towards vapor bubbles, but giving them an adjustable size, allowing for liquid evaporation into the vapor bubble and vapor condensation from the bubble [66]. The central new dimensionless parameter here is the Jakob number. We continued this line of research with **Laura Schmidt** [67] and **Raja Lakkaraju**, with whom we numerically calculated the heat transfer in boiling RB [68]. Corresponding experiments were done by **Daniela Narezo Guzmán**.

Having gotten more confidence in the point particle approach, with Kazu Sugiyama and Enrico Calzavarini we also applied it to bubbly drag reduction in TC flow [69], but were restricted to microbubble and small Reynolds numbers, where we found that the origin of the drag reduction was that the rising bubbles weakened the Taylor rolls. But with this approach, which Andrea Prosperetti sometimes has called Mickey-Mouse approach, we clearly could not describe the bubbly drag reduction in the strongly turbulent regime which we had experimentally found [50]. So also here we had to go beyond the pure point particle (or Mickey-Mouse or MM) approach and allowed the point particles to stretch and orientate themselves in the flow, building on an idea of Maffettone and Minale [70]. So MM now stood for Maffettone and Minale or for Multiscale Modelling. With such an approach, **Vamsi Spandan** succeeded to model bubbly drag reduction in TC for intermediate bubble sizes and intermediate Reynolds numbers [71, 72]. His greatest achievement however was to go even one step beyond, namely to implement, under the guidance of Roberto, fully deformable bubbles in TC flow with the immersed boundary method [73, 74]. Presently, this line of research is continued by **Martin Assen** and **Chong Shen Ng**.

Andrea Prosperetti himself followed a complementary approach, namely his Physalis method [75], both in Johns Hopkins and with **Aurore Naso** [76] and **Kristján Guðmundsson** in Twente, with which hundreds of spherical solid particle in (not too strong) turbulence flow can be treated. Yet another complementary approach on particulate two-phase flow with finite-sized particles is the Lattice Boltzmann method and **Maike Baltussen** employed it to perform simulations on sedimentation and fluidization, under the leadership of **Martin van der Hoef**, who in 2012 had joined us as part-time scientific staff on numerical simulations of particulate two-phase flow.

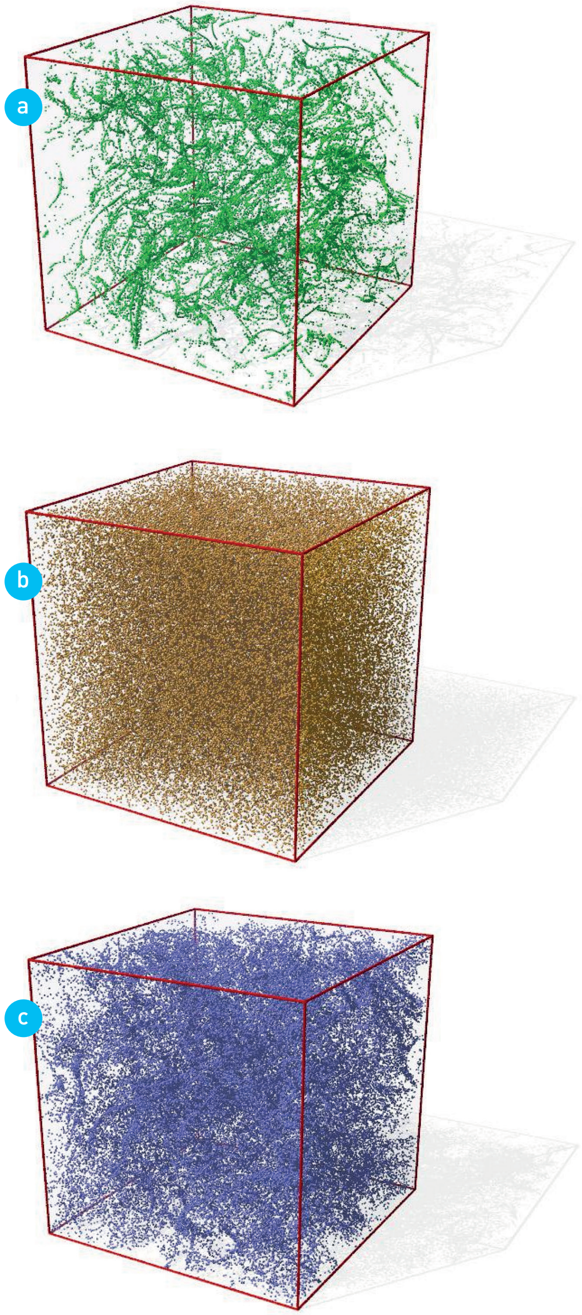


FIG. 7: Snapshots of the particle distribution in turbulent flow field for a Stokes number St = 0.6 for (a) bubbles, (b) tracers, and (c) heavy particles, all for a Taylor-Reynolds number $Re_\lambda = 75$, obtained with the point-particle approach in the spirit of Maxey and Riley [60]. Figure taken from ref. [64].

5. Single rising gas bubbles and light particles

When studying many rising bubbles in turbulence as we did with Judith Rensen and Irene Mazzitelli, it was more than natural to also look at the building block of such a system, namely at a single rising bubble in still water. Since Leonardo da Vinci it was known that such a bubble shows path instabilities. In fact, such instabilities also exist for rising large spheres with a large density contrast to the ambient liquid, and **Christian Veldhuis** experimentally studied both instabilities in detail [77].

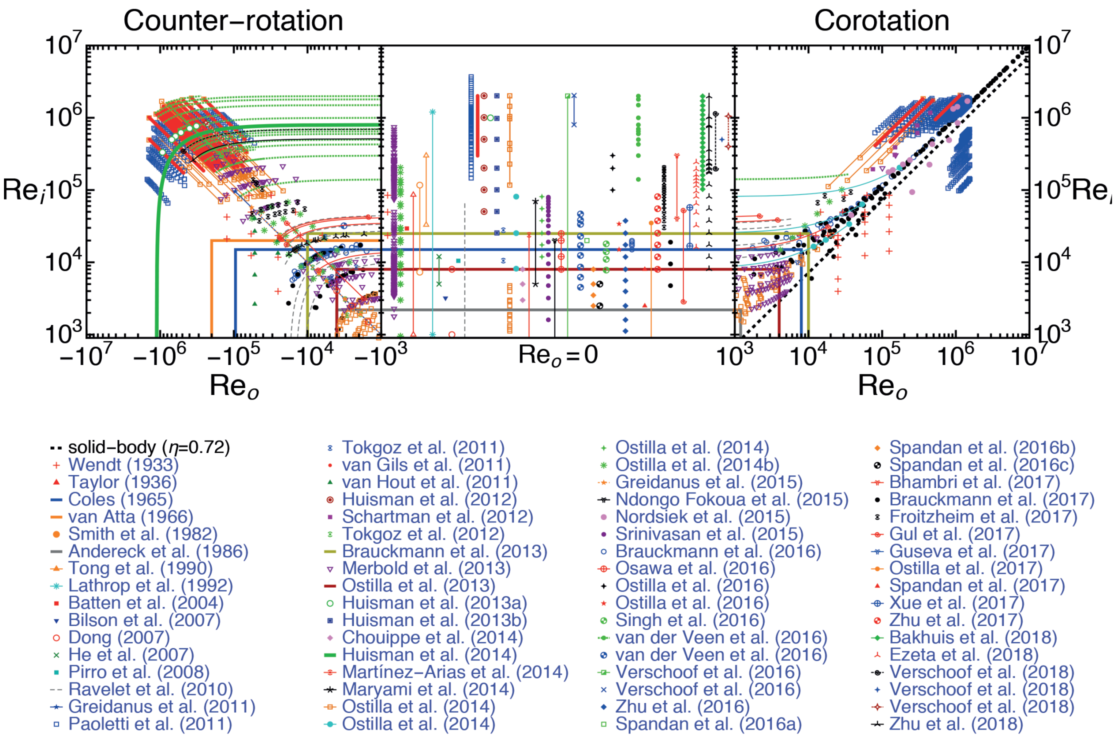
The problem with such an experimental study is that the rising bubbles or particles quickly vanish out of the focus of the high-speed camera. So one has to trap them. A very good way to do so is to put them in a water-filled cylinder rotating around its horizontal axis. This is on what **Hanneke Bluemink** focused in her thesis [78, 79], including numerical studies with Andrea Prosperetti's Physalis method [75]. Leen van Wijngaarden was closely involved in Hanneke's project and all of us keep on learning from his decade-long experience in fluid dynamics. Leen meanwhile has performed research and taught in Twente for 55 years and thus has educated – by his knowledge, his wisdom, his deep insight, his example, and his passion for science – more than 14 generations of PhD students (counting 4 years per generation), which is absolute unique, and I am very thankful to him.

FIG. 8: Photograph of the T^{3}C facility.

6. Taylor-Couette Turbulence and Bubbly Taylor-Couette Turbulence: experiments

In ref. [80], we had shown the very strong mathematical analogy between RB and TC flow, and also outlined how to apply our unifying theory of RB convection [35] to TC flow. From the late 1980s on, there had been many high-precision experiments on strong RB turbulence, mainly by the groups of Guenter Ahlers and of Ke-Qing Xia, but very little had been done on strong TC turbulence, in particular not with co- and counter-rotating cylinders. The only measurements on global transport properties in that regime were done by Wendt in the 1930s [81], and we thought that with the present technology we could be able to go beyond that work. So we planned to build a big turbulent TC setup with co- and counter-rotating cylinders. This happened from 2009 on, under the guidance of Chao Sun, with Gert-Wim Bruggert and **Dennis van Gils**, leading to what is now known as Twente Turbulent Taylor-Couette (T^3C) facility [82]. This immediately led to some very visible and ground-breaking publications [83–85] of Dennis and the second PhD

FIG. 9: Present state of the experimentally and numerically studied TC parameter space.



student on this project, **Sander Huisman**. With **Roeland van der Veen**, we could even show the existence of multiple turbulent states [86]. Next, **Ruben Verschoof** succeeded to implement controlled and varying roughness, leading to a high-impact publication with Xiaojue Zhu and the numerical part of our PoF group (see section 2) [46]. The present state of the field is shown in the parameter space of figure 9, which indeed goes very much beyond what Wendt has done, both experimentally and numerically.

We also used the setup for bubbly TC, showing massive drag reduction with only 4% bubble volume fraction [87]. Ruben and Roeland also succeeded to show that adding surfactants nearly eliminates the drag reduction effect, as the bubbles then become small due to inhibition of coalescence [88]. The work on multi-phase TC flow and TC flow with rough walls is presently continued with the present PhD students **Rodrigo Ezeta**, **Dennis Bakhuis**, and **Pim Bullee**. In particular, in the meantime, we have built an additional boiling TC facility [89], under the guidance of Sander Huisman, Chao Sun, and Gert-Wim Bruggert. With that setup, the temperature is fully controlled so that we can also study boiling TC, which Rodrigo is presently doing.

‘The only measurements on global transport properties in the TC turbulence regime were done in the 1930s, and we thought that with the present technology we could be able to go beyond that work.’

7. Ultrasound diagnostics and ultrasound contrast agents

The first spin-off from our work on single bubble sonoluminescence (section 1) was ultrasound diagnostics. How this came about I described in more detail in ref. [6]; here I only stress that medical ultrasound operates at 2 MHz – 7 MHz, which, when one wishes to visualize the bubble dynamics, automatically implies ultra-high-speed imaging. From my early theoretical work on ultrasound contrast agents back in Marburg [90], I knew **Nico de Jong** from the Erasmus University in Rotterdam, and so I was glad that in 1999 he joined us as part-time professor. Together with him, I wrote a big grant in the FOM programme "Physics for Technology", to enter the area of ultra-high-speed imaging. The proposal was granted and Nico and Michel developed an ultrafast camera, which allowed us to image 128 digital frames with a

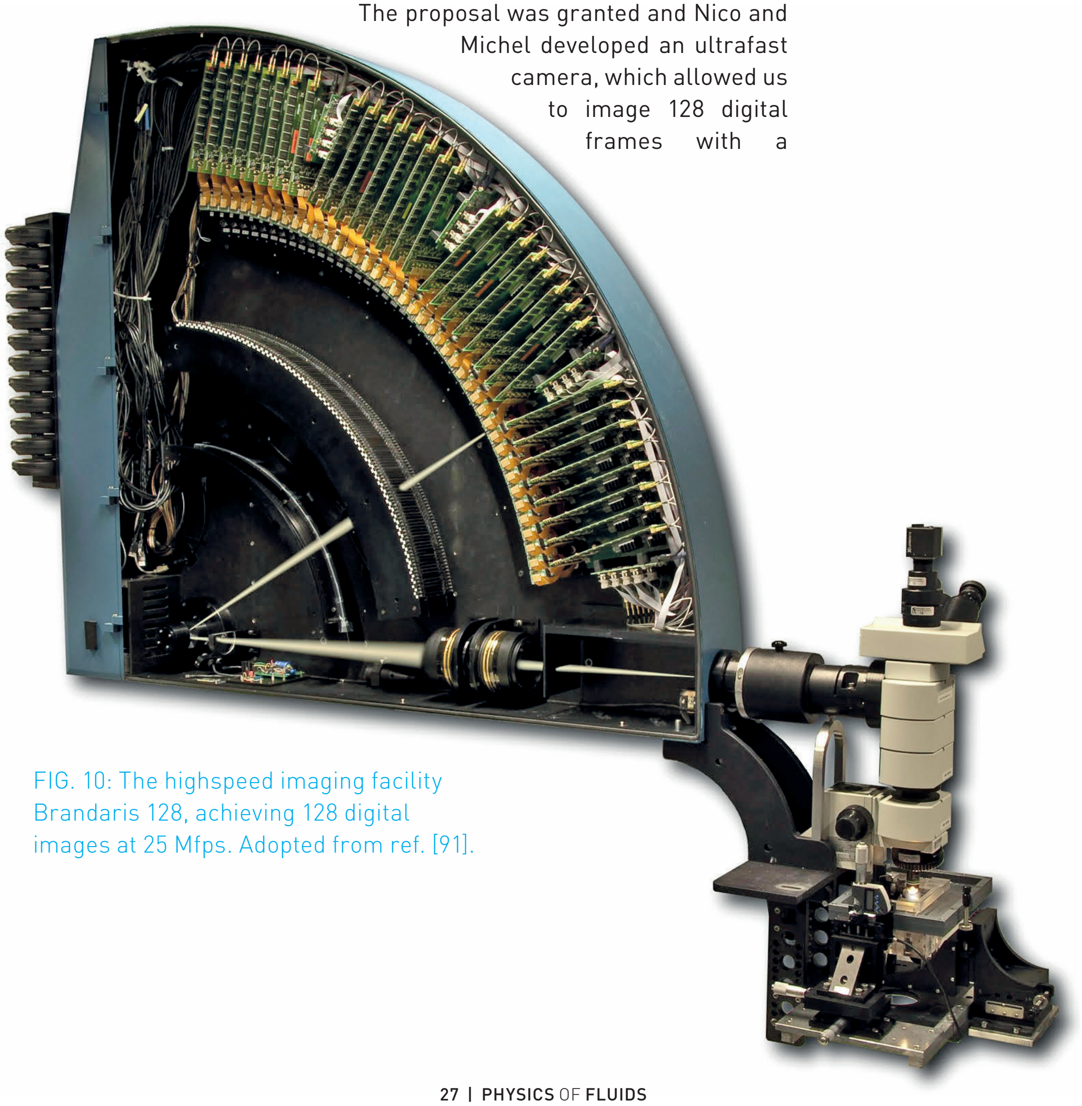


FIG. 10: The highspeed imaging facility Brandaris 128, achieving 128 digital images at 25 Mfps. Adopted from ref. [91].

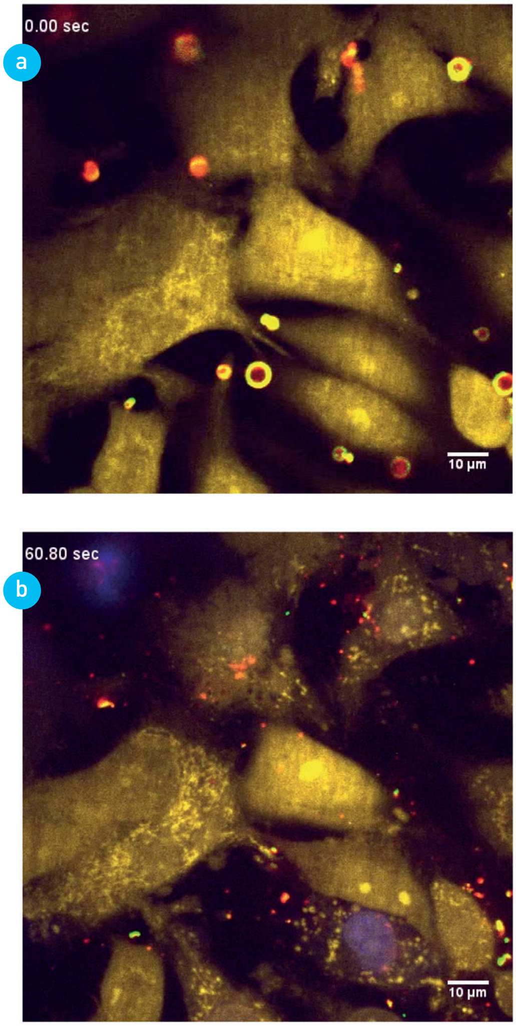


FIG. 11: Confocal recording before (a) and after ultrasound (b) of nanoparticle-loaded microbubbles inducing cell sonoporation. Cells labeled with CellTrace Yellow, fluorescent liposomes labeled in red, and influx of SYTOX Blue due to cell membrane poration results in the blue staining of the cell nucleus.

frame rate up to 25 million frames per second [91], see figure 10. We called it "Brandaris 128", as it is based on a rotating mirror, just as the famous Dutch lighthouse Brandaris on Terschelling. This camera allowed us to gain insight into the volume and shape oscillations of bubbles and their interaction among each other and with structures such as cells.

In the meantime, going way beyond "Brandaris" in many ways, Michel Versluis has established himself as one of the world's experts on high-speed imaging in general, having written a great review article on this subject [92].

Many generations of PhD students and postdocs benefitted from the unique "Brandaris" camera. The first was **Michiel Postema**, who studied the dynamics of ultrasound contrast agent bubbles. Then **Sander van der Meer**, **Jeroen Sijl**, **Marlies Overvelde**, **Benjamin Dollet**, **Valeria Garbin**, and **Todd Hay** studied the resonances of coated bubbles [93–96], focusing in particular on the strong shell-induced nonlinearity of the bubble motion, with much more pronounced bubble compressions than extensions. This so-called "compression only" behavior is excellently described by the "Marmottant-model", which Philippe Marmottant had developed earlier [10]. Valeria also considerably improved the Brandaris setup by adding an optical tweezer system [97]. An excellent recent review of the modified bubble dynamics for ultrasound contrast agents has later been written by the three involved former PoF postdocs [98].

To make ultrasound contrast agents more efficient, it is desirable to have monodisperse bubbles, resonant to the ultrasound driving frequency [99]. **Wim van Hoeve** investigated this with co-flow devices [100]. Together with Benjamin and Philippe he also showed the importance of the channel geometry on the bubble pinch-off [101]. This line of research was continued with **Tim Segers** who developed bubble sorting devices [102] and developed further understanding of the physicochemistry of the lipid coating process [103].

After 10 years of massive use, it was time for a major improvements of the Brandaris. **Erik Gelderblom** extended the facility to allow for ultra-high-speed fluorescence imaging [104]. This facility was massively used by him and by **Guillaume Lajoinie** to characterize various ultrasound contrast agents and laser-activated cavitation agents and their interaction with cells [105–107]. One example for this is shown in figure 11. Later, **Guillaume Lajoinie**'s activity spread out towards acoustics and various microscale flows, in particular those with phase change, and he became expert for various advanced fluid dynamics instrumentation in the group such as digital holographic microscopy and confocal microscopy.

In 2016, **Chris de Korte** joined the group as part time professor, bringing in his expertise in medical ultrasound imaging, in particular ultrafast plane wave imaging. These new techniques facilitated the first in-man 2D time-resolved visualization of aortic flow by **Erik Groot Jebbink** and may serve as a safe and non-invasive probe to study blood flow-stent interactions in the critically-ill patient [108].

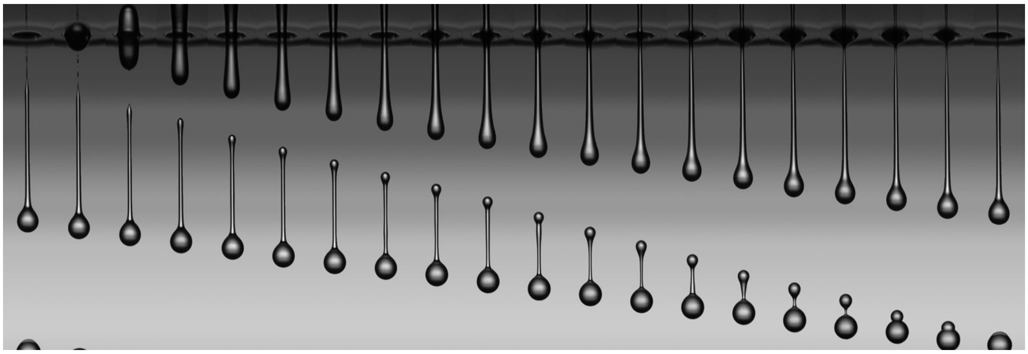
'We called the ultrafast camera of Nico and Michel the "Brandaris 128", as it is based on a rotating mirror, just as the famous Dutch lighthouse Brandaris on Terschelling.'

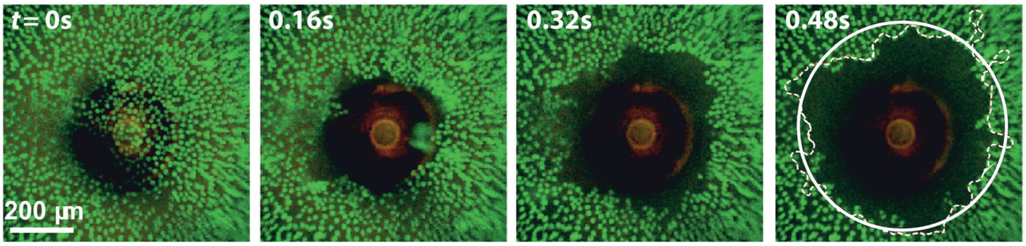
8. Piezo-acoustic inkjet printing and other printing methods

On first sight, the most surprising off-spring from the work on sonoluminescence may be our work on piezo-acoustic inkjet printing, but in both cases a bubble in an acoustic field is key. I was so lucky to meet with Hans Reinten from Océ to get to know about this subject, as I elaborated in ref. [6]. **Jos de Jong** was the first PhD student on this joint project with Océ, and he fully established the presence and dynamics of air bubbles in the piezo-acoustic ink channel [109, 110]. **Roger Jeurissen** developed a theoretical model to describe the effect of the bubble [111]. In the meantime, **Herman Wijshoff** had written a wonderful review article on piezoacoustic inkjet printing [112] with which he graduated. **Arjan van der Bos** continued with Jos de Jong's work and, together with **Mark-Jan van der Meulen**, performed high-precision stroboscopic measurements of the inkjet [113]. This was only possible thanks to illumination by Laser-Induced Fluorescence (iLIF), a trick Arjan van der Bos developed with Aaldert Zijlstra, and Erik Gelderblom, in a joint adventure of office 214a with Michel Versluis [114]. These results were one-to-one compared with the numerical simulations by **Theo Driessen**, who employed the slender jet approximation developed by Jens Eggers, Michael Brenner, and Todd Dupont in Chicago in the early 1990's [115–117]. Also Wim van Hoeve employed this slender jet approximation to predict the breakup of diminutive Rayleigh jets [118].

Theo Driessen also used the slender jet approximation to control jet breakup by a superposition of two Rayleigh-Plateau unstable modes [119], a system on which **Pascal Sleutel** performed the corresponding experiments. Those were of interest not only for Océ, but also to ASML, in the context of producing large tin droplets for efficient extreme ultraviolet (EUV) radiation. We were lucky enough that **Frits Dijksman** had joined us as industrial part-time professor meanwhile, and he was involved in the EUV project both from the industrial side (ASML) and from the university side.

FIG. 12: Stroboscopic images of the ink-jetting process. "Nature scientific picture of the Year 2014". Figure taken out of [113].





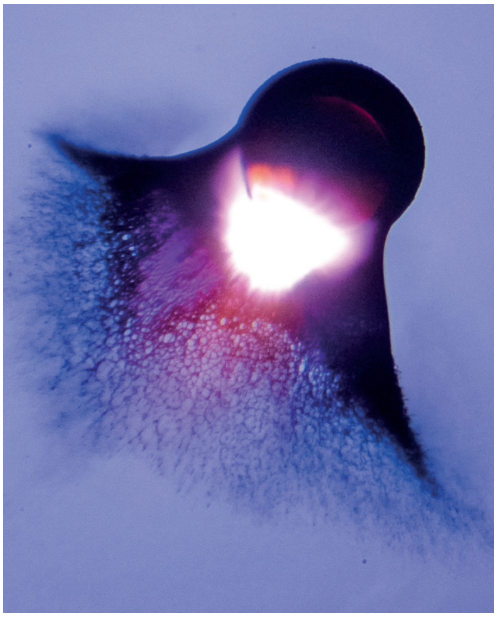
The present PhD students working within our collaboration and joint Industrial Partnership Programme (IPP) with Océ are **Arjan Fraters**, **Maaike Rump**, and **Yogesh Jethani** (mainly working on the inkjet channel and nozzle side) and **Yaxing Li** and **Michiel Hack** working on the droplet evaporation (mainly of multicomponent droplets) and wetting side, see also section 11. The numerical work on the inkjet printing project with Océ is coordinated by **Christian Diddens**, who applies a huge variety of numerical methods to droplet jetting and drying. On the experimental side, **Tim Segers** has rejoined us for the coordination.

The printing activity of the group however goes beyond piezoacoustic inkjet printing. **René Houben** graduated on equipment for printing high viscosity liquids and molten metals. Such material can also be printed with laser-induced forward transfer (LIFT), which was one of the many subjects of **Claas-Willem Visser**'s PhD thesis [121]. Others dealt with cell-printing [122] and – quite the opposite – with the removal of cells through impingement of controlled high-speed microjets [123], see figure 13. Later, the LIFT project in our group was continued by **Jun Luo** and presently by **Martin Klein Schaarsberg** and **Maziyar Jalaal**.

In this section I also want to include our activity within the joint Industrial Partnership Programme (IPP) with ASML on EUV lithography, which **Hanneke Gelderblom** is coordinating, as it developed out of our collaboration with Océ. Within that programme, **Alexander Klein** worked on the shaping of jetted droplets by laser-pulse impacts [124], see figure 14. Presently, **Sten Reijers** performs numerical and theoretical calculations on that project.

FIG. 13: Bottom view of the HeLa cell monolayer during jet exposure. The cells are stained with calcein (green) for visualization purposes. The (red) circular end of the capillary is seen in the center of each image; around this position the cells start to detach after jetting is started (t = 0 s). The dark area in the first frame is caused by poor visualization of the cells in that region. The subsequent images show the growth of the cleared area as a function of time. The last image illustrates the detected edge of the detached area (white dashed line) and a circular fit of this interfacial curve (white solid line). Taken from ref. [120].

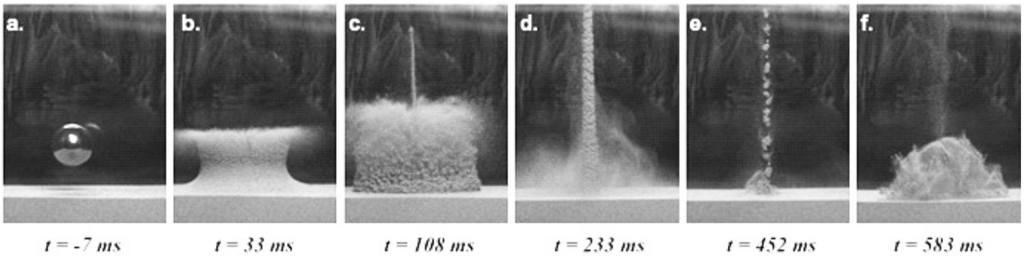
FIG. 14: Impact of a strong laser pulse on a jetted water drop. Figure taken from ref. [124].



9. Granular matter: shaking and impact

Also the work on granular matter started early on in Twente. During my time as postdoc in Chicago, I had closely followed the field, inspired by the work of Heinrich Jaeger, Sid Nagel, and Leo Kadanoff [125–127]. In particular, I was interested in the question under what conditions a hydrodynamic description of shaken granular matter [128] would break down. Leo Kadanoff had found a very nice and pedagogical example in 1D [129], and inspired by that work and by the work on shaken granular matter by Jens Eggers [130], we developed an experiment and a simple dynamical model of shaken granular matter in a compartementalized container, showing hysteretic clustering of the granulate in a certain range of control parameters [131] and the "sudden death" of this cluster in another range [132]. "We" were **Ko van der Weele** who had joined the group as scientific staff in 2000, and **Devaraj van der Meer**, whose main job those days was in the teaching group of the Physics Department. Devaraj's "hobby" soon grew out further and further and we could "buy him off" from his teaching obligations, so that in April 2004 he could finish his PhD on compartementalized granular gases, including a continuum description of such gases. After his PhD, **Devaraj van der Meer** stayed as scientific staff in PoF due to strong mutual intellectual attraction, quickly moved up the ranks, and became full professor in 2013.

FIG. 15: (a-f) Impact (at t=0s) of a steel ball on soft, decompactified sand (grain diameter typically 40 μm). The splash and the jet emerge, just as in water. The grains in the jet cluster due to their inelastic collisions. The last frame shows a granular eruption caused by the rising air bubble. Figures taken from ref. [145].



In the meantime, **René Mikkelsen** had joined us as PhD student on a project on shaken bidisperse compartementalized granular matter [133]. **Peter Eshuis** continued this line of research on shaken granular matter, in particular studying granular convection [134], again including its continuum description, and what we called the granular Leidenfrost phenomenon [135]. **Henk Jan van Gerner** included the effect of the ambient air in the dynamics of shaken granular matter, studying the competition between Newtonian and Stokesian forces through Faraday heaping [136]. **Ceyda Sanlı** replaced the air by liquid and studied the collective particle dynamics on Faraday waves [137].

The large and often underestimated relevance of air in granular matter also became clear from our work on the impact of a steel ball on soft, fine granular matter. **Raymond Bergmann** was the first to start with this activity in our group, focusing on the void collapse after impact and the subsequent formation of a granular jet [138], see figure 15. **Gabriel Caballero Robledo** nicely revealed the role of the air for the steel ball intrusion and the jet formation in detail [139]. This study was later extended and perfected in many ways by **Tess Homan** [140]. **Stefan von Kann** extended the study on intruder dynamics to that in cornstarch suspensions [141] and **Rianne de Jong** and **Song-Chuan Zhao** studied the impact of rain drops on sand [142]. An example of such an impact is shown in figure 16.

The work on shaken granular matter was resumed by **Sylvain Joubaud**, who studied the fluctuation theorem for a "granular ratched" [143], i.e. a ratchet driven by shaken granular matter. This work on granular ratchets was continued by **Loreto Oyarte**, who also continued with the work on intruder dynamics in non-Newtonian liquids [144], together with **Adeline Pons**.

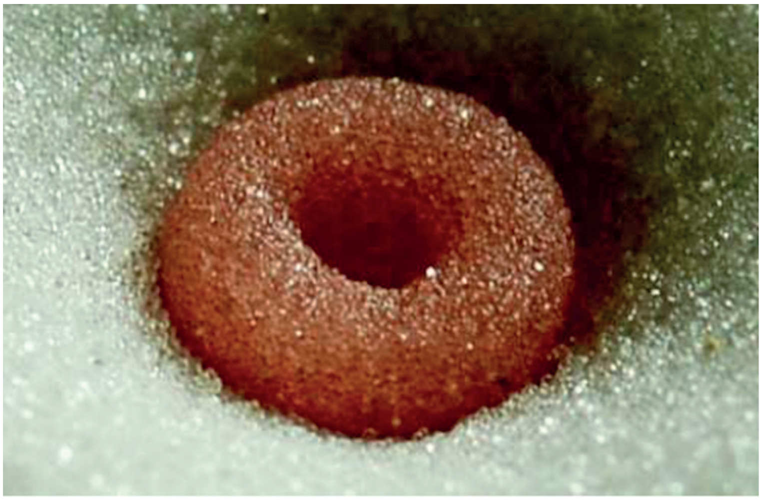


FIG. 16: The impact of a water droplet on sand can lead to a donut formation. Photo taken by Rianne de Jong.

10. Impact on liquid surfaces

FIG. 17: Void forming after the impact of a non-axisymmetric disk on a water surface. Oscar Enríquez called this photograph the "pineapple". Figure taken from [149].

As the steel ball impact on fine decompactified sand [138] has such a strong analogy with the impact on water, it was evident that we could not resist to also study that. Another reason was the analogy between void collapse and bubble collapse (which I elaborated in ref. [6]), and in this sense also this line of research is an off-spring from the work on sonoluminescing bubbles. One challenge in such impact studies of an intruder on a water surface is that the velocity of the intruder in the fluid is not constant, but determined by the forces the intruder experiences. To overcome this complication, Raymond Bergmann designed a setup in which we could set the velocity of an intruding disk to a pre-defined value (in dimensionless form, a Froude number), so that we could fully focus on the dynamics of the void emerging at impact and its collapse, which can be nicely modelled with boundary integral methods [146]. Raymond's studies were continued up by **Stephan Gekle**, who focused on high-Froude number impact and the final phase of the impact, as in both situations the role of the air flow becomes relevant [147, 148]. Correspondingly, he extended the boundary integral solver to include the dynamics of the air-phase.

Ivo Peters, with his master student Oscar Enríquez and with Stefan Gekle and Laura Schmidt, extended this study to the impact of non-axisymmetric disks [149] (see figure 17) and applied the boundary integral solver to the impact through a liquid-liquid interface [150] and to supersonic jetting [151, 152], which had experimentally been studied by Yoshi Tagawa. Presently, in our group **Shuai Li** works with boundary integral methods, to study giant bubble collapse for low-frequency sound generation for acoustic marine geophysical survey.

Tuan Tran [153], and later **Wilco Bouwhuis** from the numerical side [154], focused on the early air entrainment during droplet impact on liquid surfaces. Also **Utkarsh Jain** is in the tradition of this line of research, studying such air cushioning in water impact. Together with him, Mazi Jalaal is studying the impact of non-Newtonian droplets on liquid surfaces, among many other things. Finally, **Srinath Lakshman** works on the impact of droplets on thin liquid films. The striking phenomena which can happen during such an event are shown in figure 18.

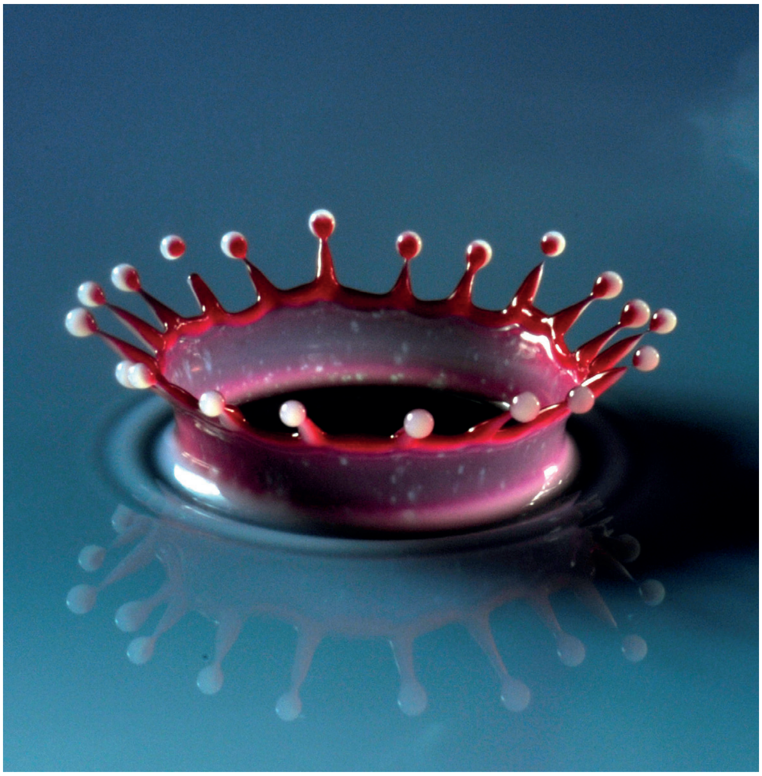


FIG. 18: A splash of red, This crown is formed by the splash and droplets of a 2-mm drop of red dye impacting on a thin layer of milk. A single droplet of red dye was released from a height above a substrate and recorded with high-speed photography. The extremely fast sequence of events following the droplet impact strongly depends on the type of liquid, droplet size, impact velocity, and the substrate. For a substrate covered with a very thin layer of liquid the impact of a droplet results in an upward jet forming a crown splash. High-speed photography reveals crown formation with tips of entrained milk covering the rim of the coronet. The rim breaks up in a number of satellite droplets determined by the most unstable wavelength of the Rayleigh-Plateau instability. Such photographs led to the logo of the PoF group, very nicely representing the work done in our group. Image taken by Wim van Hoeve, Tim Segers, Hans Kroes, and Michel Versluis.

11. Droplet impact on solids

In the last two sections I have reported on our work on the impact of droplets on water and sand. The first in our group to study droplet impact on solids was **Peichun Amy Tsai**, namely on micro- and nanopatterned (superhydropobic) surfaces [155–157]. Wilco Bouwhuis, together with Roeland van der Veen and many others on the experimental side, studied the air entrainment under the droplet and how it depends on the impact velocity [158]. The comparison between numerical simulations and experiments on droplet impact was provided by **Sander Wildeman** and Claas-Willem Visser [120, 159].

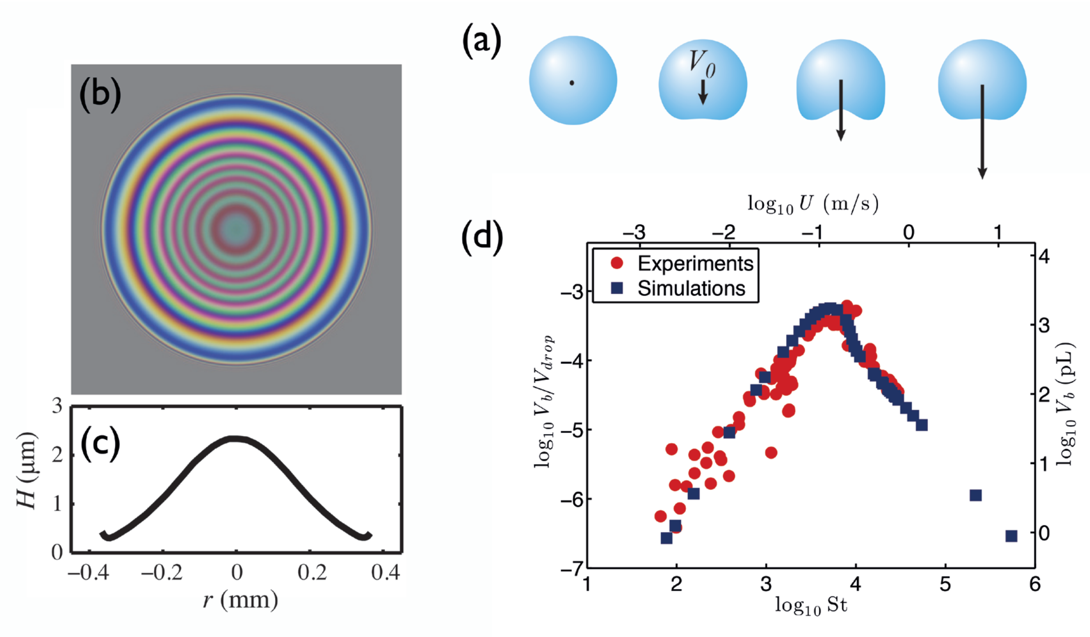


FIG. 19: (a) Schematics of the performed droplet impact experiments, with increasing impact velocity V0 (from left to right). (b) An example of an interference pattern and (c) the extracted air thickness profile. Note the difference in horizontal and vertical length scales. (d) The entrained bubble volume V_b as compared to the droplet volume as function of droplet impact velocity U = V0 (upper axis) or in dimensionless form as function of the Stokes number. Experiments and numerical simulations excellently agree and show a pronounced maximum. Left of it the impact is dominated by capillarity, right of it by inertia, with little entrainment in both cases. Figures adopted from ref. [158].

In the PoF group we let everything fall on everything. So in this tradition, **François Boyer** studied how shear-thicking liquids impact [160]. This study was continued by **Marie-Jean Thoraval**. **Marise Gielen** and **Riëlle de Ruiter** let droplets fall on elastic membranes, in the context of our IPP with ASML.

Tuan Tran, together with **Erik-Jan Staat** (also in collaboration with Océ) and later **Michiel van Limbeek**, **Minori Shirota**, and **Kirsten Harth** extended the droplet impact study towards the impact on superheated surfaces, thus exploring the physics of the Leidenfrost effect [161–163]. **Hrudya Nair**, together with Erik Jan, also studied this Leidenfrost effect on superheated carbon-nanofiber surfaces. **Anaïs Gauthier** studied how the Leidenfrost effect can be inverted, with water droplets floating and freezing on liquid nitrogen.

The opposite of superheated surface are supercooled surfaces, and more recently we have started a study on freezing droplets, performed by **Alvaro Marin**, Oscar Enríquez [164], Riëlle de Ruiter [165] and presently **Robin Koldewij** and **Pallav Kant**.

> 'In the PoF group we let everything fall on everything.'

12. Droplet evaporation

After droplet impact, volatile droplets will eventually evaporate. Also on this subject Peichun Amy Tsai was the first to perform studies [166], namely on droplet evaporation on microstructured surfaces. **Hanneke Gelderblom** and Alvaro Marin studied colloidal droplet evaporation on substrates providing pinning [167] and on omniphobic surfaces [168], see figure 20. Presently, within the ERC Starting grant of assistant professor Alvaro Marin, **Carola Seyfert**, **Myrthe Bruning**, **Jiaming Zhang**, and **Mathieu Souzy** are continuing with the line of research of particle clogging and jamming in suspension droplets and in confined geometries in microfluidics.

Huanshu Tan extended the evaporation studies to the evaporation of ternary liquids, namely to evaporating ouzo droplets [169]. A snapshot of such an evaporating ouzo droplet, showing nucleation of micro-droplets, is shown in figure 21.

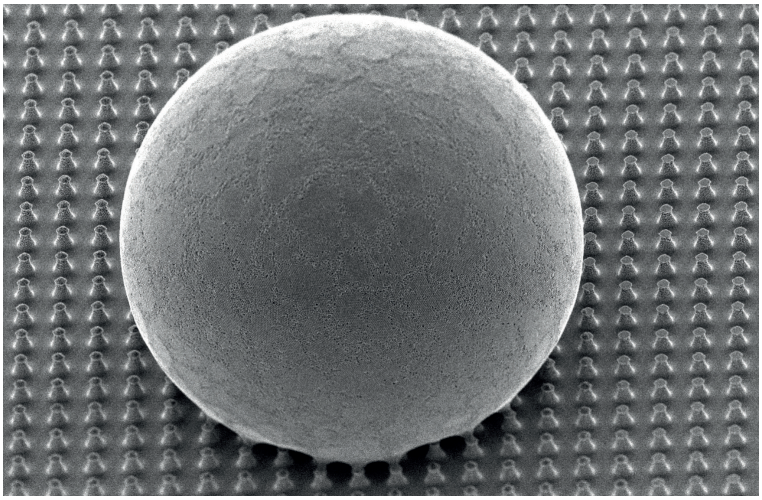


FIG. 20: The evaporation of a colloidal droplet on an omniphobic surface leads to the formation of a mini-soccer ball. Figure taken from ref. [168].

13. Surface nanobubbles and surface nanodroplets

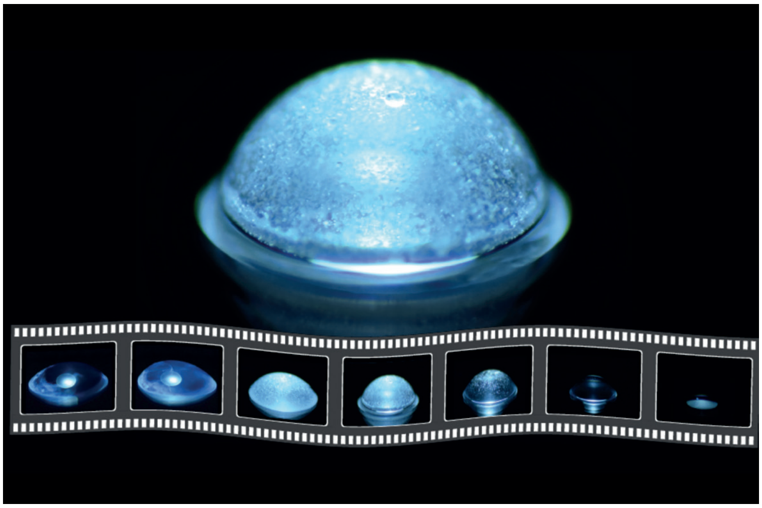
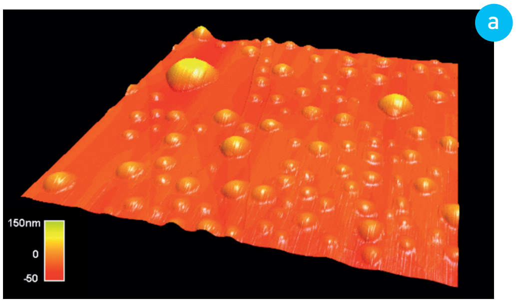


FIG. 21: Evaporating ouzo droplet, showing the nucleation of micro-droplets, first at the rim. Figure adopted from the movies of ref. [169].

In section 1 I have described how our study on single bubble sonoluminescence and cavitation had naturally led to surface bubbles trapped in cavities [13]. With **Oscar Enríquez**, **Álvaro Moreno Soto**, and **Pablo Peñas-López**, we studied the diffusive dynamics of such bubbles trapped in cavities (in controlled CO_2 oversatured liquid), finding pronounced history effects [170–172]. Presently, **Xiaolai Li** is continuing this line of research [173].

But around 2000, tiny surface bubbles had been found also on seemingly *smooth* surfaces, see our review on these so-called surface nanobubbles [174], see figure 22a. Soon after their discovery, they caught our attention. The first PhD student on the subjecty was **Shangjiong Yang**, who



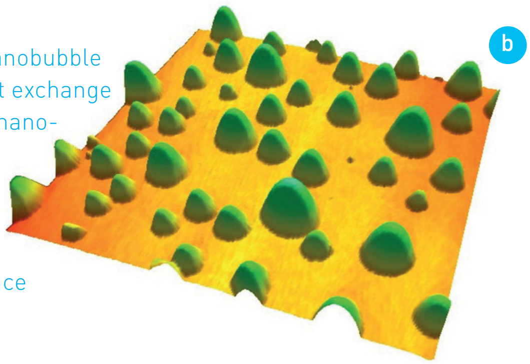


FIG. 22: (a) AFM image (4 × 4μm²) of a surface nanobubble on a HOPG surface, obtained through the solvent exchange process. (b) AFM image (30 × 30μm²) of surface nano-droplets on a hydrophobically coated Si surface, also obtained through the solvent exchange process. The color code goes from 0 (red) to 800 nm (green). Figures taken from our recent review article on surface nanobubbles and surface nanodroplets [174].

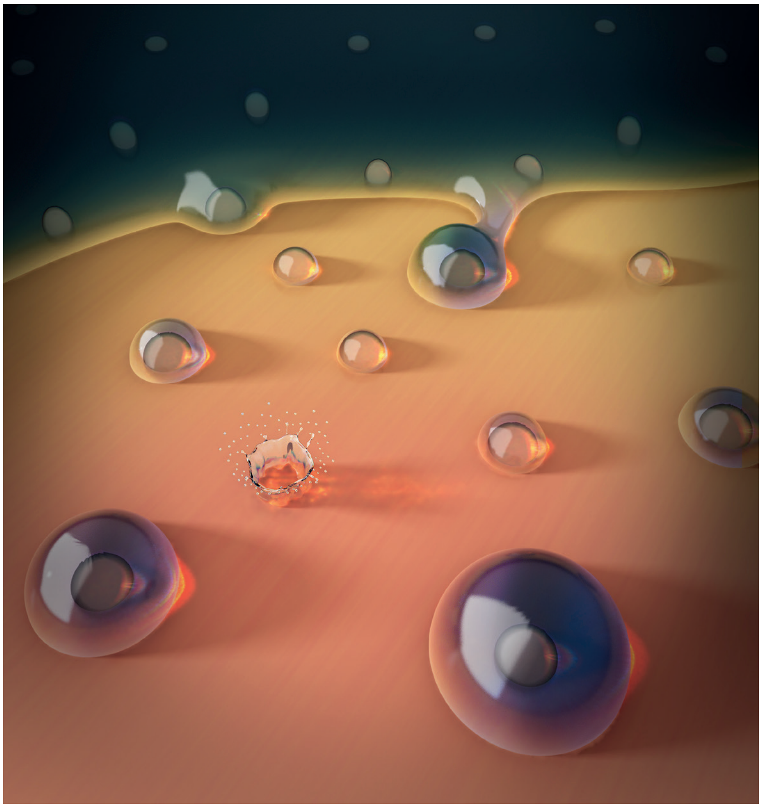


FIG. 23: Artist's view of the visualization of microdroplet nucleation by bursting nano-bubbles, based on ref. [179].

characterized such surface nanobubbles with AFM [175], in close collaboration with the group of Harold Zandvliet, who has tremendous expertise with AFM and with whom we have been collaborating on most nanobubble and nanodroplet projects. Bram Borkent [176] and **James Seddon** [177] continued this line of research. On the theoretical side, **Stefan Dammer** and **Joost Weijs** performed numerical simulation, using molecular dynamics (MD). **Robin Berkelaar** succeeded to show that in many cases the objects seen in AFM images are in fact not surface nanobubbles, but surface nanodroplets of some contaminating liquid [178].

Xuehua Zhang, with **Henri Lhuissier**, could show that under boiling conditions surface nanobubbles nucleate microdroplets [179], shedding light on the relevance of pinning. A visualization of the process is given in figure 23. They also characterized the spatial organization of surface nanobubbles [180], deducing information on the nanobubble formation process from it.

The breakthrough on our understanding of nanobubble stability was achieved with **Xuehua Zhang**, after she had returned to Melbourne as Associate Professor, namely to realize the relevance of both contact line pinning and oversaturation [181]. In the meantime, Xuehua had also been appointed as part-time professor in our PoF group, bringing to our group a huge amount of knowledge from the chemical and colloidal side. Our theory had meanwhile been supported by **Shantanu Maheshwari**'s MD simulations [182] and Xiaojue Zhu's continuum dynamics simulations. **Vitaly Svetovoy** and **Ivan Dević** included the effect of disjoining pressure into that theory [183].

Pengyu Lyu extended this line of research on surface bubbles to catalytic bubbles [184], and so does **Thijs Verkaaik**, and **Nakul Pande** to electrolytic bubbles. **Pantelis Bampoulis** used AFM to characterize strongly confined ice and alcohol-water mixtures on graphene layers [185], again in close collaboration with Harold Zandvliet's group. **Xiumei Liu**, together with Xuehua Zhang, studied the formation and dissolution of microbubbles on plasmonic nanopillar arrays [186]. **Borge ten Hagen**, together with Maziyar Jalaal and Alvaro Marin, explored how the generation of catalytic bubbles on one side of Janus particles in peroxide solutions lead to the particle propulsion, focusing on collective effects.

As it is tremendously difficult to perform AFM on surface nanobubbles, we have more and more focused on surface nanodroplets, which obey the same diffusive dynamics. An example of surface nanodroplets is shown in see figure 22b. **Erik Dietrich** was the first who did a systematic study of dissolving surface drops in our group, finding different dissolution modes [187] and for large droplets and high solubility convective effects [188]. The present PhD students and postdocs working on diffusive droplets dynamics (mainly with an ERC Advanced grant) are **Yanshen Li**, **Corentin Tregouët**, **José Encarnación Escobar**, **Ricardo López de la Cruz**, and **Lijun Thayyil Raju** on the experimental side and on the numerical side **Steven Chong** and **Vatsal Sanjay**.

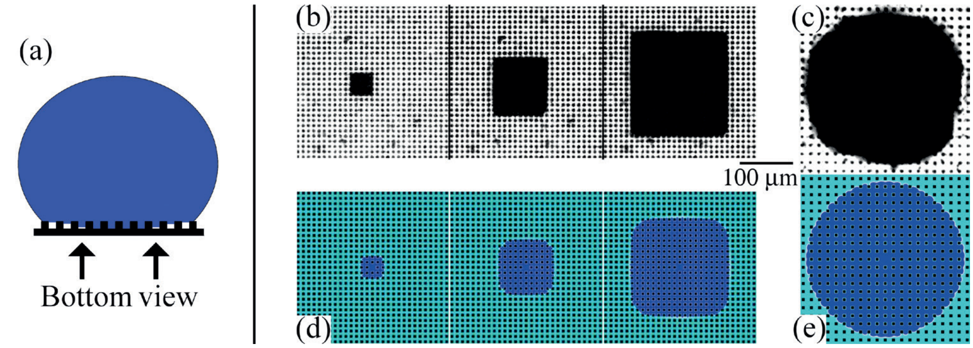


FIG. 24: Bottom views of the front evolution of the Cassie-Baxter to Wenzel "zipping wetting" transition, as sketched in (a). In (b) three snapshots for the case with a pillar distance a = 5µm are shown, leading to square-shaped wetted area. In (c) it is a = 11µm, resulting in a circular wetted area. Figures (d) and (e) show the results of the corresponding numerical simulations with the Lattice Boltzmann method with a = 5µm and 11µm, respectively. Figure taken from ref. [189].

14. Wetting

In section 11 I have already mentioned that we worked on the impact of droplets on superhydrophobic surfaces. But even when gently depositing liquid droplets on such surfaces, interesting dynamics can happen. The first to look into this in our group were **Mauro Sbragaglia** (from a numerical side, employing the Lattice-Boltzmann method) and **Christophe Pirat** (from an experimental side, employing high-speed imaging), who analysed how droplets underwent the transition from the Cassie-Baxter state to the Wenzel state on a well-structure and well-defined superhydrophobic surface, namely by "zipping-wetting" [189, 190], see figure 24.

The PoF work on wetting got tremendously accelerated when **Jacco Snoeijer** joined us as scientific staff in 2008. He introduced the subject and himself with a wonderful review article on wetting phenomena [191]. Under his guidance, **Tak Shing Chan** developed a theory for air entrainment by contact lines of a solid plate plunged into a viscous fluid [192]. **Koen Winkels**, **Antonin Eddi**, and **Federico Hernández-Sánchez** explored the spreading of droplets on substrates [193], in collaboration with ASML. **Jens Harting** performed corresponding numerical simulations.

Stefan Karpitschka, **Siddartha Das**, and **Anupam Pandey** worked on wetting on soft substrates [194, 195] and on the inverted cheerios effect [196], i.e., on studying the attraction or repulsion of liquid droplets on a thin surface. **Maxime Costalonga**, with Stefan Karpitschka and Myrthe Bruning, worked on surface droplet coalescence. Presently, **Walter Tewes**, **Mathijs van Gorcum**, **Liz Mensink**, **Diana García González**, and Michiel Hack work on wetting projects.

15. Wind farm simulations

One of the newest lines of research in the group connects to the research line "Turbulence: theory and numerics", section 2. After **Richard Stevens** had returned from Johns Hopkins University as Assistant Professor, he continued with wind farm simulations and modeling, a subject he had started there. These simulations are not DNS, but LES – large eddy simulations, but nonetheless give outstanding results. An impression is given in figure 25. Richard also meanwhile has provided a great review on this subject [197]. The present PhD students on this project are **Srinidhi Nagarada Gadde**, **Jessica Strickland**, and **Anja Stieren** and the postdocs have been **Mengqi Zhang** and **Luoqin Liu**.

Closing

As seen from the various research lines of the group, the subjects in the group have dynamically evolved with time. Some have given birth to many others, others continued, again others ceased, as problems got solved. Also the expertise in the group and of the staff has dynamically evolved. Our principle has always been to have complementary expertise on board, of course, next to scientific excellence and scientific drive. In table II, which emerged out of table I, I have tried to visualize the expertise of the present scientific staff, as long as this is possible in a two-dimensional parameter space.

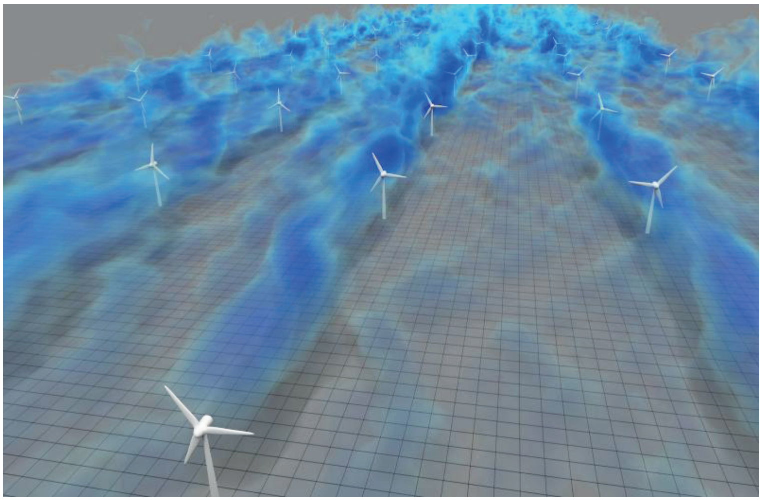


FIG. 25: Numerical simulation of a wind farm. Taken from Richard Stevens' review article [197].

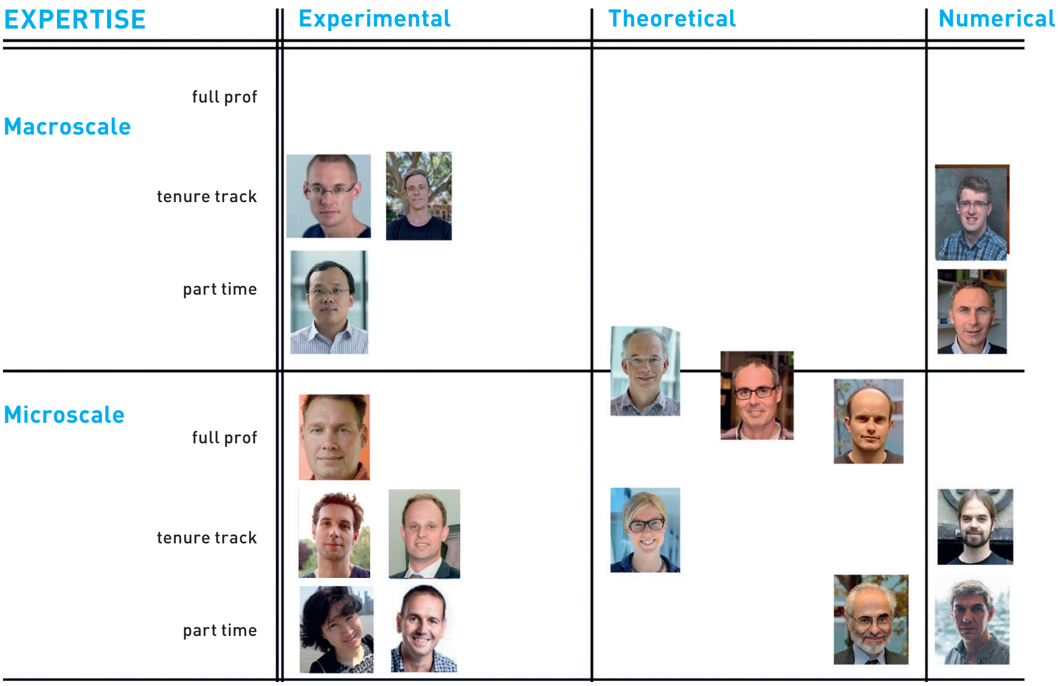
But there is also lots of expertise in Twente outside the group, and the University of Twente has provided us with an excellent scientific and technological environment and outstanding "making" facilities, be it within Mesa+ or through TCO.

There are many scientific groups in Twente with whom we have nicely collaborated over the last 20 years, originating from three different departments. Namely, in alphabetical order (and I hope not to forget anybody), I would like to thank the groups of Albert van den Berg, Niels Deen (now TU/e), Jan Eijkel, Severine Le Gac, Han Gardeniers, Bernard Geurts, Harry Hoeijmakers, Marcel Karperien, Hans Kuipers (now TU/e), Rob Lammertink, Leon Lefferts, Ton van Leeuwen (now AMC), Stefan Luding, Guido Mul, Gert-Willem Römer, Wiendelt Steenbergen, Julius Vancso, Jaap van der Vegt, Kees Venner, Matthias Wessling (now Aachen), and Harold Zandvliet for the outstanding and very long collaborations – I am looking forward to more joint endeavors to come!

I also would like to thank our industrial partners, in particular Océ, ASML, AkzoNobel, Shell, Tata, DSM, Bracco, Medspray, LAM, and Philips, and of course our many external collaborators from universities and institutes all over the world.

I close with thanking my scientific teachers, Siegfried Grossmann, Leo Kadanoff, and Andrea Prosperetti. I have learnt tremendously from all of them and I am extremely grateful to them and will always be.

Table II: Distribution of core expertise of the staff of the PoF group in 2018.



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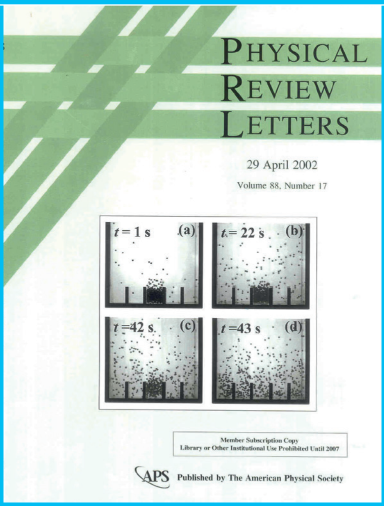

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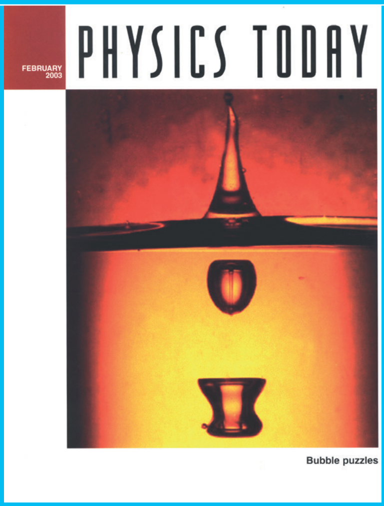

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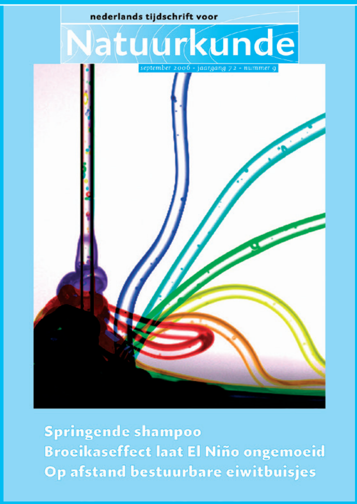


Michel Versluis, Cock Blom, Devaraj van der Meer, Ko van der Weele, and Detlef Lohse. Springende shampoo, Nederlands Tijdschrift voor Natuurkunde 72, 312-313 (2006).

Giles Delon, Marc Fermigier, Jacco Snoeijer, and Bruno Andreotti. Relaxation of a dewetting contact line, Part 2: Experiments, J. Fluid Mech. 604, 55-75 (2008)

Current PoF staff

Current PoF staff

Detlef Lohse
Professor

Chair holder Physics of Fluids,
started in 1998

Devaraj van der Meer
Professor

Physics of granular matter and interstitial fluids,
joined PoF staff in 2004

Jacco Snoeijer
Professor

Capillary flows and elasticity,
joined PoF staff in 2008

Michel Versluis
Professor

Physical and medical acoustics,
joined PoF staff in 2008

Current PoF staff

Sander Huisman
Assistant Professor

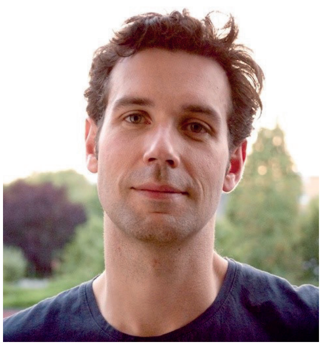
High Reynolds number turbulence and multiphase flows,
joined PoF staff in 2017

Dominik Krug
Assistant Professor

Turbulence,
joined PoF staff in 2018

Guillaume Lajoinie
Assistant Professor

Microscale flow, phase-change and acoustics,
joined PoF staff in 2018



Alvaro Marin
Assistant Professor

Confined soft matter,
joined PoF staff in 2015

Richard Stevens
Assistant Professor

Numerical simulations of turbulence,
joined PoF staff in 2016

Jens Harting
Part-time Professor

Numerical simulations in microfluidics,
joined PoF in 2013

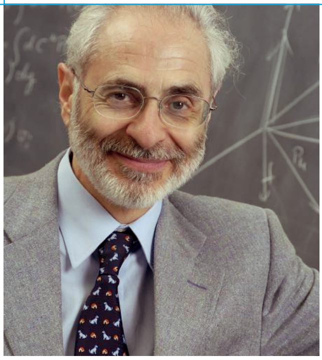
Martin van der Hoef
Part-time Associate Professor

Numerical simulation of particulate two-phase flow,
joined PoF in 2012

Chris de Korte
Part-time Professor

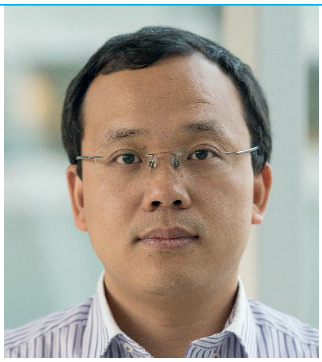
Medical ultrasound imaging,
joint PoF in 2016

Current PoF staff



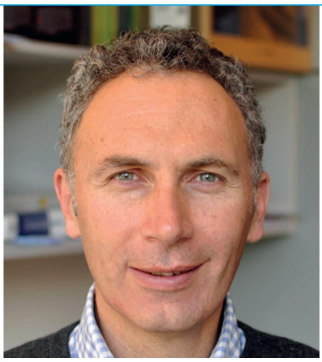
Andrea Prosperetti
Part-time Professor

Berkhoff chair holder,
joined PoF in 1998



Chao Sun
Part-time Professor

Turbulence and multiphase flow,
joined PoF in 2007



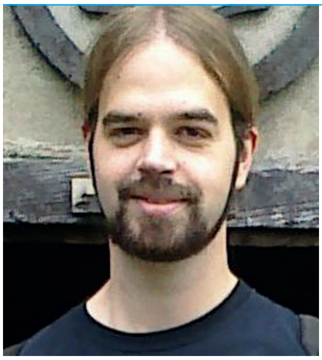
Roberto Verzicco
Part-time Professor

Direct numerical simulations of turbulence,
joined PoF in 2007

Xuehua Zhang
Part-time Professor

Surface and colloidal science and engineering,
joined PoF in 2014

Current PoF staff



Christian Diddens
Group leader

Numerical simulation of multi-component droplets,
joined PoF staff in 2017ww

Tim Segers
Group leader

Inkjet printing and microbubbles for medical applications,
joined PoF staff in 2017

Bas Benschop
Support staff

System administrator,
joined PoF staff in 2000

Martin Bos
Support staff

Technician,
joined PoF staff in 2005

Current PoF staff

Gert-Wim Bruggert
Support staff

Senior technician,
has always been there

Dennis van Gils
Support staff

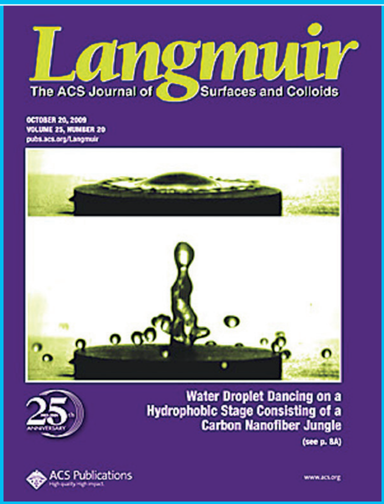
Senior research engineer,
joined PoF staff in 2015

Joanita Leferink
Support staff

Group Manager,
joined PoF staff in 2001

INTERMEZZO

Journal Covers 2009-2010



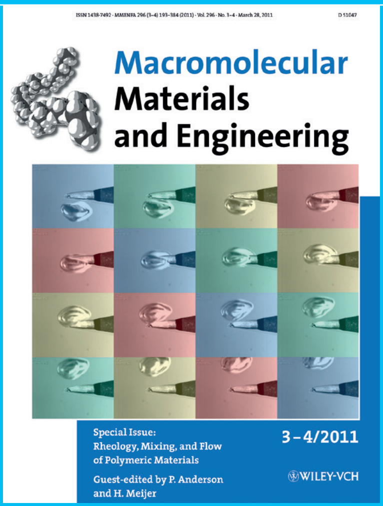
Peichun Tsai, Sergio Pacheco, Christophe Pirat, Leon Lefferts, and Detlef Lohse. Drop impact upon micro- and nanostructured super-hydrophobic surfaces, Langmuir 25, 12293-12298 (2009).

Jin-Qing Zhong, Richard Stevens, Herman Clercx, Roberto Verzicco, Detlef Lohse, and Guenter Ahlers. Prandtl-, Rayleigh-, and Rossby-number dependence of heat transport in turbulent rotating Rayleigh-Bénard convection, Phys. Rev. Lett. 102, 044502 (2009).

Stephan Gekle, Ivo Peters, Jose Gordillo, Devaraj van der Meer, and Detlef Lohse. Supersonic air flow due to solid-liquid impact, Phys. Rev. Lett. 104, 024501 (2010).

INTERMEZZO

Journal Covers 2011-2012



Thomas H. van den Berg,
Willem D. Wormgoor,
Stefan Luther, and
Detlef Lohse.
Phase-sensitive constant
temperature anemometry,
Macromol. Mater. Eng. 296,
230-237 (2011).

Peichun Tsai,
Maurice H. W. Hendrix,
Remko R. M. Dijkstra,
Lingling Shui, and
Detlef Lohse.
Microscopic structure
influencing macroscopic splash
at high Weber number, Soft
Matter 7,
11325 (2011).

Oscar R. Enriquez,
Ivo R. Peters, Stephan Gekle,
Laura E. Schmidt, Detlef Lohse,
and Devaraj van der Meer.
Collapse and pinch-off of a
non-axisymmetric impact-
created air cavity in water,
J. Fluid Mech. 701,
40-58 (2012).

Graduated
PoF PhD students
1998-2018

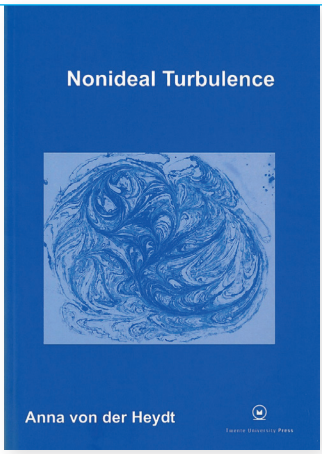
Graduated PoF PhD students

Rüdiger Tögel
thesis defense:
11 December 2002

now teacher in Marburg, and lecturer at the University of Marburg, Germany

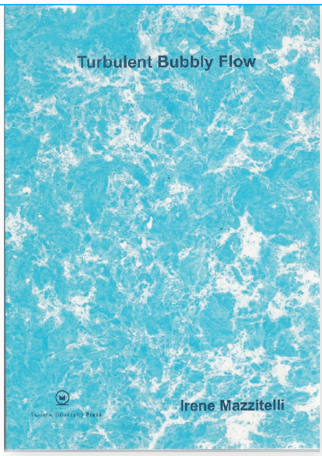
Anna von der Heydt
thesis defense:
24 March 2003

now associate professor at Utrecht University



Irene Mazzitelli
thesis defense:
25 June 2003

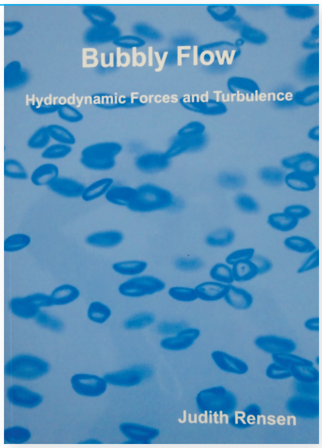
now high school teacher in Rome, Italy



Graduated PoF PhD students

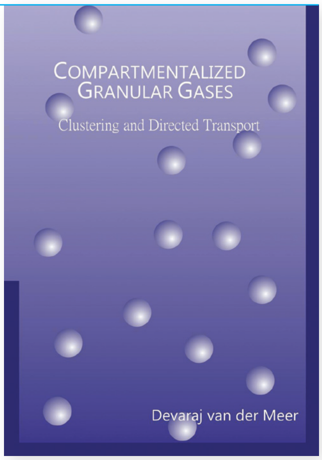
Judith Rensen
thesis defense:
26 September 2003

now design engineer at ASML, Veldhoven



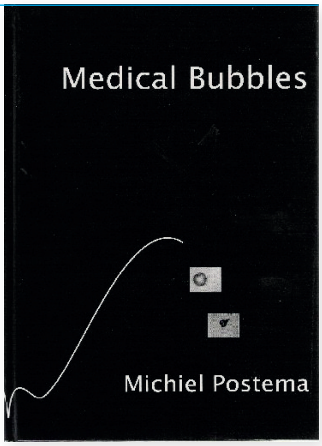
Devaraj van der Meer
thesis defense:
29 April 2004

now full professor at PoF, University of Twente



Michiel Postema
thesis defense:
17 September 2004

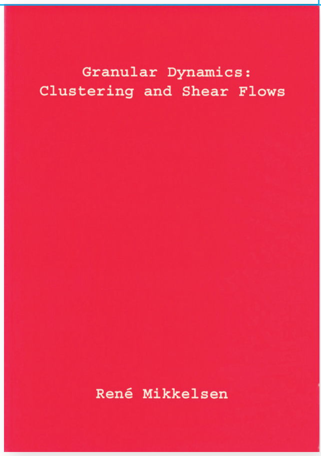
now researcher at University of Bergen (Norway) and University of the Witwatersrand (South Africa)



Graduated PoF PhD students

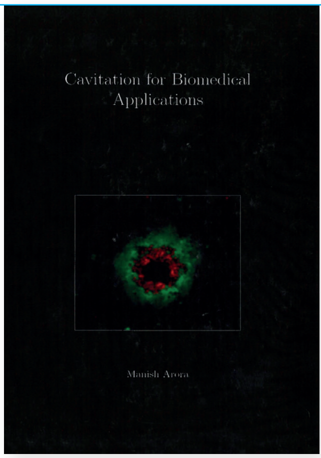
René Mikkelsen
thesis defense:
23 February 2005

now Technology director Integrated Systems at National Oilwell Varco



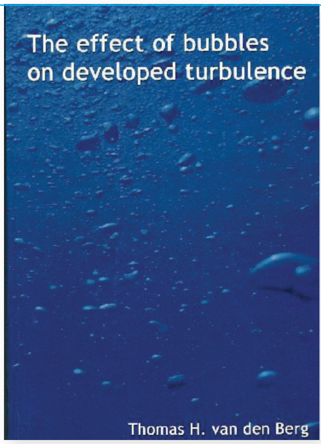
Manish Arora
thesis defense:
16 February 2006

now professor at UTSAAH Laboratory at CPDM, IISc Bangalore, India



Ramon van den Berg
thesis defense:
21 December 2006

now senior R&D engineer Thermal Conrol at NLR, Marknesse

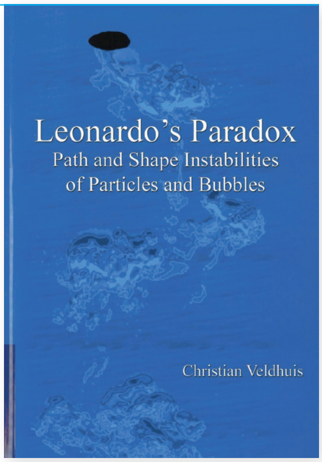


Graduated PoF PhD students

Christian H.J. Veldhuis

thesis defense:
7 February 2007

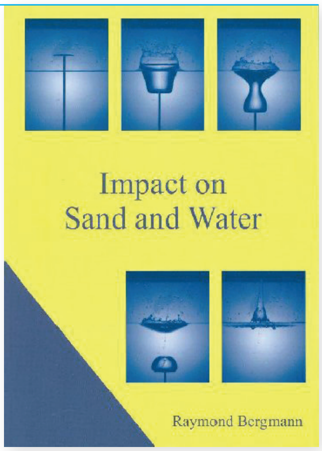
now at MARIN, Wageningen



Raymond Bergmann

thesis defense:
14 March 2007

now at Shell R&D,
Amsterdam



Jos de Jong

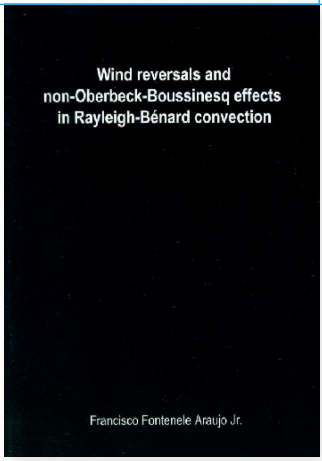
thesis defense:
25 April 2007

now at Océ R&D, Venlo

Graduated PoF PhD students

Francisco Fontenele Araujo Jr.

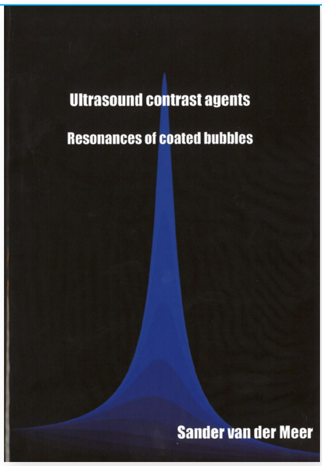
thesis defense:
7 June 2007



Sander van der Meer

thesis defense:
13 September 2007

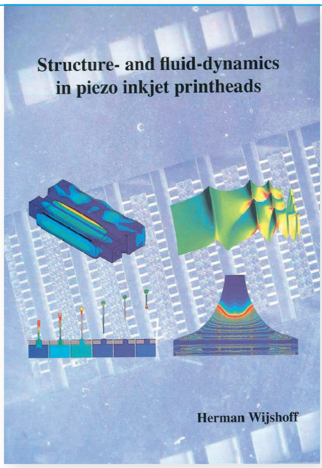
now at TNO, Delft



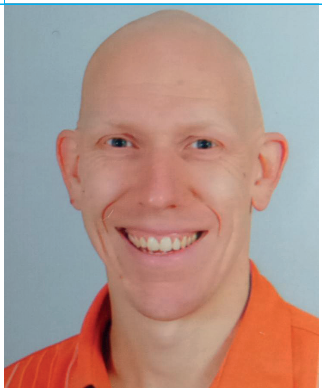
Herman Wijshoff

thesis defense:
25 January 2008

now at Océ R&D, Venlo and professor at Eindhoven University of Technology

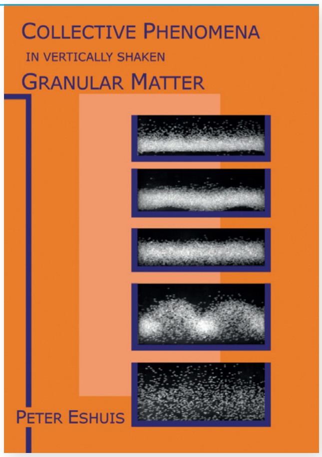


Graduated PoF PhD students



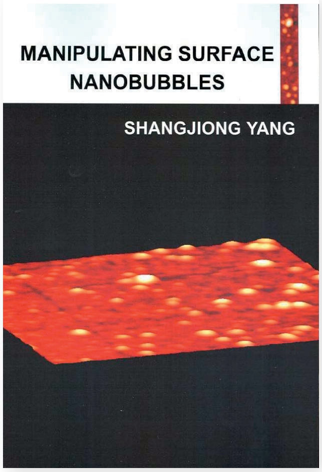
Peter Eshuis
thesis defense:
14 February 2008

now at Philips R&D,
Eindhoven



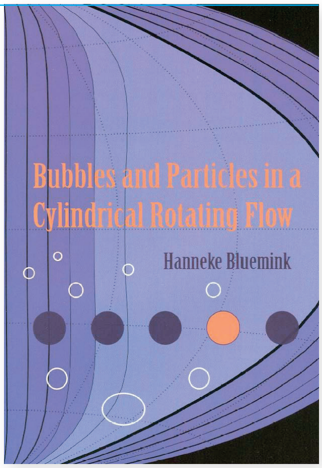
ShangJiong Yang
thesis defense:
9 October 2008

now Global product manager
at Philips Lighting,
Eindhoven



Hanneke Bluemink
thesis defense:
12 December 2008

now clinical physicist
at Catharina Ziekenhuis,
Eindhoven

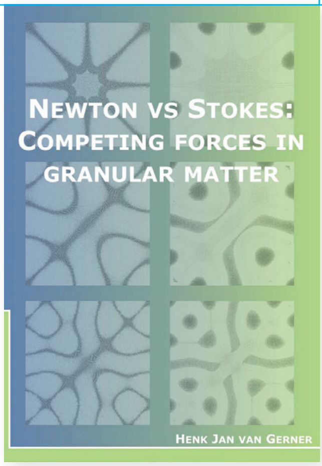


Graduated PoF PhD students

Henk Jan van Gerner

thesis defense:
17 April 2009

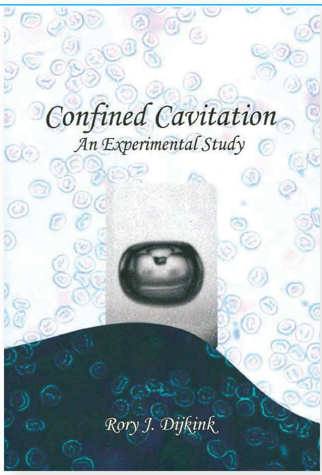
now at NLR, Marknesse



Rory Dijkink

thesis defense:
12 June 2009

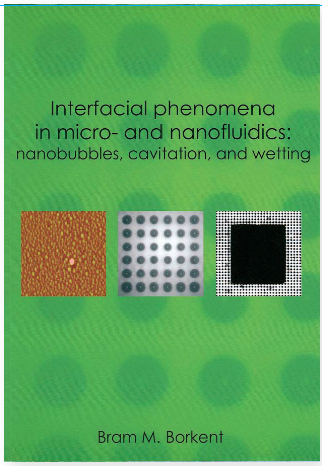
now lecturer at Saxion, Enchede



Bram Borkent

thesis defense:
2 October 2009

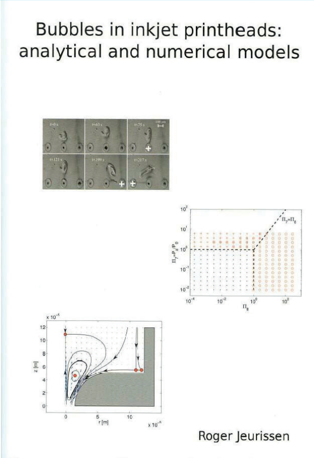
now Programme officer IPP at NWO, Utrecht



Graduated PoF PhD students

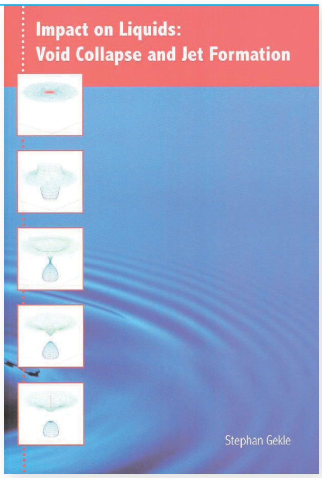
Roger Jeurissen
thesis defense:
23 October 2009

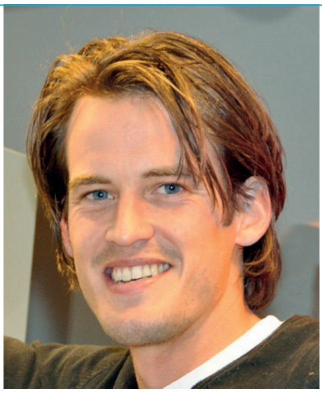
now at Eindhoven University of Technology and ACFD Consultancy



Stephan Gekle
thesis defense:
13 November 2009

now professor at University of Bayreuth, Germany





Jeroen Sijl
thesis defense:
16 December 2009

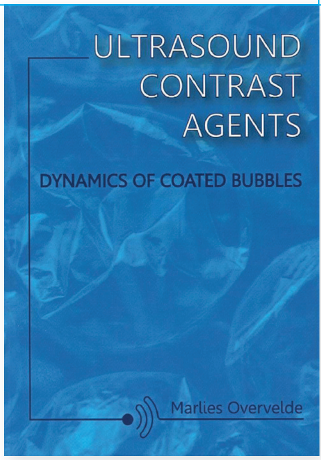
now Founder and data scientist at Smart Segments, Coffs Harbour, Australia

Graduated PoF PhD students

Marlies Overvelde

thesis defense:
9 April 2010

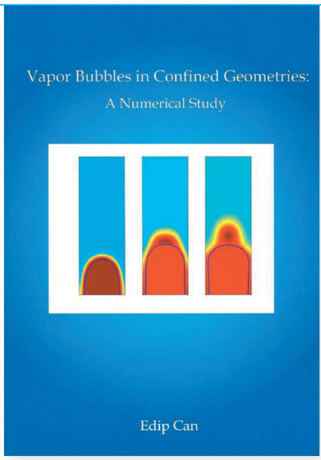
now clinical physicist at Gelderse Vallei Hospital, Ede



Edip Can

thesis defense:
12 May 2010

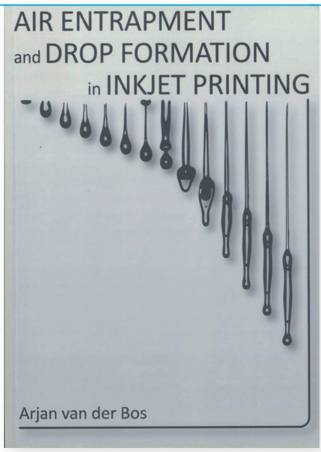
now lecturer at Saxion, Enschede



Arjan van der Bos

thesis defense:
14 January 2011

now at Océ R&D, Venlo

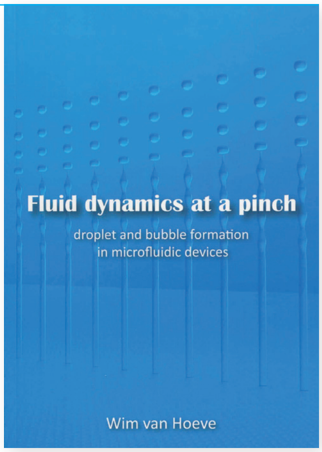


Graduated PoF PhD students

Wim van Hoeve

thesis defense:
23 March 2011

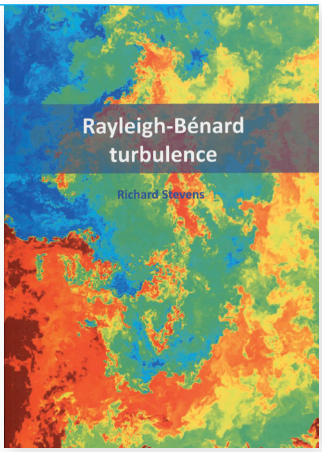
now at Tide Microfluidics, Enschede



Richard Stevens

thesis defense:
30 June 2011

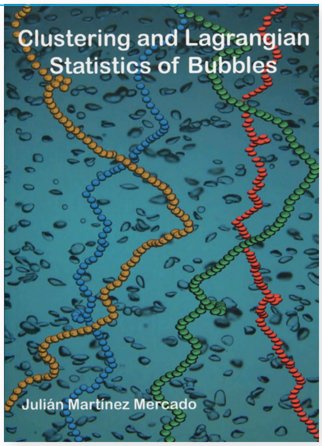
now assistant professor at PoF, University of Twente



Julián Martínez Mercado

thesis defense:
15 July 2011

now at University of Mexico City, Mexico

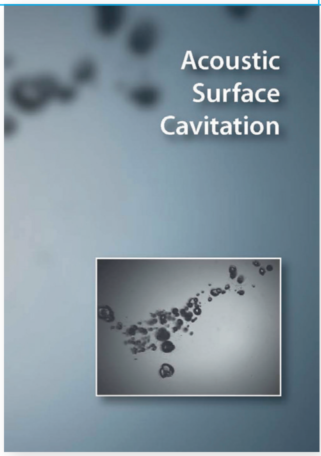


Graduated PoF PhD students

Aaldert Zijlstra

thesis defense:
2 September 2011

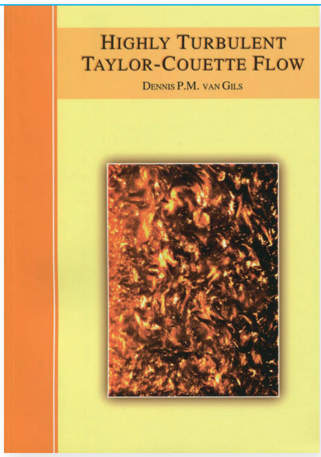
now at Philips Consumer Lifestyle, Drachten



Dennis van Gils

thesis defense:
16 December 2011

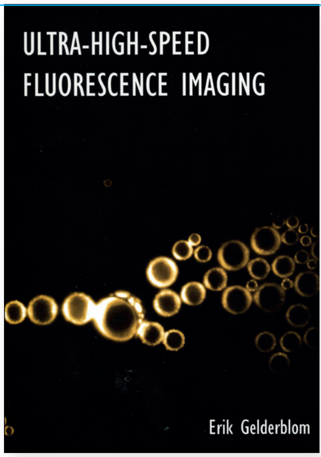
now staff member at PoF, University of Twente



Erik Gelderblom

thesis defense:
20 April 2012

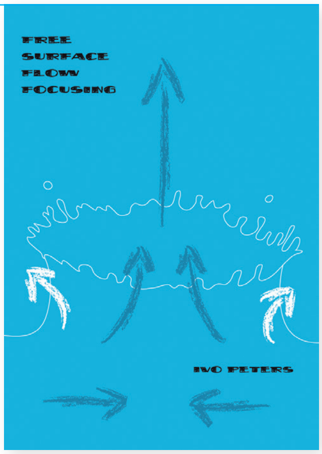
now clinical physicist at Radboud Medical Center, Nijmegen



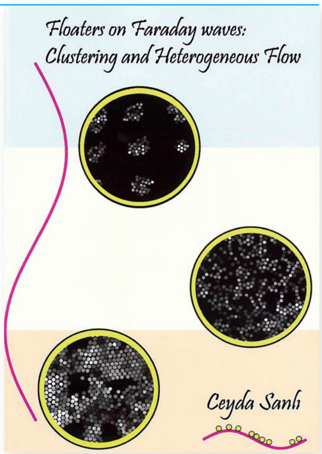
Graduated PoF PhD students

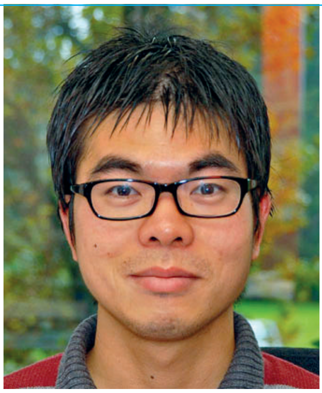
Ivo Peters
thesis defense:
29 June 2012

now assistant professor at Aerodynamics and Flight Mechanics Research Group, University of Southampton, UK



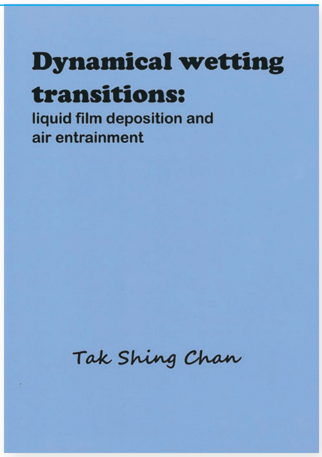
Ceyda Sanli
thesis defense:
6 July 2012





Tak Shing Chan
thesis defense:
30 August 2012

now postdoc at Department of Mathematics, University of Oslo, Norway

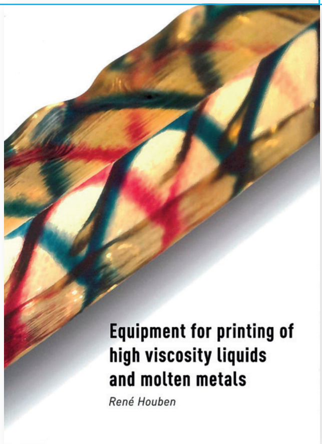


Graduated PoF PhD students

René Houben

thesis defense:
27 September 2012

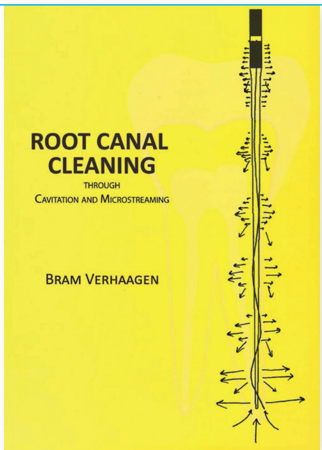
now senior scientist at TNO, Eindhoven

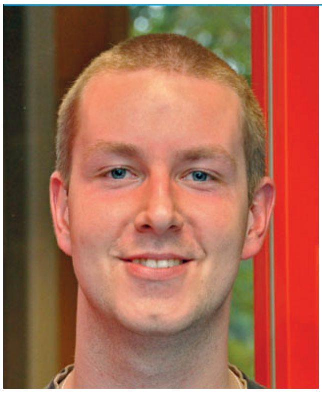


Bram Verhaagen

thesis defense:
28 September 2012

now at DEMCON, Enschede

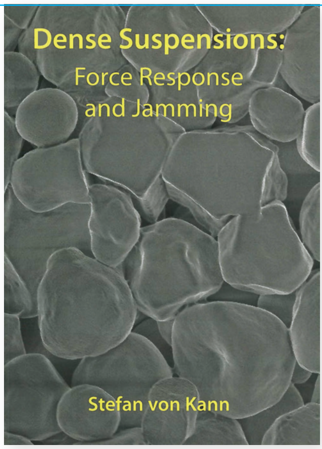




Stefan von Kann

thesis defense:
21 December 2012

now project engineer at Bronckhorst, Ruurlo

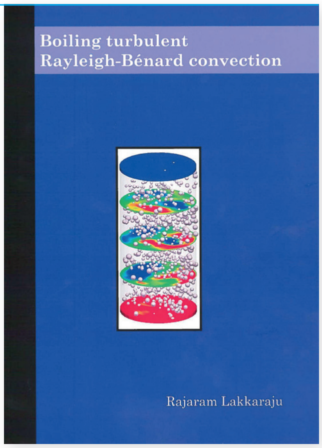


Graduated PoF PhD students

Rajaram Lakkaraju

thesis defense:
11 January 2013

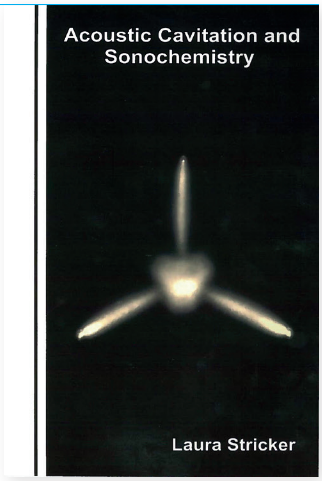
now assistant professor at Birla Institute of Technology and Science, Pilani - Goa, India



Laura Stricker

thesis defense:
16 January 2013

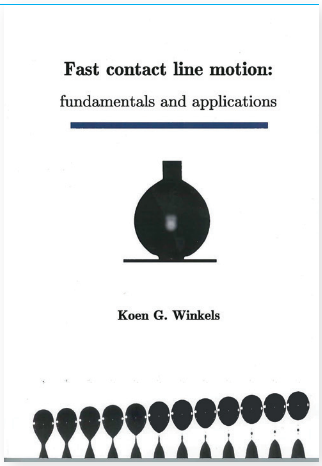
now postdoc at ETH, Zürich, Switzerland



Koen Winkels

thesis defense:
14 February 2013

now at ASML, Veldhoven

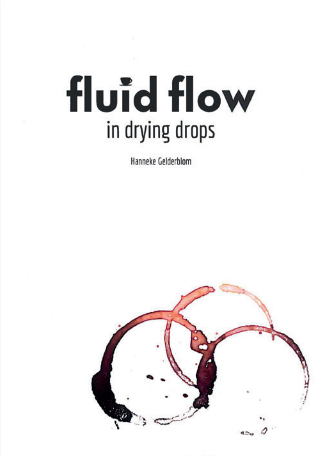


Graduated PoF PhD students

Hanneke Gelderblom

thesis defense:
10 April 2013

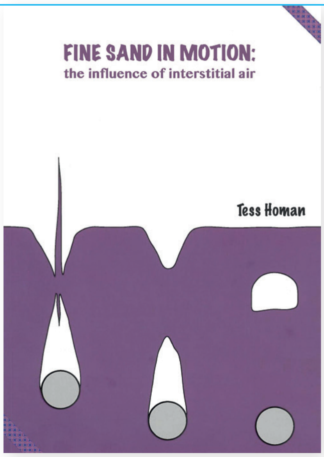
now assistant professor at Eindhoven University of Technology

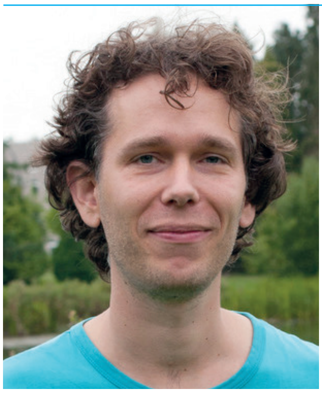


Tess Homan

thesis defense:
26 September 2013

now assistant professor at Eindhoven University of Technology

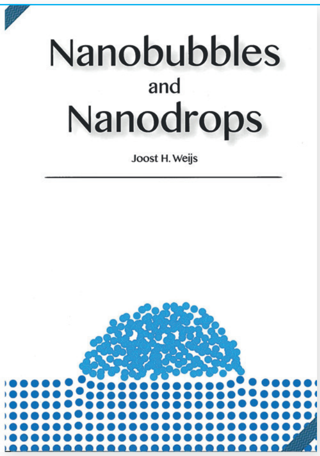




Joost Weijs

thesis defense:
26 September 2013

now software and hardware developer, private business, Eindhoven

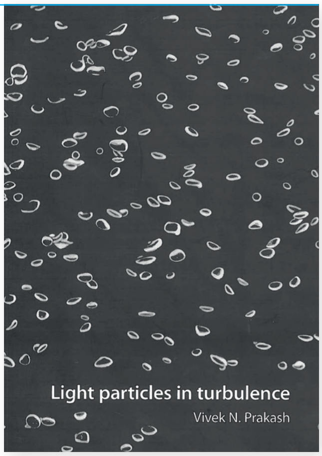


Graduated PoF PhD students

Vivek Nagendra Prakash

thesis defense:
26 September 2013

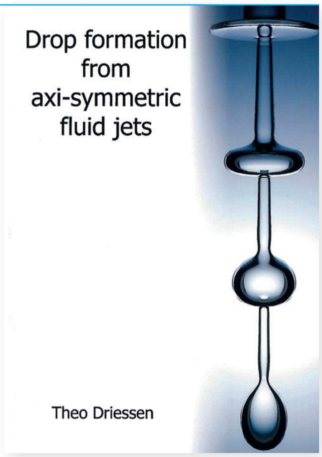
now postdoc at Department of Bioengineering, Stanford University, USA



Theo Driessen

thesis defense:
20 December 2013

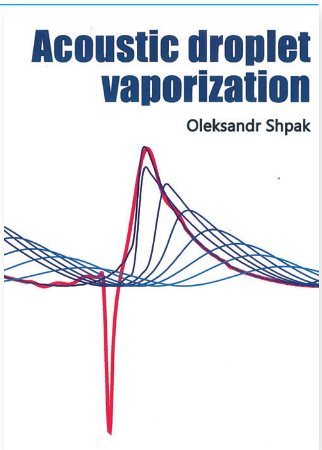
now research engineer at ASML, San Diego, USA



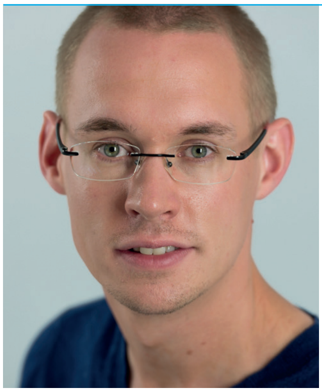
Oleksandr Shpak

thesis defense:
29 August 2014

now at ASML, Veldhovem



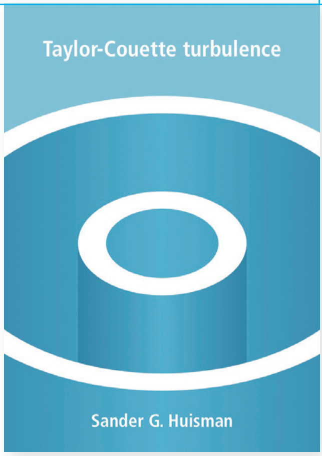
Graduated PoF PhD students



Sander Huisman

thesis defense:
19 September 2014

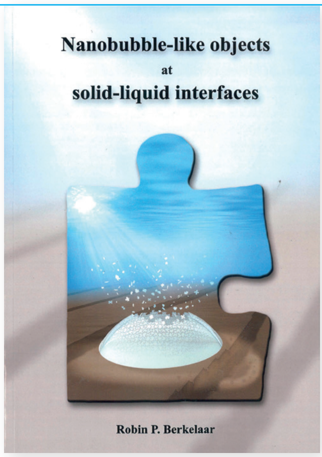
now assistant professor at PoF, University of Twente



Robin Peter Berkelaar

thesis defense:
19 September 2014

now analyst quantitative research at Rabobank, Utrecht



Claas-Willem Visser

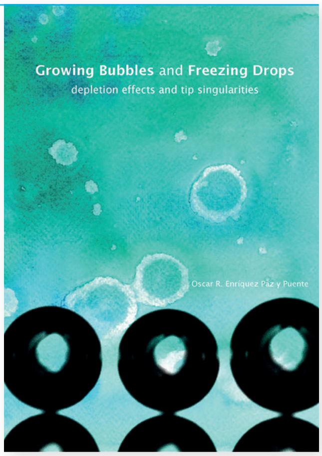
thesis defense:
19 December 2014

now assistant professor Engineering Technology at University of Twente

Graduated PoF PhD students

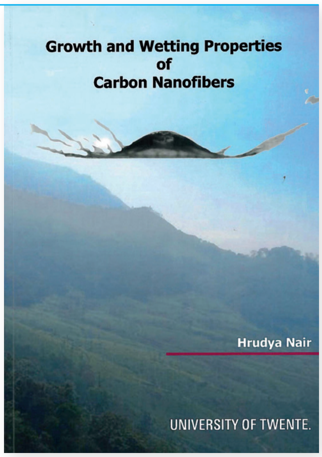
Oscar Enriquez
thesis defense:
14 January 2015

now assistant professor at Universidad Carlos III de Madrid, Spain



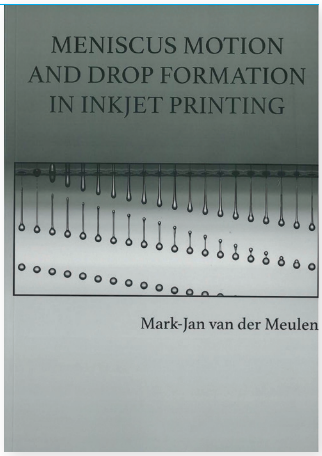
Hrudya Nair
thesis defense:
29 January 2015

now part-time faculty at North Seattle College and Intern Technical Lead at University of Washington, USA



Mark-Jan van der Meulen
thesis defense:
19 February 2015

now at NLR, Marknesse

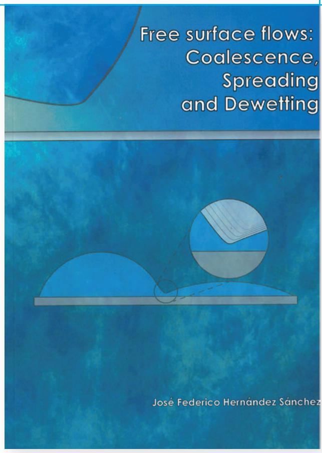


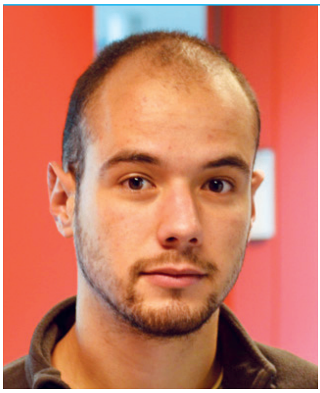
Graduated PoF PhD students

José Federico Hernández Sánchez

thesis defense:
20 February 2015

now postdoc at King Abdullah University of Science and Technology, Thuwal, Saudi Arabia





Rodolfo Ostilla Mónico

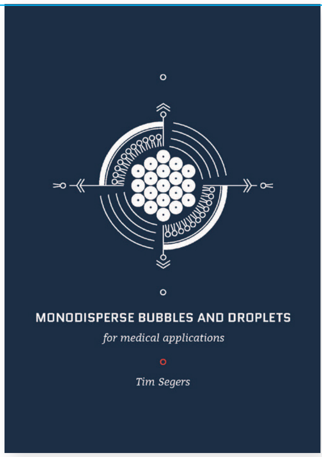
thesis defense:
20 February 2015

now assistant professor at Houston University, USA

Tim Segers

thesis defense:
29 May 2015

now group leader at PoF, University of Twente

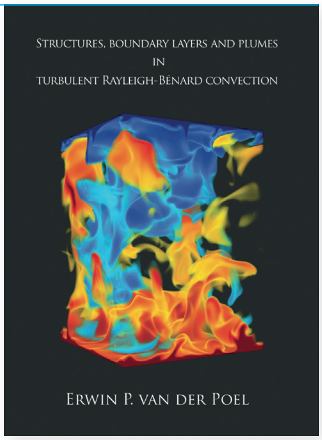


Graduated PoF PhD students

Erwin van der Poel

thesis defense:
3 July 2015

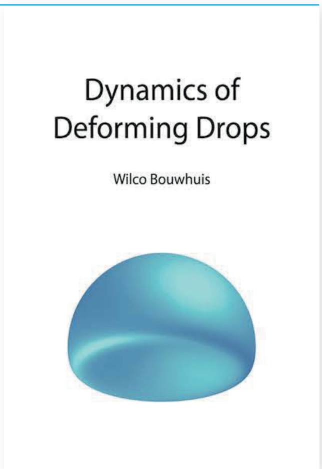
now operational analyst at Thales, Hengelo



Wilco Bouwhuis

thesis defense:
28 August 2015

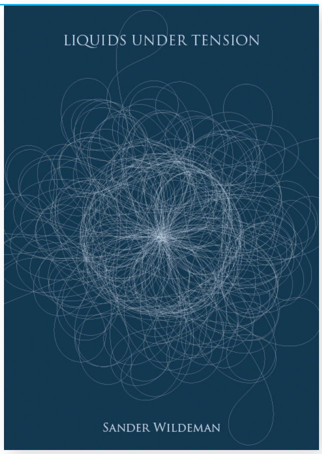
now lecturer at Saxion, Enschede



Sander Wildeman

thesis defense:
4 September 2015

now postdoc at Langevin Institute, ESPCI Paris and CNRS, France

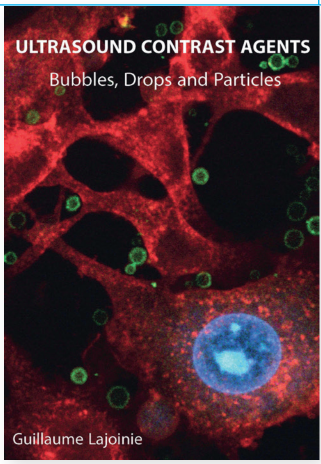


Graduated PoF PhD students

Guillaume Lajoinie

thesis defense:
24 September 2015

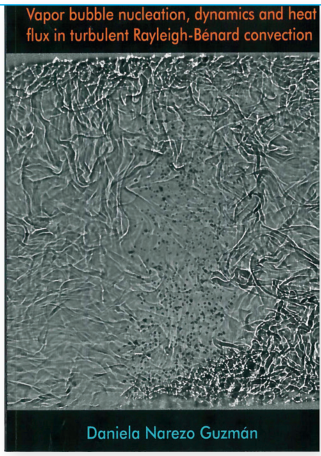
now assistant professor at
PoF, University of Twente



Daniela Narezo Guzmán

thesis defense:
18 December 2015

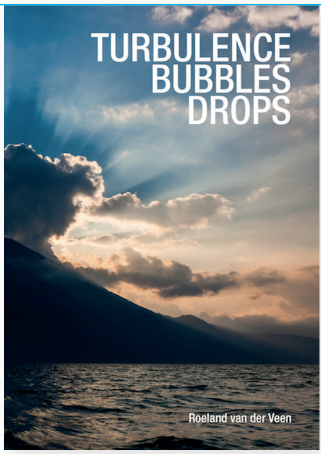
now Data scientist at
Institute of Transportation
Systems, DLR, Berlin,
Germany



Roeland van der Veen

thesis defense:
24 March 2016

now at ING Bank

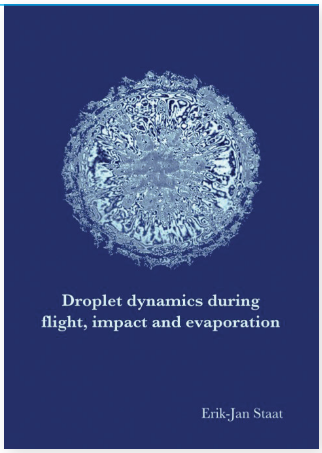


Graduated PoF PhD students

Erik-Jan Staat

thesis defense:
31 March 2016

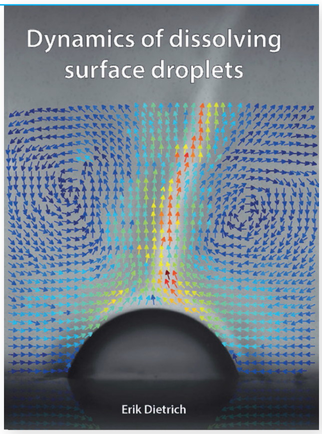
now at BDR Therma, Apeldoorn



Erik Dietrich

thesis defense:
27 May 2016

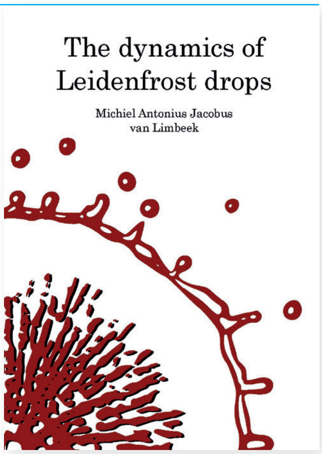
now engineer at DEMCON, Enschede



Michiel van Limbeek

thesis defense:
20 January 2017

now postdoc at EMS, University of Twente

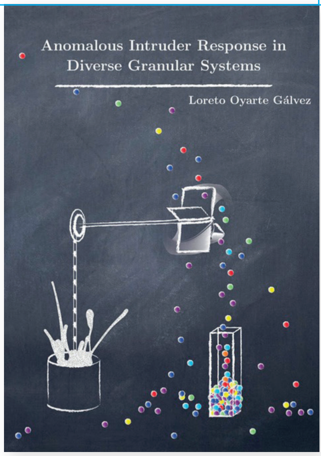


Graduated PoF PhD students

Loreto Oyarte

thesis defense:
27 January 2017

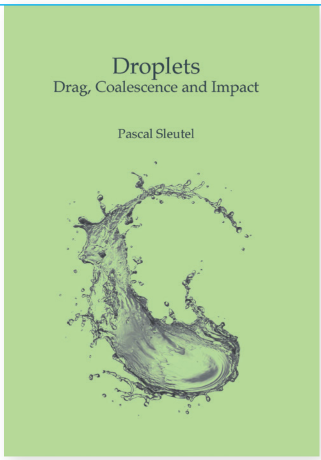
now postdoc at MCS,
University of Twente



Pascal Sleutel

thesis defense:
17 February 2017

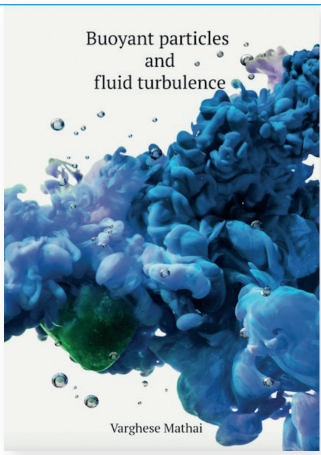
now researcher at ASML,
Veldhoven



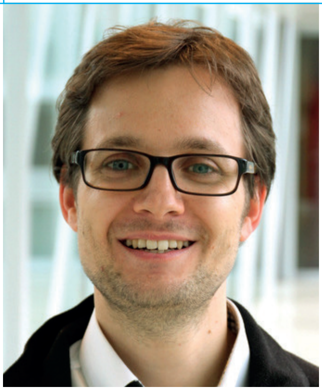
Varghese Mathai

thesis defense:
9 June 2017

now postdoc at Brown
University, Rhode Island,
USA



Graduated PoF PhD students



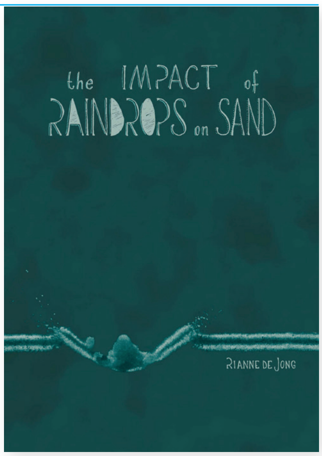
Alexander Klein

thesis defense:
23 June 017

now researcher at ASML, Veldhoven

Rianne de jong

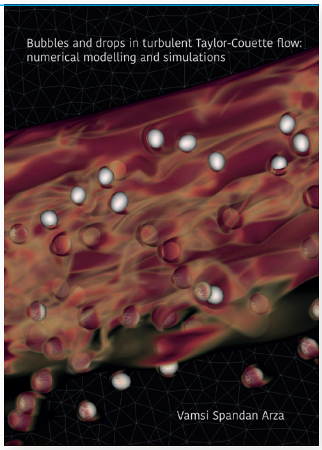
thesis defense:
7 July 2017



Vamsi Spandan

thesis defense:
14 July 2017

now postdoc at Harvard University, USA

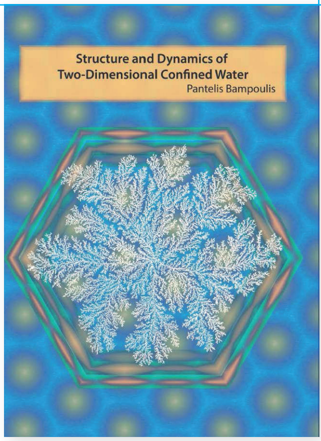


Graduated PoF PhD students

Pantelis Bampoulis

thesis defense:
1 September 2017

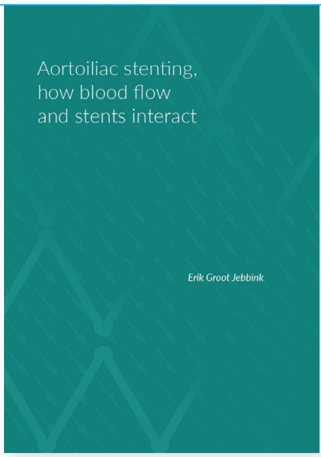
now postdoc at University of Cologne, Germany

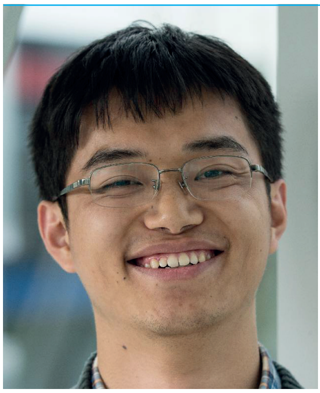


Erik Groot Jebbink

thesis defense:
1 December 2017

now postdoc at M3i, University of Twente

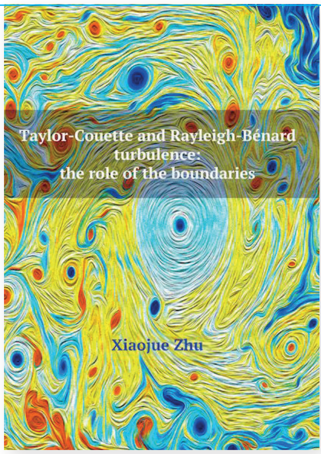




Xiaojue Zhu

thesis defense:
16 February 2018

now postdoc at Harvard University, USA

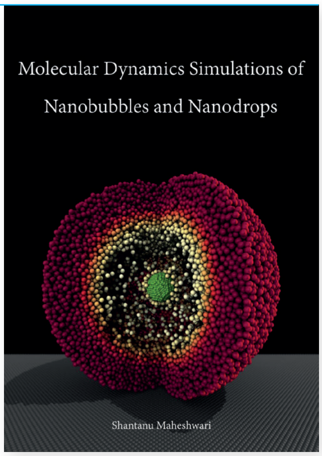


Graduated PoF PhD students

Shantanu Maheshwari

thesis defense:
23 March 2018

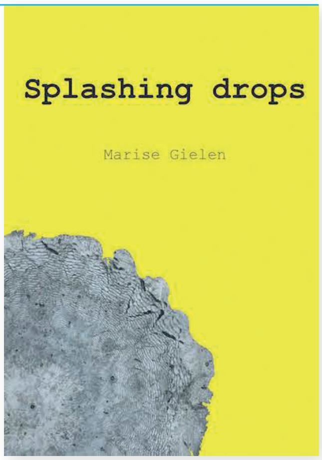
now researcher at Shell Technology Centre Bangalore, India



Marise Gielen

thesis defense:
6 April 2018

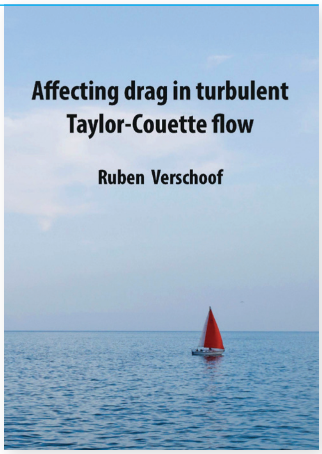
now design engineer at ASML, Veldhoven



Ruben Verschoof

thesis defense:
1 June 2018

now engineer at DEMCON, Enschede

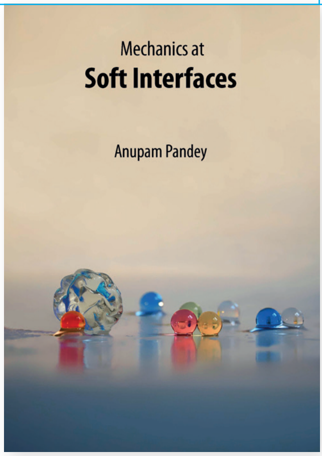


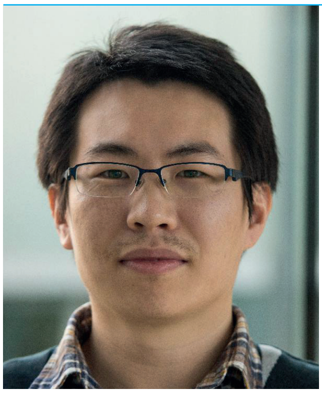
Graduated PoF PhD students

Anupam Pandey

thesis defense:
15 June 2018

now postdoc at PoF,
University of Twente

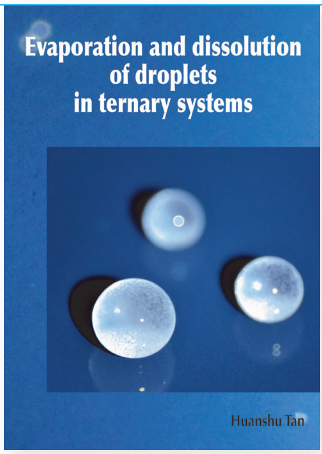




Huanshu Tan

thesis defense:
24 August 2018

now postdoc at University of
California at Santa Barbara,
USA



INTERMEZZO

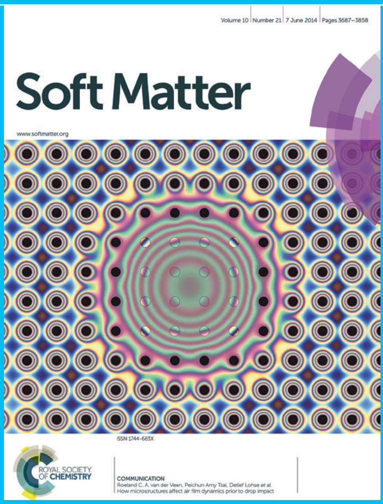
Journal Covers 2012-2014

A. Susarrey-Arce, A. G. Marin, H. Nair, L. Lefferts, J. G. E. Gardeniers, D. Lohse, and A. van Houselt. Absence of an evaporation-driven wetting transition on omniphobic surfaces, Soft Matter 8, 9765 - 9770 (2012).

Alvaro G. Marin, Wim van Hoeve, Pablo Garcia-Sanchez, Lingling Shui, Yanbo Xie, Marco A. Fontelos, Jan C. T. Eijkel, Albert van den Berg, and Detlef Lohse. The microfluidic Kelvin water dropper, Lab Chip 13, 4503-4506 (2013).

Henri Lhuissier, Detlef Lohse, and Xuehua Zhang. Spatial organization of surface nanobubbles and its implications in their formation process, Soft Matter 10, 942-946 (2014).

INTERMEZZO
Journal Covers 2014



Hrudya Nair, Hendrik J. J. Staat, Tuan Tran, Arie van Houselt, Andrea Prosperetti, Detlef Lohse, and Chao Sun. The Leidenfrost temperature increase for impacting droplets on carbon-nano-fiber surfaces, Soft Matter 10, 2102-2109 (2014).

Roeland C. A. van der Veen, Maurice H. W. Hendrix, Tuan Tran, Chao Sun, Peichun Amy Tsai, and Detlef Lohse. How microstructures affect air film dynamics prior to drop impact, Soft Matter 10, 3703-3707 (2014).

Priyanka Shukla, Istafaul Ansari, Devaraj van der Meer, Detlef Lohse, and Meheboob Alam. Nonlinear instability and convection in a vertically vibrated granular bed, J. Fluid Mech. 761, 123-167 (2014).

Postdocs and young visiting scientists of PoF 1998-2018

Postdocs and young visiting scientists of PoF 1998-2018

Federico Toschi

start date 1 May 1999
end date 1 January 2001

now full professor Mesoscopic Transport Phenomena at Eindhoven University of Technology

Claus-Dieter Ohl

start date 1 July 1999
end date 15 October 2009

now full professor at Otto-von-Guericke Universität Magdeburg, Germany

Stefan Luther

start date 1 February 2001 end date 1 October 2004

now full professor at MPI for Dynamics and Self-Organzation Göttingen, Germany

Kengo Ichiki

start date 1 May 2001
end date 1 May 2002

now chief engineer at Zenkei Corporation, Japan

Postdocs and young visiting scientists of PoF 1998-2018

Marie-Caroline Jullien

start date 1 October 2001
end date 1 October 2002

now CNRS researcher at ESPCI, Paris, France

Philippe Marmottant

start date 1 October 2001
end date 1 October 2004

now CNRS researcher at Université Joseph Fourier, Grenoble, France

Adrian Staicu

start date 15 December 2002
end date 14 June 2005

now at Carl Zeiss, Germany

Nicolas Bremond

start date 15 November 2003
end date 15 November 2005

now professor at Laboratoire Colloïdes et Matériaux Divisés -ESPCI, Paris, France

Postdocs and young visiting scientists of PoF 1998-2018

Stephan Dammer
start date 1 October 2004
end date 1 October 2006

now at Commodity risk controlling, RWE Power AG, Essen, Germany

Kazu Sugiyama
start date 1 April 2005
end date 1 October 2007

now full professor at Osaka University, Japan

Enrico Calzavarini
start date 1 April 2005
end date 1 February 2008

now professor at École Polytechnique Universitaire de Lille, France

Christophe Pirat
start date 15 September 2005
end date 1 November 2007

now professor at University of Lyon1, LPMCN, France

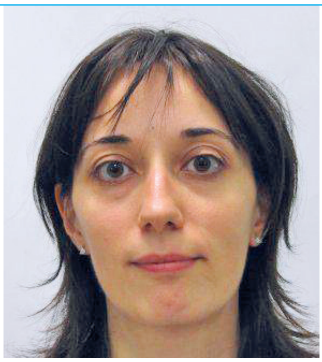
Postdocs and young visiting scientists of PoF 1998-2018

Benjamin Dollet
start date 1 October 2005
end date 31 October 2007

now CNRS researcher at University of Grenoble, France

Mauro Sbragaglia
start date 15 October 2005
end date 1 January 2008

now associate professor at University Tor Vergata, Rome, Italy



Aurore Naso
start date 15 November 2005
end date 1 November 2007

now CNRS researcher at Laboratoire de Physique, ENS Lyon, France

Gabriel Cabellero Robledo
start date 1 March 2006
end date 1 March 2008

now professor at CIMAV-Monterrey, Mexico

Postdocs and young visiting scientists of PoF 1998-2018

Paolo Oresta
start date 1 March 2007
end date 30 June 2007

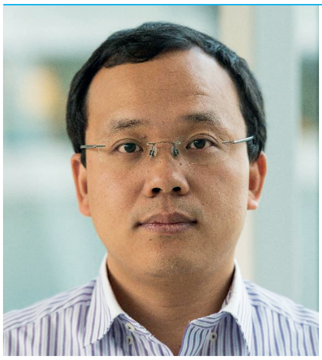
now professor at University of Bari, Italy

Valeria Garbin
start date 1 July 2007
end date 15 June 2009

now associate professor at Imperial College, London, UK

Peichun Amy Tsai
start date 20 September 2007
end date 20 September 2010

now associate professor at University of Alberta, Edmonton, Canada



Chao Sun
start date 1 October 2007
end date 1 January 2009

now full professor at Tsinghua University, Beijing, China
and part-time professor at PoF, University of Twente

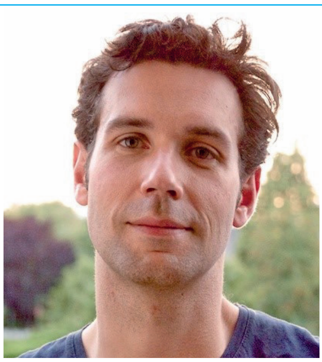
Postdocs and young visiting scientists of PoF 1998-2018

Daniel Chehata Gómez
start date 1 October 2007
end date 1 October 2009

now research scientist at Chihuahua Institute of Technology, Mexico

Todd Hay
start date 1 July 2008
end date 1 July 2009

now at Applied Research Laboratories,
The University of Texas at Austin, USA



Alvaro Marin
start date 1 September 2008
end date 1 October 2011

now assistant professor at PoF, University of Twente

Sylvain Joubaud
start date 1 September 2008
end date 22 January 2010

now CNRS researcher at ENS Lyon, France

Postdocs and young visiting scientists of PoF 1998-2018

Laura Elizabeth Schmidt
start date 1 October 2008
end date 30 September 2010

now editorial manager at Elsevier, Amsterdam

James Seddon
start date 1 January 2009
end date 30 June 2011

Siddartha Das
start day 15 October 2009
end date 15 October 2011

now assistant professor at University of Maryland, USA

Kristján Guðmundsson
start date 1 January 2010
end date 31 December 2011

now director at eTActica, Iceland

Postdocs and young visiting scientists of PoF 1998-2018

Yoshi Tagawa
start date 1 April 2010
end date 31 December 2012

now assistant professor at Tokyo University of Agriculture and Technology, Japan

Tuan Tran
start date 15 October 2010
end date 31 July 2013

now assistant professor at Nanyang Technological University, Singapore

Christos Boutsioukis
start date 1 May 2011
end date 30 April 2013

now assistant professor at Academic Centre for Dentistry Amsterdam

Henri Lhuissier
start date 1 September 2011
end date 31 August 2013

now researcher at CNRS Marseille (Guazzelli-Pouliquen Institute), France

Postdocs and young visiting scientists of PoF 1998-2018

Antonin Eddi
start date 1 October 2011
end date 30 September 2013

now researcher at PMMH laboratory - CNRS and ESPCI Paris Tech, France

François Boyer
start date 1 January 2012
end date 31 December 2012

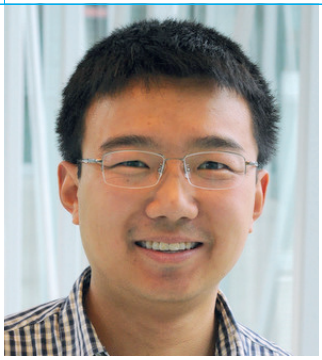
Impact of suspension droplets

Xuehua Zhang
start date 15 July 2012
end date 15 December 2012

now full professor at University of Alberta, Edmonton, Canada, and part-time professor at PoF, University of Twente

Peter van Dijk
start date 1 January 2013
end date 31 December 2014

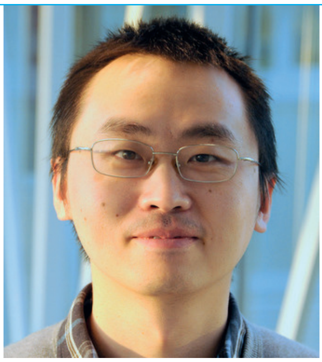
Postdocs and young visiting scientists of PoF 1998-2018



Yantao Yang

start date 31 May 2013
end date 30 April 2017

now assistant professor at University of Beijing, China



SongChuan Zhao

start date 15 July 2013
end date 14 July 2016

now assistant professor at Xi'an Jiantong University, China

Marie-Jean Thoraval

start date 15 September 2013
end date 31 August 2015

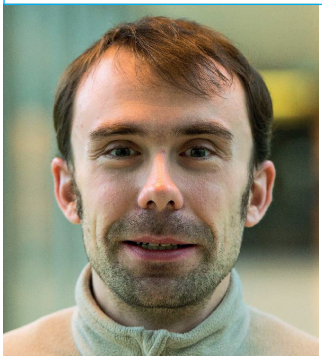
now assistant professor at Xi'an Jiaotong University, China

Minori Shirota

start date 15 October 2013
end date 31 January 2016

now assistant professor at Hirosaki University, Japan

Postdocs and young visiting scientists of PoF 1998-2018



Stefan Karpitschka
start date 1 January 2014
end date 29 February 2016

now group leader at MPI for Dynamics and Self-Organzation, Göttingen, Germany

Xiumei Liu
start date 1 March 2014
end date 28 February 2015

now assistant professor at University of Mining and Technology, Jiangsu, China

Vitaly Svetovoy
start date 1 October 2014
end date 30 September 2016

now at Faculty of Mathematics and Natural Sciences, University of Groningen

Riëlle de Ruiter
start date 1 January 2015;
end date 31 December 2016

now at ASML, Veldhoven

Postdocs and young visiting scientists of PoF 1998-2018

Adeline Pons

start date 1 January 2015
end date 30 September 2018

now at Saint-Gobain research center, Cavaillon, France

Elise Alméras

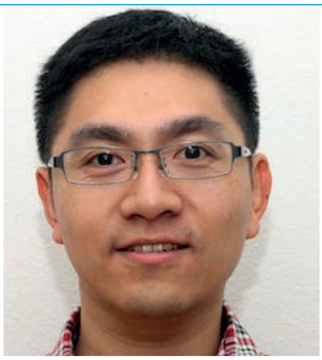
start date 1 February 2015
end date 14 December 2016

now assistant professor at University of Toulouse LGC, France

Jun Luo

start date 9 March 2015
end date 29 February 2016

now associate professor at Northwestern Polytechnical University, Xi'an, China



Pengyu Lyu

start date 1 September 2015
end date 31 August 2017

now researcher at College of Engineering, Beijing University, China

Postdocs and young visiting scientists of PoF 1998-2018

Maike Baltussen

start date 1 November 2015
end date 31 October 2016

now assistant professor at Multiphase reactor group, Eindhoven University of Technology

Yuliang Wang

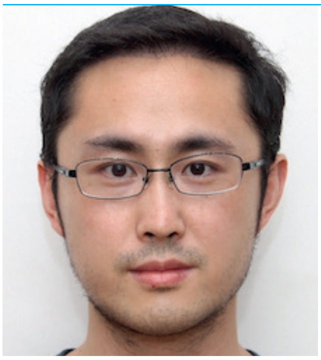
guest scientist

Robotics Institute, School of Mechanical Engineering and Automation, Beihang University, China

Maxime Costalonga

start date 1 February 2016
end date 31 March 2018

now postdoc at MIT, Cambridge, USA



Mengqi Zhang

start date 1 September 2016
end date 31 January 2018

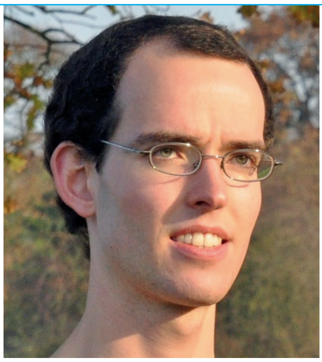
now assistant professor at National University, Singapore

Postdocs and young visiting scientists of PoF 1998-2018

Kirsten Harth

start date 1 November 2016

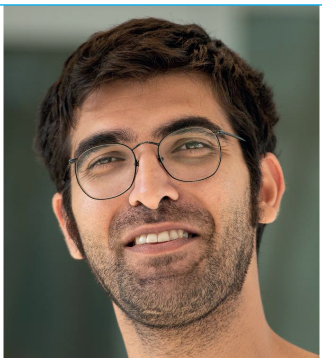
Drop impact on hot, cold, and slippery surfaces



Borge ten Hagen

start date 1 December 2016
end date 31 August 2018

now teacher at Gymnasium Hamm, Germany



Maziyar Jalaal

start date 1 January 2017

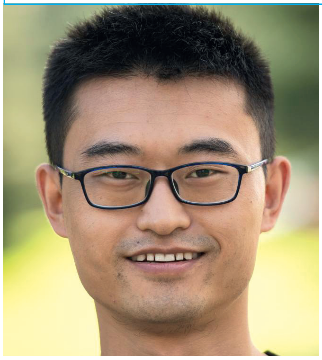
Droplet impact of non-Newtonian Fluids and active matter

Corentin Tregouet

start date 15 January 2017

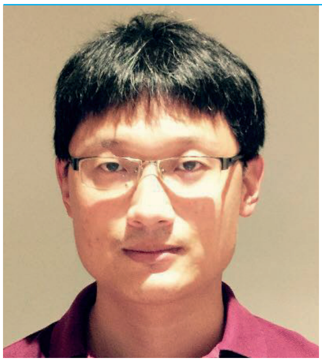
Phase separation inside microfluidic droplets

Postdocs and young visiting scientists of PoF 1998-2018



Yanshen Li
start date 1 September 2017

Bouncing Ouzo Droplets



Jiaming Zhang
start date 1 September 2017

Droplets, bubbles and 3D-printing

Anaïs Gauthier
start date 1 October 2017

Sliding drops and particles: self-propulsion and capillary interactions

Chong Shen Ng
start date 1 October 2017

Turbulent dispersed multiphase flows

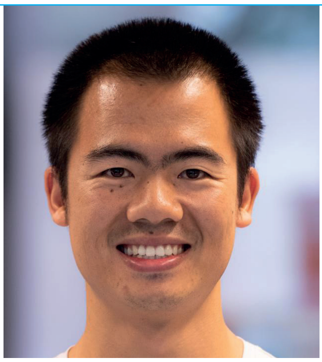
Postdocs and young visiting scientists of PoF 1998-2018

Pallav Kant
start date 1 December 2017

Contact line dynamics and droplet solidification

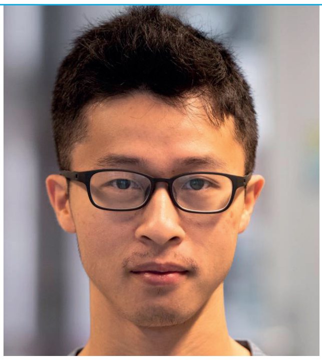
Walter Tewes
start date 1 March 2018

Modelling of liquid droplets on lubricated substrates



Shuai Li
start date 1 April 2018

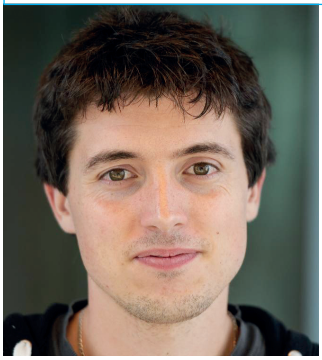
Airgun-bubble dynamics in seabed geophysical exploration



Steven Chong
start date 1 May 2018

Droplet Diffusion Dynamics with multi-component

Postdocs and young visiting scientists of PoF 1998-2018



Mathieu Souzy
start date 15 May 2018

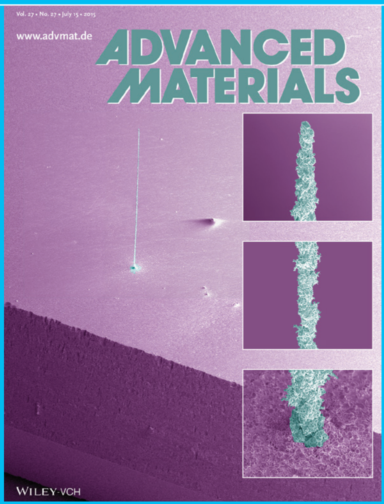
Clogging in constricted suspensions

Luoqin Liu
start date 1 June 2018

Numerical simulation and analytical modeling of wind-farms

INTERMEZZO
Journal Covers 2014-2015

Rajaram Lakkaraju, Federico Toschi, and Detlef Lohse. Bubbling reduces intermittency in turbulent thermal convection, J. Fluid Mech. 745, 1-24 (2014).

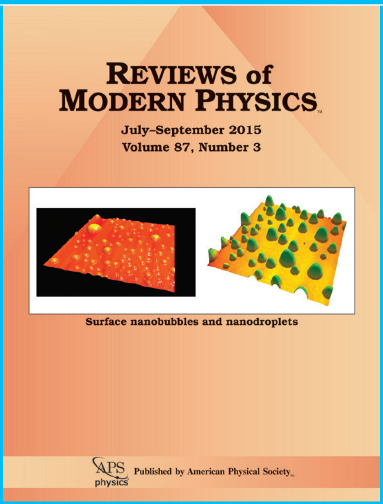


Claas Willem Visser, Ralph Pohl, Chao Sun, Bert Huis int Veld, Gert-willem Römer, and Detlef Lohse. Towards 3D Printing of Pure Metals by Laser-Induced Forward Transfer, Adv. Materials 27, 4087-4092 (2015).

Hendrik J. J. Staat, Tuan Tran, Bart Geerdink, Guillaume Riboux, Chao Sun, Jose Manuel Gordillo, and Detlef Lohse. Phase diagram for droplet impact on superheated surfaces, J. Fluid Mech. Rapids 779, R3 (2015) [12 pages].

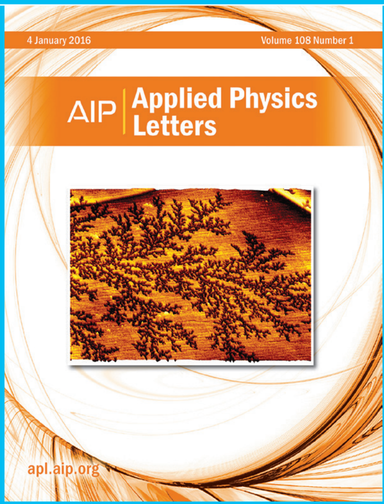
INTERMEZZO

Journal Covers 2015-2016



Detlef Lohse and
Xuehua Zhang.
Surface nanobubbles
and nanodroplets,
Rev. Mod. Phys. 87, 981-1035
(2015).

Xuehua Zhang, Jun Wang,
Lei Bao, Erik Dietrich,
Roeland C. A. van der Veen,
Shuhua Peng, James Friend,
Harold J. W. Zandvliet,
Leslie Yeo, and Detlef Lohse.
Mixed mode of dissolving
immersed nanodroplets
at a solid-water interface,
Soft Matter 11, 1889-1900
(2015).



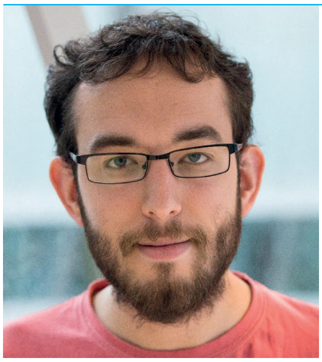
Pantelis Bampoulis,
Detlef Lohse, H. J. W. Zandvliet,
and B. Poelsema.
Coarsening dynamics of ice
crystals intercalated between
graphene and supporting mica,
Appl. Phys. Lett. 108, 011601
(2016) [4 pages].

Present
PoF PhD students

Present PoF PhD students

Arjan Fraters
start date 1 April 2014

Droplet Formation and Bubble Entrapment
in Piezo-Acoustic Inkjet Printing

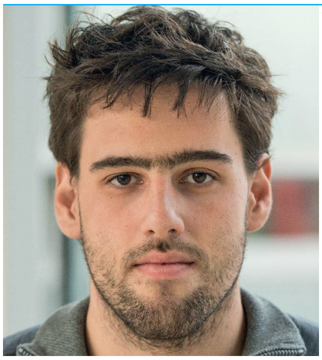


Mathijs van Gorcum
start date 1 September 2014

Dynamics of wetting on soft surfaces

Biljana Gvozdić
start date 1 September 2014

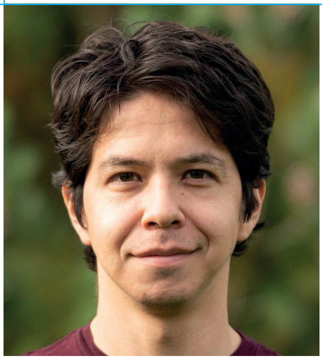
Heat transport in bubbly flows



Ivan Dević
start date 1 November 2014

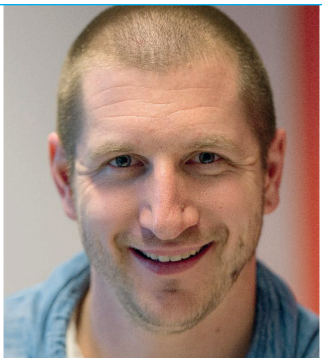
Nanodroplet and nanobubble wetting

Present PoF PhD students



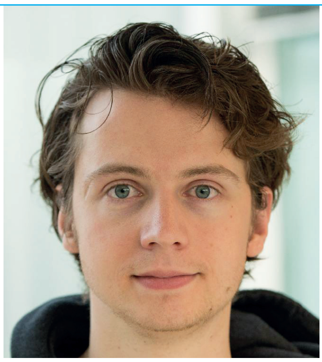
Rodrigo Ezeta
start date 15 November 2014

Boiling Taylor-Couette turbulence



Dennis Bakhuis
start date 1 February 2015

Particles, droplets, and bubbles in Taylor-Couette turbulence



Sten Reijers
start date 1 March 2015

Laser impact on droplets

Álvaro Moreno Soto
start date 1 April 2015

Diffusive bubble growth on surfaces

Present PoF PhD students

Thijs Verkaaik
start date 1 May 2015

Solar steam nanobubbles

Liz Mensink
start date 1 August 2015

Molecular Dynamics on Soft Wetting

Mikhail Zaytsev
start date 1 January 2016

Plasmonic bubbles

José Manuel Encarnación Escobar
start date 1 March 2016

Surface nano and micro droplets

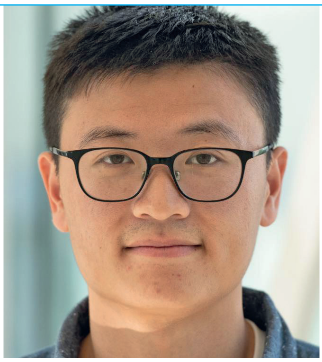
Present PoF PhD students

Pim Bullee
start date 1 June 2016

Superhydrophobic surfaces in turbulent Taylor-Couette flow

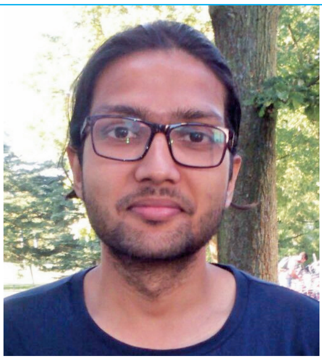
Alexander Blass
start date 1 July 2016

Sheared convection and large scale structures
in Rayleigh-Bénard Turbulence



Yaxing Li
start date 1 August 2016

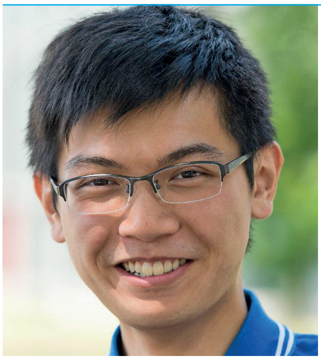
Evaporation of multi-component sessile droplets



Nakul Pande
start date 1 August 2016

Bubble growth on electrodes

Present PoF PhD students

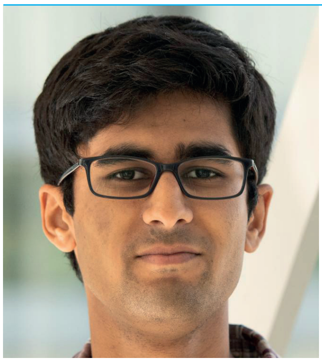


On-Yu Dung
start date 1 August 2016

Heat and Mass transfer in bubbly flow with turbulence

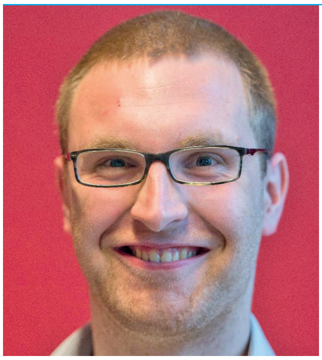
Robin Koldeweij
start date 10 August 2016

Droplets, impact, solidification and Marangoni effects



Utkarsh Jain
start date 15 August 2016

Air cushioning in water impact



Martin Klein Schaarsberg
start date 1 September 2016

Laser-induced forward transfer of complex fluids

Present PoF PhD students

Stefan Engelhard
start date 15 January 2017

Ultrasound Particle Image Velocimetry
in the Abdominal Aorta

Myrthe Bruning
start date 15 January 2017

Assembling nanoparticles via evaporation-driven techniques

Pieter Berghout
start date 15 February 2017

Roughness and spirals in Taylor-Couette flow

Jelle Will
start date 1 April 2017

Particles in Turbulence

Present PoF PhD students

Simon Overeem
start date 1 April 2017 2017

Parallel stenting in the endovascular treatment of juxtarenal aneurysms

Srinidhi Nagarada Gadde
start date 15 May 2017

Effect of atmospheric stability on wind farm performance

Jessica Strickland
start date 1 September 2017

Analytical modelling and Large Eddy Simulation of large-scale wind farms

Martin Assen
start date 1 September 2017

Numerical simulation of bubbles, drops and particles in turbulence

Present PoF PhD students

Ricardo Arturo López de la Cruz
start date 15 September 2017

Droplet nucleation in multicomponent fluids

Carola Seyfert
start date 1 October 2017

Evaporation-driven particle assembly for ultra-sensitive detection methods

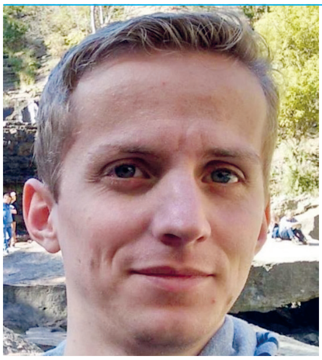
Srinath Lakshman
start date 1 October 2017

Droplet impact studies over thin slippery films

Diana García González
start date 15 October 2017

Capillary forces in microstructured soft materials

Present PoF PhD students



Michiel Hack
start date 1 November 2017

Ink drop behaviour on substrates

Xiaolai Li
start date Fall 2017

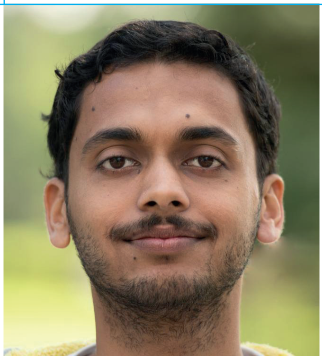
Maaike Rump
start date 1 March 2018

Droplet formation of liquids mixtures

Vatsal Sanjay
start date 1 July 2018

Numerical simulations using Molecular Dynamics and Volume of Fluid

Present PoF PhD students



Lijun Thayyil Raju

start date 1 September 2018

Diffusive Droplet Dynamics in multi-component fluid systems

Yogesh Jethani

start date 1 September 2018

Microbubbles nucleation in a jetting inkjet nozzle

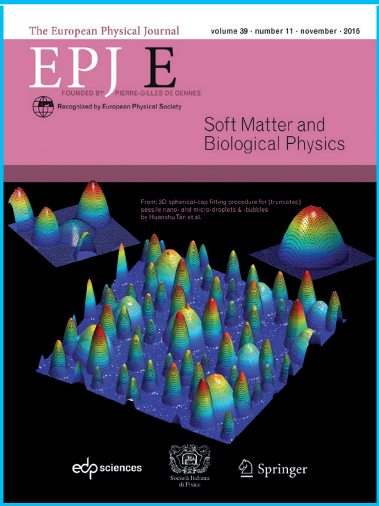
Anja Stieren

start date 1 October 2018

Interaction between large scale wind farms

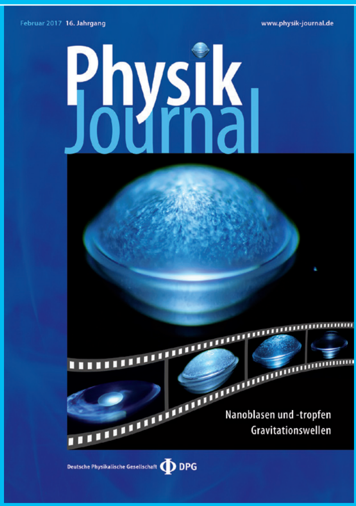
INTERMEZZO

Journal Covers 2016-2017



Huanshu Tan, Shuhua Peng, Chao Sun, Xuehua Zhang, and Detlef Lohse. 3D spherical-cap fitting procedure for (truncated) sessile nano- and micro-droplets & -bubbles, Eur. Phys. J. E 39, 106 (2016) [10 pages].

Yantao Yang, Roberto Verzicco, and Detlef Lohse. Vertically bounded double diffusive convection in the finger regime: comparing no-slip vs free-slip boundary conditions, Phys. Rev. Lett. 117, 184501 (2016) [5 pages].



Detlef Lohse. Beständige Bläschen, Physik Journal 16, Nr. 2, 29-34 (2017).

INTERMEZZO

Journal Covers 2017

Huanshu Tan, Christian Diddens, Michel Versluis, Hans-Jürgen Butt, Detlef Lohse, and Xuehua Zhang. Self-wrapping of an Ouzo drop induced by evaporation on a superamphiphobic surface, Soft Matter 13, 2749-2759 (2017).

Yuliang Wang, Xiaolai Li, Shuai Ren, Hadush Tedros Alem, Lijun Yang, and Detlef Lohse. Entrapment of interfacial nanobubbles on nano-structured surfaces, Soft Matter 13, 5381-5388 (2017).

Chenglong Xu, Haitao Yu, Shuhua Peng, Ziyang Lu, Lei Lei, Detlef Lohse, and Xuehua Zhang. Collective interactions in the nucleation and growth of surface droplets, Soft Matter 13, 937-944 (2017).

INTERMEZZO

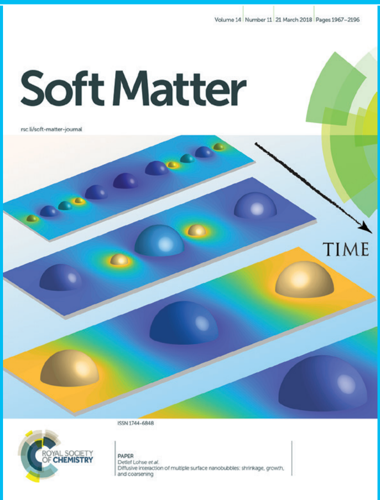
Journal Covers 2018

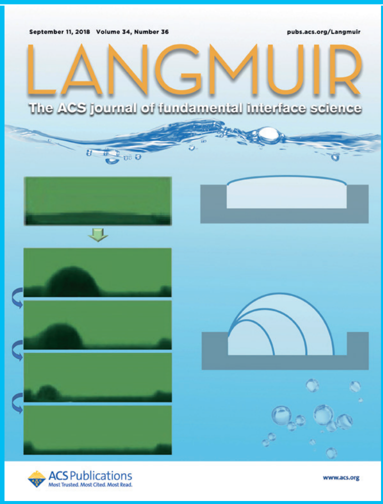
Xiaojue Zhu, Varghese Mathai, Richard Stevens, Roberto Verzicco, and Detlef Lohse. Transition to the ultimate regime in two-dimensional Rayleigh-Bénard convection, Phys. Rev. Lett. 120, 144502 (2018) [6 pages].

Brendan Dyett, Akihito Kiyama, Maaike Rump, Yoshiyuki Tagawa, Detlef Lohse, and Xuehua Zhang. Growth dynamics of surface nanodroplets during solvent exchange at varying flow rates, Soft Matter 14, 5197-5204 (2018).

INTERMEZZO

Journal Covers 2018



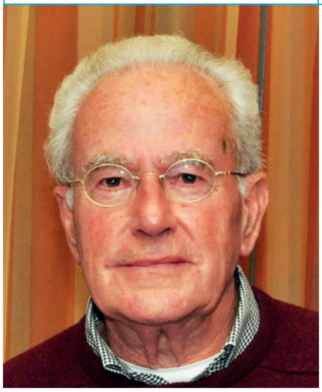


Xiaojue Zhu, Roberto Verzicco, Xuehua Zhang, and Detlef Lohse. Diffusive interaction of multiple surface nanobubbles: shrinkage, growth, and coarsening, Soft Matter 14, 2006-2014 (2018).

Xiaolai Li, Yuliang Wang, Binglin Zeng, Yanshen Li, Huanshu Tan, Harold J. W. Zandvliet, Xuehua Zhang, and Detlef Lohse. Entrapment and dissolution of microbubbles inside microwells, Langmuir 34, 10659–10667 (2018).

Former staff

Former staff



Emeritus professor Leen van Wijngaarden
1 September 1965 till 31 March 1997,
Chair holder leerstoel Warmteoverdracht en Stromingsleer

Emeritus professor Frits Dijksman
1 September 2011 till 31 August 2016

Sascha Hilgenfeldt
15 October 2000 till 31 August 2004,
assistant professor

now professor at the University of Urbana-Champaign, Illinois, USA

Former staff

Nico de Jong

1 March 2003 till 30 November 2011,
part-time professor

now professor at Erasmus Medical Center Rotterdam and part-time head of the department of Acoustical Waveform Imaging, Delft University of Technology

Ko van der Weele

1 December 1999 till 31 December 2005

now Full professor at University of Patras, Greece

Gerrit de Bruin

1 June 1968 till 30 June 2004,
assistant professor

now retired

Former staff

Marianne van der Linde

1 June 1974 till 30 November 2001,
secretary

now retired

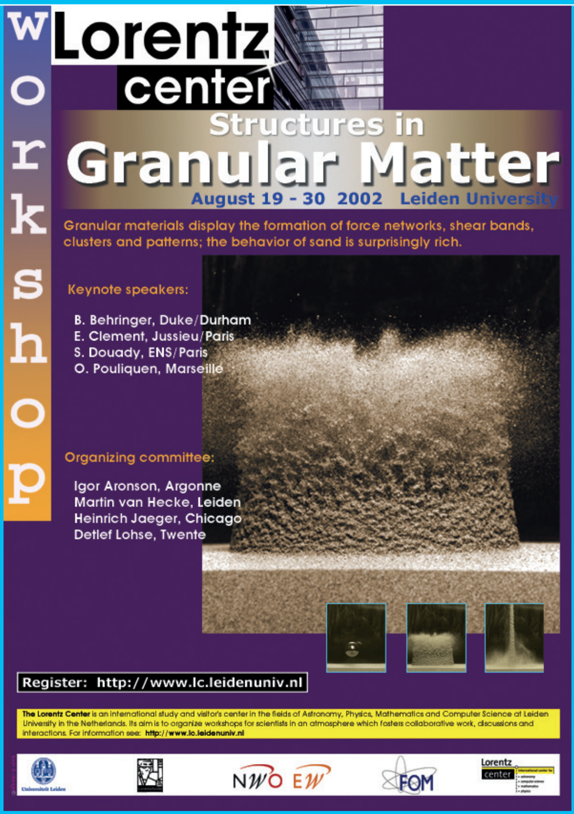
Henni Scholten

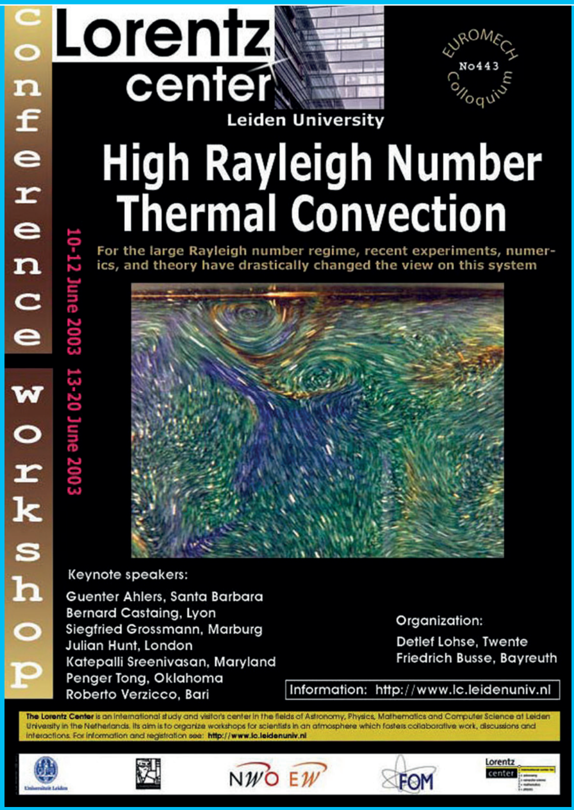
16 June 1969 till June 2002 (deceased 22 January 2006)

technician

INTERMEZZO

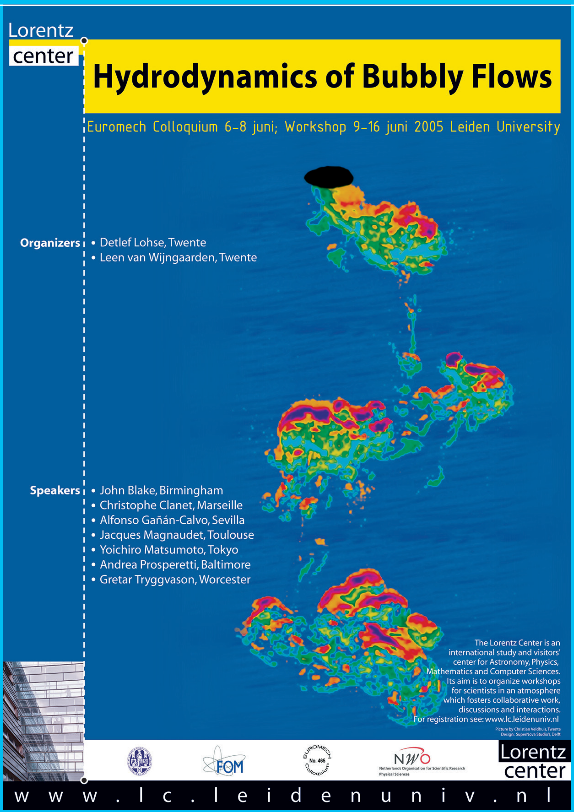
Posters Lorentz Center Leiden





INTERMEZZO

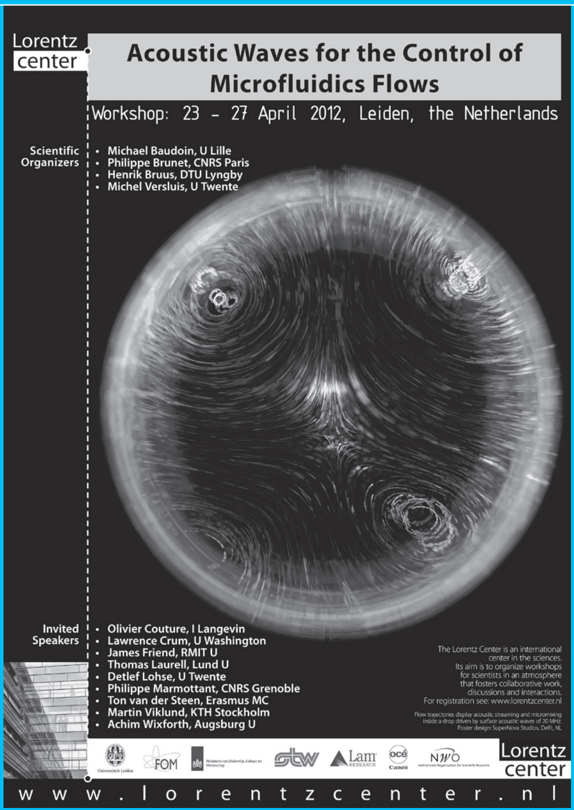
Posters Lorentz Center Leiden



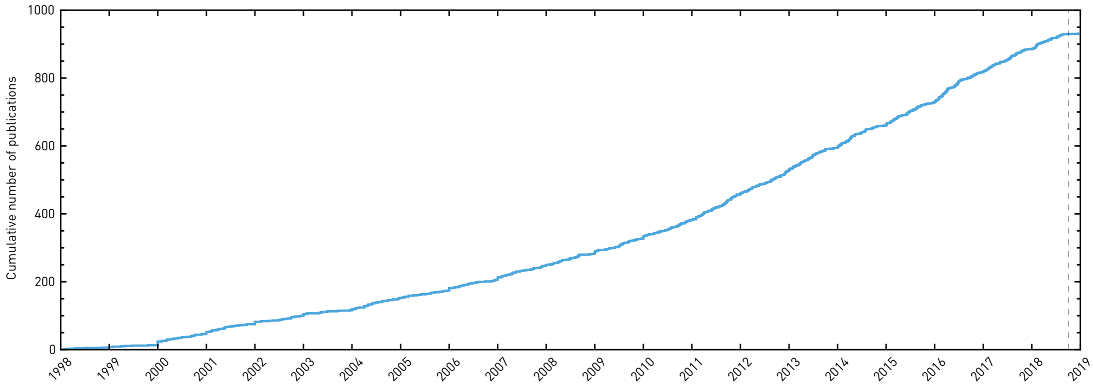
INTERMEZZO
Posters Lorentz Center Leiden

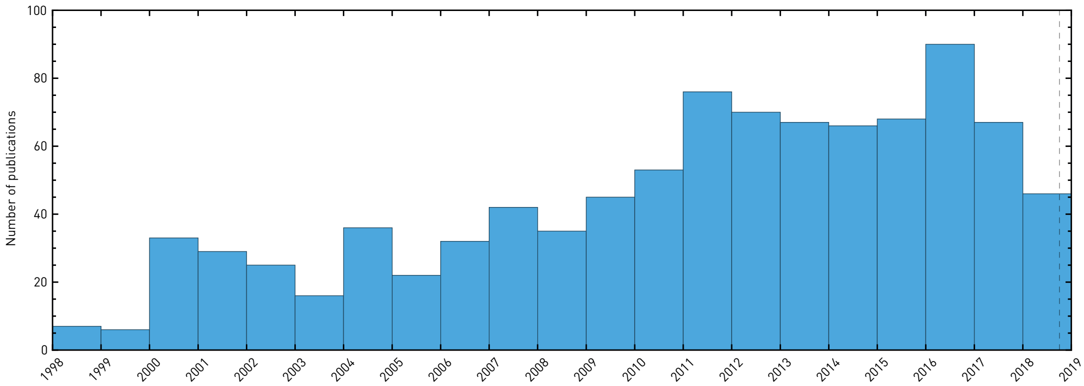
INTERMEZZO

Posters Lorentz Center Leiden



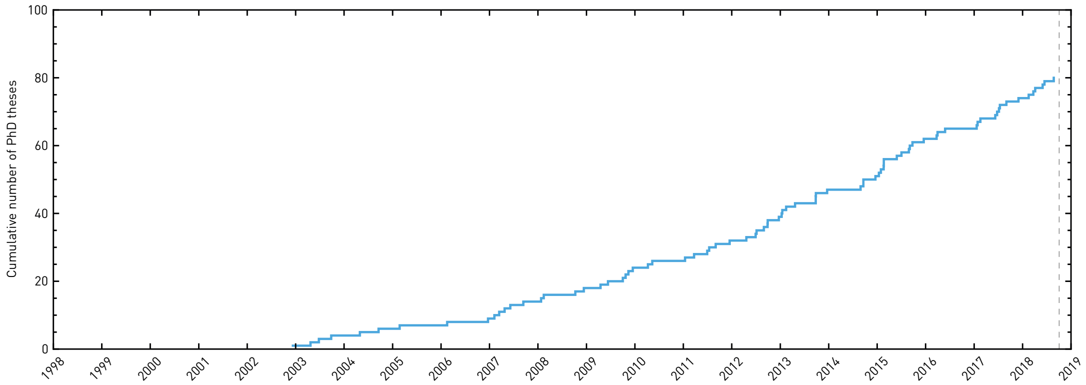
Twenty years of PoF in numbers

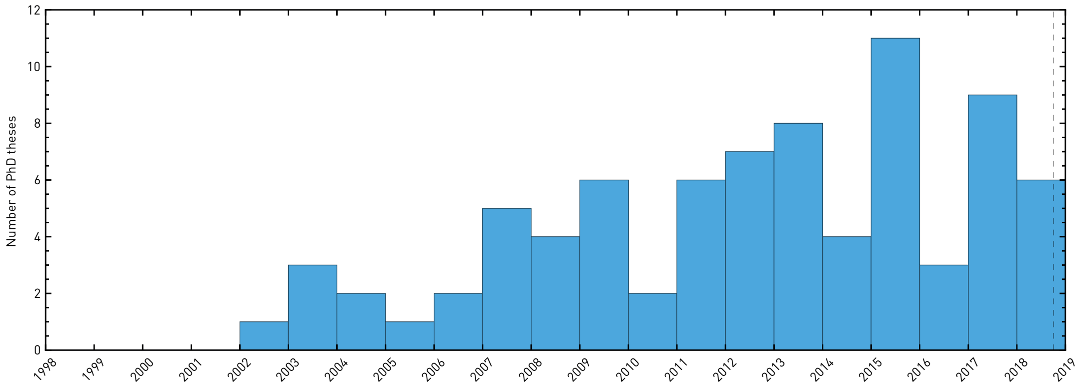




Top: Cumulative number of refereed publications in the PoF group.
After 20 years we are close to a 1000 publications.
Bottom: Number of refereed publications per year in the PoF group over the years.

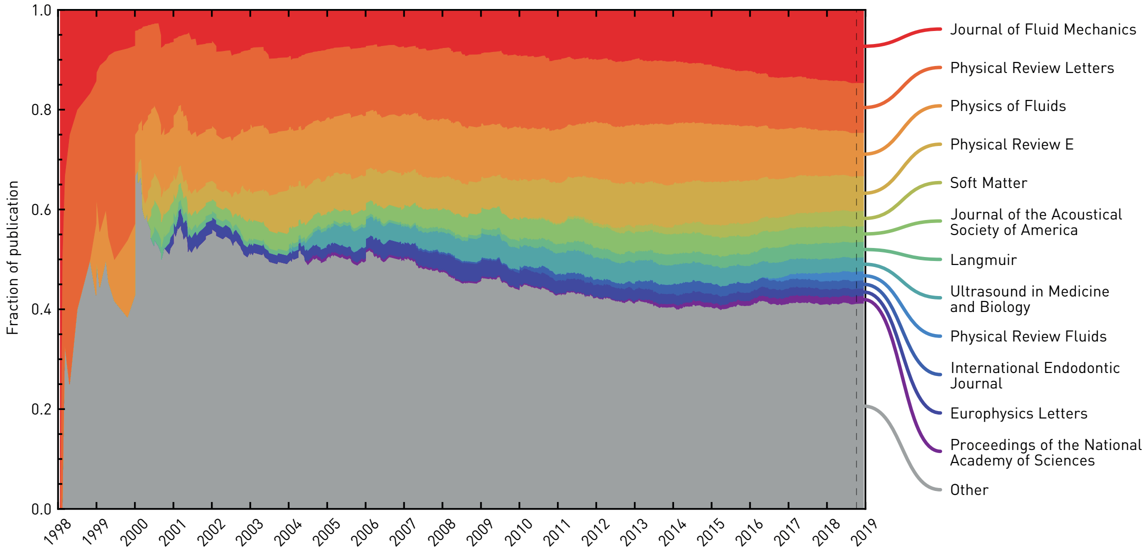
Twenty years of PoF in numbers





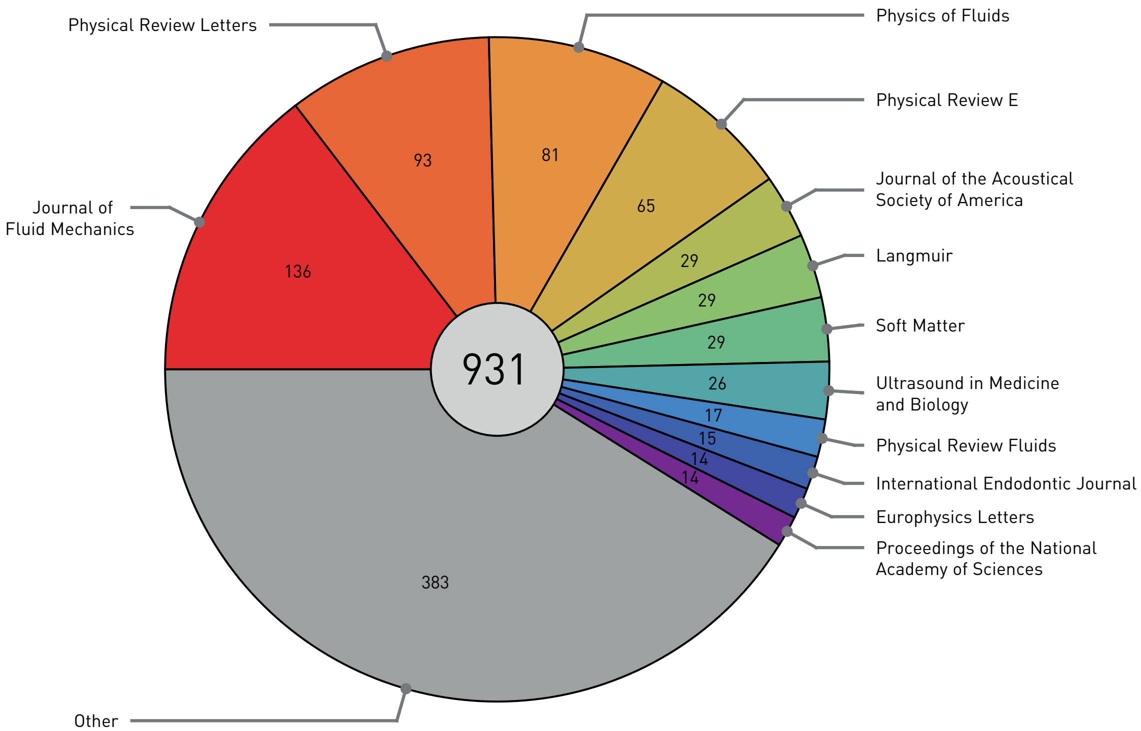
Top: Cumulative number of PhD thesis in the PoF group, after 20 years we have already 80 graduates, we will reach our 100th graduate in roughly 2 years (and he or she is already with us!).
Bottom: Number of PhD theses per year in the PoF group.

Twenty years of PoF in numbers

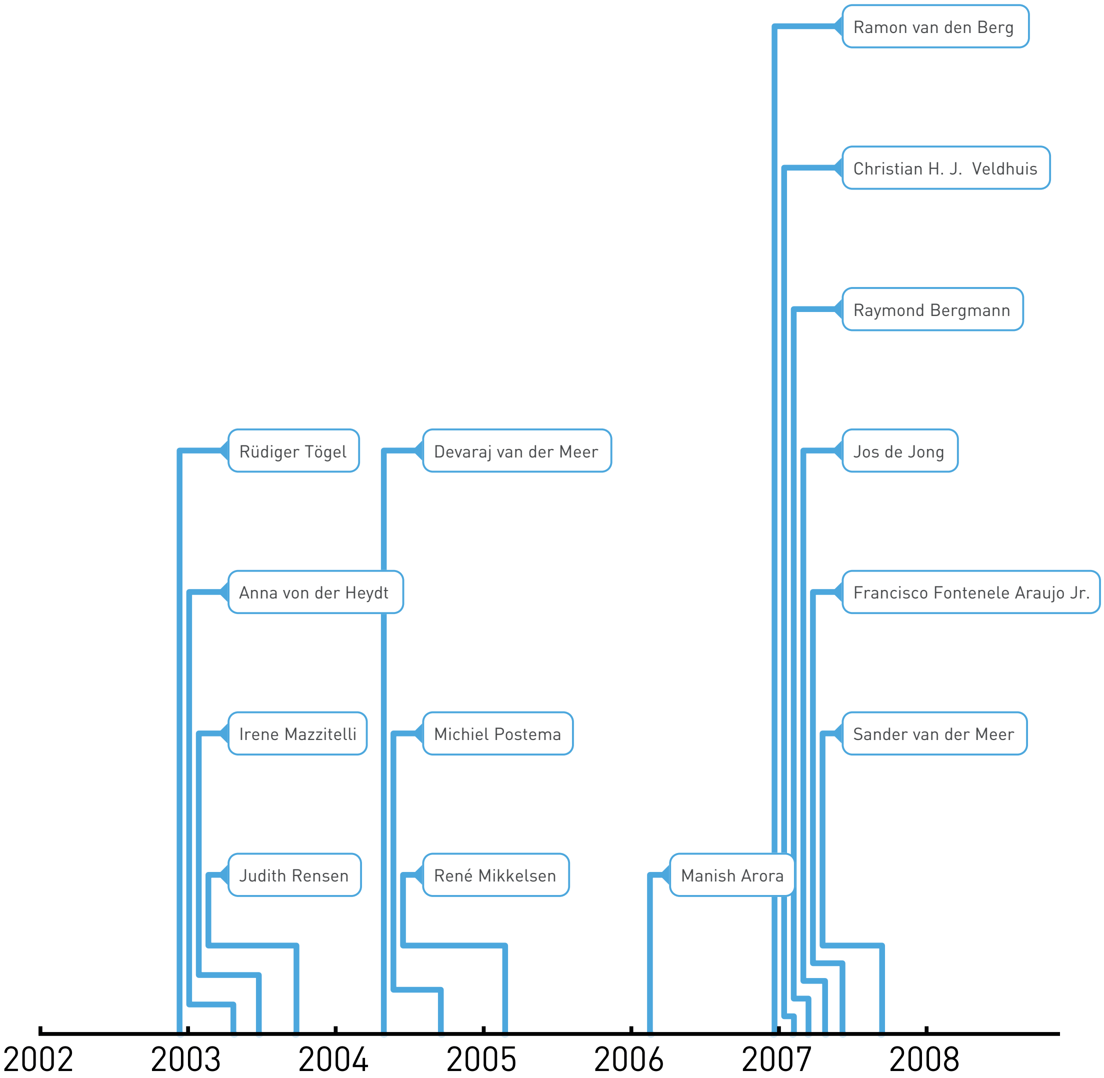


Fraction of the most popular journals (cumulative) as a function of time. One in seven papers is in the Journal of Fluid Mechanics. The group has published in more than 173 journals.

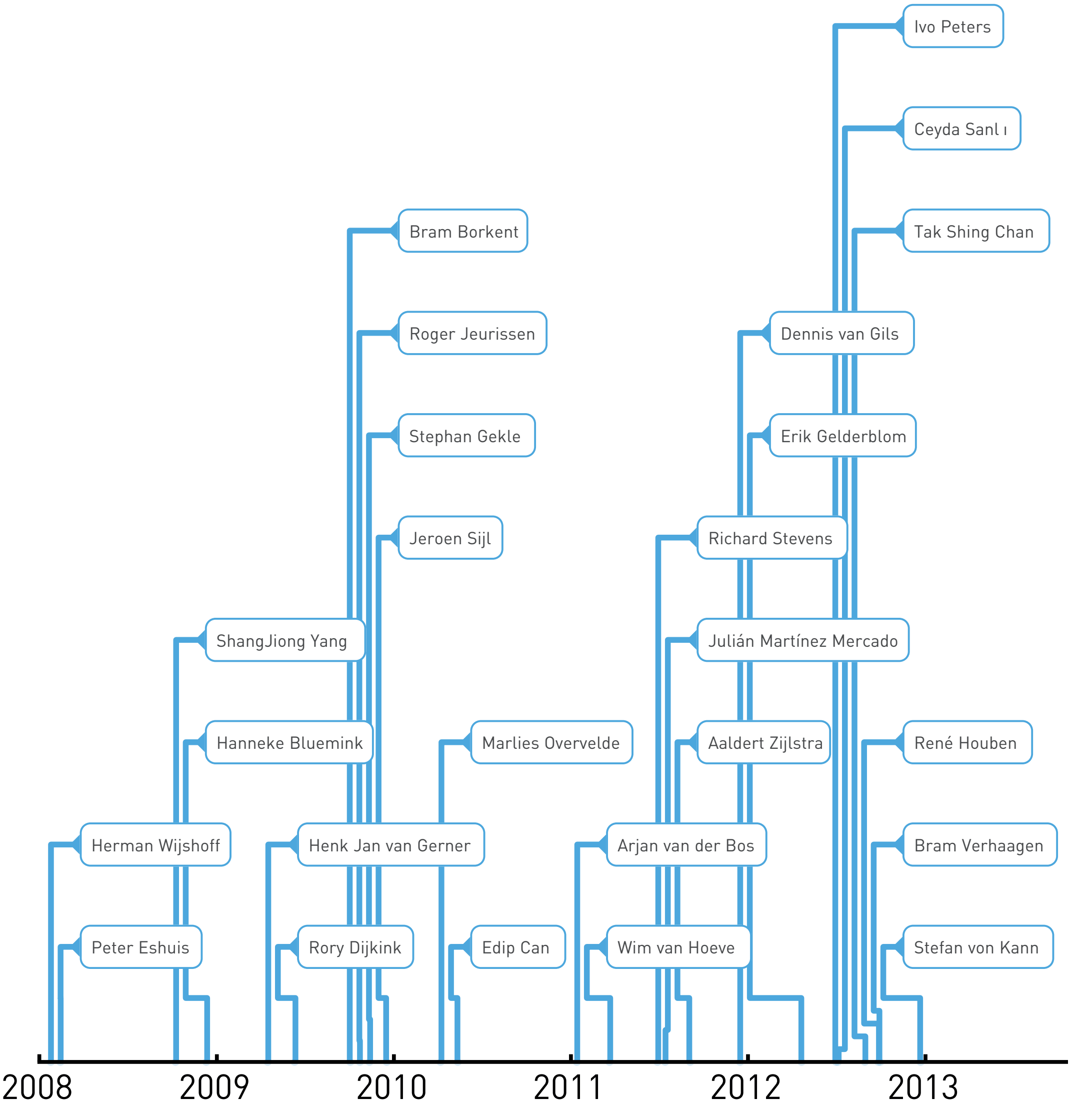
Twenty years of PoF in numbers



The Physics of Fluids group has published nearly a thousand publications in more than a 170 journals. Here we show the journals with the most publications.

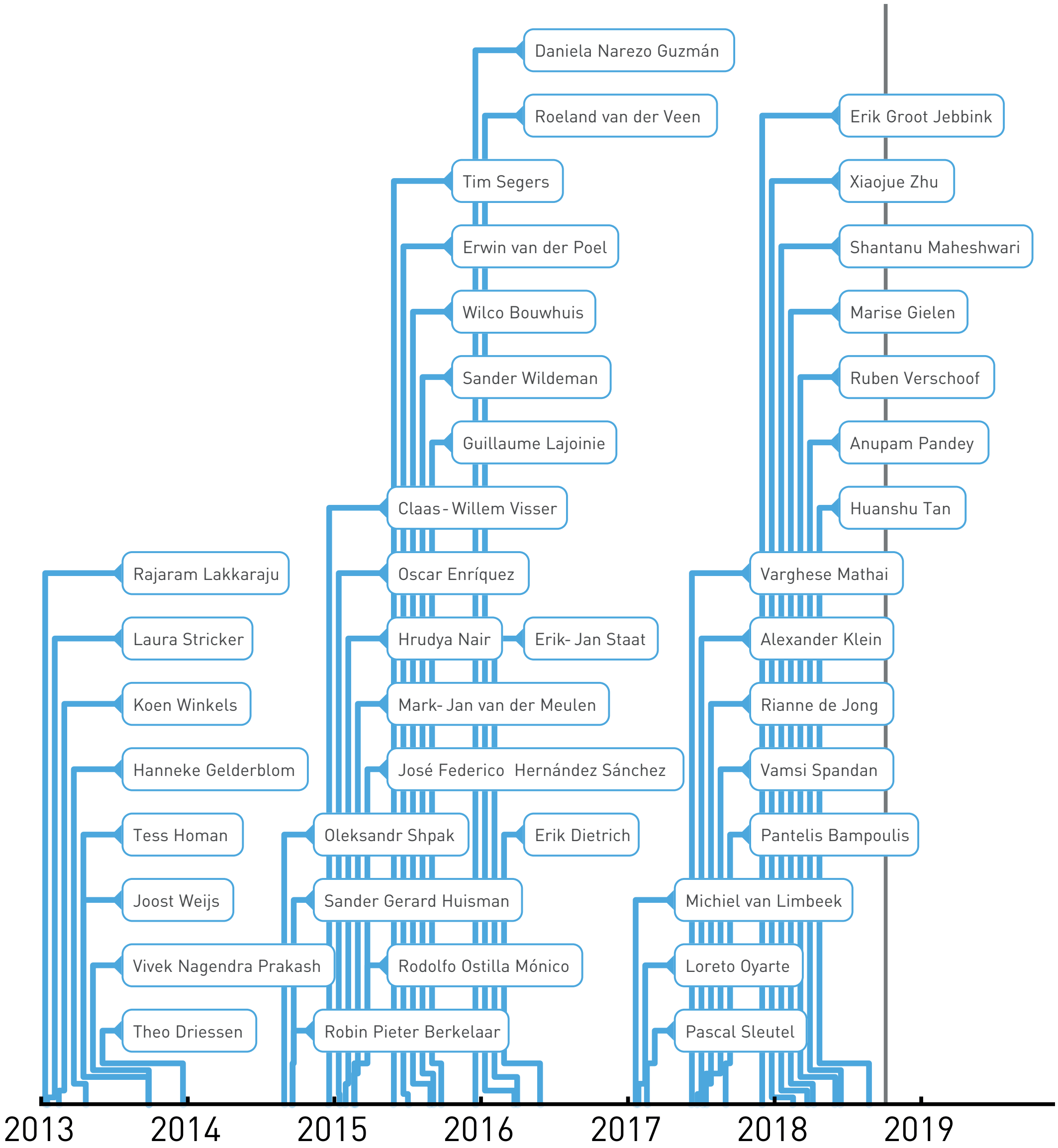


Timeline of PhD graduations

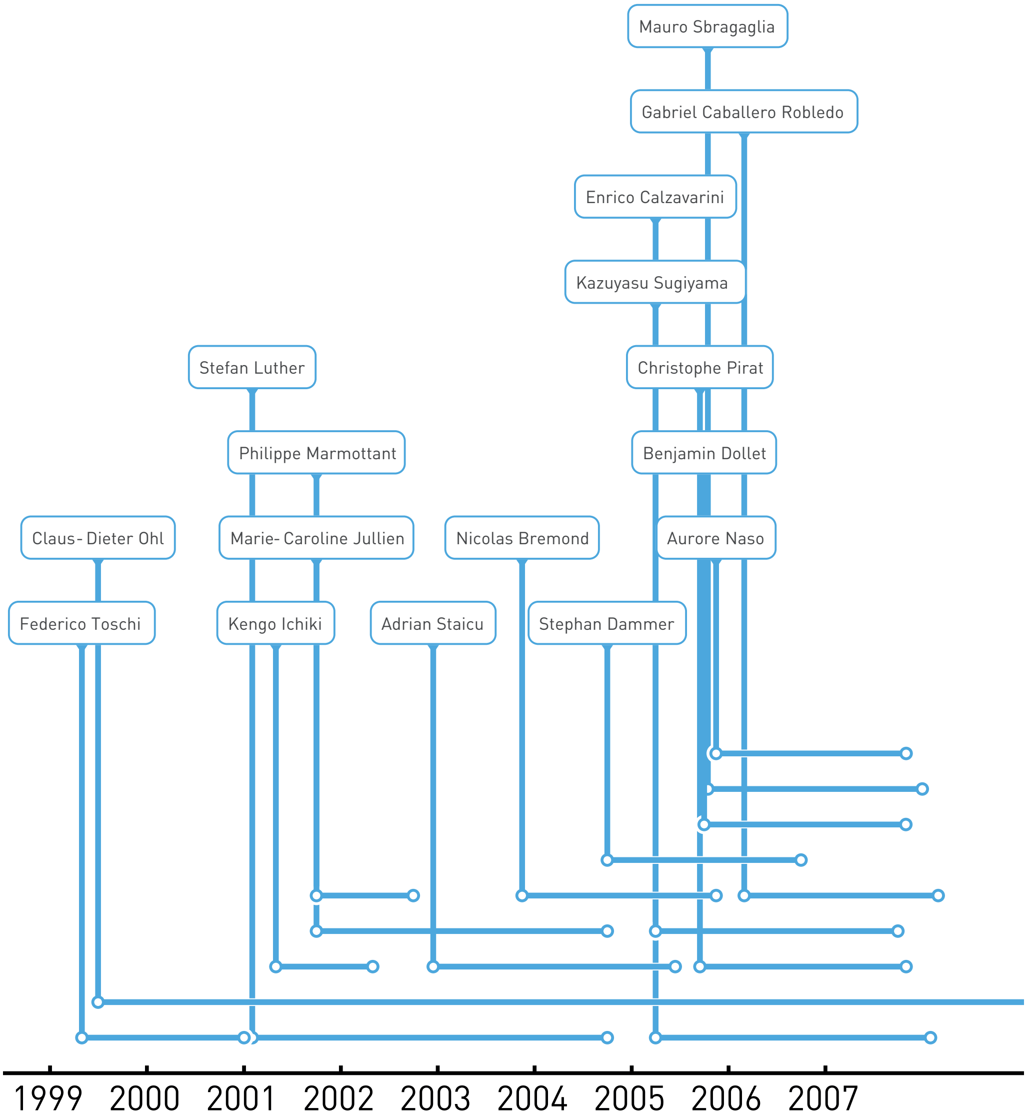


Timeline of PhD graduations

Twenty years of PoF in numbers

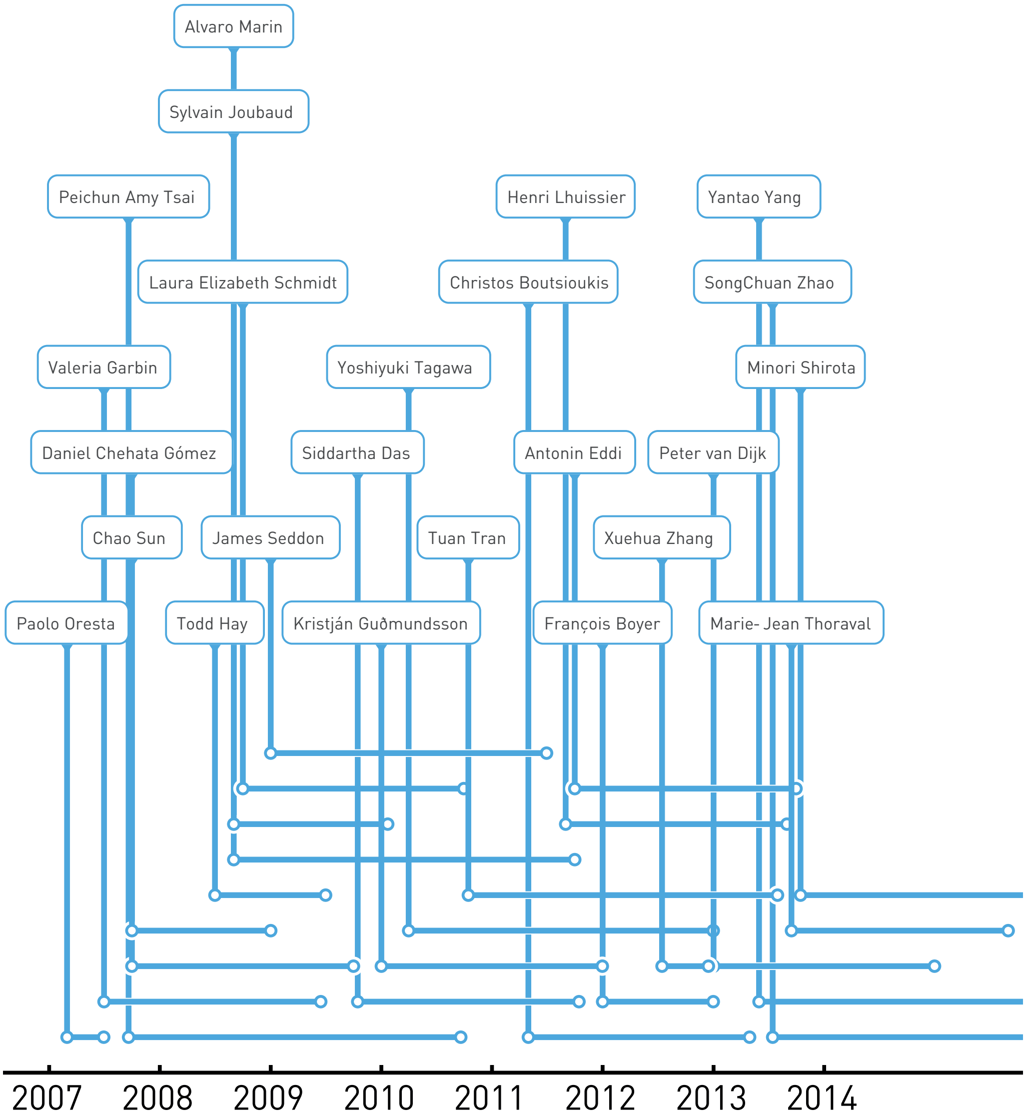


Timeline of PhD graduations

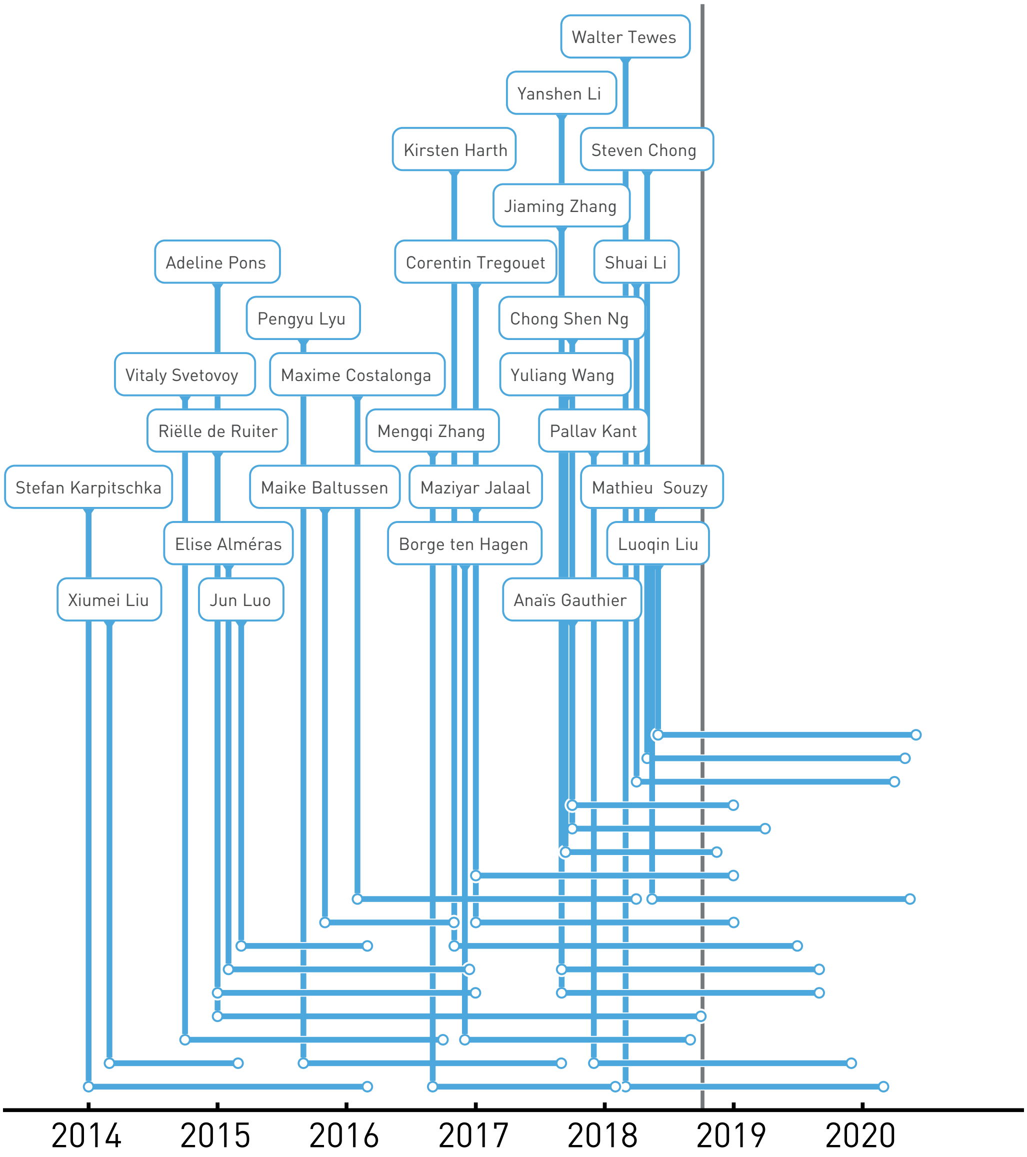


Timeline of Postdoc positions

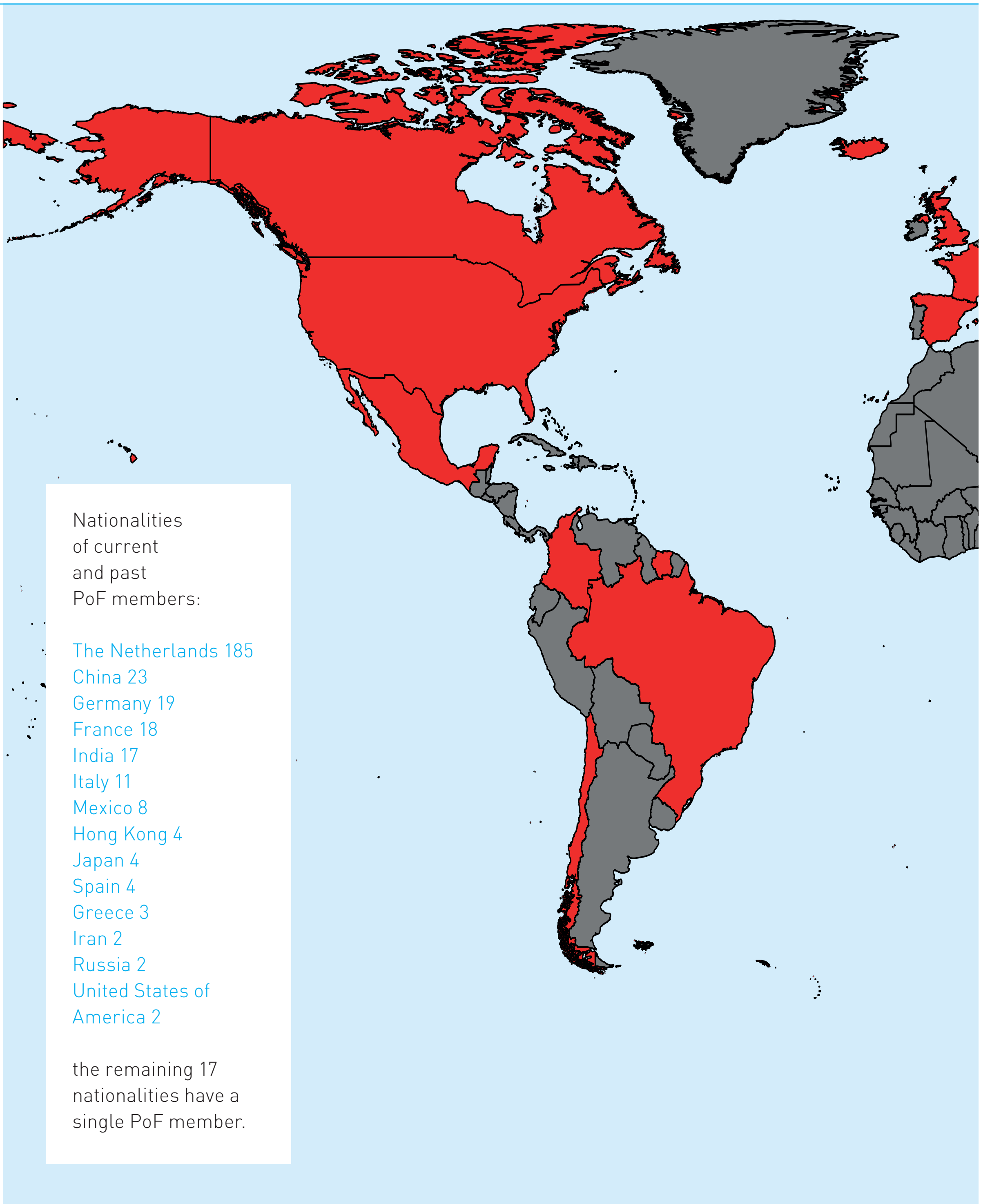
Twenty years of PoF in numbers



Timeline of Postdoc positions



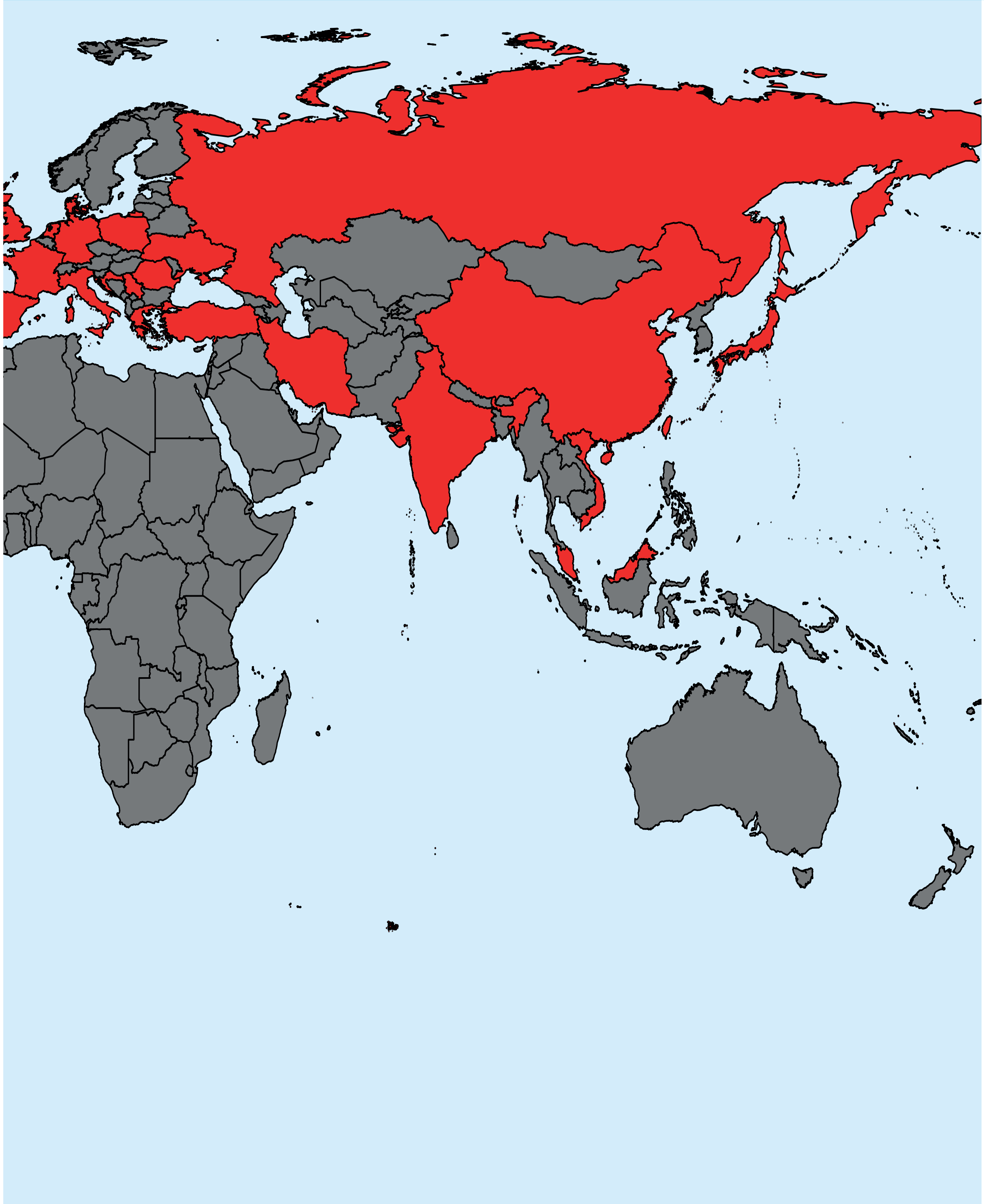
Timeline of Postdoc positions



Nationalities
of current
and past
PoF members:

The Netherlands 185
China 23
Germany 19
France 18
India 17
Italy 11
Mexico 8
Hong Kong 4
Japan 4
Spain 4
Greece 3
Iran 2
Russia 2
United States of
America 2

the remaining 17
nationalities have a
single PoF member.



Group photo August 2018

1. Sander Huisman, 2. Dominic Tai, 3. Peter Dung, 4. Huanshu Tan, 5. Liz Mensink, 6. Xiaolai Li, 7. Christian Diddens, 8. Richard Stevens, 9. Myrthe Bruning, 10. Utkarsh Jain, 11. Devaraj van der Meer, 12. Kirsten Harth, 13. Mikhail Zaytsev, 14. Javier Rodríguez Rodríguez, 15. Jessica Strickland, 16. Gert-Wim Bruggert, 17. Xiaojue Zhu, 18. Rodrigo Ezeta, 19. Chao Sun, 20. Dominik Krug, 21. Maaike Rump, 22. Alvaro Marin, 23. Pim Bullee, 24. José Manuel Encarnación Escobar, 25. Detlef Lohse, 26. Anaïs Gauthier, 27. Martin Assen, 28. Jelle Will, 29. Álvaro Moreno Soto, 30. Joanita Leferink, 31. Martin van der Hoef, 32. Mathieu Souzy, 33. Dennis van Gils, 34. Pieter Berghout, 35. Michiel Hack, 36. Yogesh Jethani, 37. Bas Benschop, 38. Srinidhi Nagarada Gadde, 39. Vatsal Sanjay, 40. Shuai Li, 41. Yaxing Li, 42. Luoqin Liu, 43. Dennis Bakhuis, 44. Martin Klein Schaarsberg, 45. Ricardo Arturo López de la Cruz, 46. Srinath Lakshman, 47. Pallav Kant, 48. Yanshen Li, 49. Steven Chong, 50. Walter Tewes, 51. Maziyar Jalaal, 52. Carola Seyfert, 53. Lijun Thayyil Raju, 54. Guillaume Lajoinie.

Group members missing on the photo are: Alexander Blass, Martin Bos, Ivan Dević, Arjan Fraters, Diana García González, Mathijs van Gorcum, Biljana Gvozdić, Robin Koldeweij, Chris de Korte, Nakul Pande, Andrea Prosperetti, Sten Reijers, Tim Segers, Jacco Snoeijer, Thijs Verkaik, Michel Versluis, Roberto Verzicco, Leen van Wijngaarden, Jiaming Zhang, and Xuehua Zhang.

PHOTO: SANDER HUISMAN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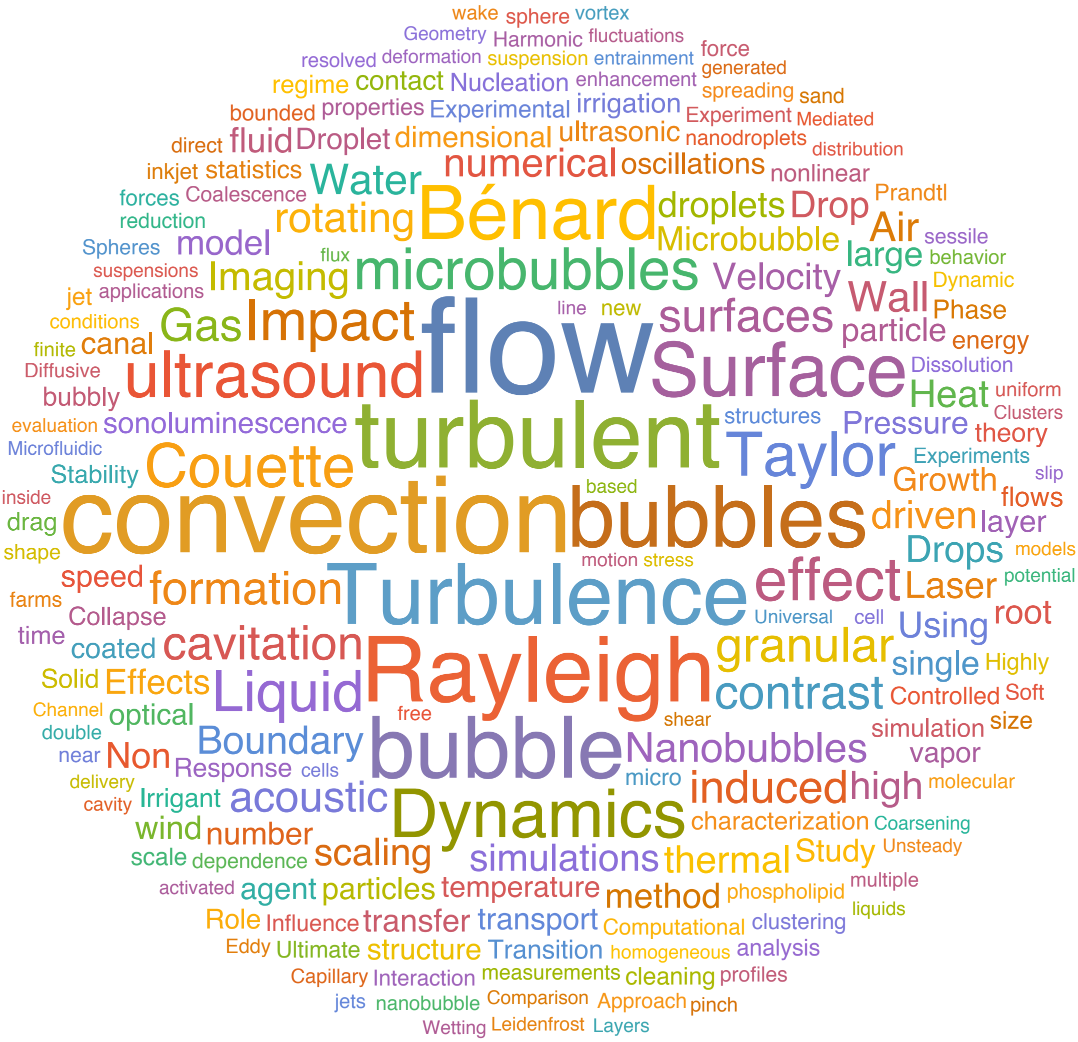
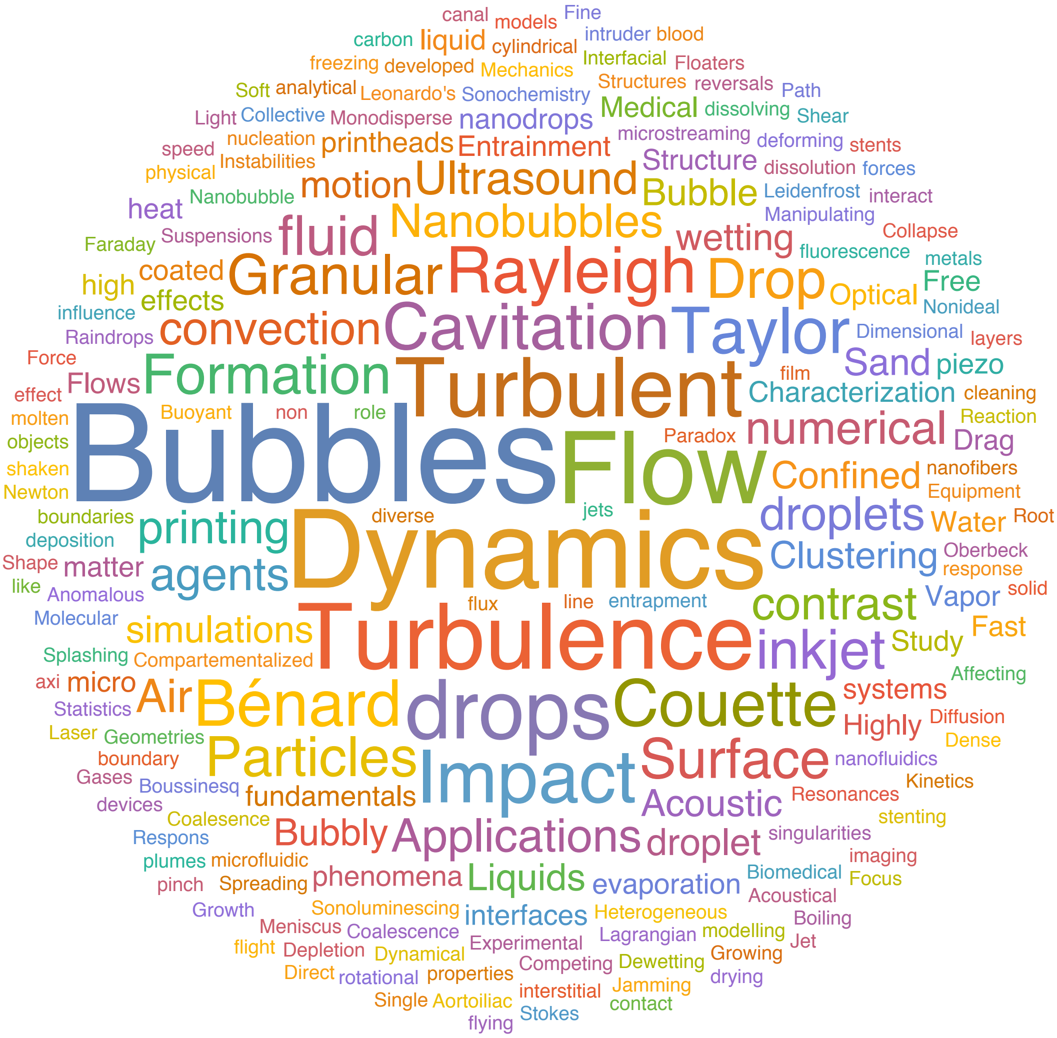
Twenty years of PoF in numbers



Word cloud made from the titles of all the refereed publications.



Word cloud made from the titles of all the PhD theses.

Colophon

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