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EXTREME FLUID DYNAMICS AND THE SEARCH FOR A NEW ENGINEERING SCIENCE

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What do avalanches, traffic, nanotechnology and the aerodynamics of space shuttles have in common?

While we could see each of these as involving “flows” — of snow or cars or air — these are not flows in the way we think of, say, water flowing down a river. So what makes these different to ordinary flows, and is the difference important?

In this lecture I will mainly concentrate on flows of extreme speed or at extremely small scale — hence my title “Extreme Fluid Dynamics”. For example, when a space shuttle re-enters the earth’s atmosphere, its extreme speed generates temperatures high enough to ionise the air around it. The shroud of hot electrically-charged gases causes the well-known “communications blackout” that shuttles suffer in the upper atmosphere. So the engineers designing new space vehicles and future high-speed aeroplanes need a good understanding of aerodynamics in the upper reaches of our atmosphere.

At the other end of the scale, nanotechnology promises to transform all our lives in the coming century. It affords the engineer an opportunity to design new devices that manipulate fluids at the smallest scales and in the smallest systems.

These emerging technologies have, however, exposed a weakness in our ability to predict how fluids flow in extreme circumstances. Some surprising and curious effects occur in these types of flows that do not happen conventionally.

I included in my title the phrase “The Search for a New Engineering Science” because engineers who are imagining and developing these technologies need a new design methodology that embodies the unusual physics of these kinds of flows.

I thought of adding a further heading: “Back to the Future”; although that movie title is perhaps a caption too far, the new engineering science needed for technologies emerging in the 21st century is, in fact, deeply rooted in the 19th century.

The radiometer


Crookes’ Radiometer

This is a radiometer, also called a “solar engine”. It is about 10cm high, and you still sometimes see them in shop windows where they are placed as attention-grabbers. It doesn’t look much, but at the end of the 19th century it caught the attention of some of the world’s greatest physicists.

The radiometer was invented in 1873 by William Crookes, who later became President of the Royal Society of London. It is a glass bulb containing a partial vacuum or low-density gas. In the bulb, four vanes are suspended on a pin. The vanes are each silvered on one side and darkened on the other. The whole spindle turns very smartly in strong light, and the reason for this perplexed physicists at the end of the 19th century.

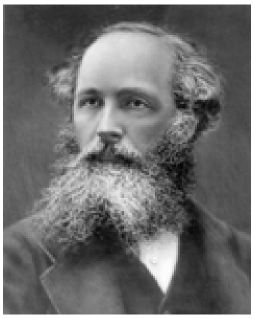
When it was first exhibited by Crookes, the radiometer caused much excitement because it was taken as evidence that light had momentum. It seemed to most physicists at the time that the vanes were turning in a beam of light like a windmill turns in the wind. This explanation is still sometimes taught in schools and colleges — but it is wrong!

The silver side of a vane reflects the light more than the dark side, which absorbs light. The change in momentum of the light is therefore greater on the silver than on the dark side. Newton’s Second Law tells us that the force acting on each side of the vane is proportional to the changes in momentum. So if the rotation is caused by the momentum of light then the spindle should be turning with the dark sides leading. But, in fact, the silver sides lead the turning.

In any case, scientists calculated that light could not exert enough pressure to turn the vanes so quickly. Following that, all sorts of other more or less plausible explanations were proffered. Some people even said that the movement of the radiometer had a supernatural cause. This explanation may have appealed to Crookes himself, who was intensely interested, as many prominent 19th century figures were, in spiritualism.

But the real explanation is, of course, physical: it just turned out to be very subtle and interesting physics. It took the intuitive genius of James Clerk Maxwell, Fellow of the Royal Society of Edinburgh and one of the greatest theoretical physicists of all time, to work out what was going on.

This year, 2006, marks the 175th anniversary of Maxwell's birth. Most people associate Maxwell with his groundbreaking work on electromagnetism, but it is his research on molecules and their interactions (called "the kinetic theory of gases") that underpins the subject of this lecture and which is coming back into such prominence for 21st century technologies.



James Clerk Maxwell
1831-1879

If the radiometer bulb is filled with air at atmospheric pressure, the spindle does not move. Likewise if the bulb is totally evacuated. So the explanation for the movement must have something to do with the density of the air.

Light falling on the radiometer warms up the black, radiation-absorbing sides of the vanes more than the silvered sides. Around the edges of the vanes there is therefore a thermal gradient caused by the temperature difference between the hot and cold sides.

By considering the gas as molecules bouncing off a surface, Maxwell (working, admittedly, with an idea of another scientist, Osborne Reynolds) discovered that a thermal gradient causes a rarefied, or low-density, gas to slip over a surface from the cold region to the hot region. This process is called "thermal transpiration" or "thermal creep". Through Newton's Third Law the momentum of the slipping gas causes the vanes to start turning in the opposite direction. This means that the cold or silvered sides lead the actual rotation — which is what is observed.

Thermal creep is just one of the curious effects that is important in rarefied flows. It is a type of physics that literally "comes out of thin air". Maxwell used physical arguments to understand why this effect arises, and to quantify it. The mathematics is not overly complex and can be found in any textbook on the kinetic theory of gases. I will return to this later when I describe new microscopic air pumps which have no moving parts.

Maxwell was summoned to Buckingham Palace to explain to Queen Victoria how the radiometer works. It seems she was mildly amused by the explanation of how movement could be generated apparently out of nothing. But, as Maxwell observed, perhaps ironically, the Queen "did not make much ado about nothing as she had much heavy work cut out for her all the rest of the day".

The motion of the radiometer indicates that flows in and around devices that operate in low-density air behave differently to what we would expect. You can immediately see the implications for an aerospace engineer designing next-generation aircraft or space-vehicles that fly high up in the atmosphere where the air is very thin.

But the radiometer also points us in the direction of other developing technologies too. The key issue here is one of scale.

Rarefied gas dynamics

Fluid dynamics is the branch of classical physics that deals with flowing material; that is, liquids and gases in motion. Mathematical descriptions of how fluids exchange heat and momentum internally were developed in the early 19th century in order to understand the behaviour of fluid flows that were central to the burgeoning technologies of the industrial revolution — like ships, pumps, engines etc.

These mathematical descriptions are the famous Navier-Stokes equations. They are still excellent for predicting the behaviour of most fluid flows, including those that are important in more recent technologies (such as aeroplanes and heart valves). However, these equations are predicated on the assumption that the bulk, or macroscopic flow of a fluid does not depend greatly on the microscopic physics of its constituent molecules, particles or grains.

For example, a fundamental physical difference between liquids and gases is that liquid molecules are constantly in contact with one another, but gas molecules are on average separated. However, in most cases encountered by engineers, a liquid flow has patterns and behaviour broadly similar to that of a gas flow. So this microscopic physical difference is not normally reflected in a difference in the macroscopic flow behaviour.

In fluid dynamics, this is called the "continuum-equilibrium" assumption. In practice, it means that in order to predict how a fluid flow behaves, we assume that the constituent molecules or particles of the flow exchange energy and momentum almost instantaneously with each other.

In a simple gas, molecules need to collide some three or four times in order to equilibrate their energy and momentum with neighbouring molecules. At normal temperatures and pressures, the average distance molecules travel between successive collisions, which is called the “mean free path”, is around 1/10th of a micrometre (where a micrometre is a millionth of a metre).

If an aerospace engineer wants to calculate the lift or drag of an aeroplane, for example the new Airbus A380, he or she will be interested in features of the airflow around the plane at a scale of centimetres or metres.

So the scale difference between the bulk behaviour of the airflow around the Airbus and the molecular behaviour of the air is a factor of a million or more. When calculating the aerodynamic behaviour of everyday air-vehicles, engineers can therefore effectively ignore microscopic molecular collision effects. The conventional continuum-equilibrium description is quite acceptable.

However, we have seen that rarefied, or low-density, gas flows behave differently to these everyday flows. The radiometer works best when the air pressure inside the bulb is 1/100,000th of atmospheric pressure. Then the air is so rarefied that the molecular mean free path is about a centimetre. The size of the vanes is perhaps a centimetre or two, so in a radiometer the macro- and microscopic physical effects are happening on very similar length scales.

In this case the continuum-equilibrium assumption of fluid dynamics no longer holds and interesting new fluid motion occurs, which causes the vanes to move due to temperature differences.

If the radiometer bulb is instead filled with air at atmospheric pressure the density of the air is higher; the mean free path drops to a 1/10th of a micrometre, scale separation becomes large, continuum-equilibrium returns and we do not get any unusual physics.

But we also see scale effects in engineering systems that are very small.

For example, if a gas at atmospheric pressure is flowing down a channel 1m wide, the scale separation between macroscopic and microscopic flow physics is a factor of a million or more (just as in the aeroplane case, above). Therefore if we want to predict the behaviour of the flow we can legitimately ignore any molecular effects and use the conventional Navier-Stokes equations. The gas can be thought of as an infinitely-divisible continuum, with flow properties defined at every point in the system.

However, a microscale channel is a million times smaller than the first. Now the mean free path — the distance molecules travel between collisions, which is greater than the average distance between molecules — is comparable to the width of the channel itself. So this is very far from being a continuum-equilibrium flow.

The Knudsen number

A non-equilibrium flow is one in which bulk properties, like flow speed or density, change over a distance similar to that which gas molecules travel on average between collisions.

An important indicator of non-equilibrium is the “Knudsen number”, named after the early 20th century Danish physicist Martin Hans Christian Knudsen. This non-dimensional number is the ratio of the gas molecular mean free path to a characteristic macroscopic length-scale of the fluid system:

$$Kn = \frac{\lambda}{L}.$$

If the Knudsen number is less than about 0.001, then the micro/macro scale separation is large and, as we have seen, conventional fluid dynamics is appropriate. However, the fluid dynamics starts to change when the Knudsen number rises, either due to the low density of the gas (which makes the molecular mean free path larger) or when the length-scale of the system is small.

Micro or nanoscale devices are usually intended to operate at standard atmospheric pressures, in which case the mean free path of air molecules is 0.1 micrometres. For devices with a typical size of 1 micrometre, the Knudsen number is therefore 0.1.

The characteristic length of a high-speed air vehicle, such as the Space Shuttle, could be the radius of curvature of its nose cone or wing — say, 10 cm. But the air flowing over the Space Shuttle when it is manoeuvring at an altitude of 100 km is so thin that the molecular mean free path is about 1 cm. Again, we can see that the Knudsen number is therefore about 0.1.

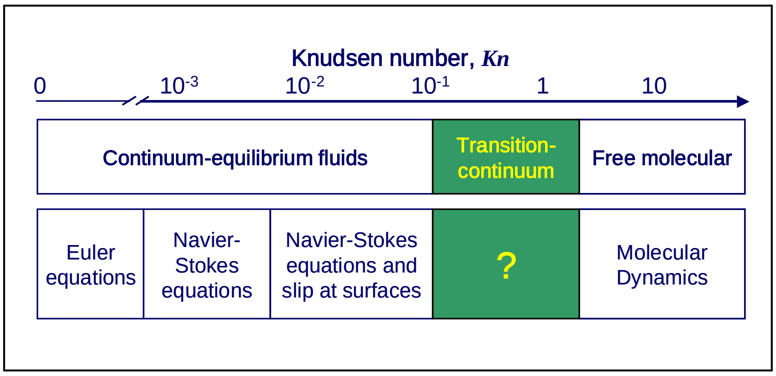
So despite these two flow situations being very different from each other, they are linked through having the same Knudsen number.

Engineers building high-altitude aircraft or micro- and nanoscale machines should not just make suitably scaled versions of current designs. If they do, they will miss out on some vital physics that changes the way their contraption works: a gas turbine that fits in the palm of your hand will work differently from the gas turbines that propel planes, even if all the lengths and continuum flow properties are properly scaled-down. Engineers at the Massachusetts Institute of Technology in the USA have been having difficulties developing a gas turbine power generator the size of a cigarette lighter. Their ultimate aim is to use this as a power source far more compact and efficient than batteries or fuel cells, but at the moment technical difficulties in the multiscale fluid dynamics and heat transfer have stalled their research programme.

So this is the “extreme fluid dynamics” of the title of my lecture. I will return to the devices and applications in which this fluid dynamics is important, but first I would like to describe some of the “new engineering science” that we are developing at the University of Strathclyde to understand these flows.

Non-equilibrium fluid dynamics

There are a number of different techniques that engineers can use to simulate and predict flow behaviour over the range of Knudsen number.



At the very lowest Knudsen numbers, which as we have seen is the realm of continuum-equilibrium fluids, the Euler and Navier-Stokes equations are effective models. All engineering undergraduates learn about these at university.

At slightly higher Knudsen numbers, the Navier-Stokes equations are still quite good, as long as you allow for the gas to slip at solid bounding surfaces.

Conversely, at very high Knudsen number, the gas molecules spend most of their time freely moving between a few, brief collisions. This situation is ideal for computer simulations which track each individual molecule or groups of molecules. But for less-rarefied flows the number of molecules that need to be tracked in three-dimensional space would occupy the most powerful computers available for decades.

So what do we do if the flow is so non-equilibrium that even the Navier-Stokes equations with slip are ineffective, but the gas is so dense that the largest computers are not powerful enough to track the individual molecules?

This is called the “transition-continuum” regime, and it is one of the uncanny coincidences of engineering that, with a Knudsen number of 0.1, our space shuttles and micro- or nano-devices lie right in the middle of it.

Extended hydrodynamics

In my research group we are investigating an approach which is called “extended hydrodynamics”.


Ludwig Boltzmann
1844-1906

One of Maxwell’s brilliant contemporaries, an Austrian physicist called Ludwig Boltzmann, devised an equation that remains the basis of all molecular gas descriptions today. Boltzmann’s equation describes how the function, *f* (which is the distribution of gas molecules at a particular place in the flow, $\underline{x}$, with a particular velocity, $\underline{v}$) evolves in time, *t*:

$$\frac{\partial f}{\partial t} + \underline{v}\cdot\frac{\partial f}{\partial \underline{x}} + \underline{g}\cdot\frac{\partial f}{\partial \underline{v}} = \left(\frac{\partial f}{\partial t}\right)_{\text{collision}},$$

The left hand side of this equation represents the drift motion of the molecules, without collisions, under the influence of a gravitational or other force, $\underline{g}$. The right hand side of the equation is the “collision function” which represents the scattering of molecules due to intermolecular collisions.

If we could solve this equation for *f* we would know the number and velocity of gas molecules at any point in a flow. Together with the mass of the molecules, we can then easily derive useful flow properties.

The problem is that the Boltzmann equation cannot be exactly solved for anything but the simplest flows. So at Strathclyde University we are working towards a good engineering solution that gives us acceptable accuracy without the need to compute expensive and time-consuming molecular simulations.

Our model is approximate, and still under development — after all, this is a “new engineering science” — but it offers interesting possibilities for the future.

Essentially, we are trying to construct a fluid dynamic model somewhat like the Navier-Stokes model, only more applicable to flows with a high Knudsen number.

To do this, we develop approximate solutions for the distribution function *f* in Boltzmann's equation as a series in Knudsen number around a local equilibrium. The more terms we take in this series the further away from continuum-equilibrium we get. The mathematical details of the technique are abstruse, but the first term in the series yields the Euler equations — which are a very simplified model of fluid interactions. The next term gives the Navier-Stokes relations — which is encouraging because this is what we would expect for a flow with only small departures from continuum-equilibrium.

However, the third term yields what are called the "Burnett equations". These are higher-order in Knudsen number and can be thought of as revised or extended versions of the Navier-Stokes equations which embody more of the physics of non-equilibrium flows. This is why models of this type are often called "extended hydrodynamics".

We could take further terms in this series to get equations even more appropriate for non-equilibrium flows. But the mathematical difficulties mount and the resulting equations are extremely cumbersome.

One advantage of extended hydrodynamics is that we can keep our efficient computer codes for solving the Navier-Stokes equations and just adapt them to take the more complex Burnett equations. Another advantage is that extended hydrodynamics reverts to the Navier-Stokes equations whenever the flow, for whatever reason, becomes continuum-equilibrium again.

But it does have some major drawbacks at the moment, which are the subject of intense research work in different countries around the world.

First of all, the details of the approximate solution technique for the distribution function can be interpreted in several ways. This leads to a number of different forms of extended hydrodynamic equations, and no-one can quite agree on which is correct.

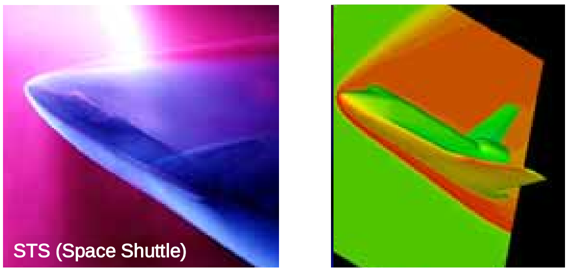
Second, while the Navier-Stokes relations are linear, first order and easy to write down, the Burnett equations are intimidatingly complex. They involve nonlinear and second-order terms, as well as a number of new coefficients which are difficult to determine.

Finally, further flow conditions need to be imposed at solid surfaces — and while we can make some guesses, no-one has yet come up with a good general theory as to what these should be.

Simple non-equilibrium applications and solutions

Researchers are still working towards a general approach to using extended hydrodynamics, but we have made substantial progress in solving specific flow problems. I will therefore show here some of our results that demonstrate the potential of extended hydrodynamics for aerosciences and microscopic engineering.

In order to design a safe and effective space shuttle, aerospace engineers need to model the flow around the vehicle numerically. The Space Shuttle re-enters the atmosphere from orbit at about 25 times the speed of sound — or Mach 25. It drives a strong bow shock wave ahead of it, which compresses the air passing through it and brings it to very high temperatures. The hot gas blows over the vehicle, and some of its heat is transferred by convection to the shuttle, which must be insulated from these high temperatures by heat tiles.



experiment

computer simulation

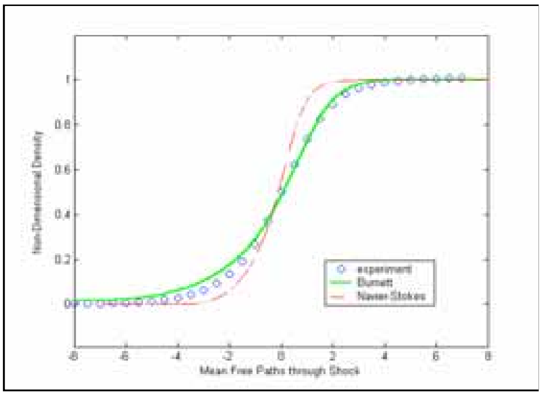
The Navier-Stokes equations can be used to perform numerical calculations of the flow around the shuttle, and they do produce a flow pattern very similar to experiments on scale models. But is it right in the fine, and all-important, detail?

Engineers generally think of shock waves as discontinuous "jumps" in the density, pressure and temperature of a flow. But real shocks have a certain thickness. So a simple question we can ask is: do the Navier-Stokes equations predict this shock density thickness correctly?

This is a particularly good test for new fluid dynamics models because there is a good amount of experimental data from the early days of the space programme. Also, if we want to try out extended hydrodynamics, we do not run into the problem I mentioned above — in defining new flow conditions at surfaces. The bow shock is established in a flow, not at a surface, so we only need to know the freestream flow conditions.

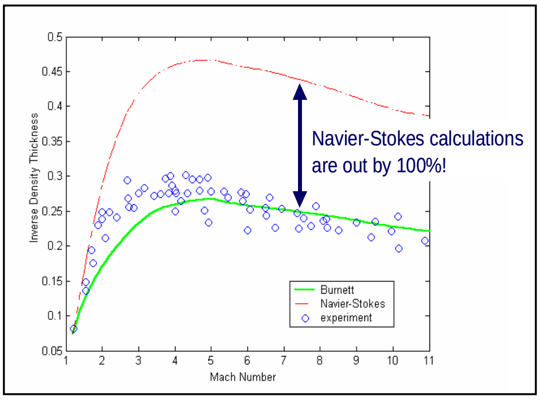
We first tried using the Navier-Stokes equations to calculate the variation in density through a shock of Mach 8 — that is, 8 times the speed of sound. This is the dashed red line in the figure. We can see that compared to experimental data — the blue circles — the Navier-Stokes equations predict a shock which is too thin.

However, if we use the Burnett equations instead we get a shock prediction that is pretty much in line with the experimental data — except there is a little divergence in the upstream region of the shock.



Problems with Navier-Stokes predictions are seen even better when calculating the inverse of the shock density thickness for a range of shocks up to Mach 11. Over most of this Mach number range the Navier-Stokes model predicts shocks which are wrong by up to 100% when compared with experiment. For a simple case like this, aerospace engineers need their calculations to be correct to within a couple of percent, so clearly the Navier-Stokes equations are inadequate.

The Burnett extended hydrodynamic equations achieve much better predictions of the inverse density thickness. While there is still some inaccuracy, mainly at low Mach numbers, these results show clearly that there is an opportunity here for an extended hydrodynamic model.



Predicting these high-speed non-equilibrium flows is important. In the case of the space shuttle, non-equilibrium real gas effects meant that the aerodynamic centre of the Space Shuttle Columbia was not at the expected point on the vehicle. This gave the astronauts on Columbia's maiden flight in 1981 some anxious moments during reentry when there was concern about losing control of the vehicle.

Non-equilibrium flows in microscopic devices might not generally have this level of safety implications, but they are certainly important in industrial design.

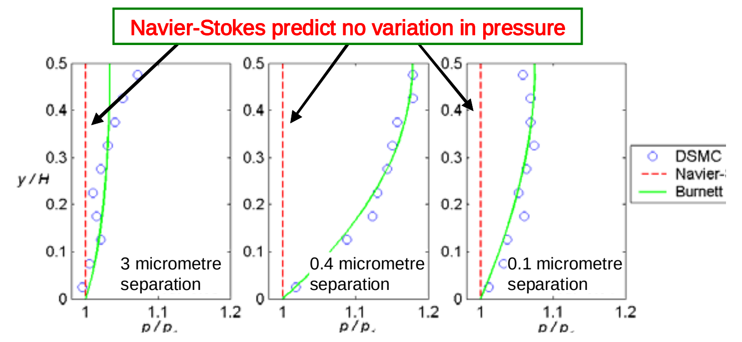
Toshiba ultra-compact hard disk drive

The world record for the smallest computer hard disk drive is currently held by the Toshiba company. Its ultra-compact disk is just over 2 cm wide, and can hold up to 4 Gigabytes of data. The urge towards miniaturisation of these devices means that more and more data has to be squeezed into a smaller disk space. Therefore the data-density of the disk increases and reader heads are being designed that are ever closer to the disk surface to resolve the fine data structure.

Floating the reader head over the disk surface is an example of a slider air bearing. Toshiba’s engineers need to understand the aerodynamics of this flow to ensure that the reader arm is able to maintain a constant separation and does not crash into the rotating disk underneath. For reader heads that are only a micrometre, or even less, above the rotating disk the physics of non-equilibrium microscopic flows becomes important.

However, a problem in investigating flows in these small geometries is the lack of experimental data. It is extremely difficult to resolve gas velocities in such small spaces. So we have to rely instead on a molecular dynamics simulation called “DSMC”, which is a computational model of the movement and interactions of millions of representative gas molecules. While it is acceptable as an experimental substitute, it is not a practical design tool in any but the simplest cases because it requires exorbitant computational resources.

The flow between two surfaces, one of which is moving (the disk) and the other stationary (the reader head) is called Couette flow. Here are three figures for Couette flow where the separation is 3, 0.4 and 0.1 micrometres. The gas pressure variations are plotted across half the separation height for clarity, but the variation is symmetric across the full separation distance.



The DSMC simulations — blue circles — show that we should expect pressure variations of between 10 and 20%. We see that the Navier-Stokes equations predict no pressure variation at all, but our Burnett equations do an excellent job of predicting the amount and shape of the pressure variation.

It is important to get these pressures right, because these simulations are showing us that the pressure between the reader head and the disk surface is higher in the middle than at the edges. Therefore the head and surface are pushing away from each other, and the reader arm needs to be designed to resist this movement.

I have shown that new fluid dynamic models can successfully capture the details and unusual physics of non-equilibrium flows — at least in simple cases. However, there is certainly much work that still needs to be done on making extended hydrodynamic solutions as robust and general as their continuum-equilibrium cousins.

In the final part of my lecture, I would like to look to the future and outline a few technological and other opportunities where non-equilibrium is either an important feature of the flow or offers us a new capability or understanding.

Hypersonic aircraft

Concorde’s cruise speed was around Mach 2, but new aircraft are on the drawing board that will travel at Mach 8 or higher. These high speeds require new types of jet engines.

A “scramjet” depends on compression of air by the forward speed of the aircraft. Air entering the intake of a supersonic aircraft is compressed and heats up. Fuel, usually liquid hydrogen, is then injected and combustion accelerates the exhaust gases to an even higher velocity, pushing the aircraft forward. The scramjet is mechanically simple, and has no moving parts, but it only starts operating at about Mach 5, so the aircraft has to be propelled to those speeds by ordinary jets or rockets. Because the flow is supersonic through the whole engine, getting the fuel to burn has been likened to “trying to light a match in a hurricane”.


a HyShot launch

The first successful test of a scramjet was by researchers at the University of Queensland in Australia. Their HyShot project uses scramjets designed by the British company QinetiQ, as well as an Australian design. The engines are launched on the nose of a sounding rocket on a high ballistic trajectory, reaching altitudes in excess of 300 km. Then the rocket is rotated to face the ground, and the combustion unit ignited for up to 10 seconds while falling at around Mach 7.6. The first successful launch was in July 2002, and there have been four further flights since. In its most recent flight in June this year HyShot reached Mach 8.

NASA had its own scramjet programme, but this has been suspended due to budget cutbacks. There were two successful flights of the X-43A. The last, in November 2004, holds the world speed record for a jet-powered aircraft of Mach 10. The X-43A was about the size of a Nissan Micra car, but unmanned, launched from under the wings of a B-52 bomber, and propelled by a rocket booster to the speeds at which its scramjet started operating. It flew at an altitude of about 30 km.


artist’s impression of the X-43A in flight

Both vehicles operate in rarefied air, and the aerodynamics of the engines incorporate shocks and high-speed flows. This is therefore an intensely non-equilibrium flow problem — which is part of the reason why it is far from straightforward to get scramjets to work consistently and for prolonged periods.

But eventually scramjets could revolutionise air travel. Design speeds of Mach 17 are viable, meaning that a passenger aircraft would be able to fly from London to Sydney in under two hours. Not enough time to watch an in-flight movie!

Micro/Nanotechnology

The fabrication of microscopic structures and devices is now almost routine. The mass-fabrication processes used for computer chips are now being used to manufacture micro-electro-mechanical systems — usually abbreviated to MEMS. While they sometimes appear to be "a solution in search of a problem", a range of applications have been proposed for MEMS. These include filters for environmental and biological monitoring, industrial and process flow controllers, and the gas microturbines I mentioned above.

An idea we are exploring in my research group exploits the fact that different gases passing down a long micro-pipe have different amounts of slip. Therefore, if the pipe is long enough the components of the gas will separate out. For example, if we pass a puff of air down a long smooth micro-pipe the gas that comes out first will mainly be nitrogen, while the oxygen emerges later. This is the basis for imagining a "sniffer" or air-sampler that works due to the physics of non-equilibrium micro-flows.

One of the most interesting devices proposed — and several have now been patented — is the "transpiration pump" or "Knudsen pump". This is a miniature vacuum pump without any moving parts. It works because pumping devices can now be made with pipes and channels so narrow that the flow is non-equilibrium even at atmospheric pressures. Then the same thermal transpiration effect that propels the radiometer can be exploited.

A prototype microscale pump developed in the USA is 2cm wide — about the same size as Toshiba's disk drive. It includes two silicon chips that serve as hot-side and cold-side thermal guards. A silicon dioxide aerogel membrane between them provides a network of nano-sized capillaries. The role of the thermal guards is to heat and cool the gas molecules on opposite sides of the aerogel membrane.

The increase in temperature along the capillaries causes a pressure rise along the capillaries because of thermal transpiration effects. A difference in pressure between the hotter and colder sides builds up. Pressure ratios of about two can be easily obtained across a single Knudsen pump, but this is expected to rise in the future as the design and performance of these devices is optimised. In any case, a number of pumps can be connected in series to make, in principle, quite large pressure differences.

I would like now to return to two flow situations I mentioned right at the beginning of this lecture, in which non-equilibrium fluid dynamics has barely started to make an impact but will, I think, produce useful insight in the future.

Kinetic theory is a powerful tool for understanding gas flows. This is why I have concentrated on rarefied gases. But there are other examples of multi-scale flow processes; any flow system which has a coarse, particulate structure can, in principle, be ascribed a Knudsen number. When this is high enough, standard continuum-equilibrium models of the system are likely to be inaccurate.

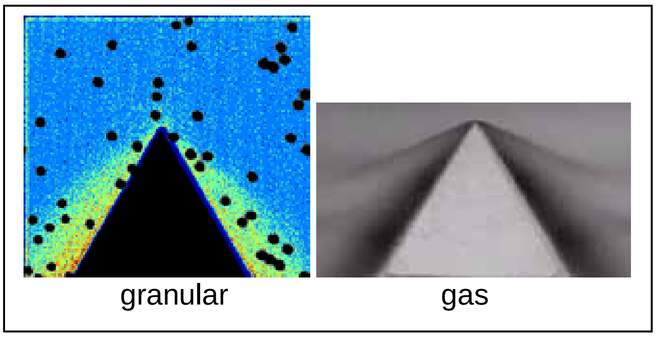
Granular flows

Understanding how avalanches flow is obviously critical to saving life, limb and property in mountainous regions. It is curious, though, that the current model that civil and environmental engineers use for avalanches is taken from that for water waves. I hope you will be able to see by now why this could be a flawed methodology.

Avalanches are from the family of granular flows which are ubiquitous in both nature and industry. In nature they include the formation and drift of sand dunes, and soil liquefaction during earthquakes. Industrial applications include mixing, drying and transporting granular materials such as seeds, pellets and pills.

Granular fluids are composed of a large number of macroscopic elements (the grains) that, when fluidised with air, undergo collisions very much like the molecules in a gas. When the time scale of grains colliding with each other is similar to the inverse of the local flow gradient, the Knudsen number is high and non-equilibrium features arise.

It is easier, however, to assess whether a granular flow is non-equilibrium or not than to model it. Unlike gas flows, simulations are complicated by the inelastic collisions between grains. Also the grains are not all the same size, and the coupling of the flow of the solid grains to the gaseous air in between them is complex.



This snapshot of an experiment (on the left) shows grains falling over a solid cone. The background colouring indicates the average density of grains over a long time. If you compare this granular flow with the density photograph on the right — which is of supersonic flow of Nitrogen gas over a cone — you can see very similar flow features.

This kind of simple granular flow can be modelled reasonably well using variants of molecular dynamics that allow for inelastic particles. But if we assumed this was a continuum-equilibrium flow and performed a fluid dynamic simulation of it, the results would not quite match up with the experimental or granular dynamics simulation. They would also likely be wrong in the detail.

With granular materials, I am now moving away from the extreme flows of my lecture title. So I would like to outline how non-equilibrium fluid dynamics may help us understand more general problems.

In principle, dynamical systems that have a “granular” aspect can also have a Knudsen number assigned to them, and they may sometimes display non-equilibrium flow behaviour. The interactions between people as they move around cities and even buildings have some parallels in the flow of grains interacting with each other. It will not be surprising, then, if we see the features of granular flows in the highways of the nation.

Traffic

Although it is an everyday experience, road traffic is difficult to model and understand. This is because of the very complex interactions between the particles — which in this case are cars or trucks. These interactions depend on the psychology of individual drivers, the driving conditions and many other factors.

Dirk Helbing at the Technical University of Dresden in Germany, is developing models of traffic flows as a fluid. Free traffic — with cars separated by the specified stopping distances in the Highway Code — corresponds to a high Knudsen number flow. Congested traffic, on the other hand, would have a much lower Knudsen number and the movement of one vehicle or particle strongly affects the overall dynamics. Again, this is a typical non-equilibrium flow condition.

We saw that shock waves were a feature of both hypersonic and granular flows. They appear in traffic too. Drivers will all have experienced these “shocks” as the traffic occasionally stopping for no apparent reason. They arise when, for example, in congested traffic one vehicle slows down a little, perhaps to allow another car in off a slip road. The car behind responds accordingly — although there is a short delay due to the driver’s reflexes and decision-making. Since all the cars behind the first change their speed in the same way, this “shock wave” propagates at a constant speed of around 15 km/hr in a direction opposite to the driving direction.

In Helbing’s model of urban road traffic, road networks are composed of nodes — road intersections, or t-junctions — connected by pipes — that are the road sections. A change of road properties, like the number of lanes or new speed limits, is represented by connecting two or more pipe sections.

The major advantage of developing fluid dynamic models of traffic is the same as that for extended hydrodynamics models of non-equilibrium gas flows. In terms of numerical efficiency, it is far easier to model traffic in a large road network as a flow in a system of pipes than to simulate each vehicle individually.

Helbing’s model is able to predict the areas of, and transitions between, free and congested traffic very efficiently. It is helping police in Germany to know where and when to introduce temporary speed limits in response to early signs of congestion.

Conclusions

We have come a long way from the quiet spinning of a radiometer spindle in a near-vacuum.

The radiometer gave scientists their first inkling that the physics of non-equilibrium or rarefied flows is different to that of everyday flows. Through the Knudsen number, I have shown that high-altitude, high-speed aerodynamics has much in common with flows in small engineering systems. And that led me finally to identify non-equilibrium behaviour in granular and traffic flows too.

In fact, non-equilibrium flows occur widely in nature as well as technologies. Supernovas are non-equilibrium astrophysical flows: the exploding star blasts out material in every direction, and shock waves feature very prominently in the expanding cloud of gases.

In my description of non-equilibrium flows I concentrated on the flow of gases because they are, at the moment, the best understood. But non-equilibrium liquid flows are a virtually untouched area for fluid dynamicists and engineers, which makes them ripe for investigation in the future.

Theoretical physics has a way of becoming practical engineering after a couple of decades, or even fewer. But it was not until the rocket programmes of the 1940s and 50s that the physics Maxwell developed to understand the radiometer in the 1870s started to become important for engineers. Increasingly now the designs of a range of new technologies need to account for this “molecularity”, or “granularity”, of fluids. In fact, this presents engineers with strange new opportunities, like tiny pumps that have no moving parts, or designs for aircraft and engines to fly at almost unimaginable speeds.

We are just at the start of a new engineering science that represents an unexpected triumph for 19th century physics in 21st century engineering. The development of exciting future technologies and processes depends crucially on engineers becoming used to unusual physics!

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