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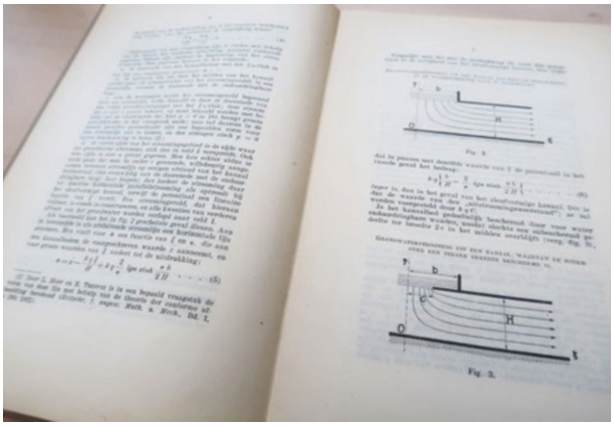
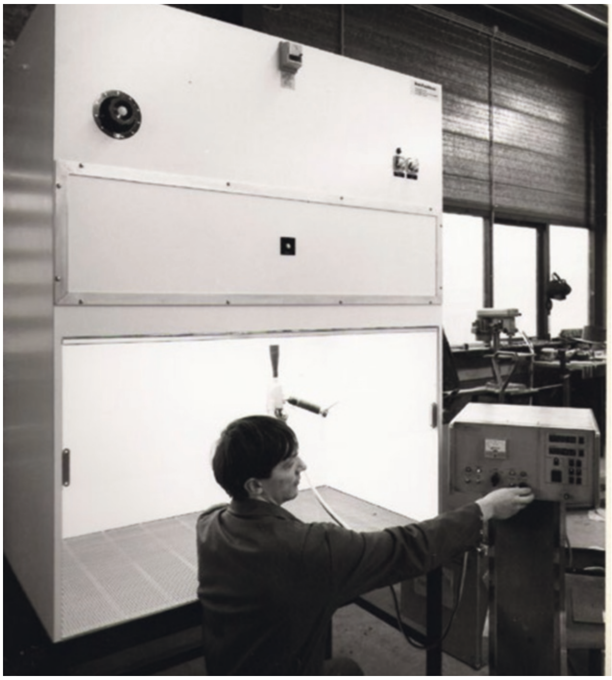
05

RESEARCH IN FLUID MECHANICS: FLOWS

Fluid mechanics, like many other fields of mechanics, has two faces: the fundamental one and the applied one. Fundamental research is mainly done at universities, much of the applied research can be found in institutes and in industry. But this division is not strict and especially in the 1950s, 1960s and 1970s fundamental research could also be found outside the academic world. As for the more fundamental studies, all kinds of flows been in the focal point and in this chapter for several of these examples from Dutch research are presented. The flows have been subdivided among three categories: single-phase flows, flows related to the field of rheology, and two-phase flows. Today, the fluids and flows in the last two categories are also indicated as ‘complex fluids’ and ‘complex flows’.



↑In the 1910s and 1920s much was written about groundwater flows in the Netherlands (see also § 6.1). The only paper by Burgers on this topic was published in 1926 in *De Ingenieur*, the periodical of the Royal Netherlands Society of Engineers (KIVI) which at that time was still more like a scientific journal. Note the drawings, indicating the assumption of a 'smooth' (laminar) flow. (courtesy of Burgers Archives / TU Delft)



↑Making laminar air flows has been one of the specialities of the Dutch Interflow company for more than forty years. Among their products are laminar flow cabinets, carefully enclosed benches designed to prevent contamination of semiconductor wafers, biological samples, or any particle sensitive materials. Air is drawn through a filter and blown in a very smooth, laminar manner towards the user. Due to the direction of air flow, "the sample is protected from the user, but the user is not protected from the sample". (courtesy of Interflow)

5.1 SINGLE-PHASE FLOWS

The flows in this category have been subdivided among seven subcategories, for reasons of convenience and clarity. For each category examples of research from the 'early period' (many involving work by Burgers and co-workers), and also of more recent times are presented.

5.1.1 LAMINAR FLOW

Laminar flows were for centuries the only flows that could be and were studied by scientists working on hydrodynamics. During the 18th and 19th centuries the theory of potential flows was developed: flows for which the velocity field is the gradient of a scalar function. These fields show no rotational behaviour (no vorticity) and could be called 'smooth'.

The study of turbulence started rather late. The transition from laminar to turbulent behaviour was investigated experimentally by Reynolds in Manchester in the 1880s, who still used the term 'sinuous' instead of 'turbulent'. This generated some interest in turbulence, but little was done particularly on the theoretical side. The reason for the almost complete absence of a theoretical approach to turbulence was simple: up until about 1920 hardly anyone had an idea of how to handle the Navier-Stokes equations regarding turbulent flows. It was only under certain assumptions that these equations became manageable. One example of this is the assumption that the inertial forces in the flow are small compared to the viscous forces (i.e., the Reynolds number Re is very small). In this case the Navier-Stokes equations can be linearized and become the Stokes equations; its solutions are called Stokes flows (or creeping flows).

As we have seen in § 2.4 Lorentz found a solution for the Stokes equations in 1896. In his paper Lorentz came up with what is now called the Lorentz reciprocal theorem. This is a very general theorem in low Reynolds number hydrodynamics, relating the stress and velocity fields on an arbitrary surface. The theorem is still used today, e.g., for the calculation of the propulsion speed of swimmers with defined tangential velocity fields (known as squirmers). The Lorentz reciprocal theorem can also be used to relate the swimming speed of a micro-organism to the surface velocity which is prescribed

by deformations of the body shape via cilia or flagella.
One of the flows for which the mathematical approach is relatively easy and which has been studied intensively from the 19th century is the flow of groundwater (see also § 6.1). This was possible as these flows were supposed to be laminar and the streamlines to be parallel to each other. Furthermore, boundary layers were (usually) not regarded in these flows.

Potential flows got the interest of fluid mechanics engineers again from the 1970s when the numerical simulation of flows started to become serious business. The available software and hardware were hardly capable of handling the Navier-Stokes equations and therefore the simulation of potential flows was taken up, even though they could not really be regarded as 'real' flows. In the 1980s Kees Vreugdenhil at the WL showed e.g., that the behaviour of waves (a free surface problem; see § 5.1.5) can, up to a certain point, be simulated by means of linearized equations and the theory of potential flows. The breaking of waves, however, remained out of reach with this approach.

• 5.1.2 TURBULENT FLOWS AND TRANSITION

Most flows are turbulent: unsteady and chaotic, not repeating in detail. The turbulent state is opposed to the laminar state. The difference is significant, since the chaotic motions of turbulent flows produce much larger values for drag, and for mass and heat transfer, than corresponding laminar flows. Despite the omnipresence of turbulence and much research on the phenomenon, it can still be described as one of the last great unsolved problems of classical physics. There is no comprehensive theory of turbulence, although much partial qualitative understanding has been achieved.

BURGERS

When Burgers started in Delft in 1918, turbulence was for the most part terra incognita. Burgers knew how Lorentz had approached turbulence some years earlier (see § 2.4) and was confident that he could contribute to the exploration of this intriguing phenomenon. To many scientists of those days turbulence still seemed a 'problem' which could be solved within a foreseeable amount of time.
It was his work on vortex motion in the early 1920s which stimulated Burgers to turn towards turbulence. In the *Annual Review of Fluid Mechanics* of 1975, he wrote:
"In 1923 I attempted to construct a theoretical model for turbulent flow between two parallel walls, in which an assumed distribution of shearing forces together with a distribution of viscous dissipation was introduced, based upon a kind of superposition of many of Lorentz's vortices. The model could be arranged in either of two ways: it could give a resistance proportional to the 1½-power of the mean flow velocity … or it could give a resistance proportional to the square of the flow velocity … As Blasius' law for pipe and channel flow said that the resistance should be proportional to the 7/4-power of the velocity, an intermediate model would be needed. It looked as if this could be obtained by introducing some randomness in the arrangement of the vortices, but no appropriate solution was found."
In the meantime, Burgers shifted his attention to the results from Van der Hegge Zijnen's hot-wire measurements in the turbulent boundary layer (see § 6.2.1). However, his main interest in turbulence still concerned the theoretical approach. Like several of his foreign colleagues, he started to study statistical theories of turbulence, but soon discovered several difficulties:
"What stuck in me was an idea about the importance of the dissipation condition for turbulent channel flow: all the energy put into the system by the pressure difference driving the mean flow should be dissipated, for a (small) part in the viscous dissipation associated with the mean flow, and for the larger part in dissipation connected with the turbulent vortex system. For several years I played with the hypothesis that a statistical theory of turbulence might be built upon the example of the statistical theory used in the kinetic theory of gases or in other conservative systems, provided the condition of constant energy content was replaced by a dissipation condition. It became clear, however, that this method would lead to 'equipartition of dissipation' for all degrees of freedom of the system, and as there is an infinity of degrees of freedom so long as one keeps to the picture that the fluid is a continuum, there is the danger of infinite total dissipation."
The results of this 'playing' were presented in 1929 at a conference in Aachen. In the same year Burgers published the first three of a series of seven papers on the application of statistical mechanics to the theory of turbulent fluid motion. In 1933, the next four of this series were published. However, he was not satisfied with his results, as he remarked to the English physicist George Trubridge who in the 1930s wanted to write a thesis on 'Burgers' theory of turbulence'. Thanks to Trubridge's reviews published by the Physical Society of London and in Science Progress, Burgers' theory of turbulence gradually became better known. However, even though Trubridge and Burgers seriously discussed the problems surrounding the theory, and the German mathematician Blumenthal (see also § 6.1) gave algebraic support, around 1936 Burgers was still not satisfied with the results he had found.
Around this time, statistics started to dominate research in turbulence: a shift took place from the 'eddy' models developed by Taylor and Prandtl in the 1920s towards a statistical description. Burgers took yet another road in the 1930s. He decided to restrict his attention to model problems, with which the essential aspects of turbulence could be treat-

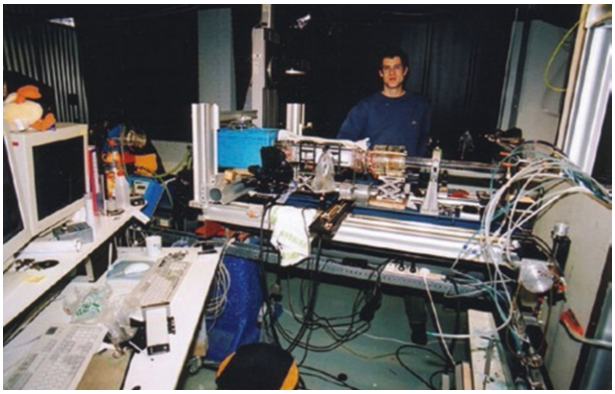
ed. This eventually led to his work on an equation which became known as the Burgers equation (see § 6.1).
After the War, and a long period of stagnation in his own research, Burgers was informed about the developments in the USA and Britain. He realized that his treatment of turbulence had taken a direction which differed strongly from others like Kolmogorov, Onsager, Von Weizsäcker, and Heisenberg. Nevertheless, he still felt convinced of the value of his work and was very much encouraged in this opinion when the famous mathematician John von Neumann visited him in 1949. Von Neumann had been sent by the US government to survey the research on turbulence at European centres of fluid mechanics. His report for the Office of Naval Research sketches a good view of the discussions on turbulence running at that time. One of Burgers' most promising results mentioned by Von Neumann, concerned a particular type of turbulence in which the vorticity is concentrated into vortex sheets.
Apart from his work on the Burgers equation, Burgers continued to work on the 'classical' statistical theory of turbulence. In 1953, he and Morton Mitchner (from Harvard University) did pioneering work on turbulent flow including a mean motion (i.e., a constant velocity gradient). The same year, he also published "some considerations on turbulent flow with shear", in which he tested "a simple expression for the relative frequency of patterns of turbulence of various scales at different distances from the wall in a turbulent boundary layer".
After Burgers' emigration in 1955, Broer and Hinze were about the only scientists in the Netherlands who could have continued Burgers' theoretical research. But they did not do so. Broer never published much about turbulence and Hinze was mainly working on his famous textbook (see § 3.3.2). In the 1960s and 1970s experiments were carried out under Hinze's guidance at the Laboratory of Aerodynamics and Hydrodynamics on the transition to turbulence in the boundary layer. During these experiments hot-wire measurements were performed (see § 6.2.1).

LEIDEN, DELFT, TWENTE

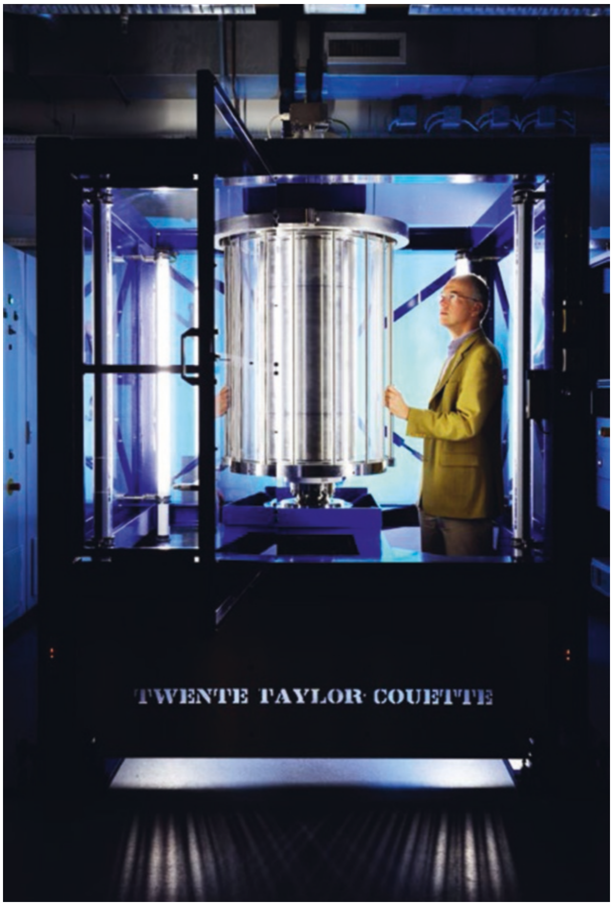
In the 1970s many in the turbulence community turned towards research on coherent structures. In Delft the Japanese Ueda did experiments related to this, which led to Hinze's only paper in the Journal of Fluid Mechanics (in 1975), entitled 'Fine-structure turbulence in the wall region of a turbulent boundary layer'. Both Ooms (successor of Hinze), and Nieuwstadt (successor of Ooms), spoke about coherent structures in their inaugural lectures and research on these structures, both experimental and numerical, became one of the priorities under Nieuwstadt.

It was not only Delft where research into the fundamental aspects of turbulence was done in the first decade of this century. Around 2003 a group of physicists from Leiden and four other cities around the world discovered a new manner in which turbulence could arise. They had performed experiments on superfluid helium (a much-studied liquid in Leiden since Kamerlingh Onnes' research of the early 20th century) and discovered that the transition from laminar to turbulent flow was determined by the temperature. Below a critical temperature it appeared that the vortex lines in the helium were no longer stretched and 'quiet', but that they started to behave chaotically and to multiply. The very low temperatures and the special characteristics of superfluid helium enabled the researchers, as they said, to study turbulence in its purest form. Their results were published in Nature.
Transition to turbulence has always remained a research theme in the Laboratory for Aerodynamics and Hydrodynamics, under Nieuwstadt and later under Jerry Westerweel. For the transition in flows of non-Newtonian fluids a 32 m long pipe flow facility was built in the 1990s. But much more publicity was gained in 2004, thanks to a publication in Science, by the results of an experiment done by PhD student Cas van Doorne, together with scientists from Germany, the UK and the USA. In Delft measurements took place in a pipe of 26 m length to find 'nonlinear travelling waves', a kind of coherent structures, which had been found by others from numerical simulations using the Navier-Stokes equations. These structures seemed to be unstable and many doubted the existence of them in real turbulent flows. The experiments showed that they did exist, and the measured velocity fields compared quite well with the numerical ones. In this experiment stereoscopic PIV was used, a technique which had largely been developed in the Delft laboratory (see § 6.2.1). "Our main contribution to the problem of turbulence is that we could show that principles from nonlinear systems theory appear to apply to this type of turbulent flow," postdoc Björn Hof told PhysicsWeb in 2004.
In 2005 another remarkable discovery was made in the same laboratory in Delft. Westerweel and others had studied the mechanics and transport processes at the bounding interface between the turbulent and nonturbulent regions of flow in a turbulent jet. Their results led them to the conclusion that there is small-scale eddying motion at the outward propagating interface (nibbling, as they called it) by which irrotational fluid becomes turbulent. The large-scale eddies, they concluded, are not the dominant eddies in the entrainment process, as was generally thought.

As the 'role' of coherent structures in turbulent flows became clearer, the idea arose that it might be possible to 'control' turbulence and get drag reduction by manipulating these structures. This initiated research on two drag reducing methods: modifying the geometry of the walls, and adding polymers to the liquid (the last had already been studied experimentally at the University of Amsterdam in



↑Cas van Doorne preparing the experimental facility in Delft with which the nonlinear travelling waves in turbulent flows were detected for the first time. For this stereoscopic PIV (see § 6.2.1) was used, with two 1000 Hz cameras. These were provided to the research team by the cameras' manufacturer; buying them was too expensive at the time. In the foreground on the right the facility with which laminar injections could be given to disturb the main flow. (courtesy of TU Delft/ Jerry Westerweel)



→Lohse at the Taylor-Couette facility at the University of Twente. In his Physica lecture of 2011 Lohse called the TC set-up one of the two 'fruit flies' of fluid mechanics; the other one is the Rayleigh-Bénard convection cell (see § 5.1.7). With these 'fruit flies' new ideas and concepts can be tested in a rather uncomplicated manner. (courtesy of TU Eindhoven archives / photo by Bart van Overbeeke)

the 1970s). STW en FOM (see § 4.4) supported the research on drag reduction in Delft and Eindhoven from 1983. In Delft the effect of micro-grooves (or riblets) was investigated. So-called ejections and sweeps were identified since their role was considered important.
Around 2005 in Twente drag reduction by means of bubble injection was investigated in a Taylor-Couette facility. By injecting bubbles in the liquid between the rotating cylinders a strong drag reduction was found (up to 30%). But when the smooth surface was made rough with perspex strips, the reduction was much lower. Application of the bubble technique to ships therefore seemed to be not very effective since ship hulls are usually not very smooth.

In 2011 Lohse had the honour to give the Physica lecture, organized by the Dutch physics community. The main message of his lecture was: the image of turbulence which had been given by the Russian scientist Kolmogorov in the 1940s and which had been a 'paradigm' for many decades, had shown fractures in recent years. In Kolmogorov's image fully developed turbulence, at high Reynolds numbers, was homogeneous and isotropic. Numerical simulations seemed to confirm this image, but doubts had arisen as to whether this image was still valid for 'real turbulence', i.e., turbulence in real containers with boundary layers. Real turbulence could switch to different states, and not just one. Among the experimental results which had led Lohse to this conclusion were those obtained by his group from studies on the flows in a Rayleigh-Bénard convection cell (see § 5.1.7).

• 5.1.3 VORTICES AND ROTATING FLOWS

Many natural and technological flows are vortex-dominated. A vortex is a 'structure', e.g., a tube, of concentrated vorticity. Vortices exist on many scales: there are small ones in turbulent boundary layers (coherent structures), larger ones under the wings of airplanes. Still larger vortices are tornados and hurricanes, and then there are very large-scale vortices like the polar vortex or the Great Red Spot of Jupiter. The generation, interaction, and dispersal or mixing of vorticity plays a profound role in a wide class of applied, geophysical, and fundamental fluid flows, and this explains the longstanding research on vortical flows.

BURGERS

In 1918 Burgers had already mentioned vortices in his inaugural speech, and gave the vortices related to the flight of birds as an example. The first experiments that were done in his laboratory in 1920–1921 were related to vortical flows (see § 6.2.1). In the early 1920s, Burgers' first three papers appeared in which the movement of bodies in fluids and the related resistance was treated: one on the distribution of vorticity around bodies, one on the connection between generated vortices and resistance, and his first attempt to tackle turbulent flow.

Though his mathematical skills proved of great value, he encountered several difficulties which led him to a search for new methods of attack. His work on vortices directed his attention to the theory developed by the Swedish physicist Oseen (see § 6.1). In the Annual Review of Fluid Mechanics of 1975, Burgers remembered: "A publication of 1920, in which patterns of flow around a body were discussed as resulting from the interplay (or 'competition') between convection of vorticity by the mean flow on one hand and diffusion of vorticity on the other, had helped me to see the meaning of Oseen's theory of flow around a body with its unexpected sheets of discontinuity, as a special case of a more general problem. [My approach] took away the strangeness of Oseen's solution and gave it a place as an instance of a method of treatment with wider possibilities."

Furthermore, Burgers could apply Oseen's theory to boundary layer theory: "I began to see a relation between certain aspects of Oseen's work and Prandtl's boundary layer theory, and I constructed an intermediate picture by making use of a transformation of the equations for two-dimensional flow, given by Boussinesq".

In a footnote to a paper of 1940, Burgers regarded an exact solution of the Navier-Stokes equation for which the vorticity can be written as (using cylindrical coordinates):

$$\omega = \frac{A\Gamma}{2\pi v}\exp\left(-\frac{Ar^2}{2v}\right)$$

where A is a constant, Γ is the circulation of the vortex, and ν is the viscosity. It still is one of the few exact solutions known and has since been called the 'Burgers vortex'. A remarkable feature of this structure is the fact that dissipation is independent of ν. Today there is a renewed interest in this flow phenomenon, due to the discovery of the emergence of high-vorticity regions concentrated in tube-like structures in turbulent flows. The tubes are generally interpreted as vortex tubes which are stretched and concentrated, in a manner analogous to the Burgers vortex.

EINDHOVEN

Since the late 1980s much research, both experimental and numerical, on vortices has been performed by Van Heijst (see § 4.1.2), Herman Clercx, and co-workers. He started this work when he was still at the Institute of Meteorology and Oceanography of the University of Utrecht and continued it at the TU Eindhoven. While in Utrecht Van Heijst became interested in ocean vortices.

One of the research projects was related to so-called 2D turbulence. Whereas in 3D turbulence energy is transferred from larger to smaller structures and the larger structures disappear in time, in situations where vortices can only move around in a flat space, the situation is the other way around. In 2D there is self-organisation into larger structures and an inverse energy cascade (energy flux to larger scales). This is clear from the coherent vortex structures which are formed in 2D situations and which are persistent. Large-scale atmospheric and oceanic flows are to a first approximation 2D and therefore the study of 2D vortices is an interesting field. The Eindhoven team succeeded in creating 2D turbulence by arousing a pattern of dozens of 2D vortices in an electrolytic liquid by means of magnets and electric wires causing Lorentz forces.

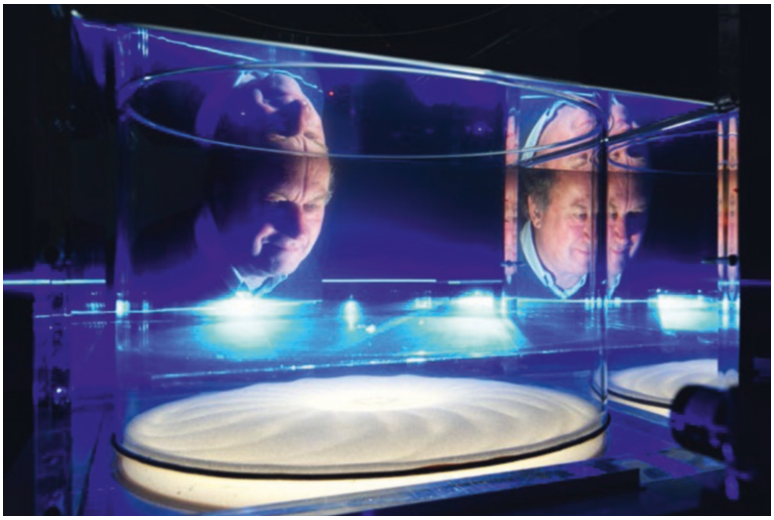
In the early 1990s research was done on dipolar and tripolar vortices and on the behaviour of 2D coherent vortex structures in stratified fluids. Van Heijst and his co-workers showed for the first time, in 1989, how tripoles could be made from a cyclonic vortex in a rotating fluid. The results gained in Eindhoven also shed light on what happens when 2D vortices encounter walls and the consequences of these effects for flows in the vertical direction, e.g., the displacement of suspended material and material lying on the bottom of the basin.

• 5.1.4 MIXING AND TRANSPORT PROCESSES

Burgers and his co-workers in Delft had never been involved in mixing and transport processes (transfer of mass, momentum, and heat) until in 1952 an engineer from India, Acharya, started to do experiments in the Laboratory on the 'momentum transfer and heat diffusion in the mixing of coaxial turbulent jets surrounded by a pipe'. Acharya was an aeronautical engineer who had somehow come into contact with Van der Hegge Zijnen. Probably Van der Hegge Zijnen had met the 'problem' of mixing coaxial jets after he had started to work for Shell (see § 3.3.2) and had suggested the subject to Acharya. The Indian would be Burgers' last PhD student in the Netherlands.

As for heat transfer, Van der Hegge Zijnen had been doing experiments on the spreading of heat from a hot-wire in a turbulent shear flow around 1950, in his laboratory at Shell. In 1951 he and Hinze had presented a paper about this research at a conference in London. In 1948 they had already presented results on the 'transfer of heat and matter in the turbulent mixing zone of an axially symmetric jet' at the 7th International Congress for Applied Mechanics, also in London.

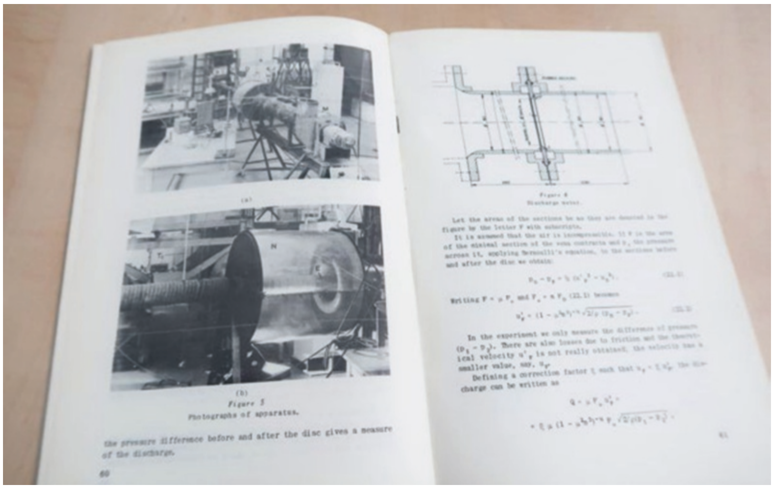
For many years, Shell was the company in the Netherlands which stimulated research into transport processes. As we have seen in § 3.3.2 Shell, or actually BPM, had an important role in the start of this research at the TH Delft. For more than a decade it was professor Kramers who would lead this research and would become well-known as an expert in



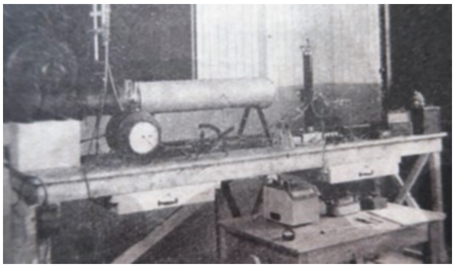
↑Van Heijst observes the pattern formation in a sediment layer, driven by a large vortex flow in his laboratory in Eindhoven. (courtesy of TU Eindhoven archives / photo by Bart van Overbeeke)

→The Earth's rotation has an influence of many a flow phenomenon in nature. In the WL in Delft model experiments were run on large water areas for which this rotation could not be neglected. To scale down the rotation in a simple but effective manner, rotating rods were placed in the water. These rods were introduced by WL director Schoemaker in the 1950s; before, one had to use large turning tables to simulate the Earth's rotation. This photo was taken during a visit of the King and Queen of Thailand to the WL in 1960. (courtesy of TU Delft / photo by Fotografishe Dienst via Beeldarchief / CC BY)

↑The Van Heijst group in Eindhoven became famous for the attractive visualisations of two merging, and later separating, counter-rotating monopolar vortices. The most common coherent structures are the axisymmetric (monopolar) vortex, with circular streamlines, and the vortex dipole, both of which have been found to arise in a variety of situations under different forcing conditions. The photo on this calendar shows the result of a head-on collision of two dipolar vortices in a stratified fluid environment. The original vortices have exchanged a partner to form two new dipoles. This result was published in *Nature* in 1989 and reached the Nature calendar for 1990, as can still be seen in Van Heijst's office. (courtesy of TU Eindhoven / GertJan van Heijst)



↑The experimental set-up as used by Acharya in Delft and shown in his thesis: two jets are produced at opposite locations and they meet in the big drum in the middle. (courtesy of Burgers Archives / TU Delft)



↑At the end of the 1940s Hinze and Van der Hegge Zijnen were both working at Shell's laboratory in Delft/Rijswijk. One of their joint projects concerned the transfer of heat and matter in the turbulent mixing zone of an axially symmetric jet. This photo of their experimental facility was published in their paper in the very first volume of *Applied Scientific Research A* (see § 6.1). (courtesy of Springer Nature)

ROBERT B. BIRD ON HANS KRAMERS

Hendrik ('Hans') Kramers was to play an important role in the development of fluid dynamics in the Netherlands. He was the son of the Islamic scholar J. H. Kramers and the nephew of the famous theoretical physicist H. A. Kramers, both professors at the University of Leiden. From 1934 to 1941 he was a student at what would later be called the Technical University of Delft. After working for several years at the TNO (Organization for Applied Scientific Research) in Delft, and at Royal Dutch Shell in Amsterdam, in 1948 he was appointed at the very young age of 30 to a professorship in Delft to develop the field of engineering physics, with emphasis on fluid dynamics, transport phenomena, chemical engineering kinetics, and process control.

Fluid dynamics, heat transfer, and mass transfer are all subjects which were developed in Europe. However, these subjects are often intertwined: it is very seldom that one of these occurs entirely alone. Hans Kramers was possibly the first professor in Europe to recognize that the three topics above should be taught in a single course, so that students could take advantage of the similarities (and differences) between the three. The mathematics used in the three areas is very similar. In 1956, Hans turned out a set of mimeographed notes entitled Physische Transportverschijnselen to use in teaching the subject of transport phenomena to engineering students.

At the same time, he and his students were pursuing experimental studies of subjects, primarily in the area of mass transfer and diffusion:

- S. Lynn, J. R. Straatemeier, and H. Kramers, Chem. Eng. Sci., 4, 49-67 (1955): diffusion into a falling liquid film (gas absorption);
- H. Groothuis and H. Kramers, Chem. Eng. Sci. 4, 17-25 (1955): mass-transfer rates during drop formation at a capillary tip;
- H. Kramers and P. J. Kreyger, Chem. Eng. Sci., 6, 42-48 (1956): diffusion into a falling liquid film (solid dissolution).

Hans had very close relations with Professor P. V. Danckwerts at Cambridge University in England. These two, although very different in personality, exchanged many ideas about mass transfer and diffusion through the years. Perhaps this interaction influenced some of the experimental set-ups in Hans's laboratory.

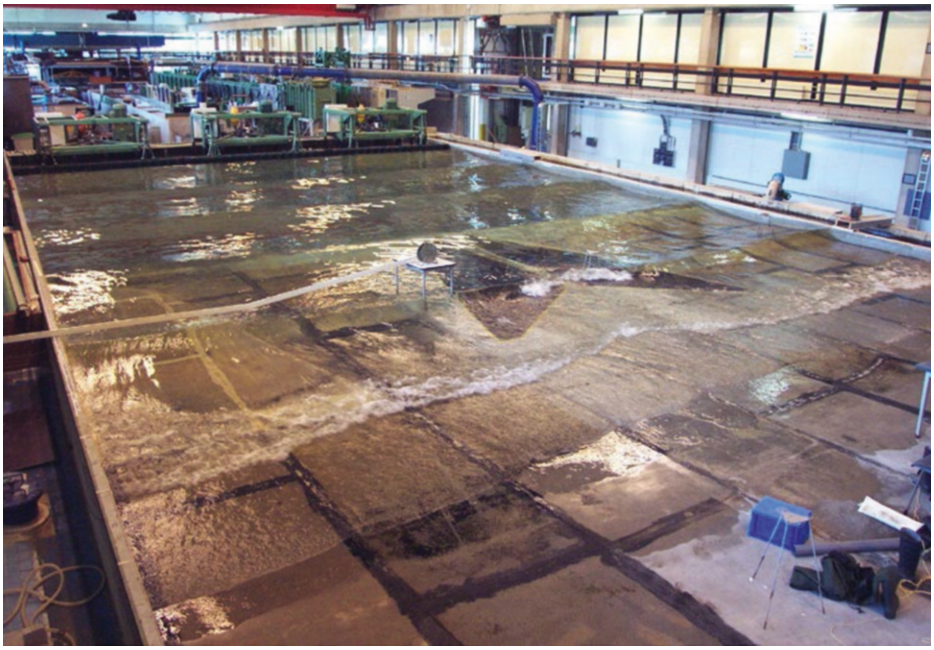
Since I had been teaching transport phenomena to graduate students since 1953 and began work on a course for undergraduates in 1957 (see Recent Advances in the Engineering Sciences, McGraw-Hill, New York (1958), pp. 155–177), I decided to apply for a Fulbright lectureship, and take a sabbatical to spend the spring of 1958 at Kramers' laboratory in Delft. He invited me to give a set of lectures during that period. That was very easy for me to do, inasmuch as W. E. Stewart and E. N. Lightfoot had joined me in preparing a first draft of what would become our textbook entitled Transport Phenomena.

I quite enjoyed interacting with Hans. He kindly offered me a room in his house, and we would walk together from his home to the lab every day and discuss many topics of mutual interest. I was intrigued by the many laboratory experiments that he had his students working on, particularly in the field of mass transfer. I was also interested in noticing the friendly way that he interacted with his students, and how much they respected him. Although he could be quite strict and critical, he always did this with a smile and a twinkle in his eye. He guided 164 students to the 'Ir.' (Engineer) degree, and 15 to the doctorate, of whom 10 went on to become professors themselves. Many of his students became prominent in research, engineering, and management.

There is no question that Hans's unification of the field of transport phenomena played an important role in the advancement of the design and operation of the industrial processes in the field of chemical technology. Of equal importance is his work in the field of fluid dynamics with chemical reactions. This work was summarized in the monograph Elements of Chemical Reactor Design and Operation by H. Kramers and K. R. Westerterp, Netherlands University Press (1968).

Hans' accomplishments have been recognized by election to the Royal Netherlands Academy of Sciences, an honorary doctorate from the Eindhoven University, honorary foreign member of the National Academy of Engineering (USA), a Knight of the Order of the Lion (Netherlands), and many others.

↑On July 2, 1963 Kramers gave his farewell lecture at the TH Delft. He told his audience that it was important to keep the training of students in research skills at a sufficiently high level. Notice the elementary mixing process drawn by Kramers on the chalkboard. (courtesy of TU Delft / photo by Fotografishe Dienst TU Delft via Beeldarchief / CC BY)



←In the large basin in the Stevin III Laboratory – today called Waterlab – of the Department of Civil Engineering in Delft waves could be studied. This photo was taken around 2005, when Battjes had already retired. Some five years later the basin was removed for financial reasons. (courtesy of Delft University of Technology)

the field which has become known as transport phenomena (‘fysische transportverschijnselen’ in Dutch).

Transfer processes in boundary layers were also studied at Shell, as is evidenced by a paper by Merk, published in the Journal of Fluid Mechanics in 1959. As we have seen in § 4.1.1 Merk had already been working on heat and mass transfer before he came to work with Shell. While professor in Delft from the early 1960s Merk turned to the field of rheology. From about 1970 he also started to lecture on and write about TIP: the thermodynamics of irreversible processes. Together with Gerard Kuiken, Merk has given a clear derivation of the Maxwell-Stefan diffusion equations and he has applied the TIP theory to rheology.

• 5.1.5 FREE-SURFACE PHENOMENA

Two phenomena involving a free surface (a surface with zero parallel shear stress) have a long tradition in the Netherlands: surface water waves and droplets. The first topic was, and still is, a field of interest for engineers and scientists working in hydraulics and the branch of fluid mechanics related to hydraulics. The interest in the second topic started mainly in the industrial world of process technology.

WAVES

Burgers never worked on either of these phenomena. It seems that only at the KNMI some interest in the theory of waves existed, at least from the 1940s. Timman got interested in waves due to his work on ship hydrodynamics (see § 6.1). Broer, who had been Burgers’ colleague for some years (see § 4.1.1), started with the mathematical approach to waves when he was still in Delft (with a paper entitled ‘On the propagation of energy in linear conservative waves’), but only became seriously involved in wave theory (which was not only applicable to water waves) after he had moved to Eindhoven in the 1960s. One of his PhD students there was Brenny van Groesen (1949) who became professor at the University of Twente. Van Groesen became a colleague of Zandbergen (see § 4.1.3) and the group called Applied Analysis & Mathematical Physics became known partly for its work on waves and their numerical simulation. One of the activities of this group has been a collaboration with researchers in hydraulics in Bandung, Indonesia.
It seems that the serious study of water waves only got its momentum in the 1970s, with the appointment of Battjes in Delft (see § 4.1.1) and a growing interest in waves at the WL. One of Battjes’ achievements has been a mathematical model for the dissipation of energy during the breaking of (irregular) waves. Battjes’ theoretical predictions were compared to the results of experiments performed by a student named Hans Janssen and therefore the model has become known as the Battjes-Janssen model. It became famous around the world and has since been used by wave researchers. Later, the model was integrated in a more comprehensive wave simulation program. The making of the program was financed by the US Navy, which insisted that it would become open source. The model became known as SWAN; it has been used worldwide and is now in its third ‘generation’.

Sloshing is a phenomenon related to wave behaviour. To study such a phenomenon without the hindrance of gravity forces, an environment of so-called microgravity is needed. One of the possibilities of creating such an environment is the performance of experiments aboard a space vehicle. The

NLR became involved in the numerical simulation of sloshing from the late 1970s when such an experiment was carried out aboard a satellite. But numerical techniques were still limited at that time and only simple 2D models of liquid motion under microgravity could be studied. A major boost took place in 1995 with the development by the FLEVO (Facility for Liquid Experimentation and Verification in Orbit) of the Sloshsat which was launched in 2005. It was a mini-satellite designed and built by the NLR to experimentally study liquid dynamics in a water tank onboard the spacecraft. Numerical researchers at the University of Groningen started simulations of the sloshing phenomenon. The development of their simulation method for fully 3D free-surface flow became known as ComFlow (see also § 6.3).

DROPLETS

When Hinze still worked for Shell in the 1950s, he derived an expression to predict the maximum size of droplets in a turbulent flow. In the formula, published in 1955, one can find a model constant, the interfacial tension at the droplet surface, the density of the carrier fluid, and the so-called turbulence dissipation rate. This correlation is still used in engineering design codes to determine, for example, the efficiency of separation processes.

For a long time it was impossible to compare (numerical) models of droplets with experimental observations. Only with the arrival of sophisticated high-speed cameras could progress be made. It was Lohse in Twente who was one of the first to acquire such cameras and to build a facility in which moving images of the deformation of droplets could be made. One of the well-known images from Twente shows the 'splashing' of a droplet which enters a liquid surface.

• 5.1.6 COMPRESSIBLE FLOWS

Compressible flows are those in which the changes in pressure from place to place in the flow are so large that the density of the fluid is changed. These flows present special difficulties: shock waves can arise which move faster than the speed of sound, and temperatures can be high and non-uniform, causing a number of effects that are difficult to predict. Compressible flows are well-known from aeronautics but there are many other areas where they occur, such as in vacuum technology and certain manufacturing processes.

ACADEMIC RESEARCH

During the 1920s and 1930s, Burgers' interest was completely restricted to incompressible flow. Though the interest of fluid dynamics scientists in compressible flows had been stimulated during the 1930s by, e.g., some papers of G.I. Taylor, it was only during the Second World War that this field of research really got full attention due to the development of (supersonic) war aircraft and missiles.

Characteristically, Burgers' approach to a field of research unknown to him was to start his first paper (1943) with a relatively simple (i.e., one-dimensional) problem. In papers of the late 1940s, Burgers continued the study of shock waves and their interaction. He also hoped to establish a new experimental direction for his Laboratory with shock tubes. Shortly before the Second World War, agreements had been signed with the NLL: Burgers' laboratory would study supersonic flow, while the NLL would restrict its attention to subsonic flows. However, after the War the NLL also took up supersonic aerodynamics (see § 4.2.4 and 6.2.2). Furthermore, the TH Delft decided that work in this area had to be concentrated in the new Department of Aeronautical Engineering. For Burgers, this must have been another frustration which strengthened him in his decision to leave Delft.

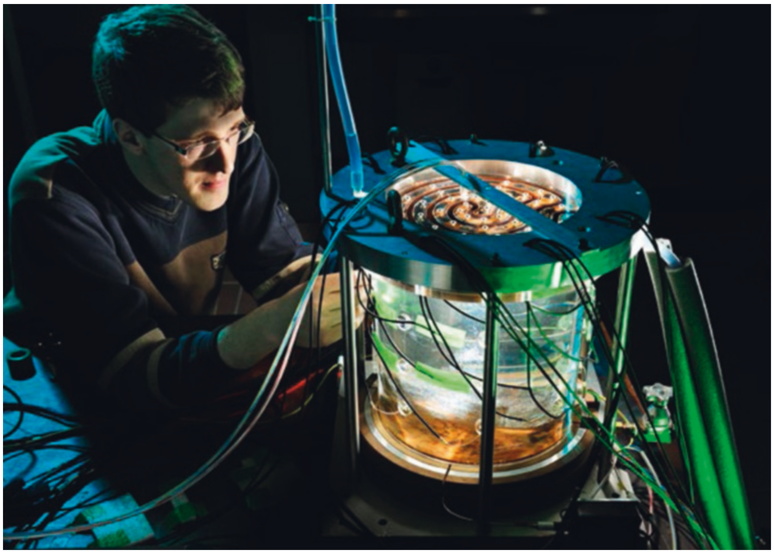
During the same period, Burgers also got interested in gas dynamics, a subject which brought him somewhat back to his origin as a theoretical physicist. This interest was stimulated by his acquaintance with problems related to cosmic or astrophysical fluid mechanics. In the 1940s the Dutch Astronomers Club invited him to give a lecture on the borderlands between fluid mechanics and astronomy and there he met the famous Dutch astronomer Jan Oort. Stimulated by Oort, who supplied the astrophysical data, Burgers started working on turbulence in rotating interstellar gas masses. After his emigration to the USA in 1955, Burgers began to specialize in hypersonic aerodynamics. He started a seminar on high-speed and high temperature flow problems and studied the relation between the Boltzmann equation for gaseous systems and the equations of fluid dynamics. In 1969, aged 74, his book Flow equations for composite gases appeared.

From about 1950 Burgers' colleague Broer had also started the study of shock waves. In the late 1950s the Laboratory for Aerodynamics and Hydrodynamics did indeed own a small shock tube in which shock waves could be studied. One of the topics on which Broer wrote was acoustic relaxation, a phenomenon that was studied (also experimentally) from about 1970 in the group of professor Vossers in Eindhoven, by Rini van Dongen and others. Leen Noordzij in Twente studied shock waves in mixtures of liquids and bubbles under the guidance of Van Wijngaarden.

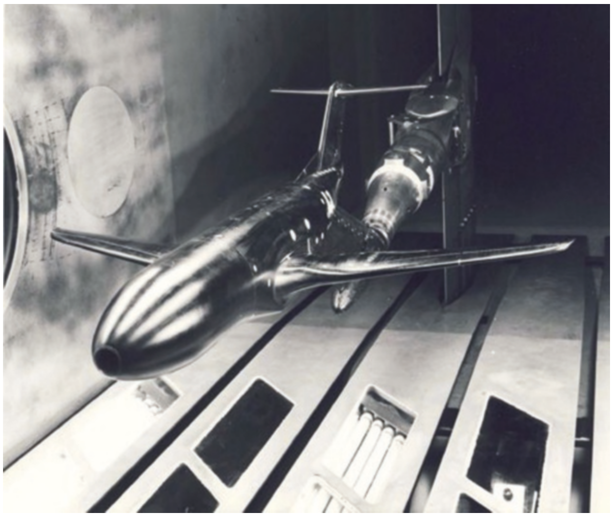
SUPERCRITICAL WINGS

During the period after the Second World War the aeronautical world was confronted with the so-called 'sound barrier', the rapid drag increase at high transonic speeds (i.e., just under the speed of sound) and the occurrence of shock waves in the flow around wings. These shock waves were caused by the supersonic flow over the wings. The formation of shock waves was delayed with increasing speed by changing the sweep angle of the wings. Highly swept-back wings, however, had aerodynamic and structural disadvantages. Vague ideas arose

↑Lohse with a photo showing results of one of his experiments on droplets. On the wall a splashing droplet can be seen. (courtesy of Océ / photo by Gijs van Ouwerkerk)



↑Richard Stevens was one of Lohse's co-workers during the research on the Rayleigh-Bénard convection cell. Their experiments were (partly) performed in the USA, but here Stevens is seen with an RB cell of the TU Eindhoven. (courtesy of TU Eindhoven archives / photo by Bart van Overbeeke)



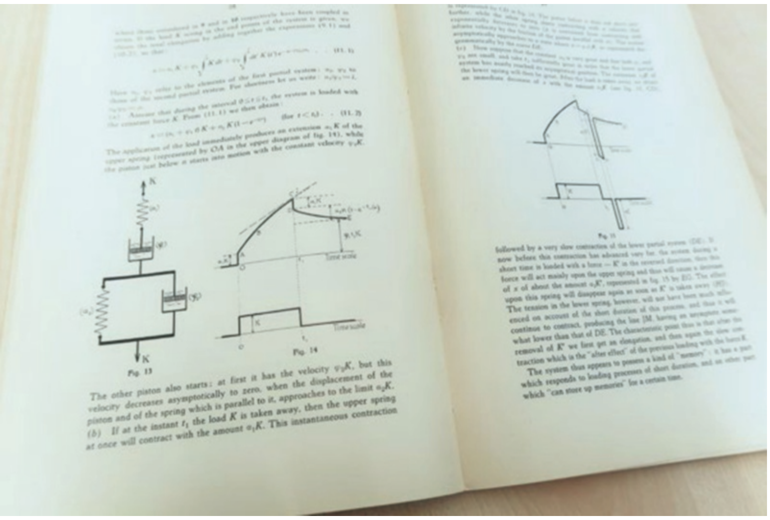
←The first supercritical wing designed by the NLR was the result of a collaborative study with Fokker. Here the wings are tested in the High-Speed Wind Tunnel of the NLR in Amsterdam. (courtesy of Stichting Behoud Erfgoed NLR)

about other means of delaying the occurrence of shock waves. Around 1960 the NLR started, as the first institute in the world, to develop shock-free aerofoils along theoretical lines, that is aerofoils with local supersonic flow on which no shock waves would appear when the local supersonic flow decelerated to subsonic flow. Several scientists at the NLR started to work on the problem. In 1967 they could show that it was theoretically possible to design shock-free transonic aerofoils and that these flows were stable. Thereafter methods were developed for the design of real 3D wings. These activities were carried out in the late 1960s when the digital computer gradually became of age and when it became possible to compute the aerodynamic forces on complete wings and aircraft configurations. In the same period wind tunnel experiments were performed which showed that the new aerofoil design was indeed shockwave-free. From 1969 feasibility studies were carried out in cooperation with Fokker in order to arrive at wing designs which could be incorporated in a civil transport aircraft. During the period 1975–1977 several wing-body configurations were designed and tested in one of the NLR wind tunnels. The final result of all the years of research (and millions of guilders) on the supercritical wing was the construction of the successful Fokker F100 in 1983–1984.

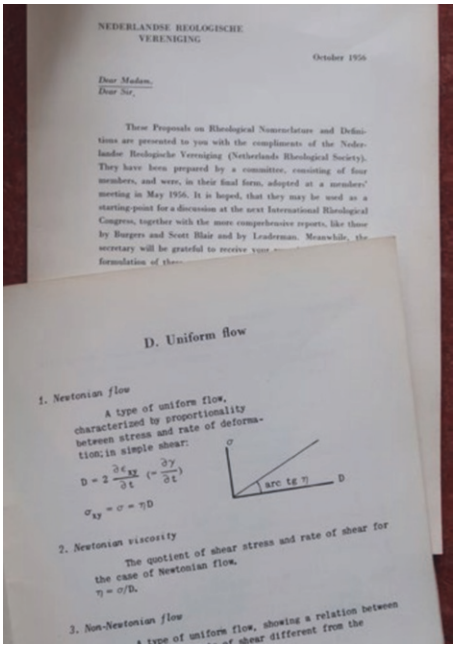
• 5.1.7 BUOYANCY DRIVEN FLOWS

The density of flowing material can differ from place to place, because of temperature variations or because the composition is not uniform. Where the density is lower, the material tends to rise, where it is higher, the material tends to sink. A flow produced by these effects is called buoyant convection (a term which doesn't have a really satisfying translation in Dutch, by the way). Buoyancy driven flows can occur in heated rooms, around fires, in energy storage systems, inside the planet Earth and in atmospheric and oceanic systems.

Many geophysical and astronomical phenomena are driven by highly turbulent fluid dynamics. These dynamical flows are of-



↑In the *First Report on Viscosity and Plasticity* (1935) Burgers introduced a combination of already existing models for visco-elastic materials. This new model has been called after Burgers for some time but today it seems to have become obsolete. Burgers stressed the fact that this model had “a kind of ‘memory’”. (courtesy of Burgers Archives / Delft University of Technology)



NEDERLANDSE REOLOGISCHE
VERENIGING

October 1956

Dear Madam,
Dear Sir,

These Proposals on Rheological Nomenclature and Definitions are presented to you with the compliments of the Nederlandse Reologische Vereniging (Netherlands Rheological Society). They have been prepared by a committee, consisting of four members, and were, in their final form, adopted at a members' meeting in May 1956. It is hoped, that they may be used as a starting-point for a discussion at the next International Rheological Congress, together with the more comprehensive reports, like those by Burgers and Scott Blair and by Leaderman. Meanwhile, the secretary will be grateful to receive your

formulation of the

D. Uniform flow

1. *Newtonian flow*

A type of uniform flow, characterized by proportionality between stress and rate of deformation; in simple shear:

$$D = 2\frac{\partial \epsilon_{xy}}{\partial t} \left(= \frac{\partial \gamma}{\partial t}\right)$$

$$\sigma_{xy} = \sigma = \eta D$$

2. *Newtonian viscosity*

The quotient of shear stress and rate of shear for the case of Newtonian flow.
$\eta = \sigma/D$.

3. *Non-Newtonian flow*

A type of uniform flow, showing a relation between
of shear different from the

↑The Dutch Rheological Society was founded in 1951 and continued the work of the Viscosity Committee with regard to nomenclature. This booklet was published in 1956. (courtesy of Ned. Reologische Ver.)

ten driven by the buoyant rising and falling of fluids of different densities and strongly affected by the rotation of the celestial body through Coriolis forces.

In the Netherlands, the amount of research projects on heat transfer by convection had been small as compared to other fields of fluid mechanics. De Vries (see § 4.1.2) had been working on this theme from the late 1950s, and Hoogendoorn (see § 4.1.1) started a new group which would study convection, by means of experiments and numerical simulations, in the early 1970s. It is not surprising that both professors took the initiative, in 1971, to start a Contact Group for Fundamental Heat Transport.

The instrument to study convection has been, for over a century, the so-called Rayleigh-Bénard convection cell: a simple container filled with liquid or gas, heated at the bottom and cooled at the top. In the 1990s most researchers considered the basic theory of the convection in this cell as basically solved. That is, the relationship between the so-called Nusselt number (an indication for the heat transport) and the Rayleigh number (an indication for the temperature difference) was known and unambiguous. But around 2000 Lohse (University of Twente) and others came with a new theory. The main idea of this was to decompose the energy dissipation rate and the thermal dissipation rate into their boundary layer and bulk contributions. From experiments and numerical simulations, also on rotating Rayleigh-Bénard cells, they discovered that the relationship between Nu and Ra was not unambiguous and apparently, different turbulent regimes could occur inside the cell.

5.2 FLOWS OF NON-NEWTONIAN MATERIALS (RHEOLOGY)

Though it must have been clear long before the 1920s that the flow behaviour of liquids like blood and paint (which are now called non-Newtonian) was different from that of water, it was only then that the first publications appeared and the name ‘rheology’ was introduced (which would finally become ‘reologie’ in Dutch, without the ‘h’).

The Dutch Rheological Society was founded in 1951, by the Royal Netherlands Academy of Arts and Sciences. Before this Dutch scientists had already been involved in research, mainly theoretical, which we would now indicate as ‘rheological’ but this term was only used from the 1950s. Today the Society is a member of the Bond voor Materialenkennis (Alliance for Knowledge of Materials), which makes clear that rheology is not just a branch of fluid mechanics. Most of all rheology is about the characteristics of non-Newtonian materials which include an important number of interesting liquids such as molten polymers.

• 5.2.1 EARLY DEVELOPMENTS IN DELFT

The area of plastic deformation had become attractive to many of the scientists working in fluid mechanics from the 1920s (e.g., Von Kármán, Taylor, and Prandtl). Burgers got an opportunity to become engaged in research in this area when in 1932-1933 the KNAW (at the instigation of Kruyt) installed the Viscosity Committee, consisting of researchers from several fields: physics, mechanics, chemistry (especially colloid chemistry), and biology. Its purposes were rather ambitious: to gather information regarding the phenomena of viscous and plastic deformation, so as they present themselves in various domains of physics, chemistry, technology, and biology; to investigate the relations existing between these phenomena; to make proposals for a nomenclature which should obviate existing uncertainties in the various domains; and to study the methods used for measurements of viscosity and of related properties of matter. Burgers, as the representative for mechanics, became the secretary of the Committee. During the 1930s, two impressive reports were published, i.e. the first and the second Report on Viscosity and Plasticity.

Viscoelastic materials can be modelled by representing the molecules as a combination of viscous dampers and elastic springs. In the First Report on Viscosity and Plasticity (1935), Burgers introduced a rheological model combining the older Maxwell and Kelvin-Voigt models. In 1956, the term 'Burgers element' was proposed by the Nomenclature Committee of the Dutch Rheological Society for this model, though today usually the term 'Burgers body' of 'Burgers fluid' is used. This model appeared to describe the response of materials such as asphalt and concrete quite well and has also enjoyed a good deal of popularity in the field of geomechanics.

In the post-war period, Burgers remained active in rheology. He became editor-in-chief of the Monographs on Rheology, founded in 1948 and published by publishing house North Holland. Furthermore, he was active, with Houwink of TNO and others, in the organisation of the First International Congress on Rheology, held in 1948 in Scheveningen (near The Hague). The Dutch contributions to this congress show the broad range of topics which were discussed: two engineers from the State Mines on the measuring of viscosity of settling suspensions; Jan (J.J.) Hermans (who became an expert in polymers) on swelling; two engineers from the Rubber Institute of TNO on the rheological properties of rubber; a researcher from the Algemeene Kunstzijde Unie (later AKZO) on the optical relaxation times in cellulose solutions; and a researcher from the Institute for Graphical Technology of TNO on 'typographic inks'.

Burgers also became secretary of the Joint Committee on Rheology of the International Council of Scientific Unions. For this Committee he wrote a paper, with the British rheologist Scott Blair, on rheological nomenclature. In 1964, when his interest in rheology had already diminished away, he was awarded the Bingham Medal of the Society of Rheology.

Of Burgers' work in rheology published after 1940, we mention one paper which had actually been a kind of occasional project. The Dutch colloid-chemist Hendrik Bungenberg de Jong (who had contributed to the first report of the Viscosity Committee) had performed experiments on the oscillatory movements presented by certain soap solutions in spherical vessels and asked Burgers for a theoretical treatment. This paper again shows Burgers' remarkable ability to handle a seemingly complex problem by using a range of mathematical tools, leading to a useful (instead of general) solution of the problem.

In the 1950s research on rheological topics was still scarce in the Netherlands. One of the first PhD theses in which rheology played an important role was published in Delft in 1951. It concerned a 'colloid chemical and rheological study' of drilling fluids. The research was partly done at KSLA and financially supported by the BPM. Burgers himself was one of the two supervisors (the other was a chemistry professor) of the research leading, in 1954, to the PhD thesis entitled Investigations on the rheological properties of clay (in Dutch).

Professor Broer, whose publications were on a broad range of topics when he held the chair in Delft, also wrote on the flow of visco-elastic fluids (see also § 6.1). But it was Broer's successor, Merk, who would give rheology and non-Newtonian fluids a more lasting status in the Laboratory of Aerodynamics and Hydrodynamics; his inaugural lecture of 1962 was about rheological models. In the 1960s interest in visco-elastic fluids also started to grow among the chemists in Delft (see § 5.2.3). In the Kramers Laboratory, for example, experiments on polymer melts were started.

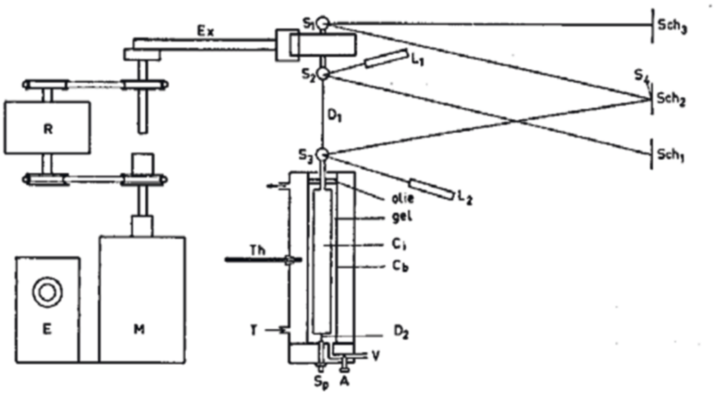
• 5.2.2 MORE RECENT DEVELOPMENTS

An activity somewhat related to rheology and with a long tradition is rheometry: measuring the properties (such as viscosity) of non-Newtonian materials. For these measurements special instruments have been used and developed, called rheometers. In the Netherlands rheometers have been developed at diverse places: TNO (during the 1960s), Unilever (see also § 4.3), the Laboratory of Physical Colloid Chemistry of the University of Wageningen (see also § 4.1), etc.

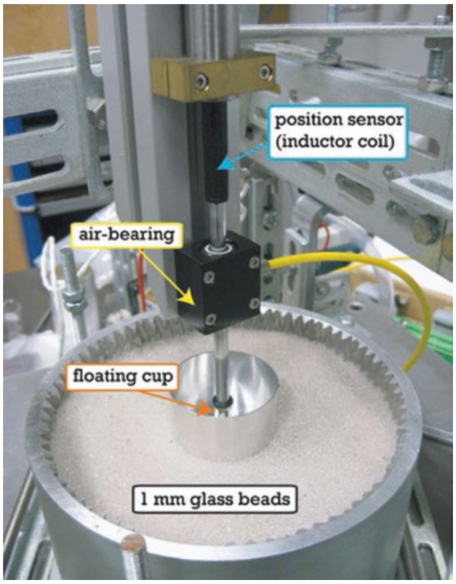
Colloid research has a long tradition with the University of Utrecht (see § 4.1.4) and Wageningen. Another place where colloids have been studied, was the University of Twente. The group of Mellema (see § 4.1.3) studied colloidal hard spheres dispersions and in the 1980s he, in cooperation with the colloid researchers in Utrecht, discovered their visco-elastic behaviour.

In his inaugural lecture of 1992 Mellema made a number of observations on the situation with regard to rheology in The Netherlands at that time:

- rheology had for a long time been a field of research which was almost exclusively populated by chemists



↑This rheometer was developed by TNO and used by several researchers, e.g., Herman Beltman for his PhD work related to "the influence of polymers on the rheology of aqueous systems" (Wageningen 1975). In the colloid group in Wageningen these kinds of measurements were usually related to research on foodstuffs. M is the engine which drives a cylinder Ci. The fluid is introduced between Ci and the cylinder Cb. Ci oscillates at various amplitudes. By means of lamps M and mirrors S light beams are pointed towards the scales Sch. The values read on these scales can be used to calculate the viscosity. (from: Beltman (1975))



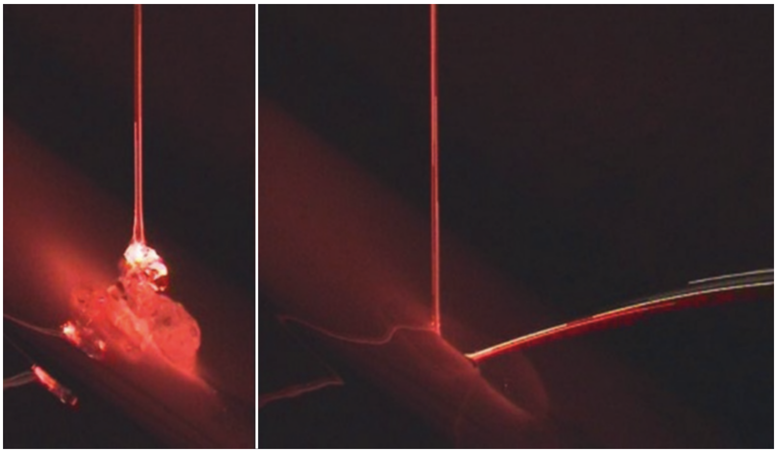
↑In the Leiden laboratory of Van Hecke experimental facilities like this have been used to study the behaviour of granular materials. If the material was stirred locally, it started to behave in a liquid-like manner and an effective viscosity could be determined for the system. It turned out that the granular medium used here is non-Newtonian. (from: Nichol (2011) / courtesy of Kiri Nichol)

but physicists were starting to become involved in this research also;

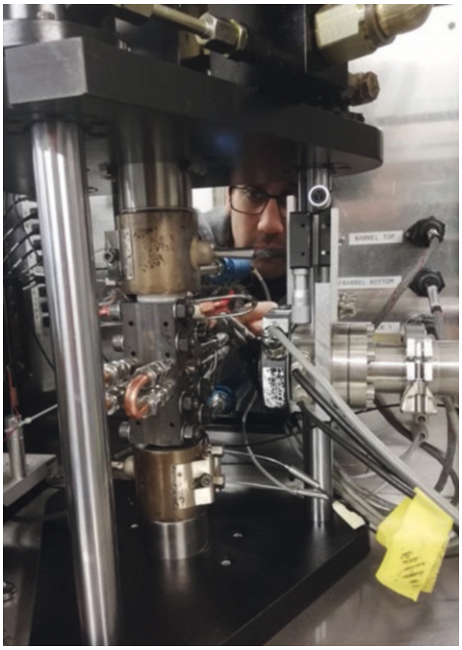
- there was still little collaboration between theorists and experimenters (which was also valid for fields outside rheology);
- rheology was finally getting recognition in the world of fluid mechanics.

This growing recognition was also due to work done in Delft and Eindhoven. In Delft Martien Hulsen started to develop numerical methods for flows of visco-elastic fluids from about 1985, under the supervision of professor Wesseling of the Department of Applied Mathematics but actually working in the Laboratory of Aerodynamics and Hydrodynamics. In his PhD thesis (1988) he showed that there was still a long way to go before numerical methods would be fast and reliable. In the 1990s Hulsen and colleagues started simulations of viscoelastic fluid flows using Brownian configuration fields, after it had become clear that a macroscopic approach based on the constitutive equations had serious restrictions. Only from the mid 1990s computer technology allowed a microscopic approach of the simulations. After Merk's retirement it took several years before the chair of Rheology was occupied again: in 1994 Ben van den Brule started a part-time professorship in Delft. Van den Brule, who had been a student of Van Wijngaarden in Twente, had worked on polymers at the Philips company and later worked for Shell where polymers are studied which can be helpful in enhanced oil recovery. A rather new field of research related to rheology was that of granular materials, particles which are much larger than the particles of colloid suspensions. In 2007 FOM initiated a research program named Rheophysics. Goal of this program was a better understanding of the behaviour of so-called 'yield stress fluids': fluids (like shaving foam) which can show the behaviour of both a solid and a liquid. The transition from a liquid phase to a solid phase is called jamming and this phenomenon was investigated by professor Martin van Hecke and co-workers at the University of Leiden.

Several surprising phenomena related to non-Newtonian fluids have puzzled researchers for decades. As for so-called shear-thinning fluids this was the case with the Kaye effect. This effect occurs when a thin stream of a solution of such a fluid is poured into a dish of the fluid. As pouring proceeds, a small stream of liquid occasionally leaps upward from the heap. Michel Versluis of the University of Twente and co-workers showed that the Kaye effect works for many common fluids, including shampoos and liquid soaps. Around 2006 they revealed its physical mechanism through high-speed imaging. Their measurements could be interpreted with a simple theoretical model including only the shear thinning behaviour of the liquid; elastic properties of the liquid appeared to play no role. One of their videos of the Physics



↑Shots from a video made with a high-speed camera of the Kaye effect at the University of Twente around 2006. (courtesy of Twente University / Michel Versluis)



↑This so-called multipass rheometer has been made and is used by the Polymer Technology group of the TU Eindhoven. This meter has a special slit (6 mm x 1.5 mm) which makes it possible to perform rheological and X-ray measurements at the same time. Since a very strong X-ray beam is necessary, the researchers have to take this instrument to European Synchrotron Radiation Facilities in Grenoble (France). With this rheometer the crystallization of polymers during their flow can be followed. (courtesy of Polymer Technology, Mechanical Engineering, TU Eindhoven)

of Fluids group of the UT was awarded, not for the first time, in the Gallery of Fluid Motion competition, organized by the *Physics of Fluids* journal.

• 5.2.3 POLYMERS

Research on the behaviour of molten non-Newtonian materials in production machines like extruders became very important after polymers had become widely used in both daily life and industry (e.g. as catalysts). But already during the Second World War Burgers got involved in a problem which can be regarded as closely related. An industrial company from Arnhem asked him to give suggestions for the improvement of the production of fibres from molten silicate for the production of glass wool. These fibres were produced by spraying the molten glass by means of steam jets. Burgers took up the problem, wrote a report but had to conclude that the changing viscosity of the silicate (due to a changing temperature) and other circumstances led to a flow problem which could not be solved with the existing theories.

As for the extrusion and molding process with polymers, finding a theory was even more challenging. The behaviour of molten polymers is hard to predict since they possess a ‘memory’: in such a liquid the momentary stress is determined by the complete deformation history the fluid has experienced. Besides, the interaction of the melt with the walls along which it is flowing, e.g., in extrusion processes, has appeared to be determining and can result in instabilities of the extruded fibres.

In the Netherlands, basic knowledge of the mechanical and thermodynamic behaviour of amorphous polymers was established mainly at the Plastics Institute of TNO during the 1950s and 1960s. Roelof Houwink (1897–1988) became a well-known polymer scientist at TNO. He had been educated in, had worked at Phillips since 1925 and from 1939 was director-general of the TNO’s Rubber Institute in Delft. At the suggestion of Henri Brinkman (of the Brinkman number; see the introduction of § 6.2) a working group for fundamental extrusion research was established at the Central Laboratory of TNO in the 1960s.

One of the TNO researchers was Hermann Janeschitz-Kriegl (1924-2018), from Austria. In 1969 he became professor of ‘Physics and Chemistry of Macromolecular Materials’ in Delft and he has been called – by professor Frits Dijksman (Twente) - one of the founding fathers of ‘industrial rheology as a science in the Netherlands and elsewhere’. Janeschitz-Kriegl was the promotor when Robert B. Bird (see § 5.1.4) became doctor honoris causa in Delft in 1977 “for his excellent merits in the field of physical transport phenomena in general and of the rheology of macromolecular liquids in particular”. In Twente professor Van der Wallen Mijnlieff (see § 4.1.3) did research on macromolecular systems, including polymer solutions, but seems to have published little.

At the University of Eindhoven rheology really got a boost in the 1990s from the Polymer Technology group. Although research on polymers had been carried out in Eindhoven from the early 1970s, an important upscaling of rheology-related research took place after 'computational rheology' reached a higher level in the 1990s and 2000s (Hulsen moved from Delft to Eindhoven in 2001). Eindhoven became the 'secretary' of the Dutch 'onderzoekschool' (research school) for polymer technology which was founded in 1994 and which became Eindhoven Polymer Laboratories some ten years later.

From the 1990s Dutch researchers developed two new simulation techniques with which a microscopic modelling of the polymers can be combined with the simulation of a complex flow in macroscopic domains. The first one is the so-called Brownian configuration field method (already mentioned in § 5.2.2) and the other the so-called deformation field approach. From about 2005 numerical simulation of non-Newtonian liquids reached the 'adult' phase. In 2016 polymer researchers from Eindhoven were the first to perform 3D direct numerical simulations of the alignment of two and three rigid, non-Brownian particles in a viscoelastic shear flow.

In the 1990s polymers also got attention from the fluid mechanics community for a different reason. As has already been remarked in § 5.1.2 research was started into the influence of polymers on drag reduction in turbulent flows. Jaap den Toonder (who became professor of Microsystems in Eindhoven) did experimental and numerical studies on turbulent pipe flows and concluded in his PhD thesis of 1995 that "the key property for drag reduction by polymer additives is the purely viscous anisotropic stress introduced by the extended polymers, while elasticity has an adverse effect on the drag reduction".

Around 2003 Daniel Bonn, then in Paris and later professor at the University of Amsterdam, discovered that so-called melt fracture ('smeltbreuk' in Dutch) is inherent to the flow of molten polymers in the tube during the extrusion process. Up to that time, engineers had supposed that fracture was due to circumstances at the entrance of the tube or at the exit of the tube. Research in Leiden and Paris showed that above a certain critical value of the ratio of elastic and viscous forces, turbulence would develop inside the molten polymer in the tube.

5.3 TWO-PHASE FLOWS

Though many single-phase flows still give researchers enough work (and headaches), some researchers have also turned their attention to flows which are usually even more complicated: flows in which liquids, gases and solid particles come together in a huge number of variations. The famous British fluid mechanicist George Batchelor sketched the situation as it was in 1971: "As a newcomer to the field [i.e., two-phase flows], I can take the position of the small boy in the fable about the emperor's new clothes and say that I see no subject. There are technical problems in abundance, intriguing observations, puzzling phenomena, and some scraps of theory about specific features, but not yet the kind of secure foundations and body of theory which turn a collection of particular problems into a subject". Despite these rather scaring prospects, Batchelor succeeded in contributing to the field, as did several researchers in the Netherlands.

• 5.3.1 EARLY DEVELOPMENTS

For the *Second Report on Viscosity and Plasticity* of the Viscosity Committee (1938; see § 5.2), Burgers had written a contribution on 'the motion of small particles of elongated form, suspended in a viscous liquid'. In 1940 he took up the subject of suspensions again when he had noticed that others had applied some of his formulae but found discrepancies between theoretical and experimental results. Burgers discussed this problem in his paper and suggested new formulae.

Apparently, Burgers kept thinking on the problems related to suspensions despite the toughness of the topic. In 1941, he contemplate on diffusion and in a paper published in 1942, he again considered suspensions. It was written, as he remarked to one of his correspondents, "with great enthusiasm and with the hope of straightening out some questions". However, "with its continuation more and more problems appeared which baffled me". Therefore, he had to admit that he was not very satisfied with the results. The problems encountered by Burgers essentially concerned the lack of absolute convergence of the sum of the separate effects of an indefinitely large number of falling spheres on a given sphere.

Though Burgers felt somewhat disappointed, today it is recognized that he was one of the first who found a method to calculate an 'effective viscosity' of suspensions. For his result he had used the theory of Oseen which he had studied so deeply in the 1920s (see § 5.1.3). From the references in his papers, it becomes clear that Burgers was well acquainted with the literature related to colloids. He also knew Kruyt in Utrecht well (see § 4.1.4) but there are no traces of any collaboration with Kruyt or one of his co-workers (after the Second World War, Burgers' brother Willy would start to give lectures on colloid theory in Delft). It seems that during the war an experiment on sedimentation in 'artificial turbulence' was started in Burgers' laboratory but due to the circumstances, was never finished.

As for the theoretical approach of dispersions of particles

TEIJIN ARAMID AND THE TWARON ARAMID FIBER

HANS MEERMAN, TEIJIN ARAMID

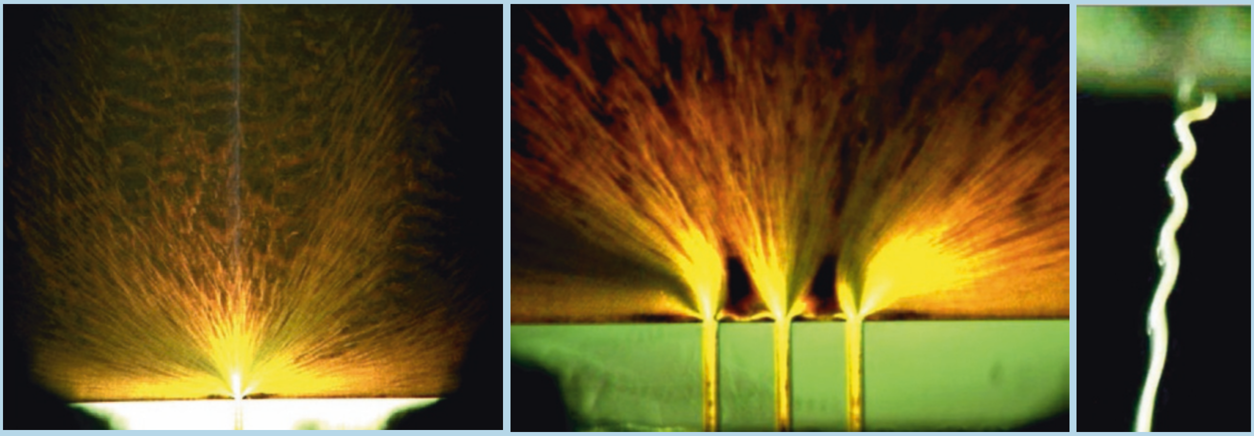
The first artificial fibers that could match wool and silk were produced at the end of the 19th century. In the course of the 20th century the focus was on the production of technically advantageous - meaning strong and rigid - fibers. Experience made clear that the molecular orientation of a polymer with sufficient molecule length is important to the strength and rigidity of fibers. In about 1970 it was understood that polymers containing sufficiently rigid and stretched polymer chains will align at higher concentrations when dissolved (liquid crystalline or LCP behavior) causing the solution viscosity to remain within reasonable limits. During the research into polymers with LCP behavior, poly-paraphenylene terephtalamide (PpPTA) turned out to be a good choice for further development for practical and economic reasons. The chain alignment taking place during the dissolved polymer flow leads to a high degree of crystallization in the resulting fiber.

The high degree of crystallization produces the fiber that is commonly known as Twaron, its high strength and rigidity being of importance to many high performance technical applications. As shown in the illustration, the formation of a high degree of alignment of dissolved polymer chains has been visualized by a dedicated visualization technique (crossed polarizers). The flow is recorded just before entering the extrusion capillary in which the fiber is created. The definitive alignment is realized by further stretching the fiber underneath the extrusion capillary and by fixing the alignment and fiber shape in water. The fixing process for shape and alignment happens within a very short time and constitutes the core of the spinning process used for the large-scale production of the super fiber under its brand name Twaron in Emmen.

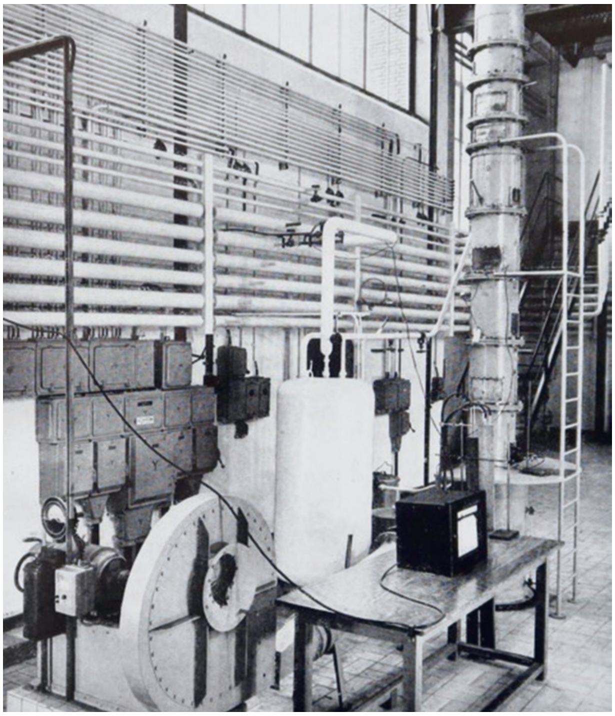
Teijin Aramid is a subsidiary of the Teijin Group and a global leader in aramid production. You will find the aramid fiber Twaron, Teijinconex, Technora or the ultra-strong (UHMW-PE) Endumax wherever strength, safety, heat resistance or light weight is needed. Teijin's products can be found globally in many diverse applications and markets, such as the automotive, ballistic protection, marine and civil engineering, protective clothing, rope and optical fiber cable manufacturing, and the oil & gas industry.

We use our high-performance materials to offer a wide range of products. Our specialist knowledge and many years of experience enable us to work continuously on new products and solutions. We are continually busy creating added value for our customers, strengthening their competitiveness with our innovations. Therefore, we invest more than 4% of our turnover in research and development at our dedicated establishments in Arnhem (the Netherlands), Matsuyama (Japan), Iwakuni (Japan), Wuppertal (Germany) and Shanghai (China) Thanks to our regional R&D centers, we are always 'close' to our source and able to be of service to our customers on a local level. It is actually our conviction that our best solutions are developed in the cooperation with our customers. By co-creation we arrive at solutions that help our customers excel in their markets. Our motto is: think global, act local. We observe and anticipate on global changes and developments, ensuring that we are and will remain to be the world's number one player in aramid manufacturing. With our world-wide sales and marketing organization, we are always close to our customers and are able to speak the language of our customers.

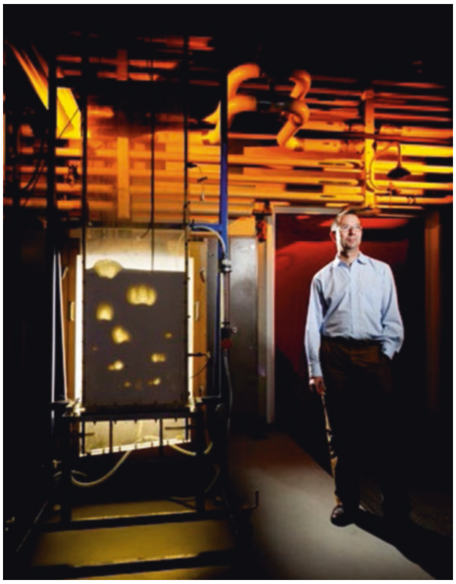
The aramid production and chemical processes take place in the Netherlands (Delfzijl, Emmen, and Arnhem), in Japan, and in Thailand. The world's biggest aramid plant is located in Emmen, the Netherlands. Teijin Aramid, a global company of 1,700 employees, established its headquarters in Arnhem.



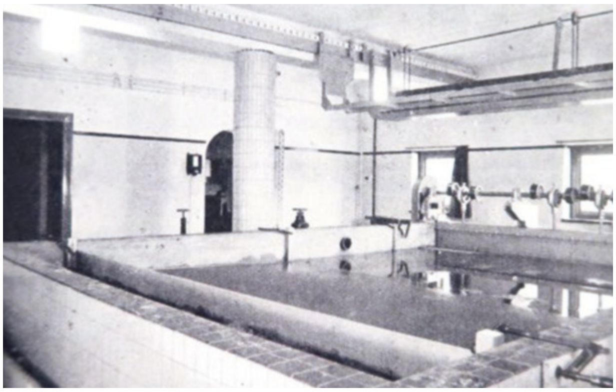
↑Flow of a liquid crystalline aramid solution right before entering, respectively, one and three extrusion capillaries, and an unstable flow exiting one of the extrusion capillaries. The alignment of the PpPTA chains is visualized by two crossed polarizers. The capillary diameter is 100 µm. The distance between the extrusion capillaries is 0,5 mm. (from: Drost (2015), PhD research supported by Teijin Aramid; courtesy of Teijin Aramid)

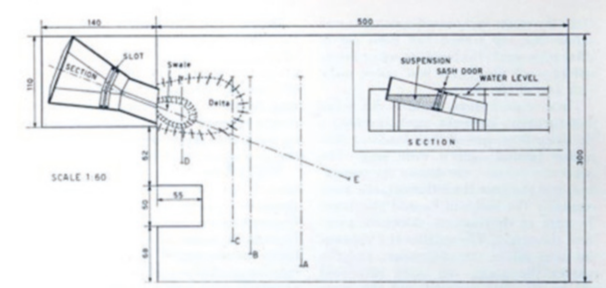


→A facility in Kramers' laboratory around 1950, for the 'merging of gas and liquid'. (from: Reynhart (1951) / courtesy of Shell)

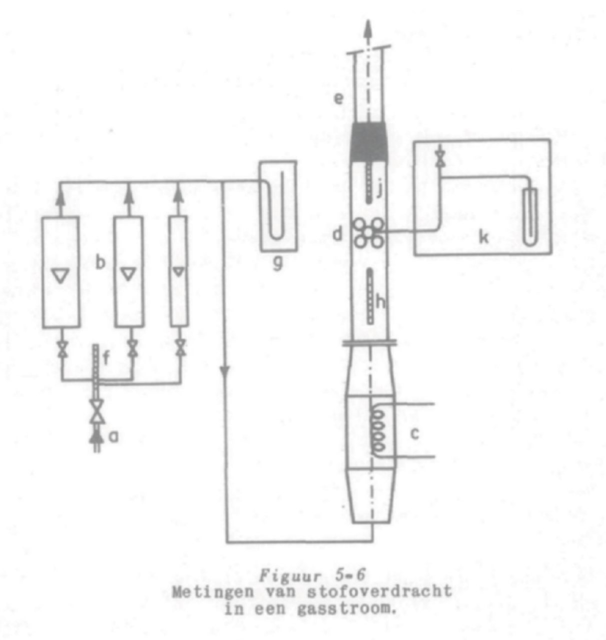


↑Since its early days researchers at the Kramers Laboratory have been studying fluidized beds. Here professor Rob Mudde is standing next to a so-called 2D dry matter fluidized bed in 2009. (courtesy of TU Eindhoven archives / photo by Bart van Overbeeke)





↑Kuenen started his career at the Geological Institute of the University of Leiden and his first experiments on turbidity currents were probably performed in this basin (about 6 x 4 m) which had a wave generator. Kuenen was much inspired by Berend Escher, a pioneer in geological experiments. Escher did, e.g., experiments with standing waves and studied their influence on an artificial beach. In Groningen Kuenen used a somewhat smaller basin in which a suspension was released on a flat slope. (from: Leidsche Geologische Mededeelingen, IX, 1937; from: Hough (1951) / courtesy of Soc. for Sedimentary Geology)



↑Kramers' second PhD student was Dirk Thoenes, who later became professor in Twente and Eindhoven and an expert in chemical reactors. His thesis (in Dutch), published in 1957, was entitled *Mass transfer by means of flow through a solid bed of granular material*. Thoenes did experiments with gas flows which were sent through a vertical tube and took with it an evaporated liquid from a porous sphere in an elementary model of a granular bed (near d). (from: Thoenes (1957)) in liquids, Burgers got assistance from a PhD student from China. In 1947 Tchen Chan-Mou defended his thesis entitled Mean value and correlation problems connected with the motion of small particles suspended in turbulent fluids.

To Burgers' successor Hinze, two-phase flows were already well-known when he started in Delft in 1956. He had published a formula for droplets (see § 5.1.5) and would continue to write on dispersions and particles in turbulent flows during the 1950s and 1960s. In 1959 the Laboratory for Aerodynamics and Hydrodynamics would see its first experimental facility for two-phase flows: a closed water circuit into which granular material could be dosed for studies on the flow of dispersions.
In the meantime another laboratory in Delft had built several facilities for research on two-phase flows. Since these flows are very common in many industrial processes, as in the oil industry, it was only natural that Kramers in his Laboratory of Physical Technology would start experiments on process machinery such as chemical reactors and fluidized beds. Kramers and his co-worker Westerterp published the first monograph on reactors ever, Elements of chemical reactor design and operation, in 1963. From the 1960s bubble columns also became familiar facilities in the Kramers Laboratory.

• 5.3.2 DISPERSIONS

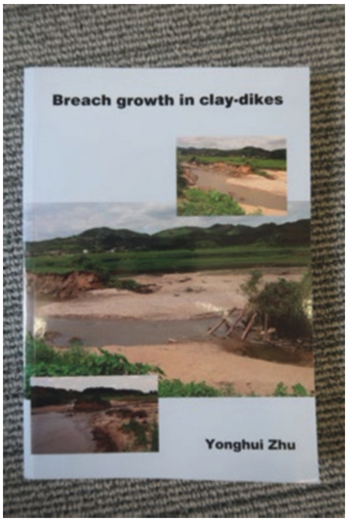
Among the several two-phase flows which can be studied, those in which particles, droplets or bubbles are dispersed have been the most studied by academic scientists in the Netherlands. One of the aspects of these flows which makes them hard nuts to crack is the 'hydrodynamical interaction' between the dispersed elements (which has been called Stokesian dynamics). For droplets and bubbles the processes are even more complicated since these can 'merge' (the coalescence of droplets has been one of the topics of the groups of Lekkerkerker in Utrecht and Bonn of the University of Amsterdam).

DISPERSIONS OF SOLID PARTICLES

One of the topics of two-phase flows on which Batchelor, whom we have met in the introduction, has published is the rate of sedimentation of small solid particles. Beenakker en Mazur of the University of Leiden (see § 4.1.4), however, criticized his results and showed that this rate depended on the shape of the vessel in which the sedimentation took place, something which Burgers had already mentioned (but could not prove) in 1941.
Dispersions of particles (and bubbles) in liquids also attracted and challenged scientists normally working in other fields of physics. For example, Ubbo Felderhof (1934) was known for his work in plasma physics and statistical physics but in 1991 published a paper entitled 'Virtual mass and drag in two-phase flow' in the Journal of Fluid Mechanics. (Some years later he was working on the theory of swimming.)

Sediments had long been a field of interest for hydraulic engineers (see e.g. § 4.1.1). One of the most intriguing aspects was the formation of ripples on sand bottoms. In 1960s experimental research related to this was done in Hinze's laboratory. In one of the wind tunnels mean velocity and wall shear stress were measured on artificial ripples with pressure holes.
Several decades later, sand transport by water over ripples in shallow seas was investigated in the group of Hulscher (originally a theoretical physicist) at the University of Twente. This transport has been one of the largest knowledge gaps in the modelling of sand transport in coastal seas. From full-scale experiments and modelling it appeared that the ripples strongly influence the boundary layer structure and turbulence intensity near the bed and have a great influence on the sand transport. In the 1990s Hulscher had already found an explanation for the emergence of sand ripples and sandbanks. Ripples were also studied by Martin van Hecke at the University of Leiden (the Lorentz Institute) and Huib de Swart at the University of Utrecht
Somewhat related to sediment phenomena are the so-called turbidity currents, akin to avalanches of sand and water on the bottom of seas and oceans. A pioneer in the experimental study of these currents was professor Philip Kuenen (1902-1976), marine geologist at the University of Groningen. While still a young scientist in Leiden, he did experiments with flumes and wind tunnels on the rounding of stones and sand grains. In 1937 he started experiments to determine the origin of so-called submarine canyons. In his Geological Institute in Groningen he built a sloping flume on which a large amount of sediment was suddenly released. In the 1950s these experiments became well-known internationally and in 1960 Hinze in Delft tried to give a theoretical foundation of these currents. More than half a century later experiments on this phenomenon were undertaken by scientists from the Department of Geosciences in Utrecht. In the Eurotank of TNO they were able to mimic the formation of underwater gullies.

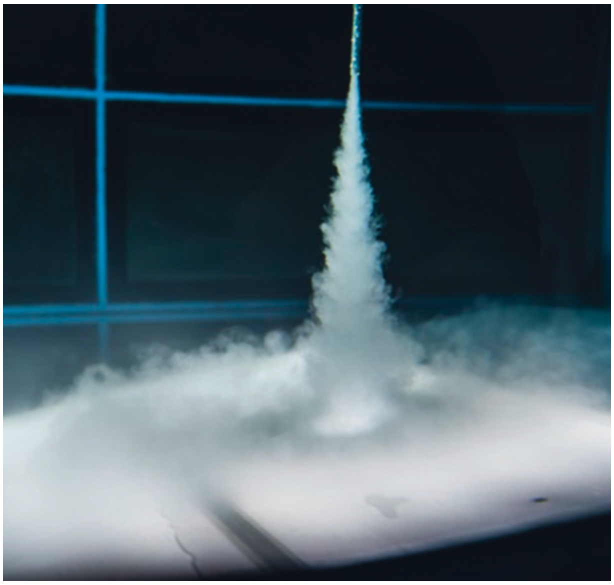
Transport, or displacement, of water and dispersed material like sand or clay can be found in many situations: the breaching of dikes, unstable breaching of sand during dredging, transport of slurries through pipelines, etc. Dispersed solid particles also occur in the mining industry. There, liquids are used to separate granular materials of different densities. The pulsating liquid flow which is used for this, is called a jig. Researcher at the Department of Mining Engineering in Delft have been successful in developing a jig with which every periodic wave desired can be generated



Breach growth in clay-dikes

Yonghui Zhu

←Clay and water can be a dangerous combination. In 2006 Yonghui Zhu, PhD student from China, published his thesis after his research done in the Waterlab in Delft to study the breach growth erosion process in clay-dikes and to obtain data to test a mathematical model. Despite the fact that dike breaches have occurred in the Netherlands (1953), in China and many other countries for centuries, the knowledge about the processes involved was still poor and the models were not very advanced. In general, the behaviour of granular materials, of which clay is just one example, is still poorly understood (see § 5.2). (from: Zhu (2006) / courtesy of dr Yonghui Zhu)



↑The behaviour of sediment is one of the main topics of the research at the Dredging group in Delft (see also § 6.2.6). One of their experiments, related to offshore deep-sea mining, is shown here: on a flat slope sand-like particles are dispersed. (courtesy of Delft University of Technology / photo by Ivar Pel)

→Today bubbles are also applied outside the chemical world. Deltares and RWS have developed a 'bubble screen': bubbles arise from the bottom, in this case in the Krammen Locks in Zeeland. This minimizes the penetration of salt water from the sea into the rivers, without hindering ships. (courtesy of Rijkswaterstaat / beeldbank.rws.nl / photo by Kees Jan Meeuse)

and this has led to a strong increase in the efficiency during separation.

Numerical simulation of these processes has been quite a challenge but the growing amount of experimental data helps to improve the models. One of the many attempts in modelling two-phase flows is the 'discontinuous Galerkin finite element method' developed in the 2000s at the Department of Applied Mathematics in Twente for shallow two-phase flows.

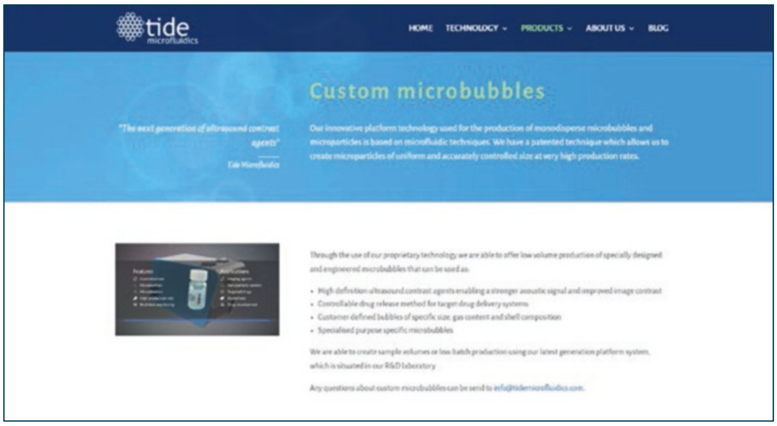
DISPERSIONS OF GAS BUBBLES IN LIQUID

As was said before, dispersions of bubbles have been in the (academic) laboratories for decades in the form of bubble columns. When Van Wijngaarden came to the University of Twente in 1966, he started to study bubbles, the beginning of a long tradition at this university. He started to do theoretical work on bubbles whose behaviour had become known to him when studying them in the wake of ships at the NSP in Wageningen where he had worked from 1962. His paper 'On the equations of motion of liquid and gas bubbles' of 1968 became well known. He was also a pioneer in modelling the interaction of bubbles and he did important work on the noise generated by cavitation. Van Wijngaarden managed to formulate a nonequilibrium mathematical model for the description of wave processes in liquids with gas bubbles. This model was later named after him and two Soviet scientists: the Iordansky-Kogarko-Van Wijngaarden Model.

Besides the behaviour of swarms of bubbles in liquids, researchers in Twente have also studied single bubbles. In a PhD thesis published in 2007 the so-called Leonardo's Paradox was demystified: why do bubbles stop to rise in a straight line from a certain diameter and start to zigzag?

In Delft bubbles have also been investigated for decades.

↑Colloidal suspensions have traditionally been studied in physical chemistry but in the 1990s physicists in Amsterdam also started to study them. Observing the scattered light of a laser, they discovered a new phenomenon. In these suspensions all particles are moving around. At the front of each particle a kind of bow wave is present and the liquid there is pushed away towards the wake of the particle. The velocity fields around all the particles influence each other. In this experiment it became clear for the first time that the velocity around one particle is shielded by the fields of all particles around it. The 'cage' of particles in which the central particle is located, determines the diffusion of this central particle. With this phenomenon they could explain why the rate of sedimentation observed in experiments is always lower than the theoretical rate. (courtesy of University of Amsterdam / Daniel Bonn)



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Our innovative platform technology used for the production of monodisperse microbubbles and microparticles is based on microfluidic techniques. We have a patented technique which allows us to create microparticles of uniform and accurately controlled size at very high production rates.

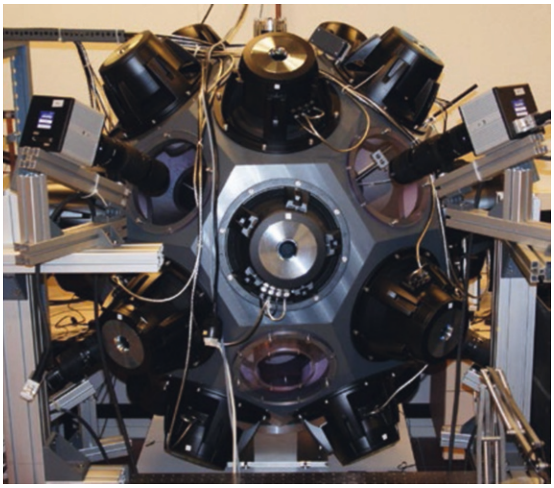
Through the use of our proprietary technology we are able to offer low volume production of specially designed and engineered microbubbles that can be used as:

- High definition ultrasound contrast agents enabling a stronger acoustic signal and improved image contrast
- Controllable drug release method for target drug delivery systems
- Customer defined bubbles of specific size, gas content and shell composition
- Specialised purpose specific microbubbles

We are able to create sample volumes or low batch production using our latest generation platform system, which is situated in our R&D laboratory.

Any questions about custom microbubbles can be send to info@tidemicrofluidics.com.

↑Bubbles have become business. The Tide Microfluidics company offers tiny particles and bubbles for medical purposes. Its origins can be found in the research groups of Van Wijngaarden and Lohse. (courtesy of Tide Microfluidics BV / Wim van Hoeve)



←The 'turbulence box' in Eindhoven used to have eight speakers but a later version (shown here) has twenty. Four cameras are used to track the droplet motion. (courtesy of Eindhoven University of Technology / Rudie Kunnen)

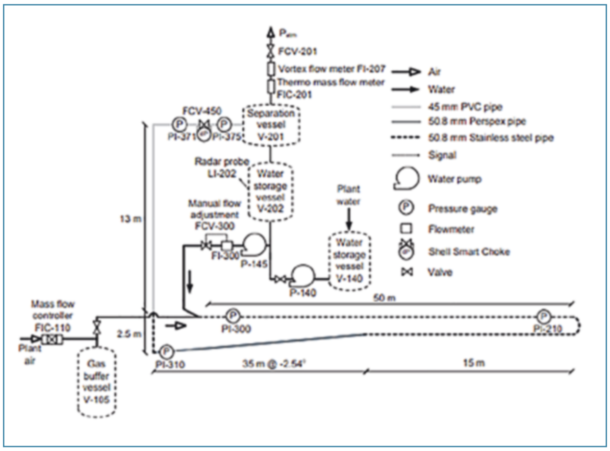
In the Laboratory for Physical Technology (the Kramers Laboratory) this led to the construction of a unique bubble column (see § 6.2.6). Fundamental research on single bubbles and the coalescence of two (and more) bubbles has been done by Chesters in the Laboratory of Aero- and Hydrodynamics.
Connected bubbles can form foams. In this context one very specific PhD thesis has to be mentioned: in 1989 Lex Ronteltap, working at Heineken Breweries, defended his thesis entitled Beer foam physics. Ronteltap had studied four phenomena: bubble formation, drainage, disproportionation, and coalescence.

DISPERSIONS OF LIQUID DROPLETS IN GAS

Examples of dispersions of droplets can be found in sprays. The breakup and droplet dispersion of sprays is an important aspect of many processes. One of them is the combustion process, where the behaviour of the droplets influences the efficiency and pollution of engines. Researchers of the Turbulence and Vortex Dynamics group in Eindhoven have used glowing sprays to find out what happens to droplets in a turbulent flow. To measure the effect of turbulence, they built a 'turbulence box' in which turbulence is created by air jets pumped by large speakers. These speakers are driven by (colored) noise signals.

• 5.3.3 TWO-PHASE FLOW AND THE OIL & GAS INDUSTRY

A large part of the research on two-phase flows in the Netherlands has been, and still is, somehow related to processes which take place in the oil and gas industry. Shell especially



↑'Severe slugging' research as presented in a PhD thesis published in 2012 (supervised by professor Rob Mudde of the Kramers Laboratory) including experiments in this large facility (the Severe Slugging Loop) at the Shell Technology Centre in Amsterdam in which slug flow in a flowline-riser system could be investigated (from: Malekzadeh (2012); courtesy of TU Delft).

Shell has stimulated research in this field, not only in their own laboratories in Amsterdam and Rijswijk, but also at the universities.

During the 1960s, 1970s and 1980s fundamental research on two-phase flow phenomena seems to have been given almost free hand at Shell's KSLA. To give an example: around 1970 the development of bubbles in a boiling liquid above a glass surface was filmed and measured. This gave the researchers important information about the rate of heat transfer in processes where boiling was present. After a reorganisation of the KSLA at the beginning of the 1980s (leading to a reduction of research space and staff) the number of joint projects between Shell and the academic world started to grow.

Since the beginning of the 70s, much two-phase (or multiphase) flow research was aimed at understanding the transport of oil, gas, water, and solids though pipelines. This required much laboratory experimentation, field data analysis, and model development. The problems were and are challenging as many physical phenomena (like turbulence, interface instabilities, rheology, thermodynamics) are involved.

EXAMPLES OF THE RESEARCH FOCUS IN HEAVY-OIL TRANSPORT

A large part of the remaining oil in underground reservoirs is very viscous and this property causes problems during its recovery, transport, and processing. Therefore, methods need to be developed to reduce the pressure drop encountered during the transport of such oil type. One well-known method to make this possible is the addition of some water to the viscous oil. Under certain conditions (such as a sufficiently high flow rate), this gives the so-called core-annular flow regime in the pipeline. This means that the oil flows in the core of the pipe, which is surrounded by a thin layer of water in an annulus along the full perimeter of the pipe. Now the water works as a 'lubricant': the frictional pressure drop along the pipeline is thus determined by the low water viscosity, and not by the high oil viscosity. One of the essential phenomena which takes place during this type of flow and which has been subject of a lot of research are the waves that are formed at the interface between oil and water. Around 1990 this kind of flow was studied at KSLA in various facilities, such as a tube of 16 m length and 5 cm diameter and a tube of 1000 m length and 20 cm diameter. Ultrasonic sensors were used to measure the thickness of the water layer.

Recently one of the facilities used in the past at the Shell laboratory has been rebuilt at the TU Delft, and the core-annular flow research has been continued. In addition to its application, core-annular flow is a very interesting configuration for fundamental research on two-phase interface behaviour, particularly the interaction between the turbulence and waves. New compared to the previous research is that now much larger computational resources and better numerical methods are available. But the application of simulation methods to interface flow is still a challenge.

Besides the core-annular flow (which is a liquid-liquid two-phase flow), the so-called slug flow regime in gas-liquid transport in pipelines has been the topic of research at various Dutch laboratories. In the Laboratory of Aerodynamics and Hydrodynamics and in the Kramers Laboratory, both in Delft, research was carried out on slug flow in pipes at various inclinations, including the extremes of a vertical and

→Separation is an important process in the oil industry. This picture shows the laboratory of the Romico company, which was founded by professor Bert Brouwers. Brouwers started his career at the Ultra Centrifuge Laboratory of UCN/Urenco in 1972, then he worked for Shell, and in 1986 he became professor of Thermal Engineering in Twente and in 1998 he became professor of Process Technology in Eindhoven. During his time at the University of Twente he devised the Rotational Particle Separator (RPS) which comprises patented methods for separating micron-size particulate matter from fluids. While still working at the university, he started his own company to develop practical versions of the RPS and to sell these. (courtesy of ROMICO Hold avv / Bert Brouwers)

←PhD student Dries van Nimwegen measureed the formation of foam to prevent slugs in vertical two-phase flow at the Kramers Laboratory in Delft around 2015. Slug flow research in this lab dates back to the 1990s when a vertical pipe of 17 m length was installed. (courtesy of NAM / photo by Levien Willemse)

a horizontal inclination. Different slug types were measured, such as Taylor bubbles, hydrodynamic slugs, and growing slugs (see also § 6.2.6). Such research is still ongoing, but now even under more complex conditions, such as the measurements for the effect of a surfactant (foam) to prevent hydrodynamic slug formation in vertical pipes. Slug flows have also been measured at one of the TNO laboratories, for example the fluid-structure interaction due to bend forces generated by hydrodynamic slugs.
Through the years much slug flow research has also been carried out by Shell researchers at their laboratories in Rijswijk and in Amsterdam. In Rijswijk Shell used the Donau-loop for three-phase flow measurements. In Amsterdam researchers could use the Severe-Slugging Loop (SSL) in which severe slugging has been measured, which can occur in a flow-line riser system (which is a horizonal or slightly inclined pipeline followed by a vertical pipe). During a severe slugging cycle, the full height of the riser is filled with liquid, as well as part of the flowline. Once the liquid reaches the top of the riser, liquid leaves the top at high velocity, which is a so-called liquid surge, followed by a gas surge. The experiments were used to derive simple correlations for the onset of a severe slugging cycle, as well as for developing dedicated control methods, in which an actuated valve at the top of the riser is used to prevent the severe slugging cycle or to mitigate the liquid and gas surges.

More recently there has also been much interest in the numerical simulation of slug flow. This means solving the time-dependent, one-dimensional (in space) conservation equations for the gas and liquid dynamics, requiring advanced numerical methods for so-called slug-capturing. This work is carried out at in the Applied Mathematics department of the TU Delft, the Centrum voor Wiskunde en Informatica (CWI) and at Shell.

Much of the core-annular flow and slug flow research as described above was or is carried out under the supervision of the professors Ooms, Oliemans, Mudde, Vuik, and Henkes.

During oil recovery from reservoirs a mixture of oil and water is brought to the Earth's surface. There the oil is separated from the water. The larger the oil droplets the easier the separation will be. In 2000 a PhD thesis on the effect of restrictions in pipelines (which are due to the presence of various valves) on the break-up of droplets was published. The experiments for this research had been done in the Dietz Laboratory of the Department of Applied Earth Sciences in Delft.
Foam also has its place in the world of oil recovery. Oil from oil-gas reservoirs is initially produced by the natural driving mechanism of the pressurized reservoir, which gives the primary production. During the secondary recovery phase water or gas are injected to maintain the pressure in the reservoir. After these two phases, more enhanced recovery techniques are used. One of these is the use of foam, which is an idea that dates from the 1950s. Foam has several applications in oil production, e.g., in drilling where foam can transport cuttings to the surface, and in deliquification of gas wells. In 2012 a PhD thesis on the modelling of foam for oil recovery was published under the supervision of professor William Rossen of the Department of Geoscience and Engineering in Delft.

FLUID FLOW RESEARCH IN SHELL THROUGH THE YEARS

RUUD HENKES & PETER VEENSTRA, SHELL PROJECTS & TECHNOLOGY

Hinze carried out pioneering work for Shell during his time in the Proefstation Delft in the years 1935 to 1956. In the 1950s his work was continued by J.G. Van de Vusse at KSLA who worked on the mixing scaling rules in process equipment. His scaling theory was tested at full scale, as is clear from the example of an educator mixer that was placed in a tank of 12,000 m3. The mixing insights of Van de Vusse are still valued in the mixing engineering community. In later years research in Shell has paid much attention to mixing, due to its importance in equipment or processes like side entry mixers, bubble columns, jet mixers, ejector mixers, in-line mixers, distillation columns, trickle bed reactors, drilling, well, pipelines, separators, etc.

In the 1960s and 1970s J.A. Wesselingh studied, among others, the scaling of storage tanks. An example is a small-scale experiment with a tank model in which the mixing of black and white miscible fluids is followed over time. This work led to various engineering design rules for fluid mechanics (such as mixing times for miscible fluids and de-mixing or stratification times for immiscible fluids), solid mechanics (such as selection of seals, bearings, and shaft), and process control. The design rules are still in use for many of the processes and processing units in refineries and chemical plants. Hans Wesselingh left Shell in 1976 to become lector and later professor in Separation Processes at Delft University; he moved to the University of Groningen in 1989 to become professor in Thermodynamics and Separation Processes.

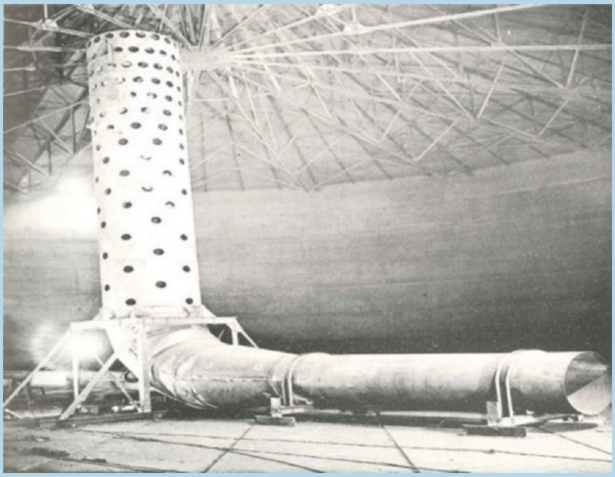
Over the years a number of university professors in fluid flow or process engineering have spent parts of their career in Shell. In addition to professor Hinze and professor Wesselingh, as already mentioned, other well-known examples include the professors Charles Hoogendoorn, Gijs Ooms, Harry van den Akker, René Oliemans, and Dirk Roekaerts. During their time in Shell they contributed to a variety of research topics in applied fluid flow. The results of their work have been described in many Shell internal reports, but some results were also presented and published at conferences, and in international journals.

Up to the 1960s fluid flow research in Shell was mainly focussed on the "downstream" part of the oil and gas business, which are the refineries and chemical plants. Thereafter there was also much interest in the "upstream" part, being the exploration and production of oil and gas, which includes the flow from the reservoir, through wells, pipelines, and risers, to production platforms or gas plants. Over the past few decades much research was done to understand the multiphase flow in pipeline systems. Starting with the oil crisis in the beginning of the 1970s, it became attractive to transport the hydrocarbons in a single multiphase flow pipeline, instead of using pipelines for either single phase gas or single-phase oil transport.

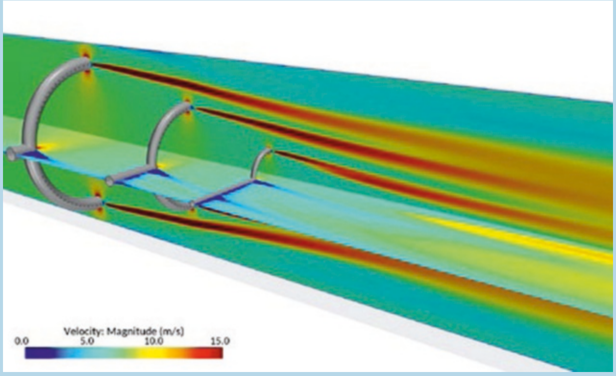
At the KSLA lab pipeline experiments were carried out to generate flow-pattern maps for two-phase flow transport in pipes. Among the lab facilities, there was a 130 m long, 50 mm diameter water/air loop, that was moved from Shell in Amsterdam to the Kramers lab at Delft University in 1999. Another valuable source of data also was found in Shell's pipeline facility at Bacton in the UK, which was directly fed by gas and condensate from the field. Measurement equipment included pressure sensors, flow visualisation through a looking glass in the pipe, liquid accumulation (liquid holdup) measurements through a gamma density meter, liquid droplet entrainment through isokinetic sampling. Mechanistic models were derived to describe the important multiphase flow parameters: flow regime, pressure drop, liquid holdup. And the lab and field data were used for the model validation. This has led to a model called the "KSLA method" for multiphase flow in pipelines. The KSLA lab was later renamed into SRTCA (Shell Research and Technology Centre Amsterdam) and is now called STCA (Shell Technology Centre Amsterdam). The flow models were also renamed into SRTCA method and are now simply referred to as the "Shell Flow Correlations".

The Shell Flow Correlations are presently still used for the multiphase flow design and improved operation of gas, condensate, water, and solid particles in offshore and onshore pipelines. The correlations are embedded in larger steady state and dynamic simulation packages. A new development is that the dynamic pipeline models are brought on-line. This means that the model serves as a Digital Twin of the actual system that is in operation. The model is fed by field measurements for quantities like the flow rates, inlet temperature, and arrival pressure, which serve as boundary conditions. The model can provide data for quantities that cannot be easily measured, such as the liquid holdup in the pipeline. In this way the model can be used for liquids management. It can tell when and how large pockets of liquid (so-called slugs) propagate through the pipeline, and whether such slugs still fit the capacity of the downstream separator or slug catcher. The model can provide direct monitoring but can also forecast for the next 24 hours or so.

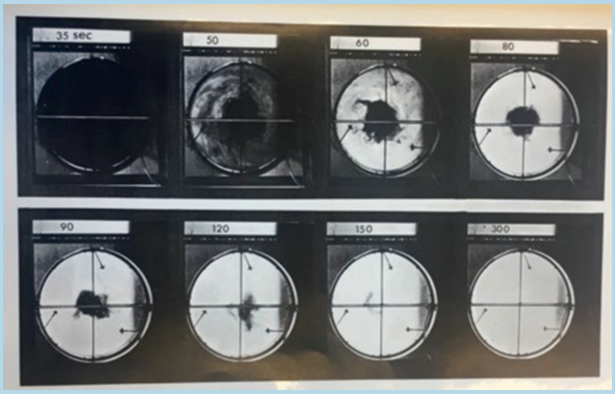
Since the 1990s, Computational Fluid Dynamics (CFD) has grown enormously as a research and design tool for fluid flow problems. In the Shell lab researchers have been and are still working on the numerical algorithms and on the physical closure correlations. This has led to Shell in-house tools based on e.g., the Lattice-Boltzmann Method (Cellular Automates), Large-Eddy Simulation (LES), and Smoothed-Particle Hydrodynamics (SPH). Increased use is also made of third-party CFD tools, like Fluent and STAR-CCM+. As partner in various Joint Industry Projects (JIPs), Shell contributes to enhancing the functionality of CFD packages. For solving practical problems, often both momentum, mass and heat transfer are important at the same time, as well as the kinetics of chemical reactions. This asks



↑Full scale mixing experiment as carried out by Van de Vusse in 1953. (courtesy of Shell)



↑CFD simulation (carried out by Shell in 2017) to determine the optimum injection of oxygen in a fabrication process of chemicals. (courtesy of Shell)



↑Results of a mixing experiment as carried out in the Shell lab by Wesselingh in 1967. (courtesy of Shell)

↑Shell Technology Centre in Amsterdam as it is today. (courtesy of Shell)

much of the computational tools, both from a numerical (computational speed and robustness) and physical view point. CFD is used for a wide range of problems, such as efficiency improvement in chemical reactors (e.g. the effect of internals), erosion of wall materials due to the impingement of solid particles in the fluid flow, fluid-structure interaction (e.g. to find the root cause of vibrations of equipment), and mixing in storage tanks.

For Shell fluid flow research will also remain important in the coming decades. This will be a combination of in-house research and leveraging through collaboration with national and international research institutes. Developments in Information Technology will also provide great opportunities to make better use of the data available from field operations. Experience from the past years in fluid flow modelling can be used to realise fast benefits from further Digitalization and Machine Learning. Having a fluid flow simulation model with direct coupling to operational data can provide better and safer operational performance, once algorithms with artificial intelligence have developed to a state that they can provide early warnings of anomalies in the monitored processes or units.

Within the energy industry, fluid flow is seen as an enabling technology. It is clear that it has been of importance for the maturation of the oil and gas industry. The heritage is a wealth of engineering design rules and dedicated design tools. Fluid flow will remain an important enabler when designing the new energy future and new technologies for chemical products. Possible research topics are plenty, for example: wind turbines, solar boilers, hydrogen production and transport, electro-synthesis of chemical products. More than in the past, fluid flow needs to become fully integrated into other technical areas (e.g., process engineering, materials, structural mechanics, information technology) to make an impact in the coming years.