Fluids, flowing across the scales

Inaugural lecture
prof.dr. Federico Toschi
June 24, 2011

/ Department of Applied Physics
/ Department of Mathematics & Computer Science

Technische Universiteit
Eindhoven
University of Technology

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Where innovation starts

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Presented on June 24, 2011
at the Eindhoven University of Technology

Introduction

"La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi a gli occhi (io dico l'universo), ma non si può intendere se prima non s'impara a intender la lingua, e conoscer i caratteri, ne' quali è scritto. Egli è scritto in lingua matematica, e i caratteri son triangoli, cerchi, ed altre figure geometriche, senza i quali mezi è impossibile a intenderne umanamente parola; senza questi è un aggirarsi vanamente per un oscuro laberinto." – Galileo (1623), Il Saggiatore.

"Philosophy is written in that great book which ever lies before our eyes. I mean the universe, but we cannot understand it if we do not first learn the language and grasp the symbols in which it is written. This book is written in the mathematical language, and the symbols are triangles, circles and other geometrical figures, without whose help it is humanly impossible to comprehend a single word of it, and without which one wanders in vain through a dark labyrinth." – Galileo (1623), The Assayer [1].

This lecture is about something that all of us experience and observe every single day: the motion of fluids.

Why should we care about the dynamics of fluids? And why is it still an open scientific problem? I hope that this lecture will be able to provide an answer to these questions. I will discuss only a few topics, taking examples from the problems on which I am currently working. My research interests focus primarily on the transport phenomena and the interplay between small-scale processes in fluids, within the context of realistic large-scale flows. I will try to discuss things at a level that is accessible to the non-specialist and to keep the discussion self-contained: should I be imprecise or incomplete, I apologize now.

Fluids are so omnipresent in our daily lives that we may forget how widespread they are: we drive, swim and fly through fluids. Fluid behaviour and fluid dynamics apply to phenomena ranging from just above the atomic scale (nanometers) to scales larger than galaxies (megaparsecs).

What do we know about fluids? Fluids do not have a shape on their own and tiny forces are sufficient to put them into motion: all of this happens under our very eyes every single day.

We also know from our experience that not all fluids flow or respond similarly when we apply a force. Some fluids are simple, others are complex. Water is an example of a simple fluid. It is said to be a Newtonian fluid because the internal fluid stresses are linearly proportional to the strain. Other fluids exhibit more complex rheological relationships, connecting strain and stresses, and when they flow, their dynamic behavior may appear odd. Toothpaste, ketchup and blood are all examples of common fluids with complex non-Newtonian properties.

Remarkably enough, even simple fluids like water can exhibit complex behavior as when the fluid becomes turbulent.

What is fluid turbulence?

"Turbulence, a scientific term to describe certain complex and unpredictable motions of a fluid, is part of our daily experience and has been for a long time." – from Scholarperdia by R. Benzi and U. Frisch.

At the end of the 15th century Leonardo was fascinated by fluid turbulence and he reproduced accurately the complexity of turbulent eddies that he observed in the river Arno (see Figure 1).

Figure 1

Studies of water passing obstacles and falling, circa 1500, by Leonardo Da Vinci.

Turbulence is the chaotic state of fluid motion, as opposed to laminar flow. Technically, a dynamic system is said to be chaotic when it is predictable in principle but not in practice. This happens whenever a system's sensitivity to small changes in its initial condition amplifies exponentially in time. Due to its non-predictable nature, a chaotic system is necessarily described only in terms of statistical quantities that provide the probability to obtain a given value when performing a particular measure: for example, observing a given velocity in a turbulent fluid.

Short history of turbulence

About 250 years ago the Swiss mathematician and physicist Leonhard Euler (1707-1783) derived the equations for the motion of an incompressible ideal or inviscid (zero viscosity) fluid[1]. Seventy years later the Frenchman Claude-Louis Navier (1785-1836) extended these equations to describe the flow of a viscous fluid. Additional contributions from the Englishman Sir George Gabriel Stokes (1819-1903) have resulted in the equations for a viscous fluid being now commonly known as Navier-Stokes equations.

One of the greatest difficulties of Navier-Stokes equations, as for chaotic systems in general, resides in their non-linear character making their solutions not expressible in terms of simple functions for most realistic flow conditions. The physics of turbulence seems to be a case where nature needs to guide us not only in writing the mathematical model, but also in figuring out its solutions. Thanks to the possibility to numerically solve the Navier-Stokes equations, we know nowadays that these equations do have turbulent solutions, in line with experimental measurements.

A distinctive physical feature of fluid turbulence is the presence of a flux of energy *flowing across the scales*: from the large scales, where energy is injected by means of some stirring mechanism (e.g. by shaking our hands in a pool of water), to the small scales, where energy is dissipated by viscous friction (and hence converted into thermal heat). This is the classical picture proposed by Lewis Fry Richardson (1881-1953) of a cascade of eddies, 'similar' among themselves but smaller and smaller covering all sizes, from the integral down to the dissipative scale. The Russian Andrey Nikolaevich Kolmogorov (1903-1987) explicitly acknowledged Richardson's cascade hypothesis as an inspiration for his classical theory of turbulence in 1941 [2].

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1 The Nobel Laureate Richard Phillips Feynman (1918-1988) referred to these equations as describing the flow of 'dry water': an expression which conveys quite neatly the importance that viscosity plays in the dynamics of fluid flow in general and of turbulence in particular.

The intensity of turbulence is defined by means of a dimensionless number called the Reynolds number (after Osborne Reynolds, 1842-1912)[2]. In general, high-speed and/or larger-scale fluid motions are turbulent, while slow and/or small-scale flows are usually laminar.

[2] The Reynolds number is defined as the product of the typical fluid velocity times the typical length scale of the flow divided by the fluid viscosity; it provides an estimate of the relative importance of advection with respect to diffusion.

Fluid turbulence: a tough problem for many

Fluid turbulence is a challenging problem. From a mathematical point of view, a fundamental and still open question is to know whether smooth, physically reasonable solutions exist for the Navier-Stokes equations in a three-dimensional space. The Clay Mathematics Institute has a 1 million dollar prize waiting for the first person to solve this problem [3].

Several quantities, like velocity differences between two points (see Figure 2), show extremely intense fluctuations that deviate strongly from a Gaussian or normal distribution. A full understanding of these physical phenomena is still lacking: as an example one would like to predict the statistical properties starting from the basic equations of motion.

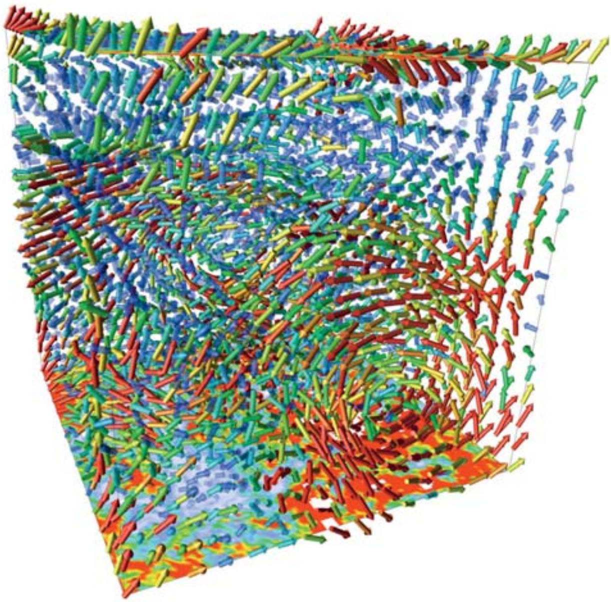

Figure 2

A visualization of a turbulent velocity field as measured from a Direct Numerical Simulation of the Navier-Stokes equation. Arrows indicate the local value of the turbulent velocity fields of the fluid. A typical statistical quantity which is often studied is the difference between velocities at two points separated by a given distance.

For engineering applications often limited information is really needed: for example, in many applications it is probably sufficient to know only the large-scale behavior of velocity and pressure. However, in turbulent flows, fluctuations at different scales interact with each other, making it a daunting task to reduce the complexity of the problem. In the lack of a deeper physical understanding, reduced models have been shown to work at best only partially.

From the point of view of computational sciences, fluid turbulence is a tough problem mainly because of the large computational resources required and the vast amount of data produced. Experiments also have difficulties in sampling large numbers of points at high frequencies, and when they do, they also produce huge amounts of data.

Fluids, *in silico*?

Numerical simulations are nowadays widely considered as the third approach towards scientific discovery, after the more classical experimental and theoretical approaches. For most fluid flows we know the equations or reliable models that can be coded on a computer. This, together with the fact that we cannot solve these equations analytically, makes numerical simulation an extremely valuable tool for fluid dynamics.

The biggest drawback of the numerical investigations of fluids is the large amount of computational resources required. Fluid turbulence is a multi-scale problem that calls for large computational capacity for moderate values of the Reynolds number (Re) that soon becomes an impeding factor at realistic values of Re[3]. Numerical investigations of laminar flows of complex fluids may also require large amounts of computational resources due to the need to model the additional physics. Recent progress in silicon technology has made a strong contribution to partially alleviating these computational restrictions, whereby state-of-the-art numerical simulations are able to compete with experiments. As an example, current state-of-the-art numerical simulations of homogeneous and isotropic turbulence can achieve Reynolds numbers three orders of magnitude larger with respect to what was possible in 1972 [4].

Numerical simulations often provide information that complements what one can obtain from experiments. Measurements or tests of hypothesis that may be experimentally difficult, if not impossible, may be easy to perform numerically (such as switching the gravitational force on or off).

In brief, the art of numerical investigations has proved to be so fruitful and flexible that it is appropriate to refer to them just as another type of experimental investigation: experiments *in silico*.

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3 The computational resources needed to simulate homogeneous and isotropic turbulence increase approximately by the third power of the Reynolds number.

Numerical modeling: again learning from nature

"Il vento è in tutto simile nel suo movimento a quello dell'acqua" - Leonardo da Vinci, Codice A, foglio 60r.
"The wind in its movement is completely similar to that of water"

The traditional approach to computational fluid dynamics is to take the equations, write them in discrete form, and solve them using a computer. Usually this is done by means of spectral or finite difference methods. Here again nature can teach us. As remarked by Leonardo, the motion of a gas ('il vento') can be very similar to that of a liquid ('acqua'). This is indeed well known from the kinetic theory of gases: a fluid behavior results when considering the Boltzmann equation at large length and time scales[4]. So why not to simulate a gas to study a liquid? In principle this sounds like a bizarre idea: the description of a gas appears to be far more demanding than that of a fluid. A gas can be described either at the microscopic level (describing the individual positions and velocities of all its molecules) or at a mesoscopic level (by means of the probability density function of finding a molecule with a given velocity at a given position). The first approach leads to Molecular Dynamics or other particle-based algorithms. The discretization of the second leads to the so-called Lattice Boltzmann Method [5]. What is remarkable about the discretized Boltzmann equation is that a small number of representative gas velocities are enough to ensure convergence to a fluid behavior. This mere fact makes the Lattice Boltzmann Method computationally comparable to (and sometimes more efficient than) other discretizations of the Navier-Stokes equation. But, most importantly, the fact that the method has its roots in the kinetic theory of gases provides an extraordinary flexibility in implementing additional physics: the idea to describe a fluid as a gas is not a bad one at all [5]. A few examples of the flexibility of the Lattice Boltzmann Method will be discussed later.

[4] Of course a gas does not always behave like a fluid, so this may give a wider application range to numerical methods based on the description of a gas.

We will now focus on a few specific examples of fluid flows. What happens when a pot of water is put on a fire? How are particles transported by winds in the atmosphere? How does turbulence influence the dynamics of plankton and bacterial colonies in oceans? How does blood flow in our veins and arteries? In the following we will see how mathematical modeling, state-of-the-art numerical investigations and experiments can help us gaining a deep insight into these important issues involving the physics of fluid motions.

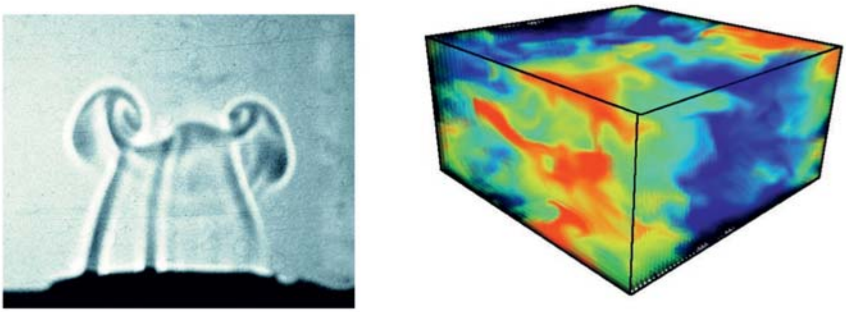


Figure 3

On the left, a picture of a thermal plume. The image is the projection of the shadow of a thermal plume when illuminated with white light. On the right, visualization of thermal plumes from a numerical simulation of a *periodic* Rayleigh-Benard cell (red, hot fluid; blue cold fluid).

Physics of turbulent heat transfer and boiling

How do turbulent fluids start to move? An important class of fluid motions is initiated and sustained by natural convection. This is the familiar motion that we observe when we put a pot filled with water on a fire. Natural convection also plays a key role in atmospheric circulation.

Localized heating of a fluid induces a variation of its density[5], when the bottom of a fluid is warmer than the top, an unstable condition is created, with denser fluid sitting on top of lighter fluid. The simplest mathematical model for thermal convection is the Rayleigh-Bénard convective cell, a closed system with two horizontal walls (the bottom one at a higher temperature than the top one) and adiabatic lateral walls. The dimensionless control parameter for Rayleigh-Bénard convection is the Rayleigh number which controls the relative importance of buoyancy forces with respect to (the product of) thermal and momentum diffusivities. The fluid starts to move every time that the Rayleigh number exceeds a critical value; under these conditions even the smallest perturbation will suffice to initiate a large-scale motion. At larger Rayleigh numbers the motion in the cell becomes strongly turbulent. An important physical property of the Rayleigh-Bénard cell is that the presence of convective motions makes the cell conduct heat much more efficiently than when the fluid is at rest (when heat is transferred only by means of conduction).

How does the heat flux depend on the Rayleigh number? Despite a vast amount of experimental, numerical and theoretical investigations, this important and basic question does not yet have a fully satisfactory answer [6]. Furthermore, the thermal convective cell is a paramount example of a strongly coupled system. The large-scale motion is started and sustained by the thermal force exerted at small scales through the creation of thermal plumes in the thermal boundary layer (see Figure 3). In turn, the large-scale circulation influences both the viscous and thermal boundary layers, confining most of the temperature drop within the thermal boundary layers.

5 If the temperature variations are not too large the density variation will be linearly proportional to the temperature (this is the so-called Boussinesq approximation).

The role of the boundary layers at very large Rayleigh numbers is still an open issue. To remove part of the complexity of the problem we exploited the flexibility of numerical modeling, investigating turbulent thermal convection in a 'periodic' box (see Figure 3). In a periodic cell one can study purely 'bulk' thermal convection. From these simulations we were able to clearly confirm that in the absence of boundary layers the dimensionless heat flux grows by the square root of the Rayleigh number, as predicted some time ago by Robert Harry Kraichnan (1928-2008). It is interesting to note that laboratory experiments performed in high chimneys were able to reproduce similar results [7]. The idea to use high chimneys to remove boundary layer effects reproducing 'bulk' convection shows how creative smart experiments can be. Furthermore, this example clearly illustrates the duality between experiments and numerical simulations: experiments can be designed to support and complement numerical investigations and vice versa. Another very important example of thermal instability where boundaries are not important is the Rayleigh-Taylor one [8]. This is the instability that occurs whenever a heavy fluid pushes on a light fluid, leading to the interpenetration of the two fluids that grows in time (see Figure 4). Depending on the temperature variations, the fluid properties, and the pressure condition, thermal convection can become even more complicated due to stratification effects or even boiling. These more complex thermal convective flows were recently demonstrated to be accessible by means of appropriate extensions of the Lattice Boltzmann Method. This is a telling example of the great potential of the Lattice Boltzmann method to explore fluid flows even under extremely complex flow regimes.

Figure 4

The beautiful geometries of the turbulent Rayleigh-Taylor instability.

Particles and droplets in turbulence

"Non è vero che uno più uno fa sempre due; una goccia più una goccia fa una goccia più grande." - Tonino Guerra.
It is not true that one plus one makes always two; one drop plus one drop makes a bigger drop.

Fluids are usually described in a Eulerian way, i.e. by their velocity at any point and at any time, as measured in a fixed reference frame, like the laboratory. What if one could sit on a molecule of the fluid and describe things from that point of view? This is precisely the so-called Lagrangian description. The two descriptions are mathematically equivalent but while the Eulerian description is the most common, for some problems the Lagrangian description is the most natural. This field, which was pioneered by Geoffrey Ingram Taylor [9] and Lewis Fry Richardson [10], is key to understanding, for example, dispersion of pollution or particulates in the atmosphere as well many other industrial applications. Its relevance to marine ecology is also considered below.

In recent years a large number of experimental and numerical investigations focused on the study of the Lagrangian properties of tracers and particles in turbulence [11,12]. Such investigations require challenging experimental techniques, capable of tracking particles at very high frequency and for very long times along their trajectories. Numerical simulations are expensive both for the computing resources required as well as for the large amount of data that need to be stored in order to achieve a good statistical convergence. In collaboration with experimental colleagues from the Max Planck Institute in Göttingen we compared

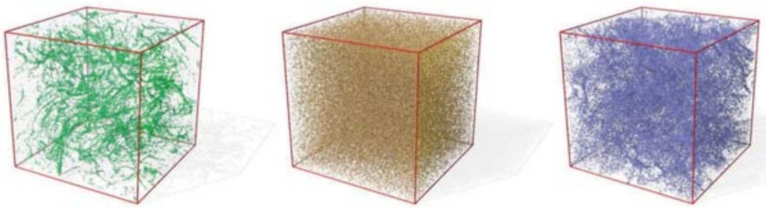


Figure 5

Heavy particles (left), fluid tracers (center) and bubbles (right) concentrate differently in the same turbulent fluid.

the outcome of numerical simulations with experimental measurements: a necessary cross-validation to understand the limits of both approaches [13]. These first studies focused on the statistics of tracer accelerations, the temporal correlation of tracer velocities (the so-called Lagrangian structure functions), as well as the statistical properties of the relative separation of pairs and small clusters of tracers.

In natural phenomena, as well as in engineering applications, particles are not always small enough to be transported in the same way as the fluid itself. The mass of the particle, its size or shape, can induce inertial effects that make particles deviate from the material line of the flow. In the case of fluid droplets, the situation is even more complex because droplets can deform, break or coalesce. In clouds, as well as in many industrial applications, phase transition, condensation and evaporation may occur.

The most important physical effects of inertia are preferential concentration (particles preferentially accumulating in some regions of the flow, see Figure 5) and filtering of the faster turbulence fluctuations (particles moving with increasingly ballistic behavior, ignoring the fluid fluctuations, see Figure 6). The contribution of both effects can be clearly identified in the behavior of particle accelerations [14]. An important consequence of particle inertia is that the collision rate among particles can increase due to larger local accumulations and to the development of caustics (a non-uniqueness of the particles' velocity field) [15].

Figure 6

The evolution of particles with different inertia in turbulent flows when passing through a small region of large localized vorticity (the so called vortex filament). Tracers (in red) experience a much greater acceleration than particles with larger inertia (green, blue, yellow, ...).

Knowledge of the collision rate between particles is fundamental to correctly estimate the aggregate formation rate (like soot production in combustion), the rate of chemical reactions or the formation of rain droplets in clouds. Turbulence plays a key role in the intensification of all these small-scale processes.

In most of our numerical investigations we have been treating particles by means of a point-wise description and almost always in the so-called one-way coupling approximation (particles are affected by the turbulent velocity field but do not react back on it). These assumptions allow the study of different particle types evolving in the same flow. However, when a large fraction of the fluid volume is occupied by particles or droplets, these can also influence the fluid behavior itself.

Refined mathematical modeling allows finite particle size effects to be incorporated even maintaining a point-particle description. These findings were validated against experiments and numerical simulations with fully resolved finite-size particles [16]. The process of rain formation involves droplets coalescencing under the combined effects of turbulence, gravity, shear, thermal convection and phase transition. We are currently studying some of these problems also in the context of a larger national program.

Large droplets in turbulence will experience deformation and break up. The study of the physical processes associated with these events requires high quality data capable of disclosing the dynamics of the full droplet shape and trajectories. To study this problem we have recently employed a multi-component Lattice Boltzmann model and we could demonstrate its effectiveness in maintaining a stationary turbulence emulsion.

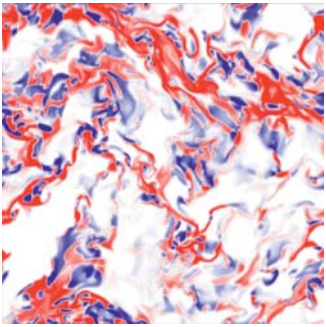


Figure 7

Numerical simulation of the Fisher–Kolmogorov–Petrovskii–Piskunov (FKPP) equation in turbulence, colors encode for the concentration of microorganisms living in a compressible and two-dimensional turbulent environment.

Life in a turbulent environment

Small living organisms like plankton and bacteria populate oceans, seas and lakes: these organisms play a key role in the marine ecosystem.

In fluid environments, organisms live, reproduce and die while being transported, together with nutrients, by turbulent currents. The reproduction time of bacteria and plankton is long compared to the smallest turbulence time scales. As a consequence, turbulent transport plays a direct role in the evolution of populations. Fluid currents responsible for the dispersion of organisms affect their local density and so have a direct effect on their reproduction and death rates.

The interplay between the dynamics of a population and the transport by means of a compressible turbulence velocity field can be investigated by means of mathematical models and numerical simulations [17]. As an example, the Fisher-Kolmogorov-Petrovskii-Piskunov (FKPP) equation can be used to describe the evolution of a population, under the effects of convection and diffusion, with growth and death processes modeled by means of a simple logistic-like term. In the absence of advection, the FKPP evolution is characterized by a wave-like solution that propagates with a constant front velocity (the Fisher wave). The striking qualitative difference in the presence of compressible turbulence is the appearance of patchy regions where the population becomes quasi-localized. In two space dimensions this compressibility leads to the production of almost one-dimensional filamentary structures that closely resemble the structures visible from satellite observation (see Figure 7). Quasi-localization has important consequences for the global size of the population (the so-called carrying capacity of the ecosystem) that can be substantially reduced [18]. Under such conditions even a mild increase in the organisms' diffusivity (e.g. by a better swimming ability) can lead to a sharp increase in the carrying capacity. A discrete description of the population individuals is better suited to the study of population genetics under flow conditions. When two or more species compete in the same environment, one must deal with genetic drift (stochastic fluctuations in the relative fraction or one species with respect to the other) and Fisher genetic waves [17]. Tools and knowledge on particle transport in turbulence are key to studying the evolution of populations in a realistic flow environment.

Complex flows or complex fluids?

It is not only turbulent flows that are challenging from a theoretical and computational point of view: laminar flows of complex fluids can be equally challenging. Examples of complex fluids include fluids laden with polymers, particles and bubbles or with multiple phases or components. The challenge is to be able, starting from the microscopic composition, to understand the mesoscopic behavior or the macroscopic rheological properties. Examination at small scale can produce many surprises due to the dominance of physical phenomena that we do not commonly observe at the macroscopic scale. Thermal fluctuations, rarefied gas regimes and the dominance of surface forces over bulk forces are only a few of the examples of the new physical effects at small scale.

Statistical hemodynamics

Human blood is a fluid with very complex rheological properties: a suspension of deformable red blood cells (erythrocytes) in a Newtonian liquid, the blood plasma. For what concerns the rheological properties of blood, other constituents like leukocytes and thrombocytes can be neglected due to their low-volume concentrations. Typical physiological concentrations for red blood cells are between 40 and 50%. In the absence of external stresses, erythrocytes assume a biconcave shape of approximately 8 µm diameter. In order to better understand pathological conditions it is important to know what the effect of red blood cells is on the rheological and clotting properties of blood. Most computational investigations of blood flows are based either on a continuum description (macroscopic approach) or on a detailed description of the cells (microscopic approach). We are currently using a mesoscopic description in an attempt to bridge the gap between the micro and macro scales [19]. In this approach, red blood cells are individually incorporated but through a minimalistic description, so enabling us to observe and study emergent non-Newtonian rheological properties at the macroscale while retaining a cell-level description (see Figure 8). This approach in particular is promising for the study of the statistical behavior of cells and groups of cells under disturbed flow conditions.

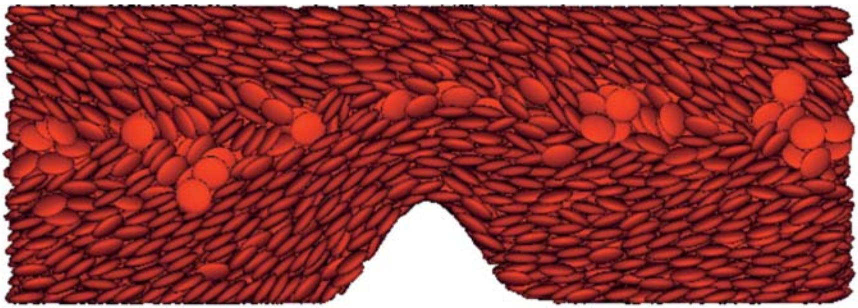


Figure 8

The cell-resolved flow of blood in a small capillary when passing over a simple geometrical model of a stenosis.

For the future...

The interaction between processes happening at multiple scales occurs naturally in fluid dynamics. A deeper understanding of the coupling and interplay between the fundamental processes happening at different scales will have groundbreaking consequences on virtually all disciplines that involve the dynamics of fluids. A new generation of super-computers together with refined numerical algorithms and smart experimental investigations are key to paving the way to the necessary breakthroughs. Much work is still needed from us and from future generations to uncover the beauty of the new mathematics and the new physics lying in wait behind these problems.

Science, education and society

I believe that breakthroughs in science result today from the efforts of many, for at least a couple of reasons. First, it is reasonable to assume that the simplest problems have been solved first, so we are probably left with the difficult ones. Second, many of the problems that science and society are facing now are extremely interdisciplinary.

It is therefore important for students to have a deeper-than-ever scientific knowledge in a specific field to be able to tackle the tougher problems. But this alone, in the future, may not be enough. Too many scientific communities have delved into their research sub-field, loosening the ties and exchanges with adjacent communities, ending up speaking different languages. I believe it is important today to make an effort to help the new generations of students to speak more than one scientific language. What can we do?

We can do more to motivate students to learn to acquire information from different research fields, to interact with different scientific communities. Students should also start early to move across national and cultural borders to get the best that the educational systems and research laboratories can offer to their personal development.

Furthermore, any stimulation of exchanges between scientific communities will help. Sharing know-how, not only in terms of scientific papers but also in terms of data, computer codes, scientific presentations and lectures will help. We have all the technologies we need nowadays to support such efforts. Moreover, the EU supports the exchange of students and researchers between different groups. Instruments like Marie Curie and COST Actions are perfect tools for tightening communities by means of supporting scientific exchanges and the organization of meetings and conferences. All these things will work if everybody chips in.

I mentioned that we have been left with the toughest problems to solve. We cannot hope that the university will be able to provide high-level education without the solid basis of a good school system. I clearly remember the key role of the high school in both my general education and in getting me acquainted with science, more specifically with mathematics first and physics later. A key priority for anybody interested in higher education should be to contribute to the quality of the school educational system.

The second consideration concerns society. As scientists we are well aware that the research we are conducting will, sooner or later, have an impact on society. And still many of our friends and citizens do not fully understand what research is, what we are doing, those things that humanity understands and those not. I think that as scientists we have a responsibility here. Anybody active in science should feel a duty to help bridge the gap between scientific research and society.

Acknowledgements

Ladies and gentlemen, this concludes my lecture.

I want to thank the Executive Board of the Eindhoven University of Technology and the deans of the departments of Applied Physics and Mathematics & Computer Science for the confidence they have in me and for giving me the opportunity to perform my research here.

That I am standing here today is thanks to many, many people. I discovered science during my high school years when a couple of excellent teachers let me appreciate the beauty of mathematics first and physics later on, an appreciation that continued during my years at the Scuola Normale in Pisa. During my PhD years I had the honor and pleasure to know and start to collaborate with Roberto Benzi, Luca Biferale and Raffaele Tripiccione. After 14 years they still are my most active collaborators! I often recall many afternoons with Roberto and Lele in San Piero a Grado, in a deserted INFN, during the days between Christmas and New Year's eve. With Luca I share the biggest part of my scientific work. This year he is visiting professor at TU/e. My special thanks go to Detlef Lohse, who was the first to trust me, offering me my first job as a physicist, as the first postdoc in his new group. I wish to thank all my colleagues in Rome and, in particular, Massimo Bernaschi, Michiel Bertsch and Sauro Succi. Thanks also to Enrico Calzavarini, Massimo Cencini and Alessandra Lanotte with whom I spent so many hours discussing and working together. I further thank all those with whom I have had the pleasure to engage in scientific discussions and all my collaborators.

I want to thank, also on behalf of the wider scientific community, the supercomputing center CINECA for the possibility to set up the iCFDdatabase.

I thank my colleagues of the departments of Applied Physics and Mathematics & Computer Science for their constant willingness to make my work at TU/e more effective in a pleasant and friendly working atmosphere. In particular, I want to thank Herman Clercx, Anton Darhuber and Gert-Jan van Heijst from Applied Physics and Bob Mattheij and Mark Peletier from Mathematics & Computer Science.

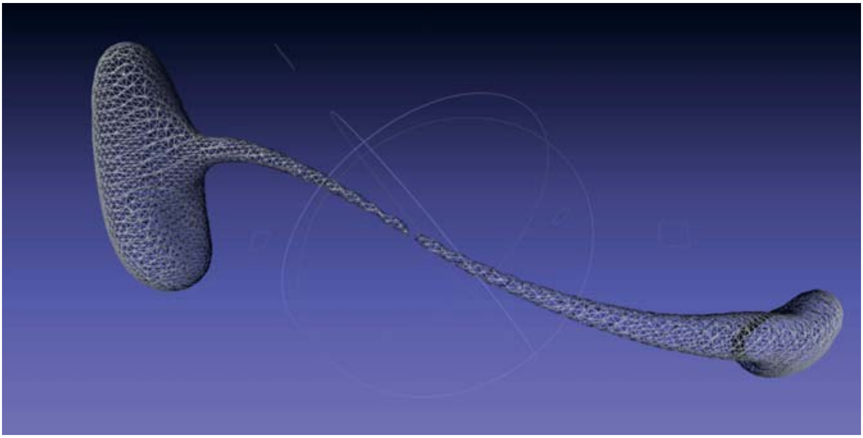
A special word of thanks goes to Jens Harting and Jan ten Thije Boonkkamp. I wish to thank all the Master's students, PhD students and Postdocs, both past and present, who have been working with me.

Finally I would like to thank my family and, in particular, my parents. With my studies and my work I left your town when I was nineteen and ever since I lived and travelled (far) away. You never complained, and yet always encouraged me to pursue my goals. I could always trust in your presence and support. I want to express to you here my deepest gratitude for all that you have done for me and all that you are now doing for my family.

Dear Marianna, thanks so much for being with me: without your help, understanding and encouragement I would not be here today.

Cara Radiana che hai già imparato quanto il mio lavoro a volte ci tenga lontani, sappi che questa lezione ed il mio pensiero, ora come sempre, sono per te.

Ho detto. Ik heb gezegd.



The last stage before a droplet breaks in a turbulent flow. From a numerical simulation based on a multicomponent Lattice Boltzmann method.

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Curriculum vitae

Prof. Federico Toschi was appointed full-time professor of Computational Physics of Multi-scale Transport Phenomena in the departments of Applied Physics and Mathematics and Computer Science at Eindhoven University of Technology (TU/e) on September 1, 2008.

Federico Toschi (1971) graduated in Physics at the University of Pisa, also obtaining the diploma in Physics from the Scuola Normale Superiore di Pisa (1995). He received his PhD in Physics from the University of Pisa (1999) with a thesis on the fundamental statistical properties of turbulence. He has worked at the University of Twente (The Netherlands), at Ecole Normale Supérieure de Lyon (France) and at the Istituto per le Applicazioni del Calcolo of the National Research Council (Italy). In September 2008 he was appointed full-time professor at TU/e. His current research interests include the physics of chaotic systems with a particular focus on multiscale fluid dynamics, turbulent transport phenomena, complex fluids and numerical modeling for fluid dynamics. He has a strong expertise in the field of high-performance computing and has been the recipient of several large-scale computing grants. He coordinates national and international projects including a European Cooperation in Science and Technology (COST) Action on 'Particles in turbulence' in which 22 countries are currently participating. He has co-authored over 100 journal publications and two reviews and he has given about 30 invited talks at international conferences.

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