by the physiologist and biologist Sven Dijkgraaf (1908–1995) of the functioning of the lateral line sensory systems of fish. For many years its functioning had remained an enigma and it was thought that the system was just there for secreting slime. Dijkgraaf showed that it is one of the most advanced flow sensing systems ever to have evolved, one with which fish can, e.g., sense objects in their vicinity thanks to the presence of a wake around these objects.
In the 1970s in de section of Theoretical Aerodynamics of Steketee in Delft some research was performed on the swimming of fish in waves. Dolphins can make an efficient use of the wave energy for their own transport. Quite recently researchers of the University of Groningen solved the so-called boxfish paradox: these rather peculiar fish were supposed to have a low drag resistance and could maintain their heading very well, but this was not in agreement with the way they behave near corals (low speed, making turns all the time). In Groningen a printed model of a boxfish (or trunkfish) was studied in a water channel and it appeared that its resistance was not as low as had been supposed and that it was not very course-stable.

## ATMOSPHERE

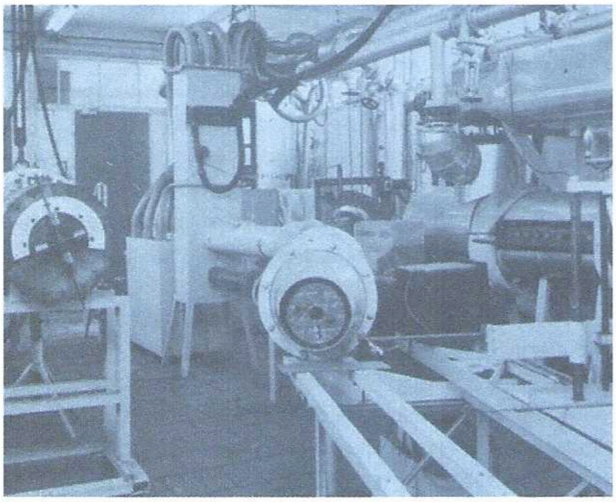
The fluid dynamics of the Earth's atmosphere was for a long time ill-understood. Only after the Second World War were attempts made to model the – turbulent – phenomena. Although concerns about air pollution would only become widespread in the late 1960s, in 1958 a Symposium on Atmospheric Diffusion and Air Pollution had already taken place in Oxford. Hinze contributed to it with a paper on heat transfer in the boundary layer.
Many aspects of atmospheric processes were still rather unknown up until around 1970; e.g., the influence of the Earth's surface on flows in the lower part of the atmosphere. In the late 1970s theory and observations of the (non-stationary and non-homogenous) turbulent stable atmospheric boundary-layer (SBL) started to develop. One of the researchers who contributed to progress in understanding the SBL was Frans Nieuwstadt (see § 4.1.1) who had started his career at the Physical Meteorology section of the KNMI in 1972. He introduced the concept of 'local scaling': the hypothesis that the (dimensionless) turbulence characteristics of the SBL can be expressed as functions of a single parameter in which the height above the Earth's surface is present. His local similarity theory has since found a lot of observational support. Nieuwstadt's second important contribution consisted of a series of nocturnal boundary-layer experiments in the late 1970s done at Cabauw (see § 6.2.6). These resulted in one of the few available data sets containing detailed mean and turbulence characteristics of the quasi-stationary SBL.
More recently research on the atmosphere has been carried out in Eindhoven, by professor Bas van de Wiel and co-workers. They studied the relationship between the dynamics of turbulence at night and the formation of ground frost and related phenomena. They succeeded in developing an explanation of the impact that cloud coverage and wind speed have on the dynamics of near-surface turbulence and hence on near-surface temperatures. In Delft air pollution has been and still is a theme of research, e.g., in the DisTUrbE project: Dispersion in the Turbulent Urban Environment.

## COASTS

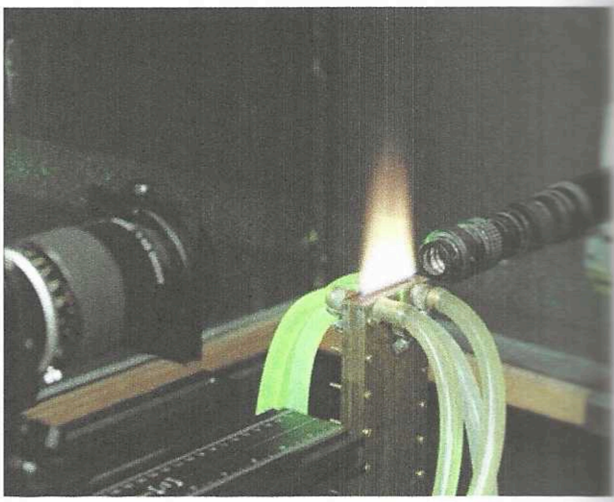
The morphological behaviour of the Dutch sea coast has been studied for more than one hundred years; the first thesis appeared in 1912. Johan van Veen (see § 3.4.1) discovered in the 1930s that the transport of sand near the coast was mainly determined by the sea surf flows. The NIOZ (see § 4.2) had a department for Physical and Chemical Oceanography from 1969 and a department for Sea Pollution from 1971 which shows the growing interest in this topic. Coastal and beach erosion was investigated experimentally with models at the WL. This kind of research requires huge basins since it is hardly possible to scale down sand grains. For more than twenty years the Netherlands Centre for Coastal Research (NCK) has been a cooperative network of private, governmental and independent research institutes and universities, all working in the field of coastal research. One of their research themes is 'Hydrodynamics'.
Coastal research became well-known with the general public thanks to the Zandmotor (Sand engine), a unique phenomenon worldwide. In 2011 a sandbar-shaped peninsula of about one square kilometre was deposited by dredgers at the coast of the province Zuid-Holland, south of The Hague. It is expected that these constantly evolving peninsulas will help to strengthen the coastline. In this way nature is used as partner of man in the constant fight against the deterioration of the coast due to wind and water flows. One of the effects which has been observed: sand grains from the peninsula are transported by the wind towards the coast and are deposited on the existing dunes or make new dunes. The Zandmotor method is expected to be more cost effective, and also helps nature by reducing the repeated disruption caused by replenishment. Evaluation of the Zandmotor in 2016 showed that it was behaving as expected. Researchers of the TU Delft study the currents around the peninsula, using dye and buoys with GPS equipment.

## COMBUSTION / FLAMES

Research on combustion in the Netherlands started at the Proefstation of Shell in Delft where processes in combustion



↑In 1965 a new Aerodynamics Laboratory was put into operation at the IFRF premises in IJmuiden. (courtesy of IFRF / Lucy Straker)



↑Research on gas flames at the TU Eindhoven in 1997. (courtesy of TU Eindhoven archives)

engines were studied from 1928 (see § 3.3.2). However, the first location in the Netherlands where flames were studied systematically was not in Delft. From 1948 the International Flame Research Foundation (IFRF) was in operation in IJmuiden, the small town where the Hoogovens company (Royal Dutch Iron and Steel Company) was located. Hoogovens needed the IFRF to find answers for urgent questions about their switch to oil burners. A new furnace was built to do tests, primarily to investigate improvements to furnace efficiency. English and French researchers came to IJmuiden for advice and help. The IFRF was not a division of Hoogovens but the company was of course involved and provided money to the committee who organized the research. It was only in 1956 that the research facility achieved official status and was renamed Nederlandse Vereniging voor Vlamonderzoek (Netherlands Association for Flame Research). An international team of researchers was changed every few years.

Among the research topics of the IFRF was combustion aerodynamics, which became especially important in the 1960s. One of the purposes was to find a means for generating flames possessing distinct fluid flow characteristics. In one of the experiments the effect of swirl applied to the combustion air stream was investigated. In 1965 a new aerodynamics laboratory was opened and one of the researchers there was Alan Chesters, who would later work on two-phase flows at the universities of Delft and Eindhoven. One of the new burners developed in IJmuiden, around 1980, was the Aerodynamically Air Staged Burner which met the increasingly stringent rules on NOx emissions. This burner had a central coal injector and a swirling combustion air stream.
One of the Dutch advisers of the IFRF was professor Hoogendoorn from Delft (see § 4.1.1). His research on efficient burners started soon after his appointment in 1971, a result of the growing concerns about environmental pollution and energy efficiency. Thanks to their knowledge about turbulent flows and mixing, Hoogendoorn and his co-workers were able to design better burners. Experiments with LDA led to their famous 'Delft double jet burner', one of the few burners with a generally recognized benchmark validation value. The fuel used was methane which is much more relevant for the design of natural gas burners than hydrogen. The Delft burner was depicted on the front cover of Hoogendoorn's farewell lecture of 1998 in which he proudly claimed that his team was now able to perform a reliable numerical simulation of an oven; though the modelling of the turbulence was still difficult...
As for many types of complex flows in which chemistry is involved, numerical simulations have largely improved. At the Multiphase and Reactive Flows group of the TU Eindhoven (with professor Philip de Goey), combustion has also been one of the main topics. As is the case with several other groups related to fluid mechanics, this group has developed software which they offer on their website to commercial users: "Simulations employing detailed chemistry and transport models are used to investigate the structure, emissions, dynamics, and stability of laminar flames. Our FGM [Flamelet Generated Manifolds; FA] model is extended to account for heat loss, fuel stratification, preferential diffusion, flame stretch/curvature effects, pollutant formation (UHC, CO, NOx, soot), and ignition/extinction. The interaction of flow and chemistry in turbulent flames is unravelled by using an in-house developed high-fidelity DNS code. Turbulent combustion models are developed and tested in an in-house LES code and validated against lab scale experiments. The knowledge from these studies is translated into efficient and accurate FGM-based models that are coupled to commercial and open-source CFD codes for the simulation of combustion in engineering applications."