Courtesy of Burgers Archives / TU Delft

F. Alkemade, *A Century of Fluid Mechanics in The Netherlands*, https://doi.org/10.1007/978-3-030-03586-0_6

06

RESEARCH IN FLUID MECHANICS: APPROACHES

For centuries fluid mechanics was mainly approached in two different manners: by using mathematics (and intuition) or by doing experiments (in or outside of a laboratory). Only from the 1950s it became possible to take the third way of approach: the numerical one; first mainly by hand, later using analogue and digital computers. In this chapter Dutch examples from all three types of approach are presented.

6.1 THEORETICAL AND MATHEMATICAL APPROACHES

As in many other fields of physics and engineering, the theoretical approach is often a tough one and the number of real breakthrough results is small. The boundary layer theory and the lifting-line theory for 'real' wings developed by Prandtl may be called such results, but there were not many others like them in the period between 1904 and the outbreak of the Second World War. The same can be said of the post-war period.

The method most often used to approach flow problems theoretically is, of course one could say, to use tools from mathematics. All flows are described by the Navier-Stokes equations (usually indicated by NS) and equations can be 'attacked' by means of methods which have been developed by (pure) mathematicians. The big issue which overshadows all these attempts is the fact that the NS are nonlinear. This nonlinearity bothered the physicists and hydraulicians of the 19th century, it bothered Lorentz when he tried to do calculations on the behaviour of the Zuiderzee in the 1920s (see § 3.4.1), and it still bothers all those who try to understand and predict flows by just using pen, paper, and their mathematical toolbox.

Lorentz chose an attractive (but to some doubtful) 'simplification' of the nonlinear equations: he linearized a component in the equations related to friction, and could prove that this did not hinder him in obtaining useful results. Some years later Dronkers, a mathematician working at Rijkswaterstaat, came up with a more accurate mathematical model of the friction term (see § 6.3.1).

Somewhat surprisingly perhaps, many years later this Lorentz linearization was studied again by another Dutchman, Sjef Zimmerman who worked at the NIOZ (see § 4.2) in the 1980s and 1990s. Zimmerman worked on so-called renormalization techniques in fluid mechanics. With these techniques he was able to find approximate solutions of non-linear partial differential equations by following a 'recipe' which he had abstracted from applications of adjoining fields of physics. With his method Zimmerman could show that Lorentz's approach can be justified.

BURGERS AND THE THEORETICAL APPROACH

When Jan Burgers started in Delft in 1918, he had no experimental facilities at his disposal and thus he was simply obliged to take the theoretical approach. For this he was well prepared, as we have seen in § 3.1: among his tutors were Lorentz himself as well as Ehrenfest. One of the mathematical techniques he applied was conformal mapping, and he became an expert in this. In the *Annual Review of Fluid Mechanics* of 1975, Burgers would recall: "Conformal mapping, as a means for obtaining contours of airfoils and of propeller blades, for a long time was a dominant subject for me. I was particularly interested in looking for the simplest formulations to be used in my lecture course. But it was also evident that everywhere in fluid dynamics attention should be given to vortex motion. Far more knowledge was required than was given in H. Lamb's Hydrodynamics, notwithstanding the importance of Lamb's work. […] I began to see that transport of vortex motion, partly by convection through the general flow field and partly by diffusion as a result of viscosity, was of decisive importance in many cases, and I formulated a relation between the resistance experienced by a body and the momentum or impulse of the vortex system generated." In fact, Burgers' very first paper on fluid mechanics, in 1920, is entitled 'On the resistance of fluids and vortex motion'.

Both conformal mapping and his knowledge of vortex motion would later appear useful in several investigations: the former was applied to the calculation of flows along fans in pumps (see § 6.3), while vorticity appeared to play an important role in the calculation of flow resistance and in the application of Oseen's theory.

Carl Oseen was a Swedish theoretical physicist who had derived equations, later named after him, which describe the flow of a viscous and incompressible fluid at small Reynolds numbers, somewhat similar to a Stokes flow. Burgers, amongst others, was intrigued by Oseen's results and he started a correspondence with Oseen which lasted from 1919 up to 1946. He even gave lectures on Oseen's theory for his students. As Burgers recalled in 1975: "In subsequent years I continued to work upon Oseen's approximation and its relation to Prandtl's theory. It appeared that Oseen's equations for the flow called forth by exterior forces acting on a fluid could be used for the description of the vortex system produced by a lifting system, and so gave a direct connection with Prandtl's theory of the finite wing. Later, I used Oseen's equations for the calculation of the resistance experienced by small particles in slow motion, at Reynolds numbers far below unity."

When he started to work on turbulence around 1930, Burgers also tried the theoretical approach. Like several of his foreign colleagues he started to study statistical theories of turbulence, but he soon discovered several difficulties and felt dissatisfied with his own papers on this matter. To the English physicist George Trubridge, who in the 1930s wanted to write a thesis on 'Burgers' theory of turbulence', he wrote in 1933: "[These difficulties are] intrinsically connected with the statistical method used in these papers, and it is not peculiar to the hydrodynamical problem. I happened to find certain systems of simultaneous differential equations which show properties analogous to those of the equations of fluid motion in so far as regards the existence of solutions representing a state of 'turbulence', although they are much simpler."

Thus, in the 1930s Burgers took yet another road to treat

↑Burgers at work, at home around the time that he published his main papers on what would become known as the Burgers equation. (courtesy of Burgers Archives / TU Delft)

turbulence. He decided to restrict his attention to model problems, with which the essential aspects of turbulence could be treated. As he explained in his valedictory lecture of 1955, he became convinced "that dissipative systems are essentially different from conservative systems. I thought that it would be necessary therefore to study the behaviour of dissipative systems, and that since the Navier-Stokes equations are so refractory, it might be helpful to replace them by a more elementary equation. It was then that I took as example the equation

$\partial v / \partial t = U v + \nu \partial^2 v / \partial y^2 - 2 v \partial v / \partial y$

and I prepared an extensive investigation of this and a few similar equations in a paper published in 1939."

The first sketches for this paper date from 1936. A year later he showed that it was possible "to illustrate the conception of correlation and the equations describing the decay of free turbulence" with his new model. To Burgers, a new road seemed to have been opened which would finally bring progress. In his valedictory lecture, he remembered: "Especially, I started to free myself from the spatial character of the flow; thus, I was not troubled by the complicated geometrical properties of the vortices; also I abandoned the continuity equation."

After the War, Burgers got acquainted with developments in the U.S.A. and Britain. He realized that his treatment of turbulence had taken a direction which differed strongly from those taken by others like Kolmogorov and Heisenberg. Nevertheless, he still felt convinced of the value of his work. Finally, the equation which Burgers would study most in his work on turbulence, became known as the Burgers equation:

$\partial u / \partial t + u \partial u / \partial x = \nu \partial^2 u / \partial x^2$.

To Burgers, they contained the essential features of turbulence: dissipation and nonlinear inertia. In a paper of 1954 he considered wave-like solutions of his equation which, he thought, could serve to illustrate the interaction of shock waves, which he had been working on in the 1940s. For this purpose, he applied a substitution which is known as the Hopf-Cole transformation and which turns the nonlinear Burgers equation into the linear heat equation (Burgers had learnt about the transformation from J.D. Cole himself when he visited the U.S.A. in 1949).

The attractive properties of the Burgers equation are the facts that it is analytically treatable and that it contains essential ingredients of turbulent flow. As Burgers remarked himself in 1954, it is "the simplest analogue of the hydrodynamic equations, in so far as it contains a nonlinear term with a space derivative of the first order, and a linear term with a second order space derivative multiplied by a factor which can be taken very small. Its properties with regard to dimensions consequently are the same as those of the hydrodynamic equations. The solutions of [the equation] exhibit the property that regions make their appearance with very high values of $|\partial v / \partial y|$ ('steep fronts'), which can be considered as analogous to the regions of high dissipation appearing in the solutions of the hydrodynamic equations (regions of very high vorticity or shock waves)".

Yet in his farewell lecture in Delft in 1955 he had to remark: "Still the problem appeared exceptionally difficult - and only in 1953/54 I thought I had obtained a foundation, on which for this simplified system a statistical treatment is possible, though for the moment only for a so-called asymptotical case. The particularities which appeared were of an unexpected nature - and unfortunately I have to remark that no through going road can be found towards the real three-dimensional turbulence. At least, however, something has become visible of the particular properties of dissipative systems with a nonlinear differential equation."

Nowadays, we know that the 'flows' which are contained by the Burgers equation are essentially different from real turbulent flows, as Burgers gradually became to realize very well himself. As he remarked in his book The non-linear diffusion equation (published in 1974 when he was 79 years old): "The equation can be considered as referring to motions in an infinitely compressible medium, without pressure, and there is nothing in the system which deals with shear or with vortex motion". The Burgers equation had appeared to be too strong a simplification.

In recent years the Burgers equation seems to have been mainly used for testing and checking numerical solvers. On the other hand one is surprised by the broad scope of modern 'tools' which have been related to the Burgers equation: Markovian techniques, multifractals, wavelets, renormalization, solitons. Also the different fields of science in which the equation has been studied is impressive; apart from 'Burgers turbulence' one finds: nonlinear waves, the dynamics of growing interfaces (e.g., those of tumours), the dynamics of large-scale structures in the Universe, phase diffusion (e.g., neural signals), sedimentation, drainage, plasmas, waves in tubes, traffic flow, and acoustics. Further, the list of the various 'forms' of the equation is impressive: the forced Burgers equation, the noisy and the noiseless, the unstable, the discrete and the ultra-discrete, the viscid and inviscid, the generalized, the perturbed, the stochastic, the nonplanar, and the time-independent Burgers equation can all be found in recent literature.

GROUNDWATER FLOWS

One particular field of fluid mechanics where several Dutch scientists and engineers have applied the theoretical approach has been the flow of groundwater, a field which belongs to hydrology. Rain water and water from canals and rivers creeps through sand (in the dunes) and the soil, which are porous media and in which capillary effects may be involved. In the 19th century the French engineer Darcy had already formulated a law describing this flow. In the Netherlands research on ground water flows had started at the end of the 19th century, both 'in the field' and in simple laboratories. Knowledge was required due to the growing demand for fresh tap water, which was partly made from rain water filtered by the dunes. After World War I the issue of ground water flows got even more interesting when a discussion arose about the consequences of the Zuiderzee project.

It was Lorentz himself who had already studied the matter in 1913 and had shown, in the magazine De Ingenieur, how one could derive a Laplace equation for these kinds of flows. Van Iterson (see § 2.3.2) also wrote about it. The first hydrologist in The Netherlands who did a serious study on groundwater flow was Jan Versluys, whom we met as a researcher in Shell's Amsterdam laboratory (§ 3.3.2). In a paper of 1912 and in his PhD thesis of 1916 he studied the theoretical and experimental results which had been published worldwide and after comparing the validity of Poiseuille's Law and Darcy's Law, he concluded that the latter gives results for flow through porous media which are accurate enough. He also warned that at flow speeds groundwater flows can become turbulent and then neither Poiseuille nor Darcy are valid anymore.

Another early Dutch contribution was a theoretical study by J. Kooper in 1914 of steady flow around a well or circular polder in a leaky aquifer. Kooper arrived at a mathematical solution with Bessel functions, which proved to be very useful in groundwater exploration and management.

In 1926 Burgers also published a paper in De Ingenieur on groundwater flow. By using the Laplace equation and applying a conformal transformation he produced steady and transient solutions for radial flow from partially penetrating canals into a low-lying confined aquifer. In the late 1920s experiments on groundwater flows were performed in Burgers' lab, probably related to the work which Gerrit de Glee (1897–1975) was doing for his PhD thesis in 1930, under the guidance of Burgers. De Glee elaborated on the solution which Kooper had proposed and came up with a formula which is generally referred to as the De Glee formula.

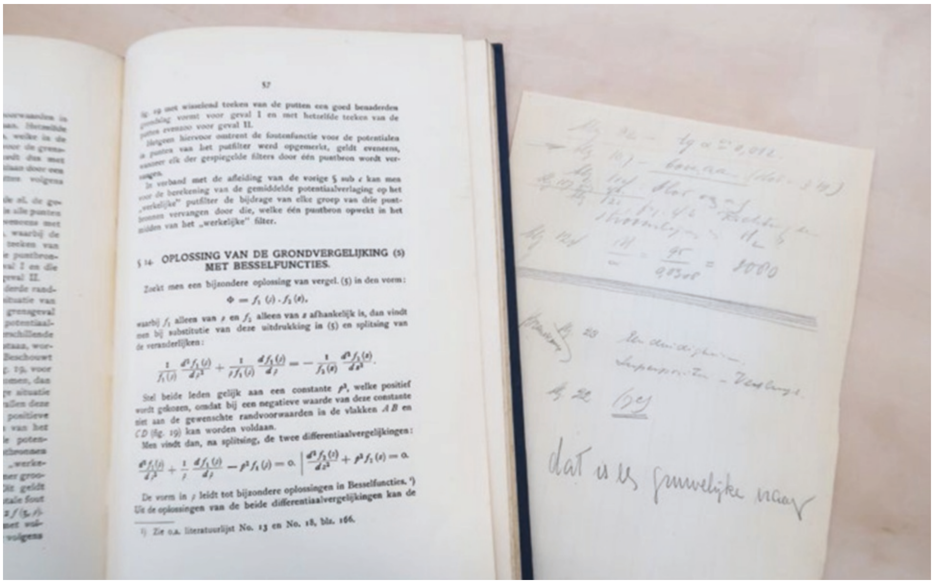
Kooper and De Glee were both engineers with the National Institute for Drinking Water Supply (RID). This organisation, which was founded in 1913 to stimulate and support central drinking water supply (notably in the rural areas), remained the central agency for groundwater exploration and research for more than 50 years.

Jan Mazure (1899–1990), an engineer with the Zuiderzee Works (and in the 1960s the chairman of the Dutch Senate), saw that Burgers had not taken into account the resistance against upward leaking in his derivation. He therefore proposed a simplified flow pattern but more realistic hydrogeological schematisation by including a leakage factor. He assumed horizontal flow in the aquifer and vertical flow through the confining layer, which resulted in a simple exponential function for the steady-state hydraulic head distribution. With this formula the rise of the groundwater level at a certain distance from a river (or other water reservoir) could be predicted. It proved to simulate the actual observed situation rather well in the first Zuiderzee reclamation in the 1930s, the Wieringermeer polder, and has subsequently been widely used in the Netherlands. In 1937 Mazure gained his doctorate under the guidance of Burgers.

In the Dutch East Indies (Indonesia) Cor Vreedenburgh (1895–1936), professor of theoretical and applied hydrodynamics at the Technical University of Bandung, used mathematical tools to show, for the first time, an exact solution for the flow through and under an earth dam. Like Burgers, Vreedenburgh applied complex function theory to solve the two-dimensional Laplace equation. He also found solutions of the equations for flow through an anisotropic medium. In both these cases the permeability is no longer dependent on the coordinates but on the direction of the flow and therefore the Laplace equation is no longer valid. Vreedenburgh also did experimental work: he simulated two-dimensional groundwater flow in an electrolyte-tank on the basis of an analogy between Darcy's Law and Ohm's Law.

After the War theoretical contributions of Dutch researchers were still made but the rise of numerical simulations also had its own influence. In 1949 Henri Brinkman (1908–1961) published an extension of Darcy's law which can be used to take account of the transitional flow between boundaries. It became known as the Darcy-Brinkman equation and still regularly appears in papers on flow in porous media and on other topics.

When Gerard de Josselin de Jong (1915–2012) became professor of applied mechanics in Delft in 1961, he had already been in California for some time where he had worked on the modelling of the transport of a pollutant in the flow of groundwater. He argued that the mechanism of dispersion in



←A page from the PhD thesis of De Glee (1930) and a note which was found in the copy present in the Burgers Archives. The handwriting at the bottom definitely is that of Jan Burgers and (in translation) it says: "that is a gruesome question". (courtesy of Burgers Archives / TU Delft)

the direction of flow differs from the dispersion in the lateral direction. This leads to a much larger effect of dispersion in the flow direction than in the transverse direction. He validated his theory by careful experiments. De Josselin de Jong also worked on the vortical motions along the boundary between fresh and salt water due to opponent flows along this boundary.

Analysis of the drainage process led in 1958 to the transient formulas of De Zeeuw & Hellinga and Kraijenhoff van de Leur (see also § 4.1.4), in which the transformation of rainfall into groundwater discharge is characterised by a reservoir factor. This factor includes the hydrological properties of the subsurface and the geometry of the drainage system. These formulas formed the foundation for the design of a drainage scheme on the basis of the required groundwater depth. The optimal groundwater depth was subsequently determined – for various crops and soils – by study of the flow of water in the unsaturated zone, and notably of the water supply by capillary rise.

Ernst (1962) developed solutions for non-linear flow processes towards drains, thereby including the geometry of the drainage channels and the influence of heterogeneous subsoil. Both the solutions of Hooghoudt (see § 6.2.6) and Ernst have been applied worldwide. In the 1970s a group of hydrologists came up with an expression (sink term) for water uptake by roots within the continuity equation for unsaturated groundwater flow. This equation formed the basis for a general numerical soil-water-atmosphere-plant (SWAP) model, to describe transient water and solute flow in heterogeneous soil-root systems. This model is also used worldwide.

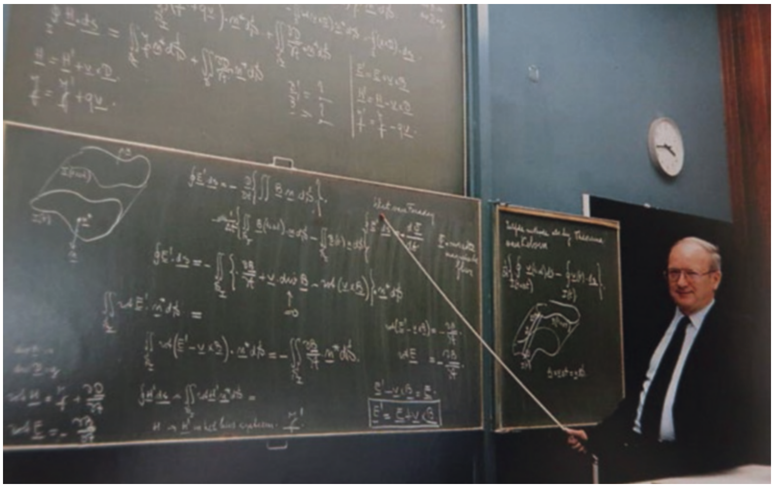
PHYSICISTS, ENGINEERS, AND MATHEMATICIANS

The mathematical approach to flow phenomena was, one could say, simply the most logical approach for physicists like Burgers and Broer. They were trained in it (Broer originally in another branch of physics) and they were good at it. Most engineers were less well-trained in this respect but naturally there were exceptions, especially among those who had chosen the more 'physical' directions, like solid and fluid mechanics at the Department of Mechanical Engineering in Delft. These were also the directions with the least students and with the stamp 'difficult' on them. Hinze and Van Wijngaarden, students of Burgers, are among these exceptions.

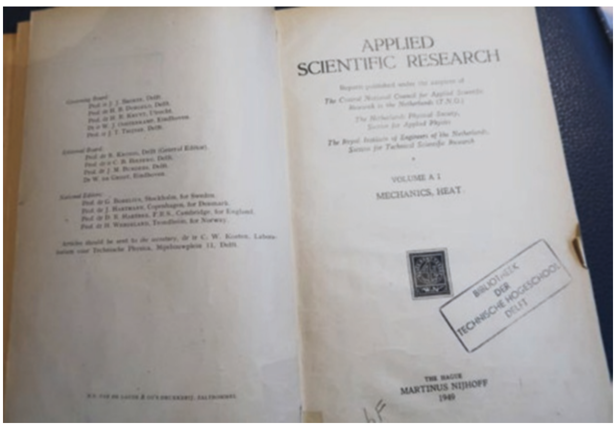
From the 1950s a 'love' of mathematics could especially be found among the Delft aerodynamicists. At the NLR many of them could find a lot of enjoyment in the theoretical groups. The Dutch poet, novelist, and essayist Gerrit Krol (1934–2013) had been trained as a mathematician and after his graduation in Amsterdam, he was looking for a job. In his book In dienst van de Koninklijke (about the time he worked for Shell), he wrote about this: "I had applied for a job at the Luchtvaartlaboratorium [the NLL; FA] in Amsterdam, had visited it and I had seen that in the shortest possible time I would become a specialist in solving differential equations there." Krol never took the job he was offered. But people like Zandbergen and Van Spiegel (see chapter 4) did.

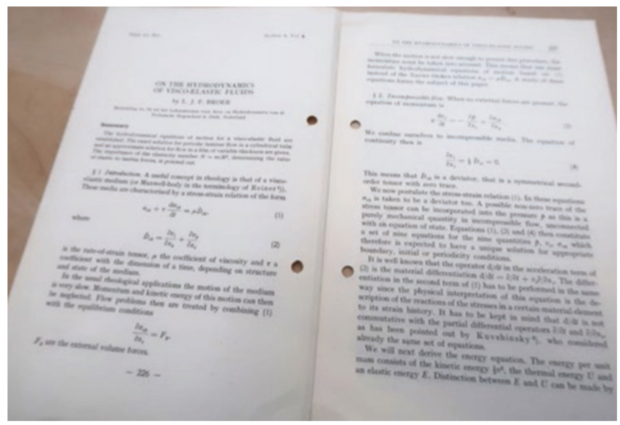
In other countries several 'pure mathematicians' had discovered fluid mechanics from about 1900. (One example is Otto Blumenthal from Aachen who fled to The Netherlands in the late 1930s where Burgers and others tried to help him. He died in Theresienstadt in 1944.) Among the Dutch mathematicians examples of an interest in flow theory are hard to find. Only from the 1950s did the situation start to change which, we can suppose, was largely due to the start of the training of 'mathematical engineers' (or 'applied mathematicians') in the TH in Delft. One of the most important pacemakers of this development was Timman (see below).

A new approach to fluid mechanics, especially turbulence,



←When Jaap Steketee retired as professor of theoretical aerodynamics in Delft in 1992, he must have been one of the last in fluid mechanics to have never touched a computer. Steketee was known for his very clear lectures and for his ability to apply mathematical techniques in aerodynamics. He had done some experimental work when still a student but had never liked that. (reprinted from Bakker et al (1992), with permission from IOS Press)





↑↗In 1947 some Dutch physicists thought it was time to start a new journal, published in their own country, in which articles could find a place which were hard to get published in the existing Dutch journal Physica, the journal of the theoretical physicists. The first volume of Applied Scientific Research would appear in 1949. Initially, the editors welcomed contributions from a broad range of physical fields but from the beginning it was also clear that fluid mechanics would be one of the prominent fields. In 1990 the editorial board, consisting of Nieuwstadt, Ooms, and Van Wijngaarden, decided to change the subtitle into Applications of Fluid Dynamics and in 1998 the title itself was changed to Flow, Turbulence and Combustion. Remarkably, Burgers himself would never publish in this journal. But Broer did and in volume 6, e.g., he wrote down the equations for a visco-elastic fluid, which – in hindsight - seems a rather bold thing to do in the 1950s. Like Burgers, Broer was much at ease with deriving and manipulating mathematical equations. (original publisher: Nijhoff, The Hague / courtesy of Springer)

came in the 1970s and found its origin in theories developed by mathematicians. The Burgers equation has been called "one of the simplest model equations which can exhibit spatiotemporal chaos". The 'chaos theory' became very popular in fluid mechanics in the 1980s (also with the general public), when it already had quite a long history. In 1971 a paper was published which became well-known, entitled 'On the nature of turbulence', written by Ruelle and Takens. Floris Takens (1940–2010) was a Dutch mathematician and professor in Groningen and became internationally known for his contributions to the theory of chaotic dynamical systems. Together with the Frenchman David Ruelle, he predicted that fluid turbulence could develop through a strange attractor, a term they coined, as opposed to the then-prevailing theory of accretion of modes. The prediction was later confirmed by experiment.

Takens also established the result now known as the Takens' theorem, which shows how to reconstruct a dynamical system from an observed time-series. This theorem has been applied to some multiphase systems used in the process industry from around 2000 by the group of Cor van den Bleek (1943), then professor of chemical reactor engineering in Delft. This monitoring method used a characteristic process variable, e.g., pressure, measured at high frequency. The obtained time-series was transformed into a so-called attractor, representing the successive states of the system during its evolution in time. The consecutive attractors obtained during the operation of the process were compared with a reference attractor reflecting the desired behaviour.

R. TIMMAN (1917–1975)

Reinier (or Rein) Timman studied mathematics and physics and found a job at the Fokker airplane factory in Amsterdam in 1939. During the war he put himself to study aerodynamics by reading all volumes of the Zeitschrift für Angewandte Mathematik und Mechanik and of Luftfahrtforschung. He discovered that some German scientist had been working on the vibrations of two-dimensional wings in flows of incompressible air (flutter). If these vibrations are not damped, then the wings can break. Timman succeeded in tackling this problem for flows of compressible air and managed to hide his results away from the Germans.

After the war Timman got his PhD in Delft where one of his supervisors was Jan Burgers. He left Fokker and got a position at the NLL where his expertise in the mathematical approach of flutter was very welcome. However, Timman's formulas had to be translated into practical results and to this end a huge amount of calculating work had to be done. This was done at the still young Mathematisch Centrum (Mathematical Centre, MC) in Amsterdam. It took several years before the MC could provide the calculated values of the aerodynamic coefficients which Timman and his team needed. But then, a terrible thing happened. An American scientist showed that the coefficients couldn't be right! The NLL tried to refute the criticism but had to admit that one of the formulas used showed an omission… After this was corrected, the recalculated air forces appeared to be correct.

Timman stayed at the NLL for six years and produced a lot of useful papers. He got involved in boundary layers and was able to extend the calculations to three-dimensional flows. He showed how to use tensors to describe the flow around a body. He considered the effect of two parallel walls on a vibrating wing profile and thus was able to provide the experimenters a method to correct their measurements from wind tunnel experiments (where the influence of the walls cannot always be neglected). Thanks to Timman the NLL got an excellent reputation, both national and international, with regard to non-stationary aerodynamics.

Despite Timman's success at the NLL, he chose to become a professor in 'pure and applied mathematics' at the Delft University, in 1952. From the first day in Delft he was aiming at the foundation of a new field of study in Delft, and of a new type of training for engineers; i.e., engineers with such an extensive knowledge of mathematical techniques would be able to tackle any problem from engineering practice. In 1956 the Ministry of Education finally gave Delft permission to start the education of 'mathematical engineers'.

Timman remained advisor at the NLL after he had left for Delft. In 1955 he also became advisor at the NSP where at that time hardly any mathematical activity took place. Scientists at the NSP started to do mathematical research on ship propellers and on 'slender bodies'. In his group in Delft the interest in hydrodynamics also grew, resulting e.g., in a thesis on cavitation. The WL also approached Timman and his co-workers for advice on the modelling of complicated flow phenomena.

Timman's reputation was worldwide, he even became advisor of the David Tayler Model Basin in the USA which did work for the American navy. In 1957 Van der Maas gave an extensive lecture before the Royal Aeronautical Society in London. One of the attendants there, praised one of the mathematical contributions by Timman to fluid mechanics: "[I would like to mention] Timman's brilliant theoretical discovery in the field of two-dimensional oscillating derivatives in high subsonic range. This beautiful analytical solution, by means of Mathieu functions, ranked high in aerodynamic theory, and was something of a shock for many predecessors who, despairing of the possibility of an algebraic solution, went the defeatist way of relying on brute computing force (the war which threatened to become a time-honoured escapist way in many parts, thanks to the monstrous development of electronic brains!). The solution was severely attacked because of some initial discrepancies between old and new arithmetical results but, as often happened, the errors were found to be computational only, and the new theory emerged victorious, to the great delight of 'algebraists'."

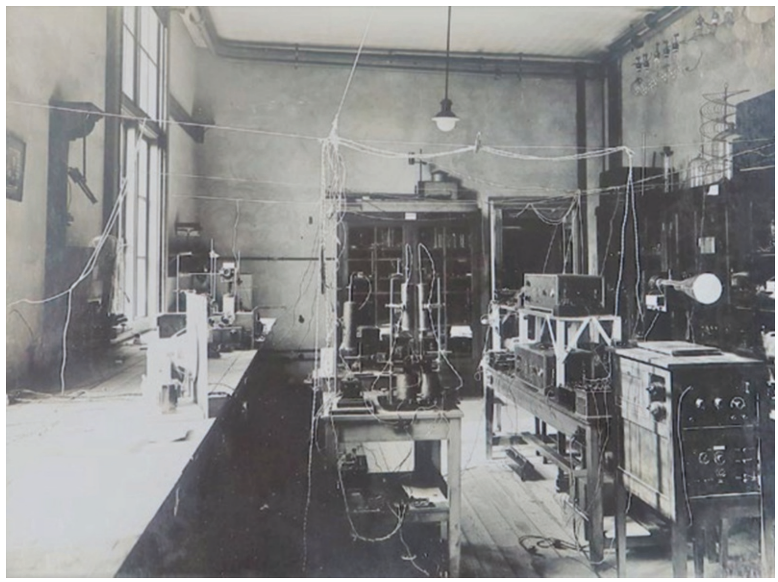
In 1975 Rein Timman gave a keynote address at the First International Conference on Numerical Ship Hydrodynamics in the USA. A few weeks later he died. One year earlier his son Jan had become a Grandmaster and had started an impressive career in chess.

↑Timman at the far end of the tabel on the left, in Paris in 1972. With Aad Hermans (whois sitting opposite Timman), he took part in the 9th Symposium on Naval Hydrodynamics. (courtesy of Aad Hermans)

Name	Standard symbol	Definition
Archimedes number	Ar	$\mathrm{Ar} = \frac{gL^3\rho_\ell(\rho-\rho_\ell)}{\mu^2}$
Atwood number	A	$\mathrm{A} = \frac{\rho_1-\rho_2}{\rho_1+\rho_2}$
Bejan number (fluid mechanics)	Be	$\mathrm{Be} = \frac{\Delta P L^2}{\mu\alpha}$
Bingham number	Bm	$\mathrm{Bm} = \frac{\tau_y L}{\mu V}$
Biot number	Bi	$\mathrm{Bi} = \frac{hL_C}{k_b}$
Blake number	Bl or B	$\mathrm{B} = \frac{u\rho}{\mu(1-\epsilon)D}$
Bond number	Bo	$\mathrm{Bo} = \frac{\rho a L^2}{\gamma}$
Brinkman number	Br	$\mathrm{Br} = \frac{\mu U^2}{\kappa(T_w-T_0)}$
Brownell–Katz number	N_{BK}	$\mathrm{N_{BK}} = \frac{u\mu}{k_{rw}\sigma}$
Capillary number	Ca	$\mathrm{Ca} = \frac{\mu V}{\gamma}$
Chandrasekhar number	C	$\mathrm{C} = \frac{B^2L^2}{\mu_o\mu D_M}$
Colburn J factors	J_M, J_H, J_D	
Damkohler number	Da	$\mathrm{Da} = k\tau$
Darcy friction factor	C_f or f_D	
Dean number	D	$\mathrm{D} = \frac{\rho V d}{\mu}\left(\frac{d}{2R}\right)^{1/2}$
Deborah number	De	$\mathrm{De} = \frac{t_c}{t_p}$
Drag coefficient	c_d	$c_d = \frac{2F_d}{\rho v^2 A}$,

↑All experimenters in fluid mechanics know: to make your model experiments relevant, you should keep the dimensionless numbers in the laboratory equal to those in the real world. In the past century many dimensionless numbers have been given a name. One of the most famous is the Reynolds number (Re). Only very few have been named after Dutchmen. We mention the Brinkman number (Br), named after the mathematician and physicist Henri Brinkman (1908–1961) which is related to heat conduction from a wall to a flowing viscous fluid, commonly used in polymer processing. Unfortunately, one can completely ignore Br since it can be replaced by Pr · Ec where Pr is the Prandtl Number and Ec is the Eckert Number, both named after non-Dutch scientists… (photo from Wikipedia: en.wikipedia.org/wiki/Dimensionless_numbers_in_fluid_mechanics [2018])

↑During Burgers' experiments on flows behind objects in the small towing tank, also stereo photos were made. These were taken by a camera moving along with the objects. (courtesy of Burgers Archives / TU Delft)



↑In 1930 all interesting places in Burgers' laboratory were photographed. This must have been the place where the experimentalists built and tested their equipment. We may suppose that some of the 'electronics' is related to Ziegler's work on amplifiers for the hot-wire technique. (courtesy of Burgers Archives / TU Delft)

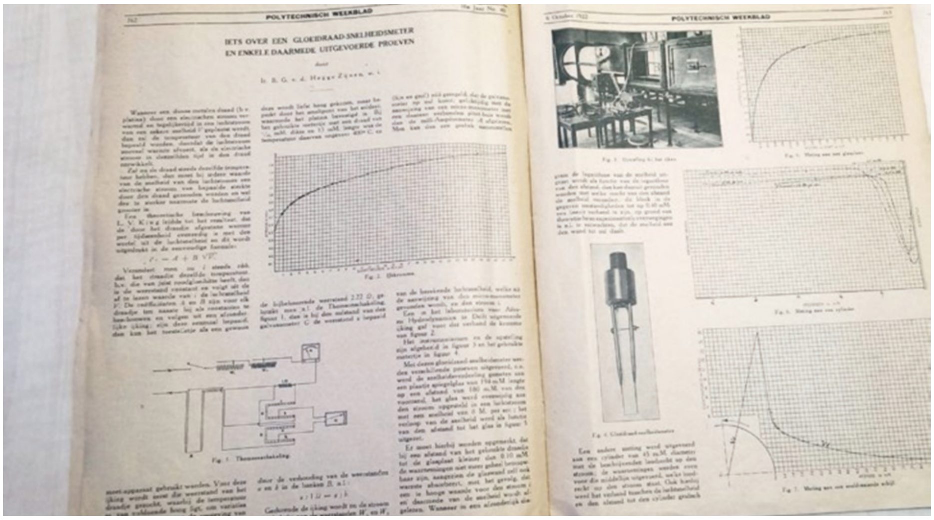
6.2 EXPERIMENTAL APPROACHES

"I would like to say some words about the science of liquid and air flows. Although here the foundations were determined a considerable time ago, the practice of these fields is somewhat different from that in mechanics because it is so much more difficult to derive results along a mathematical way. Therefore one has to resort to experiments". Thus spoke (in Dutch) the well-known physicist Hendrik Casimir in his inaugural lecture as special professor at the University of Leiden in 1939. Casimir didn't consider a third way to do research in fluid mechanics, the numerical approach (see § 6.3), which is not so strange since in the Netherlands this kind of research was hardly done in the 1930s. It was only in the 1960s, due to the rise of the digital computer, that Casimir's words would become outdated.

• 6.2.1 MEASUREMENT AND VISUALIZATION TECHNIQUES

MEASURING AND VISUALIZING IN BURGERS' LABORATORY UP TO 1955

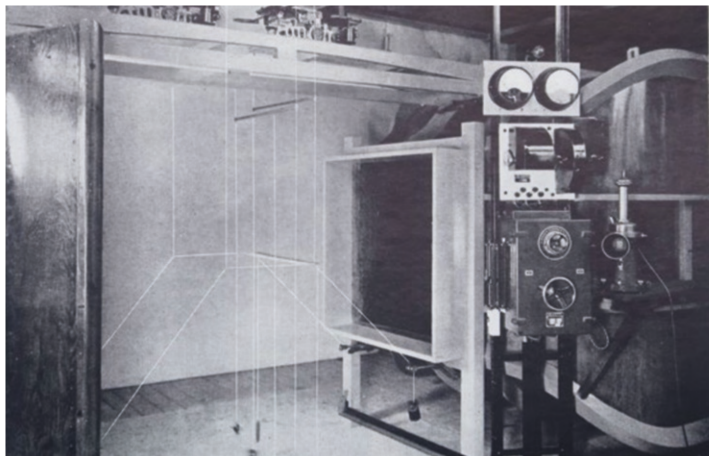
The very first experiments done in the Laboratory for Aerodynamics and Hydrodynamics were aimed at visualizing and


POLYTECHNISCH WEEKBLAD

IETS OVER EEN GLOEIDRAAD-SNELHEIDSMETER EN ENKELE DAARMEDE UITGEVOERDE PROEVEN

←In 1922 Van der Hegge Zijnen wrote about the still unknown hot-wire anemometer in the *Polytechnisch Weekblad*, a journal for engineers. He also explained how this device could be calibrated. To capture the fluctuating signal of his hot wires, Van der Hegge Zijnen used photo paper on which the signal could be depicted. (courtesy of Burgers Archives / TU Delft)

↑Van der Hegge Zijnen turned out to be a clever experimentalist. In the 1920s he also developed a special Pitot probe with five holes. With this the static pressure and both the value and the direction of the flow velocity could be measured. This probe has also been used for an investigation into a problem in one of the huge ventilation systems of the State Mines (see § 3.3.1). It detected a 'disturbing vortex' in one of the channels which could easily be removed by placing a small partition. Here we see the special probe on the left, together with other Pitot tubes which are conserved in a showcase at the section of Fluid Mechanics in Delft, the successor of Burgers' laboratory. (courtesy of Burgers Archives / TU Delft)

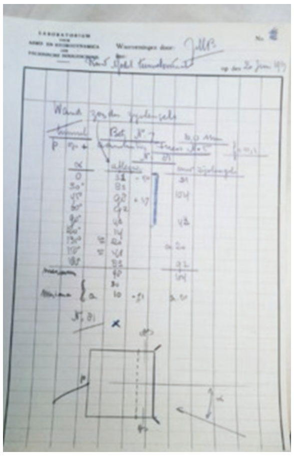


↑Besides flow velocity and pressure, sometimes forces on objects induced by air flows had to be measured in Delft. Since up to 1953 Burgers' Laboratory was the only place of the TH where aeronautical research could be done, research on aerofoils had to be done in one of the wind tunnels of the Laboratory for Aerodynamics and Hydrodynamics. To measure the forces on a wing profile an ingenious construction of weights and balances was built. This same mechanism was also used to measure the characteristics of several models of windmill sails (see § 3.4.2). (from: Havinga (1959))

observing flows around, and especially behind, objects like cylinders, flat plates, and aerofoils (or airfoils). These objects were towed in the water tunnel/towing tank of the laboratory (see § 6.2.4). The flows were made visible by means of aluminium powder floating on the water.

The idea of the boundary layer had been introduced by Prandtl in 1904 but up until about 1920 nobody was really able to do measurements on it. In 1921 Burgers got acquainted with the research that Von Kármán was intending to do in Aachen and this inspired him to also take up experiments on boundary layers. In the early 1920s there were only three institutes, Göttingen, Aachen, and Delft, that were interested in this subject. In the period from 1904 to 1924 in scientific journals only about twenty papers on boundary layer problems were published.

Burgers read about a new measurement technique in which tiny metal (e.g., platinum) wires were used which were connected to a battery (the resistance was kept constant so that the change in current strength could serve as an indicator of the air speed). Attempts were made in Delft to use these wires in the towing tank but these appeared to have been



←To write down measurements Burgers' Laboratory had its own special forms. This document from the Burgers Archives shows that by 1939 Burgers himself did some measurements in one of the wind tunnels. (courtesy of Burgers Archives/ TU Delft)

↑Flow visualization in the 1930s. Around 1936 a temporary 'shed' was built close to Burgers' Laboratory for experiments on the ventilation channels of the Maastunnel (see § 3.4.3). Parts of the model were made transparent and strings were placed inside which would follow the air flows. On the left one sees one of the many Betz precision manometers which were then used in the laboratory. Outside the building a model of the complete ventilation building was tested using smoke. (courtesy of Burgers Archives / TU Delft)

not very successful. In 1923 Van der Hegge Zijnen, Burgers' main research assistant for many years, started the now classical experimental work on the flat plate boundary layer in one of the wind tunnels of the laboratory. He improved the hot-wire technique and became the first who was able to measure velocities as close as 0.05 mm from the wall. He could confirm a result which had been predicted by Prandtl and Von Kármán some years earlier, namely that the mean velocity in a turbulent boundary layer increases as y1/7 with y the distance from the wall of a flat plate. In 1924 Van der Hegge Zijnen finished his PhD thesis on this research.

Subsequently the hot-wire method was increasingly used in the Laboratory to measure turbulent fluctuations and correlations. Burgers invented some new hot-wire anemometers himself, one of them with two parallel wires. It became clear that this equipment required more knowledge of electronics than was available among the staff. It was a great help when, in around 1928, another assistant could be appointed, Marc Ziegler, who had an electronics background (and would leave Delft after only a few years for Philips). One of the interesting results which was obtained has been described by Burgers as follows:
"When making oscillographic records of the velocity fluctuations in the boundary layer along a glass plate, he (Ziegler) again found that the boundary layer can be steady and laminar over a certain distance, while in the region of transition this laminar flow appeared to be interrupted at irregular intervals by short periods of complete turbulence. These periods were found to grow in duration and number as one goes downstream. Ziegler thus observed the intermittency of incipient turbulence."

Despite many broken wires and a growing number of alternate, and sometimes more convenient, techniques, the hot-wire technique kept its place in the Delft laboratory until well into the 1990s. In the 1950s the equipment had already become so shock-proof that it was used for boundary layer measurements aboard the Koolhoven FK 43 plane of the Department of Aeronautical Engineering. The principle changed from 'constant current' to 'constant temperature' which allowed a much higher frequency response, much needed for research on turbulent flows. Another improvement was the replacement of a single wire by two wires arranged in an X. This made it possible to measure the so-called Reynolds stress in the flow (the friction caused by the turbulence). The last probe made in the Laboratory even had four wires and was fabricated by a specialist in a special workshop under a microscope in 1994.

WATER-RELATED MEASUREMENTS ELSEWHERE

←A typical situation which one could encounter for decades in the Waterloopkundig Laboratorium in Delft. This photo was taken in the 1950s, when the use of self-registering instruments was still not common practice. For most measurements the people at the WL sometimes had to be inventive since no standard equipment was available to do the job. It is known that sometimes Meccano elements and letter scales were used. (courtesy of Deltares)

→In the 1930s Rijkswaterstaat had started to do research on the Delta area. Some of their engineers started to perform measurements, e.g., on the speed and direction of the water flows near the bottoms of tidal inlets and on the movements of sediments. To this end they had to develop specific measuring instruments which could be used on special measuring ships. On the tidal movements near the Dutch coast, still hardly anything was known and therefore RWS decided to install self-registering tide measuring devices. For the investigations on sediments, RWS could make use of this invention by J.J. Canter Cremers, an engineer who had been involved in the state committee that had studied the consequences of a continuation of the deepening of the Nieuwe Waterweg (see § 2.1.1). He designed a 'zandvanger' (sand catcher). This page from Van Veen's description of the measurements at sea also shows a 'bottom flow meter'. (from: Van Veen (1936))

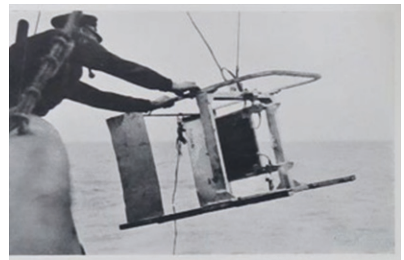
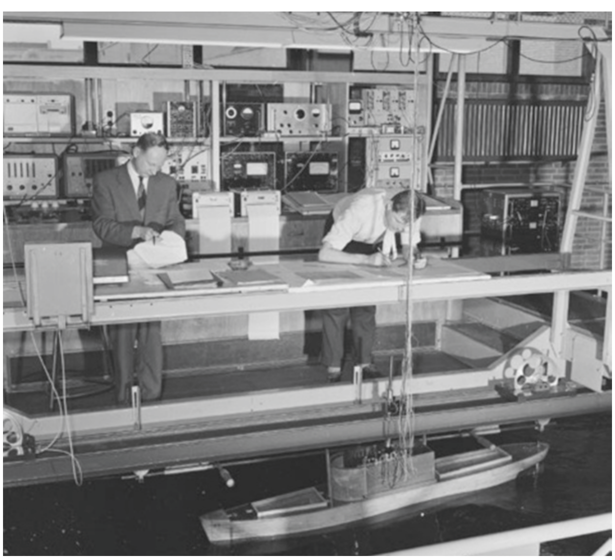
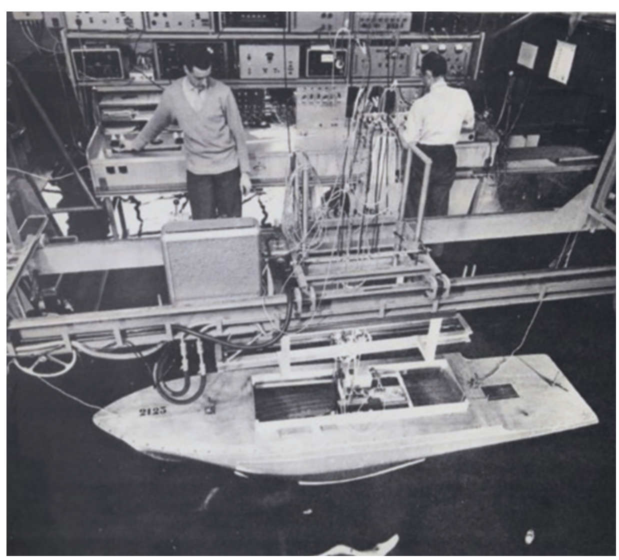


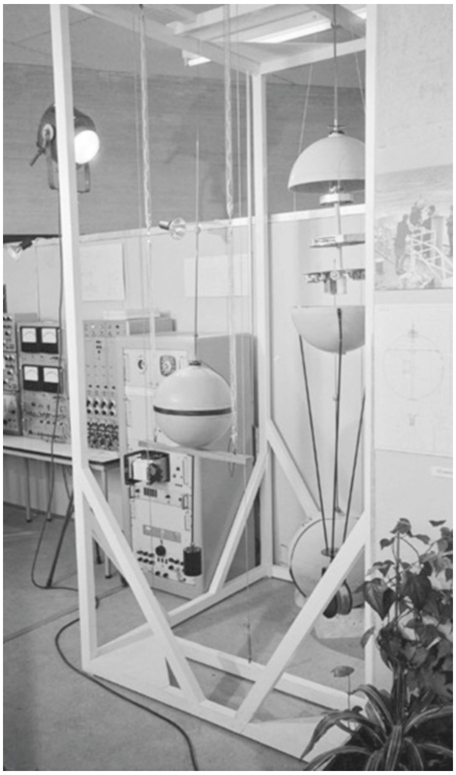
Fig. 130. Bodemstroommeter voor stroomen op 0,15 en 0,50 m + bodem.

Fig. 132. Het ophalen van den zandvanger.





↑Around 1960 the use of electronic equipment had become common in the towing tanks of the Shipbuilding Laboratory of the TH Delft. But some handwriting was still necessary (note the pipe). Ten years later, at the NSP in Wageningen, the researchers seem to have been definitively liberated from pen and paper and the equipment looks even more impressive. (courtesy of TU Delft / photo by Fotografishe Dienst via Beeldarchief / CC BY; courtesy of MARIN)



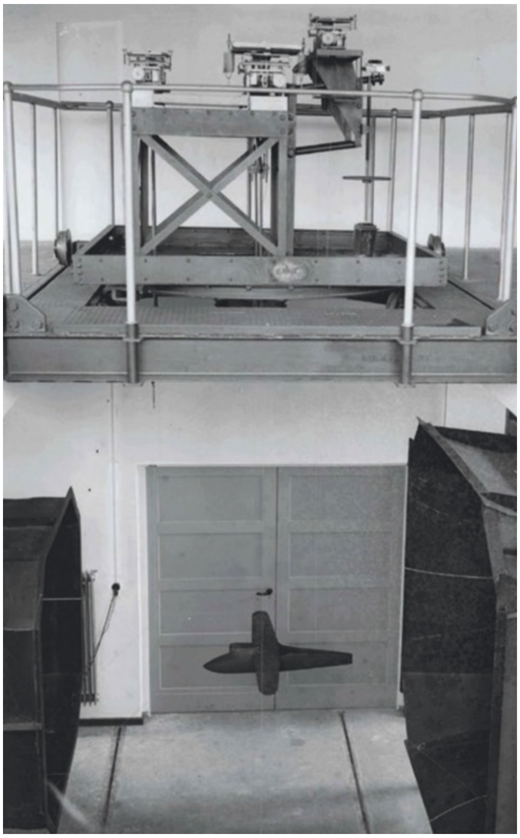
←Measurements outside the laboratory sometimes required the invention of new and robust measuring devices. These buoys could be used for measuring wave heights at sea. According to a description given by a TH Delft newsletter in 1967 the procedure was as follows: “At the start of the measurements a buoy, equipped with a accelerometer and a radio transmitter, is thrown into the sea. The measured acceleration signal – frequency modulated – is emitted and received on board, demodulated and integrated in time twice, to find the wave height.” (courtesy of TU Delft / photo by Fotografishe Dienst via Beeldarchief / CC BY)

↑In the world of dredging the equipment is always robust. This is a combined speed and concentration meter, developed by Krohne and IHC and exhibited at the National Dredging Museum in Sliedrecht. With this meter the ‘zuigbaas’ (suction boss) can be constantly informed about the precise composition and flow speed of the slurry which is taken from the bottom of the waterway. The working is based on principles from electromagnetics and radioactivity.

AIR-RELATED MEASUREMENTS ELSEWHERE

↑The measurements like those with the balances delivered a stream of data which had to be ‘processed’. Up until the 1950s calculations on these data were done by hand at the Uitwerkdienst (Data Processing Service) of the NLL. This photo of about 1946 suggests that this Service was completely run by women. (courtesy of Stichting Behoud Erfgoed NLR)

↑From the 1980s full-scale wind turbines were tested in the dunes at the Energy Centre of the Netherlands ECN in Petten. In 1993 Gustave Corten invented the so-called stall flag method as a PhD student in Delft. Corten continued the development of the method at ECN. The method is still the only option to visualize the dynamic stalling behaviour of full-scale wind turbines. The stall flag is a sticker-like indicator with a hinged flap covering a reflector. When during the rotation of the blades separation occurs at a certain spot, the flow will be reversed and the flap will turn over. An observer in the field with a lamp can see the flagging separation. The method was used to study dozens of turbines in several countries. Corten’s company applies the method to detect and solve premature stalling problemsn by the application of the so-called vortex generators and thus increasing the energy yield. (courtesy of Gustave Corten / CortEnergy)

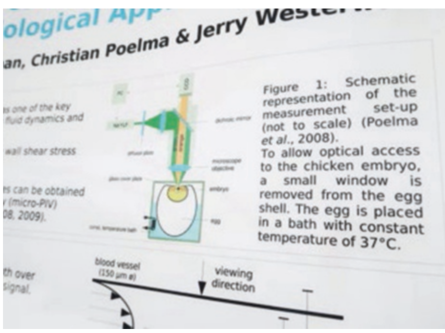


←The design of airplanes involves the testing of aerodynamical properties. To this end models and wind tunnels were used almost from the start of aviation. The Fokker F.II was tested upside down in the first wind tunnel of the RSL around 1920. The strut was connected to the so-called Eiffel balance, mounted above the test section. The picture shows a testing session around 1945, in the small low-speed tunnel of the NLL (tunnel no. 4). The model is suspended on wires attached to an external 'overhead' balance. (courtesy of Stichting Behoud Erfgoed NLR)

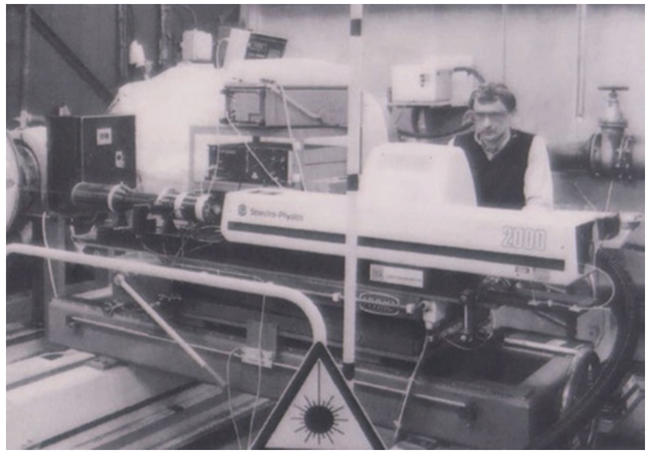
↑In the 1950s the operators' areas of wind tunnels became more 'professional' and resembled that of industrial process plants. This is the first wind tunnel of the Department of Aeronautical Engineering in Delft, where in 1963 a group of visitors gets an explanation of the tunnel by professor Van der Maas himself (leaning on the console). Note how all guests are focussed on the small printing device. Data from the wind tunnel tests could now be recorded automatically. (courtesy of TU Delft/ photo by Fotografische Dienst via Beeldarchief / CC BY)

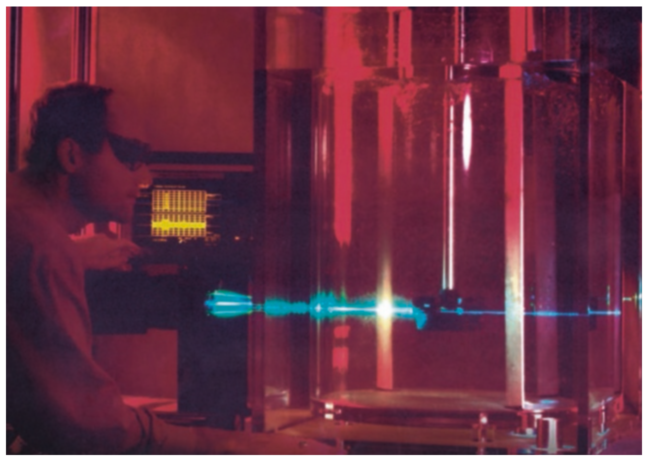
↑In the world of aeronautical research, one sometimes needs a real airplane to do full scale measurements for other real airplanes. This Cessna Citation was a 'laboratory plane' of the NLR around 2000. For a large international project called S-Wake, it was equipped with a 'nose boom' on which flow vane sensors could measure the wake behind planes. If two planes at an airport take off after each other, there is a chance that the vortex wake of the first one will cause a crash of the second one. It was still unknown at that time which distances between planes could be regarded as safe. (courtesy of Stichting Behoud Erfgoed NLR)

↑To determine the locations of transition spots where the laminar boundary flow had turned into a turbulent flow, the NLL used the so-called China-clay method. Here, in 1957, the method has been applied to the rotor blade of a helicopter. The dark parts indicate a laminar flow. (courtesy of Stichting Behoud Erfgoed NLR)

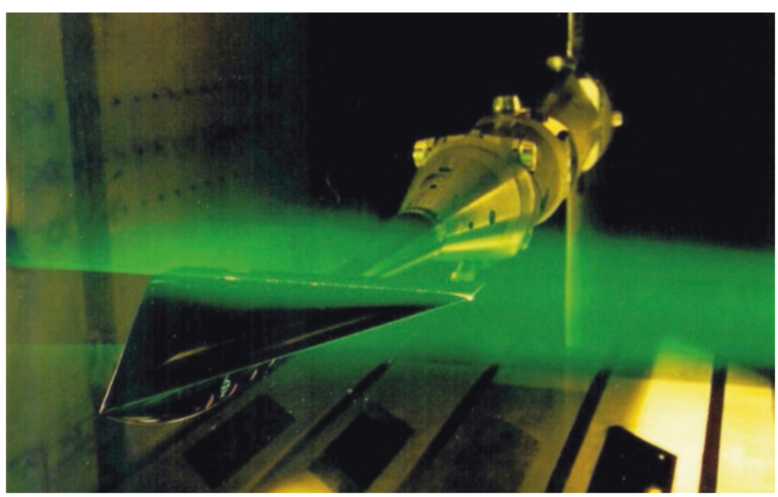


↑Westerweel and Poelma have been involved in several PIV-related investigations. One of their first posters on their results can probably be claimed as the only scientific presentation poster which is completely wordless. It shows a flow field of 40 x 40 mm showing details of 2 micrometers. The other photo shows a detail of a poster on blood flow measurements. PIV is by far the most suitable method for this since other methods, like LDA, imply a temporal resolution which is longer than typical heart rates. The project involving a chicken embryo was a project in cooperation with medical groups in Leiden and Rotterdam. In a research project which started around 2005 PIV was used to investigate whether extra-embryonic flow influences heart development. This was based on the speculation that heart development is linked to the wall shear stress patterns within the forming heart. In vitro studies have shown that shear stress can modulate gene expression.





↑Two applications of LDA. At the IFRF laboratory in IJmuiden (see also Ch 7) LDA has been used to measure the (turbulent) flows related to flames and burners.(courtesy of IFRF) At Shell LDA was used from the 1970s but only with the arrival of powerful computers in the 1980s this technique became really fruitful. (courtesy of Shell / Peter Veenstra)



↑Also in research on airplane models PIV has greatly improved the possibilities of obtaining data. Around 1985, in the wind tunnel of the NLR, a probe had to be moved along the model. Today the flow field can be measured much quicker by using a green laser sheet and PIV technology. (courtesy of Stichting Behoud Erfgoed NLR)

THE LASER ERA

Soon after lasers became reliable and (more or less) affordable in the early 1960s, they became used for many purposes. One of them was the measurement of fluid flows. The laser entered the laboratories and warning signs ('laser on') and protective sheets of black and blue 'agricultural plastic' appeared everywhere.

In 1964 Laser Doppler Anemometry or Velocimetry (LDA, LDV) was introduced to the scientific and industrial world. In LDA the Doppler-shift of light scattered by a small particle that moves with the flow is determined. This Doppler-shift provides a measure of the velocity of the particle, and therefore the flow velocity. The main advantage of the technique over conventional measuring techniques, such as hot-wire anemometry and pressure probes, is that it does not require a physical probe in the flow, i.e., it is a non-intrusive technique. Therefore, the flow is not disturbed during a measurement.

It is not known when LDA was used for the first time in the Netherlands but in the Kramers Laboratory in Delft the technique was used from the early 1970s. At the Technisch Physische Dienst TNO-TH (known as TPD) LDA was tested and developed in 1971. Soon LDA would enter almost all fluid mechanics laboratories, e.g., the flame research facility of the group of Hoogendoorn in Delft.

But LDA and hot-wires are one-point measurement techniques, and therefore not able to reveal the instantaneous spatial structure of a flow. For the detection of coherent structures in turbulent flows, and for other phenomena, a more sophisticated technique was needed. This became Particle Image Velocimetry, or PIV. In this technique a flow is seeded with small particles. These are illuminated in a plane by means of a laser light sheet and are recorded by a camera. By taking two exposures of the same image separated by a small time fraction, one records for each particle two positions displaced by a small distance. By means of a correlation analysis one can measure this distance and after dividing this by the time interval one obtains the velocity vector field in the light plane.

PIV had already been developed in the USA in the 1980s but was then in an 'analogue' and therefore time-consuming version. Around 1990 Jerry Westerweel in Delft, under the guidance of Nieuwstadt, started to develop a digital version of PIV, independently of the American researchers working on the same topic. In his PhD thesis of 1993 Westerweel was able to show that Digital PIV (DPIV) was a fast and reliable technique which could produce results of "acceptable accuracy".

From then on, PIV started to conquer the world of fluid mechanics and soon several variants of PIV appeared. For Stereoscopic PIV (SPIV) two cameras were used. (SPIV was used e.g., by the group of Clercx and Van Heijst for experiments on rotating Rayleigh-Bénard flows; see § 5.1.3). Then came the quest for PIV variants with which 3D patterns could be found in flows. One of these variants was Holographic PIV, another was Tomographic PIV. An important early contribution to Tomo-PIV came from Gerrit Elsinga in 2006 (for which he was awarded the Leen van Wijngaarden Prize in 2012). The technique was also further developed by Westerweel and Christian Poelma.

Since 2000 PIV has been used for many purposes: to detect coherent structures in the compressible wake of a 2D model in a supersonic freestream; to measure blood flow in a chicken embryo; to study cavitation on hydrofoils; to investigate the flow above rippled sand beds; etc.

For some flows, PIV does not work. One of the difficulties with experiments in multiphase flows is the opaque nature of most multiphase systems. Consequently, laser-based techniques are of limited use. However, matter is to a certain extent transparent to X-rays. The group of Rob Mudde in Delft (professor of Multiphase Flow at the Department of Chemical Engineering) has used a fast X-ray CT scanner. With this device they could reconstruct the spatial distribution of the various phases in two parallel cross sections of a model reactor. Poelma (also professor of Multiphase Flow, but at the Department of Mechanical, Maritime and Materials Engineering) is working on 'tomographic reconstruction using X-rays'.

Other non-PIV techniques have also become more or less common in fluid mechanics. The high-speed camera has proved itself to be very useful in the investigation of the behaviour of droplets and bubbles (e.g., in the group of Lohse in Twente). MRI has been used for flow measurement by professor Daniel Bonn of the University of Amsterdam. The Applied Molecular Physics group of the University of Nijmegen is working on APART: Air Photolysis and Recombination Tracking. In this latter measuring technique velocity information is obtained by following tagged molecules in the flow, so it does not require particle seeding, as does the PIV technique. (The University of Nijmegen has been the only general university with a chair in fluid mechanics, at the Physics Department.)

• 6.2.2 WIND TUNNELS

The 'general public' will associate fluid mechanics most of all with wind tunnels. The first wind tunnels were built in the last decades of the 19th century and there was a tremendous increase in their number, performance, and variety, during the 20th century, which continues even today. On the other hand, wind tunnels are disappearing from fluid mechanics, mainly due to the rise of CFD. For instance, at Shell's KSLA the wind tunnel was removed when the computer models become 'good enough' to investigate and evaluate the fluid flows relevant for the company. Some (remarkable) Dutch wind tunnels are treated in this section.

EVERYTHING FLOWS, BUT HOW DO YOU MEASURE THAT?

JOOST GROEN, VSL B.V.

In the current-day world, particularly in western society, fresh water flows from our kitchen or bathroom tap when we open it, we can get petrol from a station close to where we are, and high-pressure natural gas flows through massive pipelines over large distances, often crossing national borders. It's as simple as that. We also pay for all this based on measured data, and we assume that the amount of water, petrol, or gas that we pay for is correct. Why is that? Indeed, we take it as read that the data supplied by the flow meters directly relate to the real amounts. In other words, that the meters are calibrated.

How should you calibrate a flow meter? A straightforward way is to use scales, or a flask of known volume and a timer, but you could also use another flow meter. However, such a calibration only holds water (so to say) if those devices are actually more accurate, and are themselves also calibrated. Clearly, that requires other, even more accurate, calibrated equipment, and so on. This chain can continue for a while, but soon it runs out of links. At that point you have arrived at the most accurate, highest measuring standards that exist. These are guarded, maintained, and improved by the National Metrology Institutes (NMIs) of the world.

Metrology is the science of measurement. Measuring properly and accurately, particularly at the highest level, is certainly a craft, and by many even considered as an art. In any case it is not straightforward. The NMI of the Netherlands is VSL, or Van Swinden Laboratory. Jean Henri van Swinden was a Dutch scientist who was one of the people who formed the basis of the current Système International d'Unités, better known by its abbreviation as the SI. In 1799, Van Swinden handed the original meter (a platinum rod) to the French government. In 1816 the Netherlands was the first country to have a Metrology Act and in 1929 became a member of the Metre Convention. Since 1937, VSL and its predecessors have been responsible for the Dutch measurement standards, by request of the Dutch government.

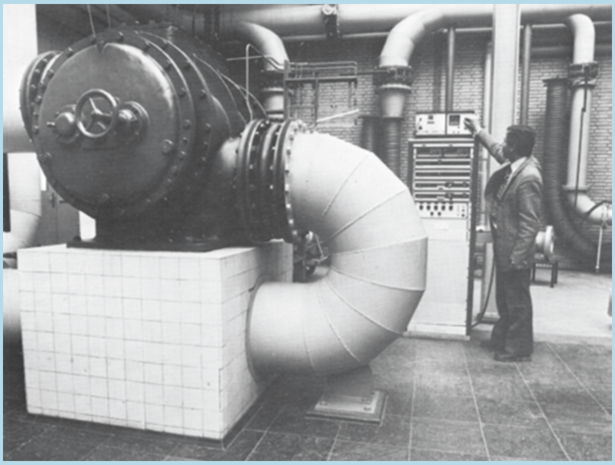
Just a small clarification: the flow meters in your home are not really calibrated, but they are verified. This means that they are checked against a (calibrated) standard and if the deviation of the meter is below a certain value (the maximum permissible error), it receives the "OK" stamp. Calibration is a more complex process, where for several values of the flow range of a meter, the deviation with the standard is determined and documented. What's more, for each of these values, the uncertainty of that measurement is assessed. Uncertainty is a key parameter in everything VSL does. The lower the uncertainty of a given measurement, the more accurate the measurement. A proper uncertainty determination relies on an unbroken chain of well-documented calibrations from the measurement under consideration all the way to the highest measurement standards. If that is the case, the measurement is said to be traceable to the SI. Without traceability, a measurement result formally means nothing.The determination of the uncertainty is almost a science unto itself, often involving complex calculations. Particularly for industrial applications, uncertainty can be difficult to determine. A flow meter is more often than not used at a different temperature and pressure as well as for a different medium than used in calibration. These differences are all accounted for in extra uncertainty terms, often after long debates. While a value of 0.25% uncertainty, let alone a difference between 0.24 and 0.25% uncertainty might seem small or even insignificant, if a very large amount of, for instance, natural gas flows through the meter (which happens with the meters at the borders of our country), the amount of "uncertain" gas can be huge. When the discussion turns fiscal, in other words when the measurements are used to charge for the fluid measured, the impact can be massive.

Over the last century developments in liquid and gas flow measurement have been immense. Current ubiquitous mechanical flow meters for instance involve bluff bodies that generate Von Karman vortex shedding, turbines, and rotors. Flow meters using temperature differences, an electromagnetic field, or ultrasound, do not physically reach into the flow. Coriolis flow meters measure mass flow rather than volume flow. Magnetic resonance is used to measure more phases than one and distinguish between them, facilitating the measurement of multiphase flow. But also well-established flow meters that have been in use for decades (such as Pitot tubes and bellows meters) still are and will remain to be in widespread use.

New developments do not only pertain to new measuring principles or types of flow meter. Flow meters are also increasingly equipped with on-board diagnostics that can let the engineer know that something might be going wrong soon or that they should arrange maintenance shortly. By diligent research much more has become known about the impact of the flow profile, swirl, and equipment geometry (particularly the need of leading and trailing undisturbed pipe lengths, bends, valves, contractions, etc.) on measurements. Furthermore, flow meters are being deployed in extreme conditions or with media that hadn't been thought of when those meters were invented.

Gas and liquid flows are being measured traceably over a very wide flow range, from the tiny (less than one millilitre per hour for drug delivery in intensive care units in hospitals), to the massive (tens of thousands of high-pressure cubic meters per hour in the case of fiscal metering of natural gas flows), and effectively everything in between. Moreover, increases in pressure and temperature range, and the addition of new media for which the flow should be measured, add to the complexity of flow measurement.

All flow meters have their vices and virtues in different conditions and with different media, and all have to be calibrated to give sensible results.



↑A large rotor gas meter which was used for calibrations in one of VSL's former laboratories in Dordrecht. (courtesy of VSL / photo by Cees Mastenbroek)

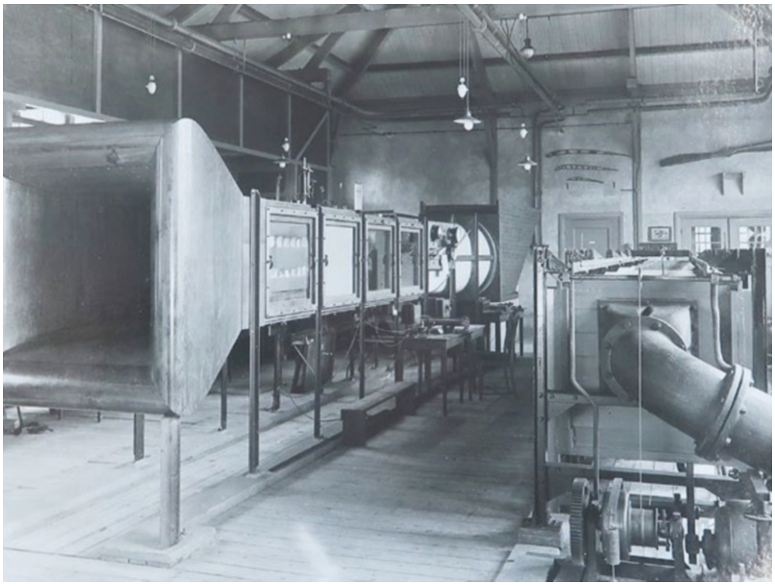
↑In one of VSL's so-called bell provers the Dutch cubic meter is born. This is the primary gas flow measurement standard in the Netherlands. Calibrations of flow meters using the left bell prover have a measurement uncertainty of below 0.1%. (courtesy of VSL / photo by Fons Alkemade)

↑One of VSL's gas flow calibration facilities, showing various reference standards against which other flow meters can be calibrated. (courtesy of VSL / photo by Fons Alkemade)

↑During the 6th European Flow Measurement Workshop, held in Barcelona in April 2018, nearly 200 delegates from 28 countries discussed how the newest developments in fluid flow measurement help them to stay in control of their processes. (courtesy of VSL / photo by Marcel Cloo)

In recent years, the energy transition has fuelled various new developments in flow measurement. The transport and storage of Liquified Natural Gas (LNG) takes place at -160°C, where many flow meters simply don't work. Systems where natural gas users not only receive gas, but also can supply to the grid (for instance farmers who generate biogas) have their own measuring challenges, if only because of the differences in composition of the various (even if small) flows involved. Hydrogen, seen as a key future energy carrier is such a small molecule that it is notoriously hard to measure at all. This was also shown clearly during the 6th European Flow Measurement Workshop which was held April 2018 in Barcelona, co-hosted by VSL, and where many exciting new developments in equipment and applications were shared. Indeed, everything flows: the field of flow measurement is itself in constant motion.

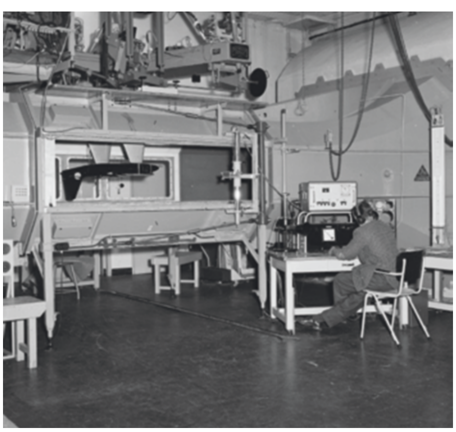
One question you might have: how does an NMI know that the values of the national standards are correct? What happens is that we compare our highest measurement standards to those of other NMIs in so-called round-robin tests, which are regularly held by groups of NMIs. These measurements are then compared, and the uncertainties of the measurements at the different NMIs are evaluated. Agreements are then made on how the various national standards compare to each other, and on the related uncertainties. The result of this is that calibration performed in the Netherlands should give the same results as those of a calibration in any of the other countries. By collaborating at the highest possible measurement level, countries make a joint best effort to make sure that the most accurate measurements are available everywhere and always, for everyone.



↑Burgers' laboratory in Delft around 1930, with the largest, open-end wind tunnel on the left. (courtesy of Burgers Archives / Delft University of Technology)

↑The Low-Speed Wind tunnel Laboratory around 1960. To the right was the main building of the Department of Mechanical Engineering. Behind the Low-Speed building the new Laboratory for Aerodynamics and Hydrodynamics would be finished in 1962. (courtesy of TU Delft/ photo by Fotografishe Dienst via Beeldarchief / CC BY)

→One of the two main halls of the 'new' Laboratory for Aerodynamics and Hydrodynamics, around 1990. At that time lasers had already become a familiar part of the equipment, and so were large sheets of plastic. Since 1962 the fluid mechanics engineers had plenty of space here, though the wind tunnels have never been very large. In the cellar most of the experiments involving water were done. The initial name of the Laboratory was still used when the Fluid Mechanics section had to leave this building in 2000 but officially it had already been abolished (Leen van Wijngaarden already called it an 'old-fashioned' name when he came to Twente in 1966). The building was completely demolished in 2017. (courtesy of Burgers Archives / TU Delft / photo by Fons Alkemade)



↑Measurements of an airplane model in the Low-Speed Wind tunnel Laboratory around 1958. Notice the headphones on the head of the researcher. (courtesy ofTU Delft / photo by Fotografishe Dienst via Beeldarchief / CC BY)

→The most recently opened facility at the LSL is this partly 3D printed vertical wind tunnel for aero-acoustic research. With wind speeds of up to 60 m/s, its height of 3.6 m and diameter of 3.0 m it is the largest of such facilities in the world. In this tunnel the sound production of e.g., the propellers of wind turbines can be investigated. For the designers of the tunnel, it was quite challenging to get the tunnel itself silent. Microphones are important measuring devices here.

DELFT

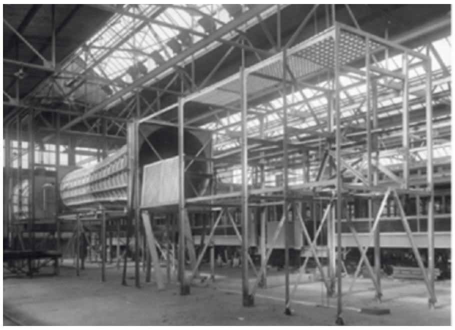
As we have seen in § 2.3.3 the very first wind tunnel was in use around 1913 in Delft but it didn't survive the First World War. The first wind tunnel in Burgers' laboratory was ready for use in 1922. In 1927–1928 a second tunnel was put into operation. Around 1949 the Laboratory for Aerodynamics and Hydrodynamics had four wind tunnels. The largest of these couldn't be used for some time since its 20 Kw transformer had been confiscated by the Germans during the Second World War.

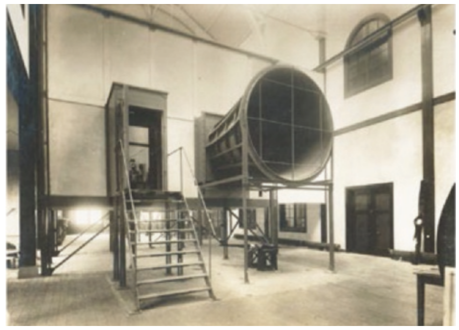
The first wind tunnel on the new 'campus' of the TU Delft, in the Wippolder, was not in the new Laboratory for Aerodynamics and Hydrodynamics of the Department of Mechanical Engineering. It was in the Lage Snelheids Windtunnel Laboratorium (Low-Speed Wind Tunnel Laboratory, LSL) of the Department of Aeronautical Engineering. This laboratory was also the very first building on the campus and when it was put into operation in 1953 one could still find grazing cows and small farms around it.
This low-turbulence wind tunnel, much larger than those in Burgers' laboratory, had been designed in cooperation with the NLR. It contained a quite revolutionary concept: the measuring section could easily be changed to another one. It was thus possible to have students doing their practical work (on a model of the Fokker T-5, for example) in the morning and to have researchers doing other research in the afternoon (or night). In 1977 the building was modified and extended. Among the new facilities was a unique vertical wind tunnel, which was named after professor Eise Dobbinga who had become Lecturer in Aerodynamics in 1954. Later a special boundary layer wind tunnel was completed. Around 1960 research was done here on boundary layer suction; one of the researchers was Henk Tennekes who got his PhD in 1964 under the guidance of Steketee (see § 4.1). He then went to the USA and became known internationally after publication of the textbook *A first course in turbulence* which he wrote together with John Lumley and which was published for the first time in 1972. Later, Tennekes would become research director of the KNMI.
The LSL also became well known for its study on the prediction of the transition of two-dimensional flows around wings. In the course of time it also gained much knowledge on wing profiles for low speeds, and on those for sailplanes.

In 1959 a second wind tunnel was acquired by the still-young department. A supersonic tunnel (measuring section 15 x 15 cm) was installed in the cellar of the Laboratory. Initially it could only run for 90 seconds per day! From 1964 it was partly used for research on delta wings, a project related to the development of the Concorde supersonic airliner.
In 1967 the Department of Aerospace Engineering got its new main building in the southern part of the campus, where there was plenty of space to expand (see also § 4.1.1). Two years later a separate laboratory building, the HSL, with two high-speed wind tunnels was inaugurated. Today this Aerodynamics, Power and Propulsion Laboratory (containing both the LSL of 1953 and the HSL of 1969) has a number of high-speed and low-speed wind tunnels for aerodynamic measurements, including a low-turbulence wind tunnel, a large open jet facility and a 0.27 m diameter hypersonic facility. The open jet facility is a unique wind tunnel for testing model rotors of wind turbines. The hypersonic wind tunnel is one of the few in Europe based on the so-called Ludwieg-tube principle which makes it possible to reach Mach numbers between 6 and 11.

RSL / NLL / NLR

Th second wind tunnel in the Netherlands was the first tunnel for the RSL. In 1918 its construction was started and on 5 April 1919 it was officially opened in a building on the Navy Wharf in Amsterdam (see § 3.2.1). Not much is known about the first measurements which were done in this tunnel of the 'Eiffel type'. The results were somewhat disappointing: the flow appeared to be not uniform and the maximum air velocity appeared to be 25 m/s and not the expected 33 m/s. Later in April 1919 there were already plans to insert a closed measuring section in the tunnel. This would be the first of a whole series of modifications.
For years this would be the only wind tunnel for the RSL. Only in 1938 was it decided to build two new tunnels, this time of the 'Göttingen type', a tunnel with a closed return circuit. In the biggest tunnel maximum speeds of 80 m/s could be reached. The new tunnels were installed in the new NLL building on the outskirts of Amsterdam and were almost finished when in May 1940 the Germans occupied the Netherlands. Ironically, the tunnels went into operation under the supervision of a 'Beauftragte', who reported on the developments at the NLL to the well-known aerodynamicist Betz, director of the Aerodynamische Versuchsanstalt (AVA) in Göttingen. In a discussion with Betz in July 1940 it was agreed that the NLL would not contribute directly to the war effort but could continue basic research activities in consultation with or even under contract from AVA.
During the War studies were done to transform one of the new tunnels into a facility for the study of high, but still subsonic, speeds. This appeared to be technically unfeasible and it was not until 1948 that new ambitious plans were announced: a huge High-Speed Tunnel (which became known as the HST) for speeds up to Mach 0.95; a low-speed low-turbulence tunnel for aircraft development; and a small compressor driven supersonic facility (the SST).
As we have seen in § 3.2.1 the construction of the HST could only be started in 1955. But the first supersonic tunnel, in fact the first in the Netherlands, was already operational in 1948. It had been designed by the German engineer Erdmann (see § 4.1.1), it had a test section of 3 x 3 cm, and could reach speeds of Mach 4.
After the completion of the HST around 1960, the NLL and its wind tunnels got an excellent reputation throughout the world. International cooperation developed, e.g., via the

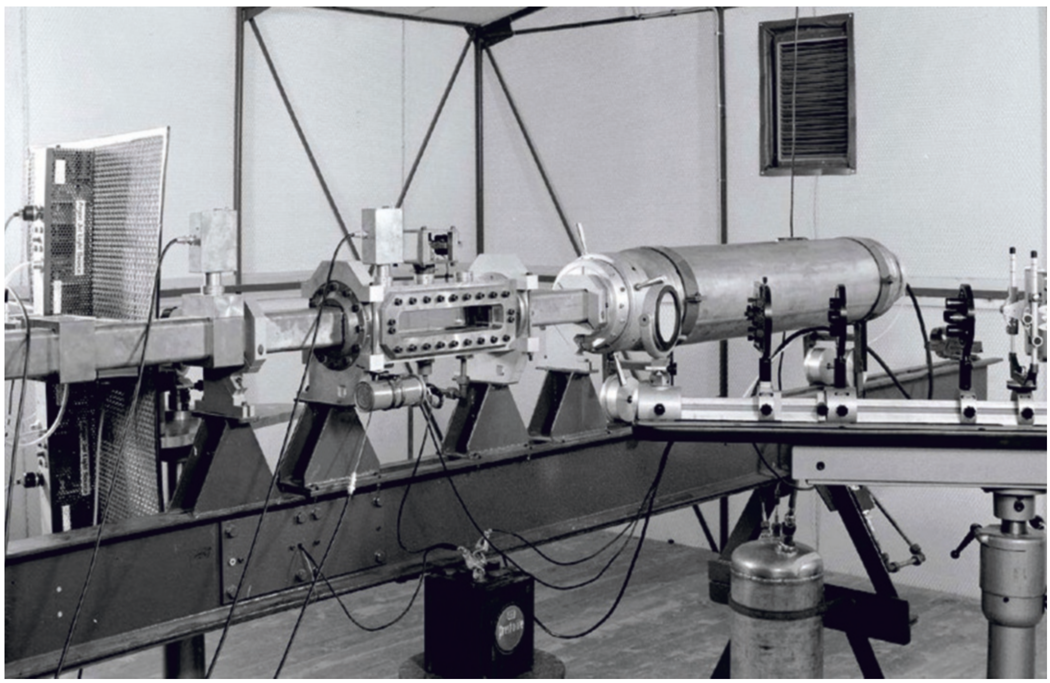




↑↗The Eiffel type wind tunnel of the RSL under construction at the Werkspoor company in 1918 and the official photo of the same tunnel made at the opening in 1919. Soon after the opening a range of modifications were made since the performance of the tunnel was somewhat disappointing. The entrance of this tunnel was changed to a so-called bell-mouth shape. (courtesy of Stichting Behoud Erfgoed NLR)

↑Selling the DNW services: brochures from about 1990.

→The shock tube at the NLL location in the Noordoostpolder in the early 1960s. Some years later the TH Eindhoven would also have a shock tube for research. (courtesy of Stichting Behoud Erfgoed NLR)

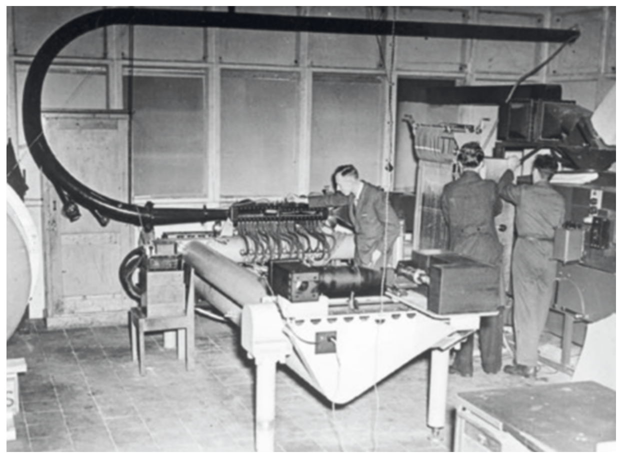


AGARD, the Advisory Group for Aeronautical Research and Development (related to NATO). Van der Maas appeared to be an excellent chairman of the NLL and accomplished much. In the Noordoostpolder, the new land which had been part of the Zuiderzee, a new location of the NLL was founded. Here the noisy experiments with the ramjet engines of the Dutch Kolibrie helicopter could be performed, as well as those with rocket propulsion. To study the phenomena which are involved in flows at high temperatures (where dynamic effects have very small time-scales) a shock tube was built there in the early 1960s.
In the 1960s the NLL also made plans for a new low-speed wind tunnel with a much larger test section than in the existing tunnels. For years nothing came of these plans and in the 1970s doubts were raised about the workload and hence the economical operation of such a wind tunnel. This led to a cooperation between West Germany and the Netherlands and in 1976 a foundation was established, the Duits-Nederlandse Windtunnel (DNW). It was only in 1979 that the new facilities in the Noordoostpolder were ready for testing and calibration, and in 1980 the new impressive wind tunnel with test section of 9.5 x 9.5 m and two smaller ones were put into operation. Since then they have been used for the investigation of airplanes (sometimes full-scale) but also of cars, trucks, and other vehicles, for customers from Europe but also from countries like Brazil and China. The DNW tunnels have also been used for aero-acoustic investigations.

EINDHOVEN EN TWENTE

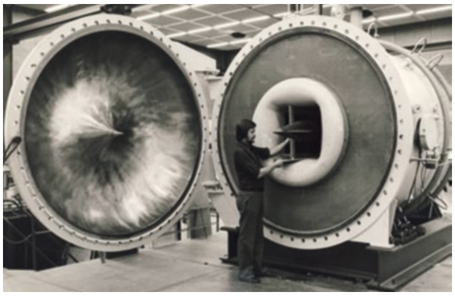
Compared to Delft, the universities of Eindhoven and Twente never had many wind tunnels. Neither had aeronautical departments and in the late 1980s it was decided that Delft

←↑The HST of the NLL was – and is - impressive, both from the outside (see § 3.2.1) and from the inside. Its operation demanded a large increase of the output of the power plant of the institute. The operators and researchers of the tunnel were located in a special room. By 1960 one the means to get control of the operation of the tunnel was the use of closed-circuit television. (courtesy of Stichting Behoud Erfgoed NLR)

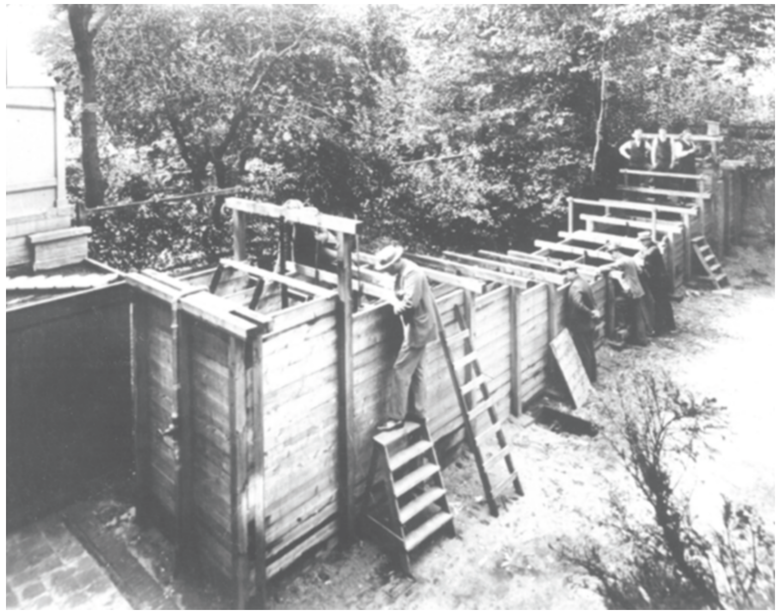


↑The first supersonic wind tunnel in the Netherlands around 1948, with Erdmann in the centre. In later years, an alternative test section was added as a pilot facility for the larger NLR wind tunnels. In 1967, the installation was donated to the University in Delft where Erdmann became professor. (courtesy of Stichting Behoud Erfgoed NLR)

would be the main location for turbulence research.
In Eindhoven, from the late 1960s research was done with a shock tube by Rini van Dongen and others. This would become the start of a long tradition. In later years expansion shock tubes were used. Their main advantage is that moving parts are avoided and the fastest possible expansion of a gas can be realized. It can take pressures of up to 100 bar, which was chosen to make it interesting for the natural gas industry. In this tube nucleation was studied.
One wind tunnel in Eindhoven became well-known through newspaper articles and broadcasting in 2017. It is the huge Atmospheric Boundary Layer Wind Tunnel which allows the study of flows in a built-up environment on a model scale, but also full-scale studies, e.g., of racing cyclists.
In Twente a so-called freon tunnel was in operation in the early 1970s. Wind tunnels in which freon is circulating, instead of air, were already known in the 1950s. Thanks to the fact that freon allows a much lower speed of sound, this kind of tunnel can reach transonic flows more easily and this saves energy. Furthermore, much higher Reynolds numbers can be reached than in similar air-based wind tunnels. Freon tunnels have also been used for research on rotating machinery and flutter.
The only wind tunnel in operation today at the UT is mainly used for aero-acoustic research. It is known as the 'silent' wind-tunnel because its walls can absorb practically all the noise produced by the air flow, which can reach speeds of up to 240 km/h. This tunnel is suited for measuring simultaneously the aerodynamic behaviour and the noise production of applications related to aviation, drones, green energy production, and home appliances. Since this tunnel got a 'makeover' in 2017, it has its own Facebook page.



↑The freon tunnel of the TH Twente in 1971. Eindhoven also had a freon tunnel at that time. (courtesy of Beeldbank UT)



↑In the garden of the office of the Dienst der Zuiderzeewerken in The Hague a rather primitive wooden flume was erected in 1919 to study the wave run ('golfoploop' in Dutch) on dike models. The man with the hat in the front is studying the wave generator. (courtesy for use of reproduction of Stichting Historie der Techniek, Eindhoven)

↑The official opening of the Atmospheric Boundary Layer Wind Tunnel in Eindhoven in December 2017 was a huge event. (courtesy of TU Eindhoven archives / photo by Bart van Overbeeke)

↑The open jet test section of the wind tunnel in Twente is located inside of a large anechoic chamber which has dimensions 6 × 6 × 4 m. Here research is done on the vortex generated by the flapping wing of a robotic bird. (courtesy of Kees Venner / University of Twente)

↑The opening of the renewed Deltagoot of Deltares in Delft, 2015. The high officials, seen on the right of the flume, were surprised by a huge tsunami-like wave and got wet. (courtesy of Deltares)

• 6.2.3 FLUMES AND BASINS

The first flume ('goot' in Dutch) for research purposes was probably that which was erected in the garden of the Dienst der Zuiderzeewerken (see § 3.4.1). It was 15 m long; the garden didn't allow a longer flume. Waves were generated by means of a simple hand-driven generator.

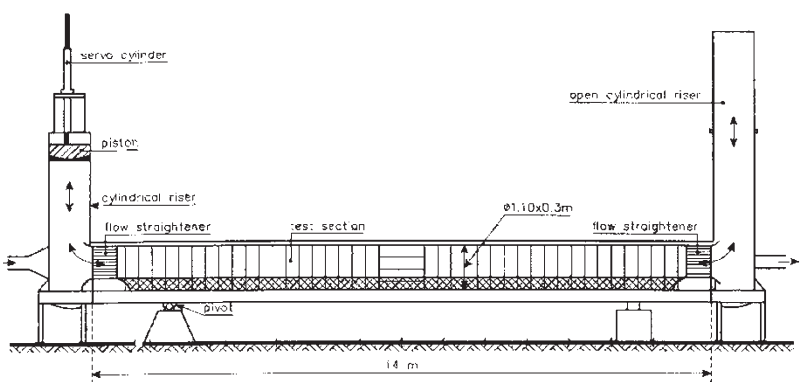
WL / DELFT HYDRAULICS / DELTARES

In 1935 the WL had built a wind flume of 50 m length (later 60 m) in which waves were excited by air flows. Up till then only 'regular waves' had been generated in the traditional way by means of a 'board'. With this new unique facility (for years no similar one existed in the world) not only more 'natural' waves could be generated but also the energy transfer from air to water could be studied. Further, researchers could investigate the deformation of waves due to hydraulic structures (dams etc.) and the pressure caused by the waves on these structures. Thijsse was one of the main investigators in this field.

For many years the WL has had one major topic in its research: the Delta area. Even before the Storm Surge

↑↗Two examples of research done at De Voorst in the 1980s. As in Delft, De Voorst had a wave flume. The photo shows research in which the effect of waves on dunes is studied. The other photo shows a model of the Amsterdam-Rhine Canal and a model of a towboat with barges. The researchers wanted to know how this floating combination would find its own 'drift angle' while moving along the canal. (courtesy of Rijkswaterstaat / www.beeldbank.rws.nl)

↑One of the early models built in De Voorst, seen here in 1957: the situation near Arnhem where the river IJssel branches away from the river Rhine. (courtesy of Deltares)



←This drawing from Jebbe van der Werf's PhD thesis *Sand transport over rippled beds in oscillatory flow* (2006) shows one of the remarkable flumes at Deltares. (courtesy of J. van der Werf)

Disaster of 1953 the WL had built and tested a rather large model of the northern Delta area, on the terrain next to its premises in Delft (see § 3.2.2). The purpose of the research was to discover the behaviour of tidal movements under different circumstances. Five minutes of flow in the real world could be simulated in about one second in the model and to investigate the happenings during a storm of four or five days it was enough to study the model for just twenty minutes. From 1951 onwards parts of the Delta area, e.g., the Haringvliet, were modelled in the annexe (dependance) of the WL which had been opened in 1951 in a corner of the Noordoostpolder where there was still plenty of empty land. This second location was called De Voorst but became better known as the Waterloopbos. When it was closed down in 1995, it contained 35 large scale models of sea arms, harbours (that of Lagos, for example), and rivers. With these models the influence of hydraulic constructions like dams and locks could be investigated. From 1957 De Voorst had a unique 'wind- en stroomgoot' (wind and flow flume) in which it was possible to study the transport of granular material on the bed of a canal.

From the late 1960s more and more of the facilities in De

Voorst became covered by means of halls; the measuring equipment suffered quite heavily from wind and rain. After the closure in 1995, several of the models were left to nature and the 'ruins' can still be found in the Waterloopbos, which is now a protected monument.
On the new location of the WL in Delft (see § 4.2.2) one of the most remarkable flumes was the Delta flume (Deltagoot). It was opened in 1969 and from the start large, full-scale waves could be generated and studied. Full-scale waves are a necessity in research since small waves cannot be compared to actual waves occurring in seas and rivers. The flume was rebuilt and deepened some years ago and reopened in 2015. Today, with a length of 300 m and a depth of 10 m, it is the largest wave flume in the world. Its wave generator can make waves of any required spectrum and is programmed to suppress waves which are reflected by the tested structure.

DELFT

Some forty years after the start of the WL, the TH Delft opened its own laboratory for hydraulic research, the Stevin III Laboratorium or Laboratorium voor Vloeistofmechanica. In 1969 the huge concrete building (almost 100 m long and 18 m wide) was put into operation as one of the three laboratories attached to main building of the Department of Civil Engineering. In the early years it contained a flume of 30 m length and 0.60 m depth in which waves could be generated. One of the types of research which was undertaken in this flume was the behaviour of waves on slopes.
In the 1990s the TU Delft managers started to think about reducing the research area of the hydraulic researchers, and even of cancelling the whole laboratory, as square meters were expensive. After long discussions the reduction took place around 2010. The wave tank of 20 x 16 m had to be broken down. In 2014 a 'memorandum of understanding' with Deltares was signed in which it was agreed to exchange knowledge and researchers (including students).
Today the Waterlab, as it is now known, still contains several straight flumes, two long flumes (about 40 m) with a wave generator for the study of sediment transport, and a rotating annular flume. In a flume of 5 m width riverbeds can be studied. One of the subjects that can be measured there is the rheological properties of mud.

WAGENINGEN

At the University of Wageningen (or Landbouwhogeschool at that time) the first flume was put into operation in 1950. It was also meant for practical work by students (up to 1956 all students in Wageningen had to follow a course in hydraulics during their first year).
The first primitive and very small laboratory for hydraulics in Wageningen was opened in 1959 but by 1963 it had been seriously extended. Research was done on spillways and on models of groundwater flows. In 1970 the Laboratory for Hydraulics and Drain Hydrology got a new facility. It was a sloping flume of 15 m length of which the angle with the horizontal could be changed. It was initially intended for measuring the shear stresses on the walls of open ducts but soon a sprinkling installation was mounted above the flume for research on the drain of rainwater on paved surfaces.
In 2010 a new laboratory was put into operation, containing several flumes, and it still has a rainfall simulator. The experimental research is mainly focused on morphological responses to channel flow and overland flow. The laboratory was named after its founder, Kraijenhoff van de Leur (who had been a student of Thijsse in Delft).

UTRECHT

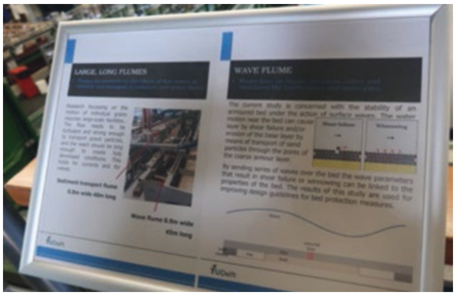
The Physical Geography Laboratory at the University of Utrecht has a soil and sediments lab, an experimental flume lab, and also the Metronome. To create reversing tidal flow and sediment transport on scale, professor Maarten Kleinhans built a 20 m long and 3 m wide flume tilting back and forth every 30 seconds at a small slope. This tilting-principle causes Waddensea-like basins and estuaries to form in a pilot setup with sand created from a small table with one leg sawed off and replaced by something like a metronome. Using this immense research instrument, Utrecht researchers simulate how river mouths are formed.
For some years Kleinhans and his team also studied possible flow patterns on the planet Mars. Experiments with water and sand showed that an eruption of groundwater can be held responsible for what is visible on the surface of Mars. Study of photos made on the planet and calculations led to the conclusion that water had been flowing not for thousands of years but for much shorter periods.

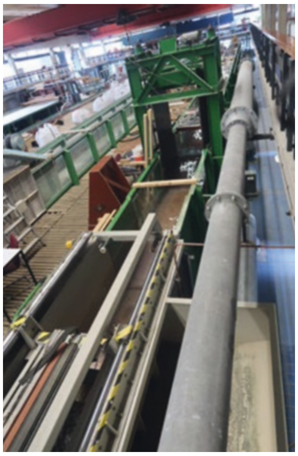
6.2.4 TOWING TANKS

DELFT

The very first facility which Burgers could use in his laboratory can be regarded as a towing tank. It was 8 m long and a small cart could be pulled along the tank on top of it. Objects like cylinders could be drawn through the water and a camera on the cart was used to take photos (see § 6.2.1 for some results of the experiments). The tank could also be used as a water tunnel in which water could be pumped around at a maximum speed of 12 m/s. Further, the tank could be used as a flume in which waves could be generated. This towing tank was demolished in 1934 to make room for another wind tunnel.

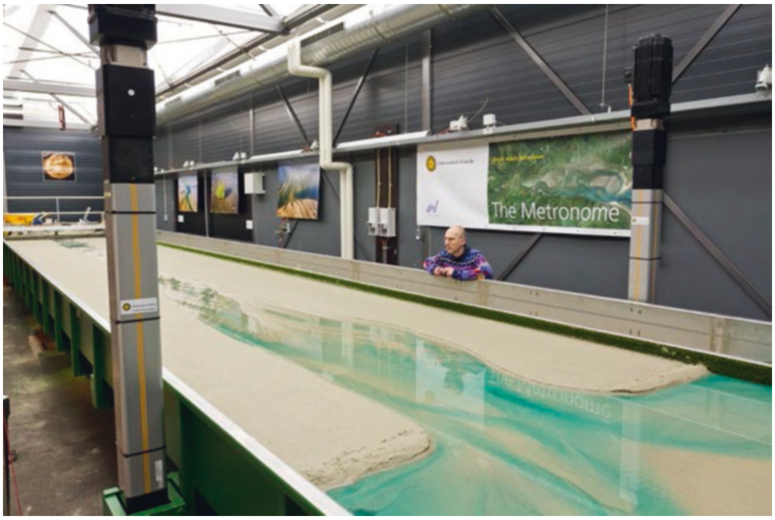
As we have seen in § 4.1.1, the first towing tank (or model basin) at the Department of Naval Architecture in Delft was built in 1937. It had a length of 37 m and a width of 2.7 m. Towing was done by an unmanned small carriage carried by



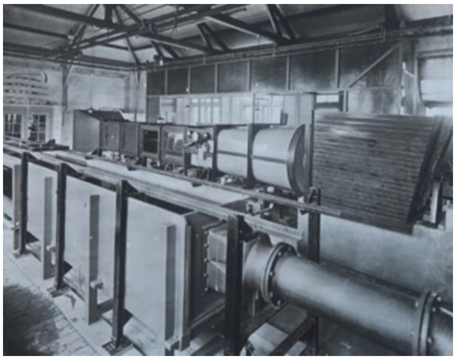


↑↗→The Waterlab today. Visitors have a nice view of all research activities from the balustrade which encloses the large hall. On the balustrade several instructive signs tell them about the facilities below.

↑The sloping flume in Wageningen around 1971, with the 'rain simulators' above it. (courtesy of Wageningen University & Research)

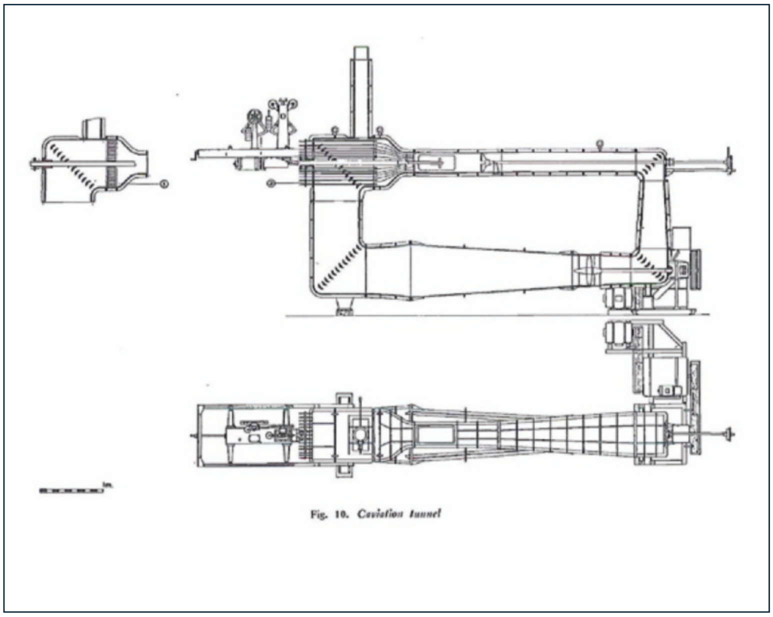


↑The Metronome in Utrecht. (courtesy of Utrecht University / photo by Jarno Verhoef)



↑The towing tank/water tunnel/wave flume in Burgers' laboratory in Delft around 1930. (courtesy of Burgers Archives / Delft University of Technology)

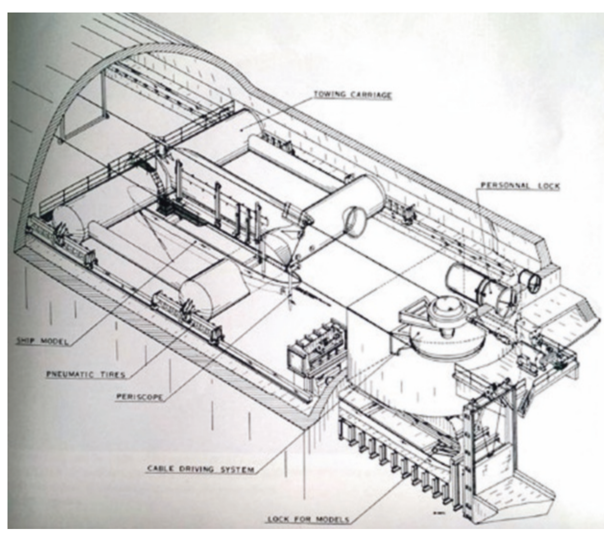
↑The long towing tank of the TU Delft today, with tested models on the wall. Besides the long and the small towing tanks for research, a much smaller tank is in use today, mainly for the training of students. It has been named Bruno, after the towing tank pioneer Tideman (see § 2.3.1).



←The cavitation facility in Delft as it was built around 1956. The so-called elbow number 1 was used when a propeller had to be investigated in a homogeneous velocity field. A specified velocity distribution over the screw disc analogous to that occurring behind a ship could be realized by using elbow 2. This non-homogeneous field was produced by a velocity regulator, containing 146 elements. By means of some type of check valve each of the elements could be (more or less) shut off, which affected the velocity of the water flowing through the elements. The tunnel had two cross sections, both of 300 x 300 mm. One was for measuring friction drag reduction by air lubrication, the other for measurements on cavitation vortices. (from: Gerritsma (1957) / with permission from IOS Press / publication is available at IOS Press through http://dx.doi.org/10.3233/ISP-1957-43001)

←For many years all activities in the Ship Hydromechanics Laboratory have been recorded on hundreds of photos. This is one of the impressions made in 1958, when the long towing tank had just been put into operation. (courtesy of Delft University of Technology / Cornel Thill)

↑The Wave and Current Basin of the NSP in the late 1960s. (courtesy of MARIN)



↑The Vacuum Tank of the NSP as it was originally built in 1972. (courtesy of MARIN)

↑The Twente Water Tunnel. (courtesy of Physics of Fluids group / University of Twente)

↑The cavitation/water tunnel of the TU Delft as it is today. Here research is done on drag reduction by means of air lubrication along a flat plate. Measurements are performed with PIV.

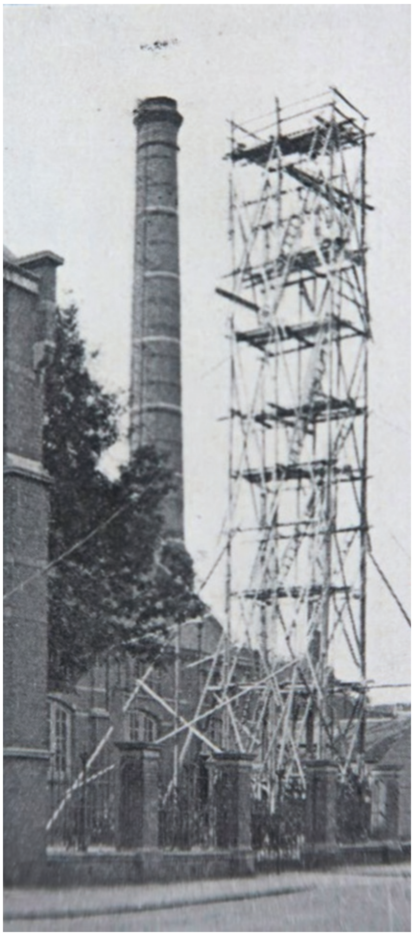
a rail over the tank. This carriage carried a resistance dynamometer with which the resistance of a model (maximum length 1.5 m) could be measured. In 1953 a wave generator of the 'flap type' was installed with which waves with a length of 3 m and a height of 9 cm could be generated. Around 1956 a new tank was built, with a length of 97 m and a width of 4.3 m and an 'ordinary' water depth of 2.5 m. This tank was equipped with a wave generator of the pneumatic type. In 1957 the staff of the tank prepared for the construction of the first electronic dynamometer, for momentarily measuring torque and thrust.

Since 1957 the Ship Hydromechanics Laboratory encompasses three test facilities: one large tank (142 m long, model speeds up to 8.0 m/s), one small towing tank (75 m long), and a cavitation tunnel (see § 6.2.5). All have been exploited in the context of hydromechanical research both in the maritime and offshore domain and are extensively used for education, scientific research, and cooperation with industry, both nationally and abroad. Beside these, there are two very small towing tanks, mainly used by students.

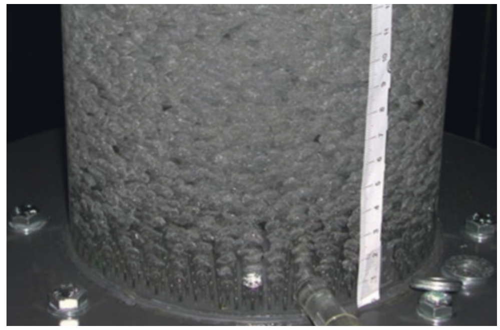
NSP / NSMB / MARIN

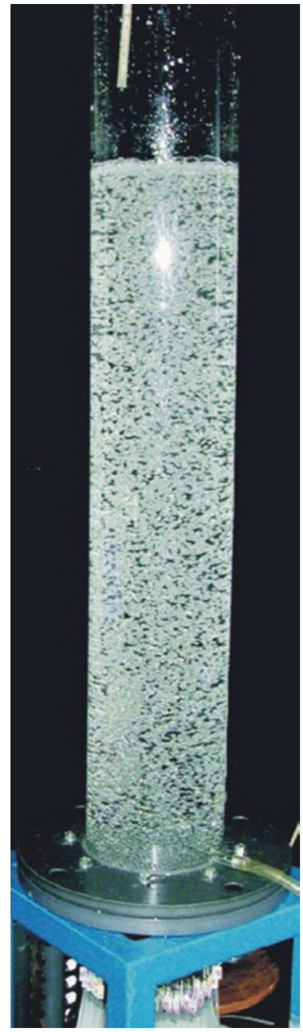
As we have seen in § 4.2.3, in the 1950s and 1960s the NSP was expanding. The great demand for specialist research required the building of more sophisticated test facilities. The first one was the Seakeeping Basin (1956) for research into ship behaviour in waves. Next came the Shallow Water Basin (1958), for tug boats, inland shipping, and merchant shipping in shallow water. In 1965 a High-Speed Basin and a Wave and Current Basin were put in operation. In the Wave and Current Basin (today known as the Offshore Basin) wind, current, and waves were simulated for research into the behaviour of structures during complex operations at sea, such as oil and gas production and dredging operations. In 1972 the institute was further extended with a Vacuum Tank (not in Wageningen but in nearby Ede), which had dimensions 240 x 18 x 8 m and in which the air pressure can today be lowered to 2500 Pa. This facility was and still is used for research into 'wave impacts with air entrapment' and propeller cavitation. The need for low pressure comes from the rules imposed by model experiments: the smaller a ship model with its own rotating propeller, the smaller the air pressure should be.

In 2000 and 2001 the institute was (again) thoroughly updated. The Seakeeping Basin and Wave and Current Basin were replaced by a new Seakeeping and Manoeuvring Basin (170 x 40 m) and a new Offshore Basin. The first is one of the largest testing facilities in the world for this type of testing. It is designed for making arbitrary (high-speed) manoeuvres in realistic waves from arbitrary directions. Models of up to 8 m can be tested. The Vacuum Tank was completely renovated,



↑Schmid's experimental facility in Delft around 1929. (from: Schmid (1930))





↑→The bubble column in Delft as it is today. It was the first in its kind with so many needles and such large diameter. Besides, the bubble flow remained uniform for a long time; only at a volume fraction of 55 percent the water started to circulate. (courtesy of TU Delft / Rob Mudde)

←The facility at the Laboratory for Aerodynamics and Hydrodynamics of the TU Delft in which Taylor bubbles could be observed, around 1994. (courtesy of TU Delft / René Delfos)

getting flap-type wave makers on two sides of the tank; it is now called the Depressurized Towing Tank.

6.2.5 WATER TUNNELS

As we have seen in § 6.2.4, the first experimental facility in Burgers' laboratory (1921) was a towing tank which could also be used as a water tunnel. There is however no evidence that it was ever used as such. It is known that in 1933–1934 this laboratory had an experimental setup with which the flow through water pipes and cavitation could be investigated. At the end of the 1930s Burgers was asked to advise on the design of the cavitation tunnel which the NSP was planning to build (see § 3.2.3).
This tunnel of the NSP was put into operation in the 1940s. It meant a breakthrough in the research on the cavitation phenomenon which occurred around ship propellers. Some years later, around 1956, a cavitation tunnel was put into operation at the new Shipbuilding Laboratory of the Department of Mechanical Engineering and Naval Architecture in Delft (see § 4.1.1). This laboratory also had a flow channel which was 45 m long, 2.8 m wide and had a water depth of 0.6 m. The water in this channel was pumped around with a velocity of up to 2.5 m/s but experiments in stagnant water were also possible. The flow velocities in this channel were measured with either a Pitot tube (which was not so accurate) or a small propeller.
A completely different kind of water tunnel, and much more recent, can be found at the University of Twente. The Twente Water Tunnel is an 8 m high facility in which strong turbulence can be created using a so-called active grid. Light particles like small bubbles and hollow spheres can be suspended in the turbulent flows. These particles may be made to rise with or against the flow and can be observed and followed in the measuring section for long-duration tracking.

6.2.6 OTHER FACILITIES

Besides wind tunnels, flumes and basins, towing tanks and water tunnels, many other experimental facilities have been built during the last hundred years for the study of flows. Below a short and rather arbitrary selection of these.

↑←Two experimental facilities at the dredging laboratory in Delft. The pipeline has a total length of about 60 m and has been used to investigate the wear of its inner walls caused by slurry flows. The facility with the sloping bottom is used to do research, using acoustic devices, on the downhill flow of slurries

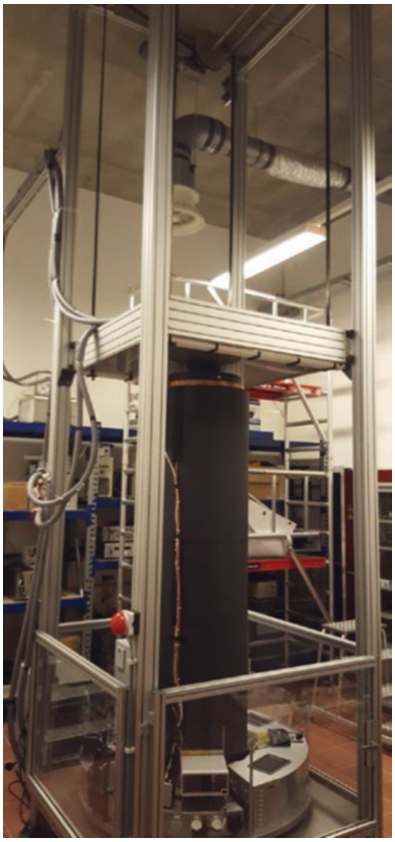
↑The mast near Cabauw has 9.4 m long 'protrusions' which are placed at distances of 20 m. With these it is possible to avoid disturbances caused by the tower during the measurements. (courtesy of KNMI / Wouter Knap)

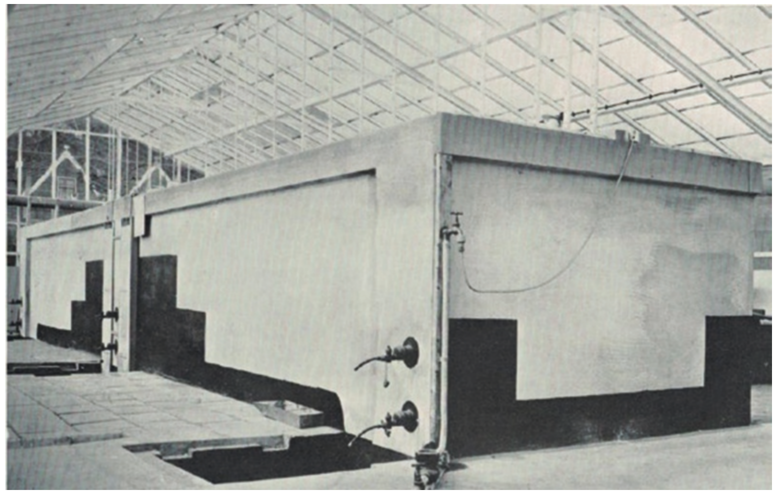
MULTI-PHASE FLOWS

The gas-lift, or air-lift, technique is a gravity-driven pumping process applied in the oil industry for many years. It enhances oil production by injecting gas (air) in the production pipe to decrease the hydrostatic weight of the oil column: the rising gas takes the oil with it, as it were.
At the end of the 1920s Burgers was consulted by a PhD student of one of his colleagues at the Department of Mechanical Engineering. Wilhelm Schmid, who would become professor in Eindhoven in 1957, was working on measurements on an air-lift which was built outside the building of the Department. It was a huge gantry of about 20 m height which held a tube with an inner diameter of about 5 cm. Water was taken from a source which was 36 m below ground level. In this tube Schmid was able to let single, rather large air bubbles rise and was able to measure the rising speed. His thesis (Schmid (1930)) can be considered as one of the first Dutch publications related to two-phase flows.

Some seventy years after Schmid's research, gas-lift was again studied in Delft. In 2004 a PhD thesis entitled B*ubble size effect on the gas-lift technique* appeared, based on experiments with a vertical upward bubbly pipe flow, with a height of 18m and a diameter of 72mm. The flow velocity conditions investigated in the experiments were representative of practical gas-lift circumstances. The work was supervised by professors Gijs Ooms (see § 4.1.1) and René Oliemans (who had been working on multiphase flows at Shell's KSLA from 1982 and at the TU Delft from 1990). Some ten years earlier related research was done by René Delfos in Delft, also under the supervision of Oliemans. He used an experimental set-up in which he could realize a stationary so-called Taylor bubble. With this he could study the phenomenon of gas-liquid slug flow, a phenomenon well-known in the oil industry where efficient transport of oil-gas mixtures through pipelines is required.

Two-phase flows of many bubbles rising in a liquid are well-known from chemical reactors and were the subject of research at the Kramers Laboratory (see § 3.3.2 and 4.1.1). From about 2000 the construction of a so-called bubble column was built, containing a sparger (bubble generator)





↑For his experimental research Hooghoudt built this huge facility in the late 1930s at the Rijkslandbouwproefstation in Groningen where all kinds of agricultural research were performed. (from: De Vries (1982); courtesy of Co de Vries)

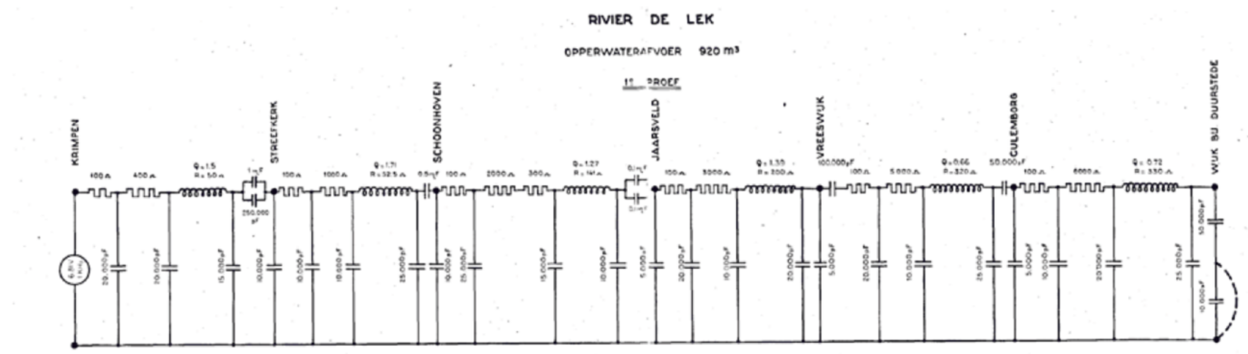
←The TROCONVEX in Eindhoven was still growing in 2018. (courtesy of TU Eindhoven / Rudie Kunnen)

with 560 special needles from which bubbles with virtually all the same velocity and size could rise. This facility has been used to investigate the conditions under which large scale structures arise; these are usually undesirable in industrial reactors.

Quite different two-phase flows occur in the world of dredging. Dredging is a combination of fluid mechanics and soil mechanics (rock, mud) which makes modelling very challenging. Research into the flow phenomena related to dredging started in 1937 when a laboratory was opened in Haarlem (after the TH Delft had refused to make laboratory space available). It was used to do experiments on the suction of sand. It wasn't till the end of the 1960s that serious research on the dredging process was started in Delft. At that time the WL was already doing experiments in this field, mainly related to the Delta Works.
For several years the TU Delft has contained the Dredging Engineering Research Laboratory, one of the very few in its kind around the world. Several PhD students have done their research there, using the unique facilities in which slurries can flow. Some of the big dredging companies in the Netherlands have their own experimental facilities but in Delft the more fundamental research is done.

GEOPHYSICS

During the 1960s the need for more data about the atmosphere led to plans for a new facility. This led to several attempts by the KNMI to find existing masts and build new ones from which measurements could be performed. Since its construction in 1972 the mast near the village Cabauw (213 m high, 2 m diameter) has become a leading atmospheric observatory in the world. The first measurement program with this mast, in 1973, was related to air pollution. The observatory is one of the few that can characterize the atmosphere from the ground up to the top of the atmosphere, by combining in situ sensors on the ground, along a 213 m measurement tower, and ground-based remote sensing to reach higher altitudes for measuring wind, turbulence, aerosols, trace gases, and clouds and radiation.
Since 2002 the facility became known as CESAR: Cabauw Experimental Site for Atmospheric Research. The station has become a focal point of experimental atmospheric research in the Netherlands, and a core station in the global network of observatories. The observatory provides essential state-of-the-art data to understand atmospheric processes, validate satellite observations, and detect long-term trends. The freely available data are used to improve climate, weather, and air quality models. Today, three universities and five major research institutes collaborate in CESAR. Thus, the facility has a strong integrating effect on atmospheric and environmental science in the Netherlands.
Many geophysical and astronomical phenomena are driven by highly turbulent fluid dynamics. These dynamics are often



↑A river transformed into an electrical circuit. This was the kind of analogon that Van Veen proposed to RWS and finally led to one of the first analogue computers in The Netherlands. (Scheme from 'De voortplanting van het getij bepaald met behulp van de electrotechniek', a report prepared by H.J. Stroband for Van Veen in 1944/1945. (courtesy of Min. van Infratructuur en Waterstaat).

←Women played an important role in scientific calculating during the 1930s until the 1950s. At the start of the Mathematical Centre in Amsterdam a group of girls who had just left high school were hired and trained to become 'calculators'. They not only learned to use the mechanical and electro-mechanical calculators of those days but also to operate the first computers. This photo was taken around 1955 In Burgers' laboratory in Delft. It is not known whether this lady was especially hired to do scientific calculations. (courtesy of Burgers Archives / TU Delft)

driven by the buoyant rising and falling of fluids of different densities, known as convection (see § 5.1.7), and strongly affected by the rotation of the celestial body through Coriolis forces. One useful approach to understanding geophysical and astrophysical flows is to study a reduced problem known as rotating Rayleigh-Bénard convection in a laboratory setting.

While studies of rotating convection began over a century ago, only recently have major developments occurred toward understanding the problem in settings of exceptionally strong rotation or convection, such as geophysical systems. Modern laboratory and numerical studies have found that many novel behaviours emerge only under extreme conditions.

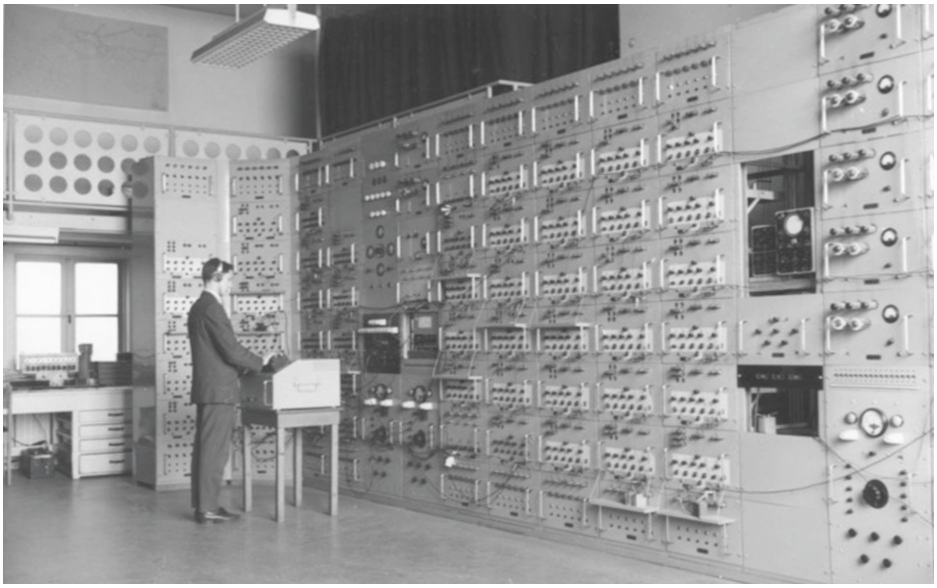
One of the facilities built to do research under these extreme conditions is the TROCONVEX (Turbulent Rotating Convection to the Extreme) at the TU Eindhoven. With a maximum tank height of 4 m, the rotating TROCONVEX can generate stronger convective and rotational forces than any other laboratory rotating convection device to date (2018).

DRAINAGE FLOWS

As we have seen in § 6.2.1 groundwater flows and drainage have long had the attention of quite a number of Dutch scientists. Besides theoretical and numerical research, experiments also have a long history in the Netherlands. Scientific research on land drainage was stimulated by the wish to reclaim and develop the new Zuiderzee polders in a rational manner. This successful research programme began in the 1930s under Sijmen Hooghoudt (1901–1953), a chemist by training, at the Experimental Station and Soil Science Institute in Groningen. This led to a basic understanding of the drainage process, and the emergence of extensive basin-scale studies of groundwater discharge regimes, and the related drainage requirements for different hydrologic and topographical conditions, in connection with the improvement of land and water management. Hooghoudt also became known for a formula, named after him, which is still used in drainage studies.

6.3 NUMERICAL APPROACHES

The ability to calculate flows has in part replaced experiment and has become an essential part of research into the fundamentals of fluid flows. Furthermore, in the engineering design process, it allows for rapid evaluation of changes in design parameters. Many believe that the numerical approach only started when the digital computer was maturing in the 1960s but in fact this approach was already used before the Second World War when even the analogue computer didn't exist.



←The Electric Model of Waterways around 1960 and one of its operators. During the design of the machine, RWS came to realize that it would not fit in one of their offices and therefore they had to find a place somewhere else. It was finally installed in the building of the Freemasons in The Hague. (courtesy of beeldbank. rws.nl, Rijkswaterstaat)

• 6.3.1 PIONEERS

One of the places where tough and long-term calculations were necessary in order to predict flows was Rijkswaterstaat (RWS). The work that had been done by the Lorentz Committee on the closing of the Zuiderzee (see § 3.4.1) had shown that the amount of calculation work was enormous. There was one engineer at RWS who was convinced that there had to be an alternative which would give results much more quickly: Johan van Veen (1893–1959). Van Veen has become one of the best-known engineers in The Netherlands. Soon after he entered RWS in 1929 he was put on the study of sand transport in the North Sea. Van Veen could make use of the measurements that were done in 1933 by the RWS measuring ship De Oceaan and was able to finish his thesis in 1936, becoming one the very first, and for decades one of the few, civil engineers to become a doctor in science.

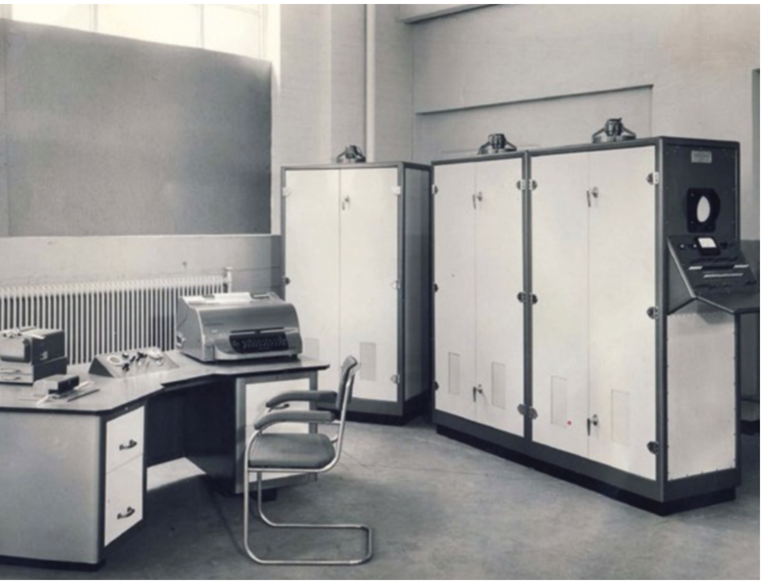
At the end of the 1930s, Van Veen saw similarities between the formulas for electric currents and those of tidal currents. And since electrical formulas rule the change of current, voltage, etc., in electrical circuits, he suggested building models of waterways from wires, resistances, capacitors, etc. Van Veen showed that it worked (to a certain level of exactness) and that he could replicate the results which Lorentz and his Zuiderzee Committee had found.

But not everyone was convinced of the value of this method. RWS refused to use Van Veen's method to do calculations on the lower rivers. Instead, they used the so-called 'exact method' which had been developed by the mathematician Jo Dronkers (1910–1973), the first to have been hired by RWS. Dronkers managed to refine the approach which had been used by Lorentz and his Zuiderzee Committee to calculate the influence of the construction of the Afsluitdijk (see § 3.4.1). Whereas Lorentz had used a 'linearized resistance' in his model, Dronkers used a quadratic one and was able to simulate tidal movements much more accurately. With this approach to tidal movements the Netherlands took a leading position in the world. In 1964 his influential book Tidal computations in rivers and coastal waters was published.

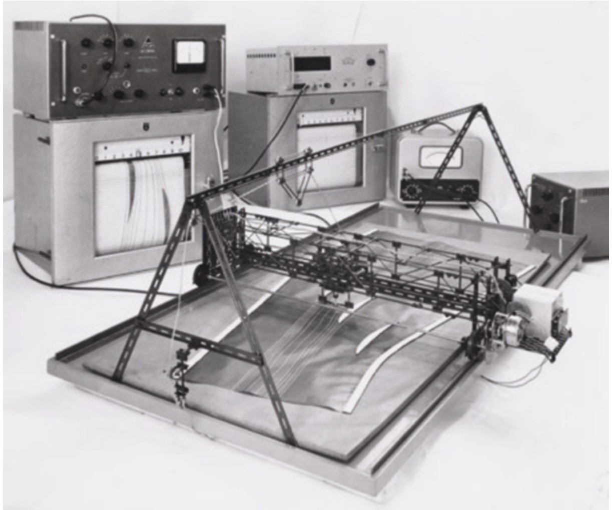
Van Veen's 'calculations' with his electrical analogon circuits led him to the conclusion that the Netherlands should seriously fear the high water levels which would occur during heavy storm surges. The dikes in Zeeland province and other areas would not be able to withstand these levels. Others were not convinced that his figures were correct and were of the opinion that the situation would never get so bad. The infamous Flood of 31 January – 1 February 1953 would show that Van Veen's concerns had not been exaggerated...

• 6.3.2 THE FIRST COMPUTERS

In the Burgers' Laboratory annual report for 1945–1946 we read how, slowly, the facilities and equipment were reinstalled and supplemented. There was a gift from the Department of Marine: high pressure compressors and reservoirs from demolished submarines which could be useful for the starting research on high-speed flows. Furthermore, some books could be bought. Also mentioned are the components which could be bought in England thanks to the Help Holland Council, a kind of relief fund from Great Britain. Burgers



The first computer of the NLL, the ZEBRA, was used from 1958 for data reduction of the High Speed Tunnel. (courtesy of Stichting Behoud Erfgoed NLR)



↑Around 1963 this analogue machine was used in the Physical Laboratory of the Stork company for research on the flow around the fans of pumps and similar machines. (courtesy of Historisch Centrum Overijssel / Fotocollectie Stork)

managed to acquire capacitors and transistor lamps for his optical equipment and also arranged a deal with the famous Meccano factory: it would produce some extra boxes of Meccano parts (against 'pre-war prices') for the 'differential analyser according to Hartree' which the Delft group wanted to build.

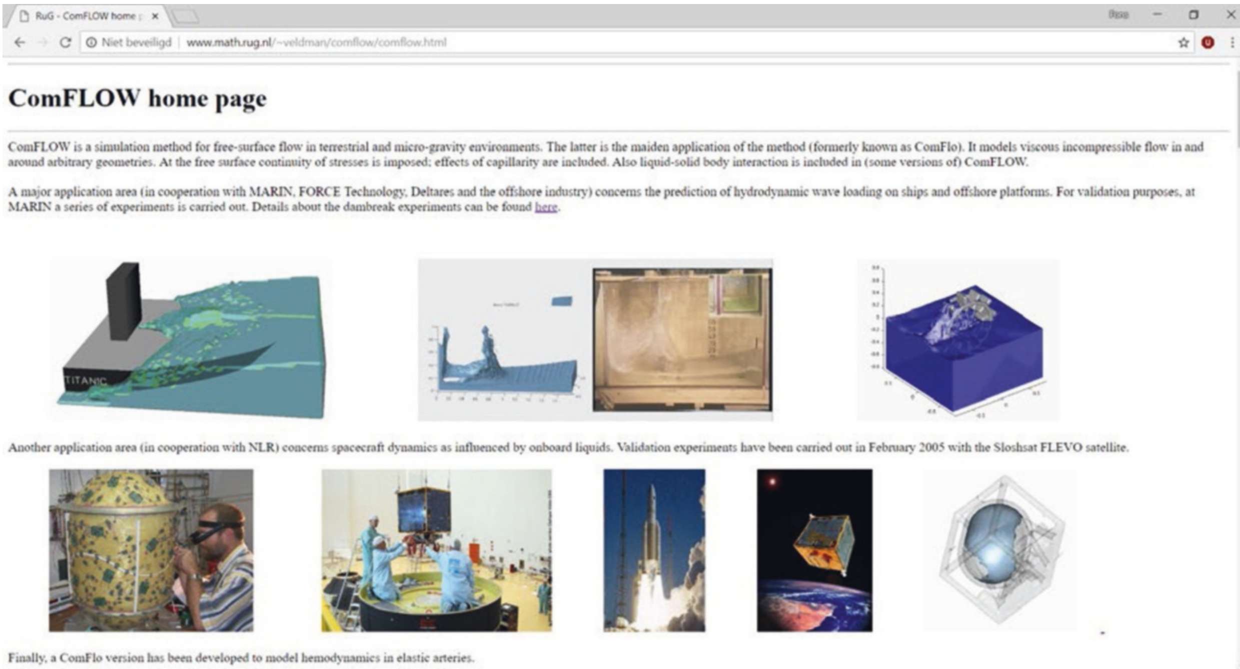
This, at first sight rather remarkable, purchase shows something of the situation around 1945 with regard to the practice of scientific calculations. The first primitive computers had just been built but these were still far out of reach for the academic world, for institutes, and industry. They were also still of little value since their performance was still very poor. It is not known whether the Hartree-machine was ever built (and used) in Delft. Maybe the building of such a machine was harder than the Dutch scientists had thought. Or perhaps they decided to abandon this project since they were told that much better electronic calculating machines would become available in the near future.

One of the Delft engineers who was convinced of this, was Aad van Wijngaarden (1916–1987). He had been a student of naval architecture in Delft and became involved in research done at Burgers' laboratory during the War. In an interview Van Wijngaarden later recalled: "It wasn't nice. It didn't give the level of insight that I wanted. I tried hard to do certain calculations; these were calculations for which you wouldn't get anyone today without offering him a computer. It was wartime. Day in day out I was behind my Marchant electric calculator at home; that saved me the time that was needed to go to the lab and back. Rising early in the morning, calculating the whole day and back to bed late in the evening. That is how it went, week in week out. … It was about a problem from fluid mechanics: boundary layer equations. These were non-linear third order partial differential equations. It was huge task, you could only come further by just going on and on. … After some weeks I had finished one of the equations." [translation by FA]

Finally, Van Wijngaarden decided to leave the Burgers group and wrote his PhD thesis under the guidance of Biezeno, the professor of solid mechanics. After the War Van Wijngaarden became aware of developments in computing when in 1945 the Help Holland Council supported his visit to England. In 1946 Van Wijngaarden became the director of the 'calculation department' of the recently founded Mathematical Centre, the precursor of the present CWI. In 1947 he and some other young men started to build the first Dutch computer, the ARRA. The second version of this machine would become the first computer used for fluid mechanics: the Fokker aircraft company bought the FERTA (Fokker's Eerste Rekenmachine Type ARRA) in 1955, mainly for calculations in aerodynamics.

Despite the doubts about Van Veen's ideas, RWS decided to build an electrical analogon machine for calculations of the (tidal) flows in the lower rivers of the Netherlands. The machine was called Electrisch Model van Waterlopen (Electric Model of Waterways) and it was completed in 1954. It never worked very satisfactorily and in 1955 RWS had already decided to build a new analogue computer.

The new machine became known as the DELTAR: the Delta-tij-analogon-rekenmachine (Delta-tide-analogon-calculator). The Deltar has become known as one of the first



↑As academic groups developed software which was interesting for many users, they started to offer their services. The origins of ComFLOW of the CFD group of the University of Groningen can be found in their activities during the late 1990s. Other groups are also offering their software on the internet, e.g., the Multiphase and Reactive Flows group of the TU Eindhoven. (courtesy of University of Groningen / Arthur Veldman)

successful analogue computers in the Netherlands. It certainly proved to be helpful in the prediction of the behaviour of the Delta area but soon RWS had to conclude that doing calculations on digital computers, based on the mathematical models proposed by Dronkers, was a better way to go forward. Despite this, the DELTAR was used until 1982.

In 1958 the first Dutch transistorized computer reached the market and from then new developments followed each other quickly. That same year the NLR would buy its first computer (see also § 4.2.4) and one year later the first Dutch university would do the same. At the start of the 1960s many Dutch scientist and engineers became convinced that the computer would soon be a wonderful and indispensable tool for their work.

"The use of mathematics and computers has already been mentioned as an indispensable aid. The rapid developments in this field give reason to investigate whether some hydraulic problems solved hitherto only by means of models can be solved entirely or partially by means of computer techniques. Unsteady flow in networks of canals and flow in two horizontal dimensions under the influence of the topography are already, in theory, fit for treatment in computers. It is only a matter of the training of the programmers and the availability of computers." This was written in… 1963 by Harold Schoemaker (1913–2011), Thijsse's successor at the WL in Delft (and professor for irrigation studies at the TH Delft from 1967). It shows the enormous optimism about the developments of computational fluid dynamics (CFD) during the 1960s. But as for the WL (and other research centres with experimental facilities) it would take some decades before the first model basins were dismantled as faith in the reliability of computer models grew to a high enough level.

• 6.3.3 CFD

During the 1960s institutes like the WL and NLR started to develop their software for numerical simulations of flow problems. At the end of the decade, activities in what would become known as CFD (Computational Fluid Dynamics) also reached the academic world.
At the University of Leiden there was one location where a somewhat special brand of fluid mechanics was studied. It was at the Leiden Observatory in the late 1960s that the student of astrophysics Bram van Leer got interested in CFD for the sake of solving cosmic flow problems, especially shock waves. From the 1960s flows in shock tubes could be solved by a method disclosed by the Russian scientist Godunov, but this method showed wiggles: instabilities in the results which are physically wrong. Van Leer came up with an improved model which was more accurate, more efficient, and showed no wiggles. His method also became much used in aerospace aerodynamics. In the 1980s Van Leer emigrated to the USA where in 2010 he received the AIAA Fluid Dynamics award for his lifetime achievements.
In the 1970s many groups around the country were working on CFD and in 1974 some of these started the Kontaktgroep

Numerieke Stromingsleer (Contact Group Numerical Fluid Mechanics). Its purpose was "to provide an opportunity for researchers in numerical fluid mechanics to meet regularly and to inform each other about their research in an informal atmosphere."

It was Pieter Zandbergen (see § 4.1.3) who played an important role in the rise of CFD in the Netherlands. Around 1985 he took the initiative towards a joint effort in CFD which emerged from his NLR connection and led to the the ISNaS project (Information System Navier-Stokes). Subsidised by the Dutch Ministry of Education and Sciences and the Ministry of Transport, this project established a strong collaboration between two universities (Twente and Delft) and two laboratories (NLR and WL), with Zandbergen in the chair of the project control board (1987–1993). Later the University of Groningen, ECN, and MARIN, also joined the project.

The ISNaS-project aimed at providing tools for computer-aided design and engineering in aerodynamics and hydrodynamics by developing an information system for the simulation of complex flows based on the Navier-Stokes equations. Major components of the project were the development of a so-called method-shell and of accurate as well as robust solvers for both compressible and incompressible flows. For the incompressible case, guided by typical applications in the field of river and coastal hydrodynamics, a solution procedure was developed which was capable of handling complicated geometries, including free surface effects, in particular for high-Reynolds number flow regimes.

Within the ISNaS project a strong need for adequate turbulence models became apparent and consequently, Zandbergen and his group started investigations on the issue of turbulence and large-scale computations in 1990. In line with the subject of large-scale computing in 1993 Zandbergen became chairman of the national initiative on High-Performance Computing and Networking.

Together with the improvements which were reached in the development of software, big steps were also made in hardware. Besides 'parallel computing' the word 'supercomputer' became one of the buzzwords in the 1990s. In 1996, for example, the TU Delft proudly announced that it had installed the most powerful computer in the Netherlands, a Cray T3E for parallel computing. Among the main users of this supercomputer were the research groups in fluid mechanics, especially those working on turbulent flows. This Delft record, by the way, didn't last very long as soon an even more powerful computer was installed elsewhere. Some research groups started to develop their own hardware, special one-off computers. The group of Hoogendoorn in Delft, for example, built a processor to directly solve the convection-diffusion algorithm for the finite control volume method as well as the transport equations. It was called the Delft Navier-Stokes Processor (DNSP) and it appeared that the DNSP could execute certain calculations with a speed comparable to those of the supercomputers used by others. The finite-volume flow solvers developed within the ISNaS project had an appreciable impact on the research of the participating university groups. Piet Wesseling at the Department of Applied Mathematics in Delft (originally an aeronautical engineer) became an expert in so-called multigrid methods and wrote a well-known textbook on the topic in 1991. Arthur Veldman (whose career started at the NLR) and his team in Groningen succeeded in the simulation of 2D turbulent flows by using DNS, but around 1995 this still required clever solutions for the spatial discretization problems. Numerical methods were also developed at the Centre for Mathematics and Computer Science in Amsterdam (CWI). Some research groups started to use 'commercial software', of which Fluent was and is a well-known example. Others mistrusted these packages or discovered that they lacked the 'precision' and applicability which was needed for their flow problems; they developed their own software. Thus, RWS came up with its WAQUA package for the simulation of flows in waterways and for the transport of sediments. For the ECN team working on the aerodynamics of wind turbines (see also Ch 7), the turbulence models in existing software appeared to be inadequate, as the turbulence around turbines covers a large array of length scales and is neither isotropic nor homogeneous. Other groups, like the Multiphase and Reactive Flows group of the TU Eindhoven, also developed software, in this case for combustion, which could be coupled to commercial and open-source CFD codes.

Since the early days, computer simulations of fluid flows had always raised doubts, especially if researchers did not, deliberately or otherwise, compare their numerical results with measurements from the real world. Or if simulation programs were used by people who had little knowledge of 'real flows'. The last issue was addressed by professor Hoogendoorn in his farewell speech in 1998. Part of this speech was about his views on the developments in CFD:

"The 'ultimate' model with complete DNS [Direct Numerical Simulation] for all kinds of flows is still far away. Therefore, turbulence models needed for time-averaged equations will continue to play a role for a long time. This is a controversy. In top research do you solely aim at a complete and exact description, or should you improve incomplete but useful models? But alas, what is more challenging for top researchers than controversies about important questions in their field? I myself expect that models can be validated by means of DNS in the coming ten years. Validation is also required for the applications in technology. The 'trustworthiness' of much-used models is of decisive importance. It is therefore gratifying that the Burgers Centre will participate, in the context of ERCOFTAC (European Research Community on Flow, Turbulence and Combustion) in a validation program with so-called benchmarks. The interest in CFD in industry and the Grote Technologische Insituten [Big Technological Institutes] ... is big and means an important support for research. ... For the future I see an important growth for CFD. One point of concern for me: within some sectors of the industry the in-house expertise with regard to physical fluid mechanics threatens to disappear due to dismantling of R & D. This is dangerous: before you are aware of it you will make the wrong calculation." [translation by FA]

Doubts about computer simulations were also raised in the mind of professor Frans Nieuwstadt in 1999 when he was present as member of the committee during the defence of the PhD thesis of Arthur Petersen. Petersen has written about this 'incident' in his book on the value of simulations of the atmospheric boundary layer and of climate models (Petersen (2012)). Some months before Petersen's defence the issue of the reliability of models had become a national debate in The Netherlands after one of the senior statisticians of the Netherlands National Institute for Public Health and the Environment had published an article in a national newspaper in which he warned that the Institute was leaning too heavily on its computer models.

"On June 7, 1999, I publicly defended my doctoral dissertation 'Convection and Chemistry in the Atmospheric Boundary Layer'. In this dissertation, the main body of which consisted of three journal articles based on computer simulation, I argued that one of the uncertainties in regional and global computer models of air quality was significantly smaller than was previously thought. Formerly, it was not known whether the influence of turbulence on chemical reactions in the

PERFORMING NUMERICAL CALCULATIONS IN THE 1930S: BURGERS AND THE BLADES

In the early 1920s Burgers was asked by Werkspoor to help in improving the efficiency of the centrifugal pumps of the yet to be built Lely pumping station, near Medemblik (see also § 3.3.1 and 3.4.1). The idea was that giving the blades – which looked rather similar to aerofoils – the right contour, could not only increase the performance of the pumps but also put an end to suction problems. Werkspoor also wanted to have a method with which the pressure distribution along the blades could be calculated since this gives an indication about probable spots where cavitation problems can occur.

Burgers set out to apply the method of conformal transformation (see also § 6.3.1) to find a calculation procedure for the flow between the blades. This was developed from about 1925 but it seems that only in February 1929 were the first numerical calculations performed by some of his staff. Apparently, Burgers concluded that there was still room for improvement as in June 1930 he decided to give the blades a shape which show 'only a tiny deviation from a logarithmic spiral'. With his conformal transformation he could give the blades a shape for which the flow around it is simpler and already known. He also considered taking another direction: replacing the blade by a 'system of vortices' which was already done at that time in the lifting-line theory for wings of airplanes. Finally, he decided to take the route of the conformal transformation, a method he knew well and which produced faster numerical results.

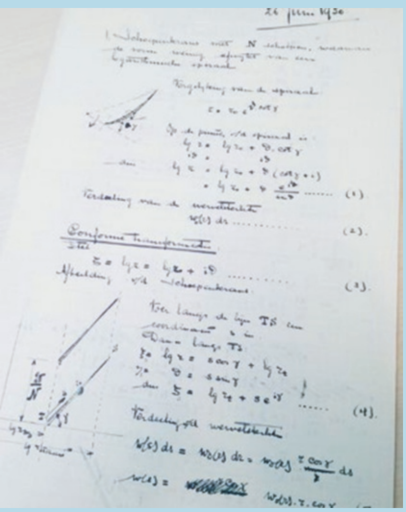
At the end of 1930 Burgers and Van der Hegge Zijnen could present an impressive report about their project. In it Burgers explained the reason for the long duration of the project. It had become clear to him that he needed four transformations to get the desired shape. "The search for these transformations required several months of almost continuous calculation labour. Though it is probable that in case of a repeat of such a calculation the goal will be reached faster, this remains an objection against the method of conformal mapping." Burgers also stressed the 'difficult pliability' of the method: even if the shape of the blades was changed only a little bit, all the calculations had to be done all over again. All the calculations had to be done with six decimals in order to get enough confidence about the usability of the transformations.

In September 1931 the pumps were ready and the installation in Medemblik was tested. But even thereafter Burgers came up with some additional calculations. In his final report of 1933 he explained that the goal of these calculations had been to give more insight into the flow around the 'nose' of the blades, but that the efficiency had been somewhat disappointing. What they did learn was that the pressure would become quite low around the nose. Later, during the operation of the pumps, cavitation was indeed observed at this location.

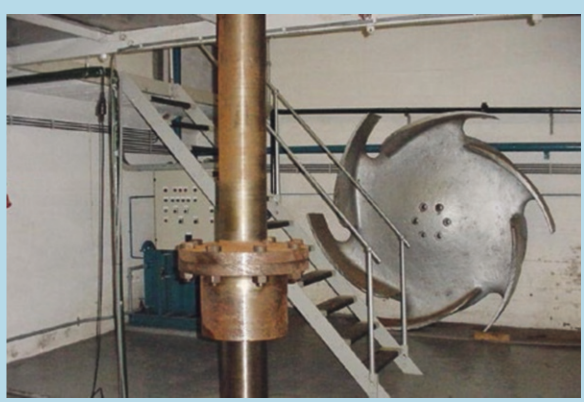
Had Burgers' calculations indeed led to better pumps? In fact, during testing the efficiency of the pumps appeared to be only 67%, whereas during model testing in the WL 87% had been found. Thanks to Burgers' findings Werkspoor discovered that the cause for this had to do with the 'huge dynamical diastolic pressures at the entrance of the fan' and they managed to design a new fan which indeed showed an efficiency of 87%, under all circumstances.

Burgers' calculation method has been used for several other centrifugal pumps at the WL. From about 1960 the computer took over the annoying parts of it.

atmospheric boundary layer could be neglected. I, together with my colleagues from the Institute for Marine and Atmospheric Research Utrecht (IMAU), using a hierarchy of computer models, had shown that this neglect was allowable. One of the opponents, Professor Frans Nieuwstadt of Delft University of Technology, sternly questioned me about the reliability of my research results until he was satisfied with my final answer, that I was confident about my research results only within a factor of two. His main problem with the work was that only simulation models of different complexity had been compared with each other, and no comparison had been made with experimental or observational data. My contention was that the most complex simulations that I had done using the national supercomputer of the Netherlands were more reliable for answering my research questions than were any of the sparse experimental or observational results reported in the literature. This was judged by Professor Nieuwstadt to be a 'medieval position'. I disagreed since the large-eddy simulation (LES) model that I had used had been rigorously compared with experimental and observational data. The only thing I had done, I claimed, was to apply this model to a somewhat different problem, which was extremely difficult to approach experimentally or observationally. After this minor public controversy, the episode ended well since the doctorate was awarded by the committee without any objections." [references have been left out of this text]



↑The Burgers Archives in Delft still contains loads of papers showing thousands of computed figures which were needed for the design of the impellers for the Lely Pumping Station. Van der Hegge Zijnen, Burgers' main assistant, must have spent hundreds of hours on the (mechanical) calculating machine. Burgers himself worked out the calculation method using conformal transformations (see also § 6.3.1). (courtesy of Burgers Archives / Delft University of Technology)



→The impellers with the blades which Burgers designed for the Lely Pumping Station in the 1930s have been used for many decades. They seem to have been replaced by fairly similar replicas in the 1980s (after which the cavitation problems continued to show up). The Hoogheemraadschap which is responsible for the station recently decided to install new fans, which are 'fish-friendly' and have a higher volume output. Radial fans have become rather outdated and many have been replaced by mixed-flow or axial fans. (courtesy of Leo Broers / Hoogheemraadschap Hollands Noorderkwartier)