Measuring in a wall of air

Researchers at TU Delft's aerodynamics laboratory are developing a unique method for visualising fast airflows. The research, led by Professor Dr Fulvio Scarano, received a welcome boost this year in the form of a European Research Council grant and a professorship. The research project aims to help create quieter aircraft and safer space shuttles.

Jos Wassink

It was twenty years ago that Joris Ivens completed 'A Tale of the Wind'. In what was to be his last epic, the old master of cinema set himself the impossible task of capturing the wind on film. The result was a whirlwind of associations and memories from a rich life, in which the veteran film maker was propelled by – here it comes – the wind. "The wind sees everything," Ivens explained, "it is the grand force that moves mankind along."

Although today's researchers at the aerodynamics laboratory have the same goal, to capture the wind on film, their approach to the problem is rather more pragmatic and focused, and the results are likely to be somewhat less poetic.

When the experiment is about to start in the wind tunnel hall of the *Hypersonic Test Facility Delft* (HTFD), most of those present are wearing ear protection to protect them from the engine noise of the compressors and the vacuum pump. The equipment stretches the length of the hall, at the end of which sits the faded green vacuum tank, in front of which is the measuring section with a porthole through which two cameras are pointing. Inside is a scale

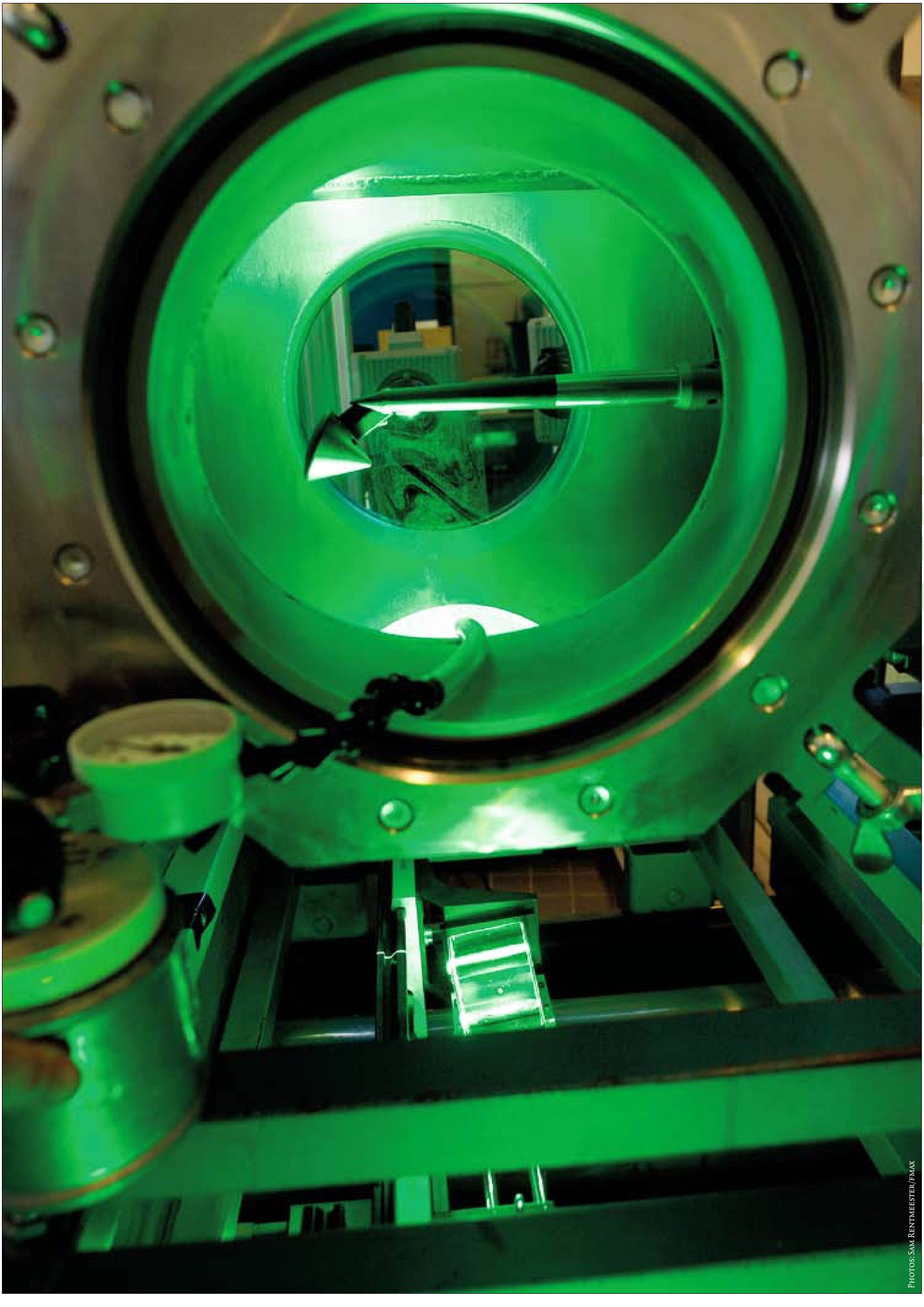
A bang like cannon fire reverberates through the hall

model of a space capsule that is smaller than a sparrow. The whole structure has been screened off as much as possible to contain the literally blinding green light of the one hundred kilowatt laser within. The researchers wear special goggles that filter out the laser light. Once a vacuum has been created at one end of the equipment, with eight hundred degrees Celcius air at a hundred times atmospheric pressure pushing against the other side of the valve in the Ludwieg tube, everything is ready for the test. The laser light is switched on, the cameras start to run at a thousand frames per second, and someone gives the go-ahead. Then a bang like cannon fire reverberates through the hall. In slightly over one-tenth of a second all the air has rushed from the high-pressure chamber into the vacuum tank, passing the test object at speeds of up to a thousand metres per second – or as fast as a bullet in flight. Converted to the scale of the model in the wind tunnel, this corresponds to six to eleven times the speed of sound (Mach 6 to Mach 11), which is enough to simulate a space capsule during re-entry at an altitude of sixty to seventy kilometres. A returning space shuttle initially reaches Mach 24.

Heat

"During re-entry a spacecraft has enormous kinetic and potential energy levels," says Professor Dr Fulvio Scarano. In March of this year, Scarano was appointed professor of aerodynamics at the Faculty of Aerospace Engineering, specialising in experimental aerodynamics. "Just imagine driving a truck at seven kilometres per second and having to descend a one hundred kilometre high mountain," Scarano says. "There's no chance your brakes would survive that. To a space ship coming down through the atmosphere, the air feels like a brick wall." The heat rises to thousands of degrees, causing the gas molecules to disintegrate and form a plasma that attacks the skin of the spacecraft. The heat, like the pressure, is a serious challenge facing spacecraft engineers. This is the type of problem being investigated with the help of the hypersonic wind tunnel.

"We didn't pick the altitude of sixty to seventy kilometres at random," aerodynamicist Ir. Ferry Schrijer adds. "It's the height at which the airflow, which starts as a laminar flow along the surface, ▸▸



|Back|GROUND

Photos: Sam Rentmeester/fmax

Ir. Ferry Schrijer: "The airflow becomes unstable at a height of between sixty to seventy kilometres"

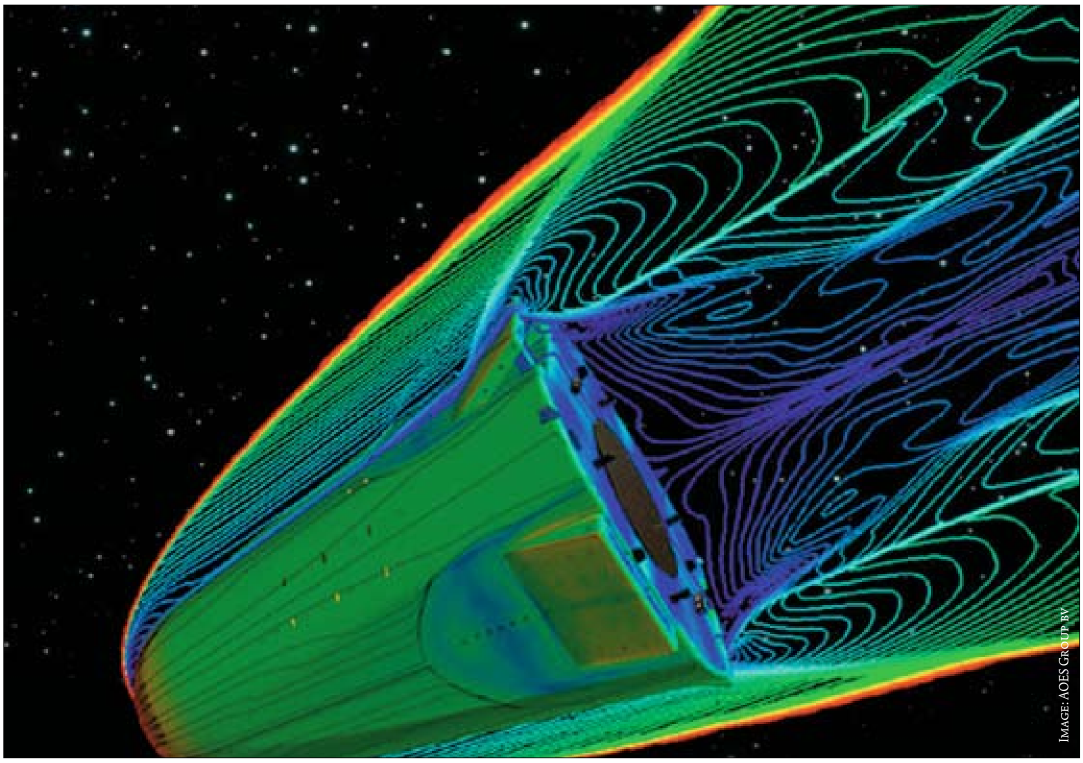
begins to become unstable, so that the least disturbance will transform it into a turbulent flow that detaches itself from the surface. The result is a much more pronounced mixing of air, tripling the amount of heat transferred to the space capsule."
In the hypersonic wind tunnel, Schrijer and his colleagues are investigating the extreme airflows around models of space capsules in order to gain more insight into where the heat is most likely to build up, and how the shape of the capsule affects this. Traditionally, this type of research uses solid steel models featuring dozens of ducts and tubes acting as pressure probes. Such models are a real challenge for the model workshop, as well as a source of pride to the lab, but they are also difficult to make and therefore expensive. A new imaging technique renders the steel models superfluous, however, as it is now possible to use solid plastic scale models.

Filming air

The method used by researchers to visualise airflows is called *particle image velocimetry* (PIV) and uses minute, white titanium dioxide globules (half a micrometre in size) that are mixed with the airflow. Titanium oxide, TiO_2, is a whitener, best-known for its use in toothpaste and primer. The globules, about ten of them to each cubic millimetre of air, are illuminated by the laser using two ultra-short (two hundred nanoseconds) flashes separated by a pause of one microsecond. A rough PIV image can be recognised by its pattern of dot pairs about a millimetre apart. A computer program converts the distance between the dots of each pair into a local flow velocity and a flow pattern for the object as a whole. This reveals where laminar flow breaks up into turbulent flow, and how a shock wave progresses along the model.
The use of two cameras rather than one also makes it possible to measure the velocity across the airflow in the direction of the cameras. The stereo PIV tests on an angle beam in the wind tunnel show that the velocity in the observation direction is considerable in turbulent regions. This means that a 3-D image of the flow was required, in particular in the case of a realistically formed model of a capsule.
In a proposal submitted in 2005, Scarano wrote: 'Flow turbulence is intrinsically three-dimensional and its full description requires the application of measurements able to capture instantaneously its three-dimensional structure, the complete stress tensor and the vorticity vector.' In the article, which he wrote together with Dr Ir. Gerrit Elsinga, Dr Bernd Wieneke, and Dr Ir. Bas van Oudheusden, Scarano lays the foundations for a PIV system capable of creating a three-dimensional image of the airflow in a volume the size of a mobile phone. The system requires more cameras, at least three, and for practical purposes often four or five. Each of the cameras records images of the titanium globules illuminated by the laser pulses. This results in two sets of camera images separated by a microsecond. A computer algorithm converts the camera images into a three-dimensional distribution of the

> *'For the first time we can actually see how complicated the air turbulences are that cause a flag to flap and flutter in the wind'*

illuminated particles, similar to the way a hospital scanner constructs a three-dimensional view of a human body using a large number of sectional images. The process, known as tomographic reconstruction ('tomography' meaning 'writing in sections'), results in a set of three-dimensional particle distributions with a one-microsecond interval. These can be used to reconstruct the flow pattern in three dimensions. For practical purposes the researchers use the average value of at least thirty images for a single reconstruction in order to be able to distinguish patterns from random turbulence. The first images to be recorded using this process exposed the vortices behind a cylinder. Scarano shows them on his laptop computer: "You can actually see the airflows!" he exclaims. "This is a completely new field of research. For the first time we can actually see how complicated the air turbulences are that cause a flag to flap and flutter in the wind."
To develop this technique, Scarano recently received funding to the tune of 1.5 million euros from the European Research Council (ERC), in the form of



An impression of the airflows around the experimental European space capsule EXPERT. The shockwaves against the nose and the rear flaps are clearly illustrated.

a Starting Independent Researcher Grant. "This support gives me ample autonomy to lead the research and appoint doctoral students," says Scarano, who also received his professorship in late March. "This degree of freedom is very important to me, because some countries, including my native Italy, will not give a young researcher the opportunity to lead a research project and decide about expenses."

In his application to the ERC, Scarano emphasised the importance of knowledge about air turbulence to create quieter and more economic aircraft. He gesticulates to show how the air flows along a wing surface, and how turbulence is created in the process. The turbulence induces the vibrations we hear as hiss, noise, or rumble. Knowing how exactly the air flows will help contribute to the construction of quieter aircraft and silent helicopter rotors. However, before we can reach that point, a lot of laboratory work will first have to be done. Calculating the speed of each of the approximately hundred thousand dots in the research cavity currently takes an 8-processor computer no less than three weeks. Together with two post-doc researchers and a doctoral student, Scarano expects to be busy until 2012 accelerating the processing of the video images. He thinks that smart algorithms running on larger computers can speed up the calculations 10,000 times. In addition, Scarano intends to increase the size of the available research cavity, which is currently only twenty cubic centimetres or approximately the size of a mobile phone. This will require an even more powerful laser.

As a specialist field for TU Delft, Scarano sees unique opportunities in the application of three-dimensional PIV in hypersonic conditions. "As far as I know nobody else is doing this yet," he says. "Certainly not in Europe." The European research programme, EXPERT (European eXPErimental Re-entry Testbed), which focuses on exploratory research into the feasibility of a re-usable European spacecraft, is in dire need of just such a test facility, according to the TU Delft researchers. At a later stage, Russian Volna rockets (left over from the Cold War) will carry research capsules outside the atmosphere, from where they will re-enter the atmosphere at speeds of five, six, even seven kilometres per second. A Perspex model of the EXPERT capsule is already ready and waiting to go at the Delft lab.

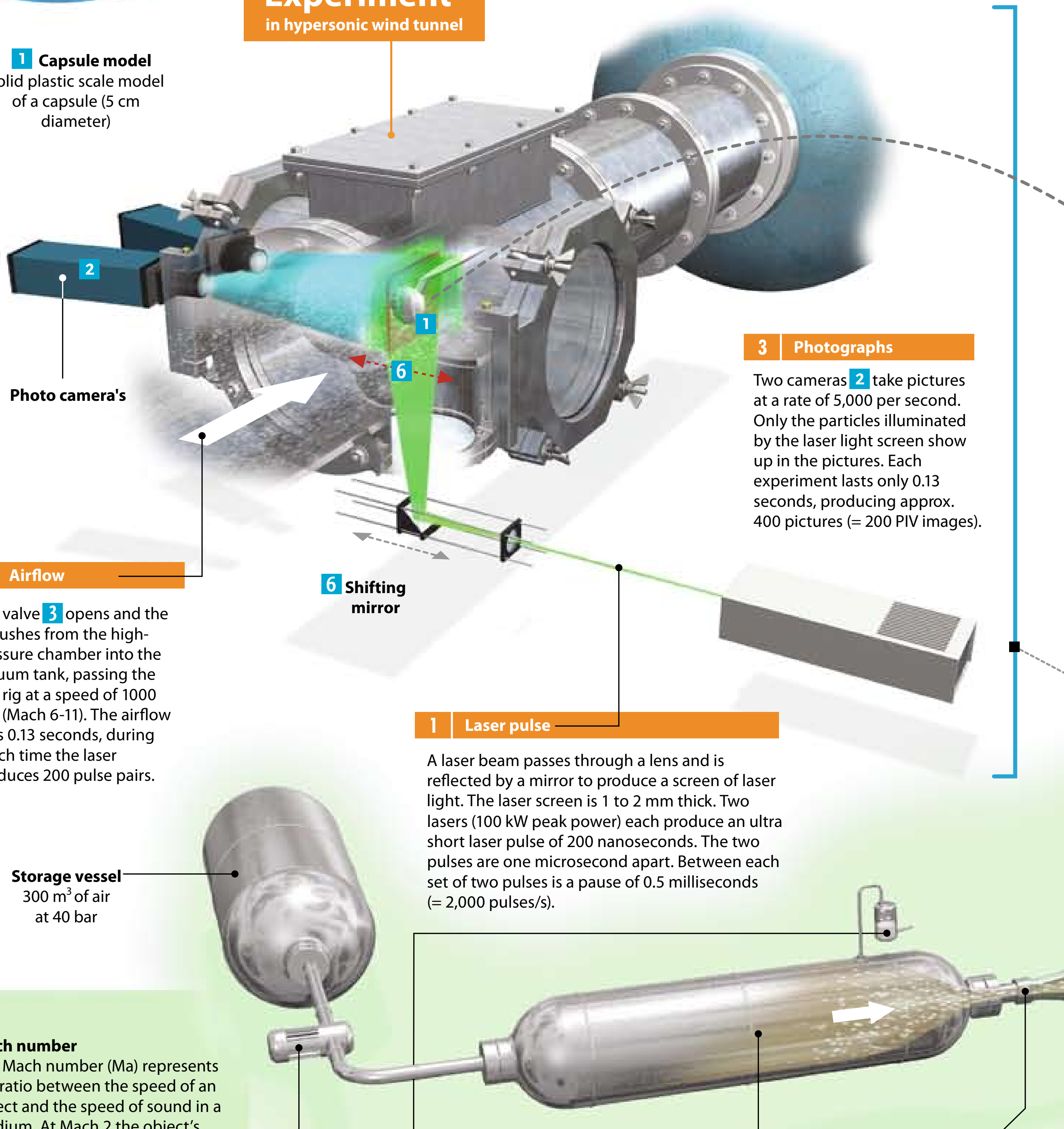
Prof.dr Fulvio Scarano: "You can actually see the airflows!"

[Back]GROUND

Orion space capsule during re-entry
The velocity of a satellite in orbit around the earth is 7.5 km/s. A capsule returning from space drops back into the atmosphere at the same speed of 27,000 km/h (Mach 25). During re-entry a capsule needs to provide as much resistance as possible while generating as little heat as possible in order to reduce its speed without burning up. Friction from the air heats up the surface of the capsule to very high temperatures, several thousand degrees Celsius.

Orion capsule
NASA is working on a new capsule for missions to the Moon and Mars. The Orion capsule (5.5 m diameter) is to replace the Space Shuttle in 2014. Advanced insight into the airflow around the Orion is to result in an improved capsule design.

Experiment
in hypersonic wind tunnel



1 Capsule model
Solid plastic scale model of a capsule (5 cm diameter)

Photo camera's

6 Shifting mirror

3 Photographs

Two cameras 2 take pictures at a rate of 5,000 per second. Only the particles illuminated by the laser light screen show up in the pictures. Each experiment lasts only 0.13 seconds, producing approx. 400 pictures (= 200 PIV images).

2 Airflow

The valve 3 opens and the air rushes from the high-pressure chamber into the vacuum tank, passing the test rig at a speed of 1000 m/s (Mach 6-11). The airflow lasts 0.13 seconds, during which time the laser produces 200 pulse pairs.

1 Laser pulse

A laser beam passes through a lens and is reflected by a mirror to produce a screen of laser light. The laser screen is 1 to 2 mm thick. Two lasers (100 kW peak power) each produce an ultra short laser pulse of 200 nanoseconds. The two pulses are one microsecond apart. Between each set of two pulses is a pause of 0.5 milliseconds (= 2,000 pulses/s).

Storage vessel
300 m^3 of air
at 40 bar

Compressor

Reservoir containing white particles
White titanium dioxide particles (0.5 micrometres across) are mixed with air (approx. 10 particles per mm^3 of air) and injected into the high-pressure chamber.

High-pressure air chamber
100 bar, 500°C

Valve
3

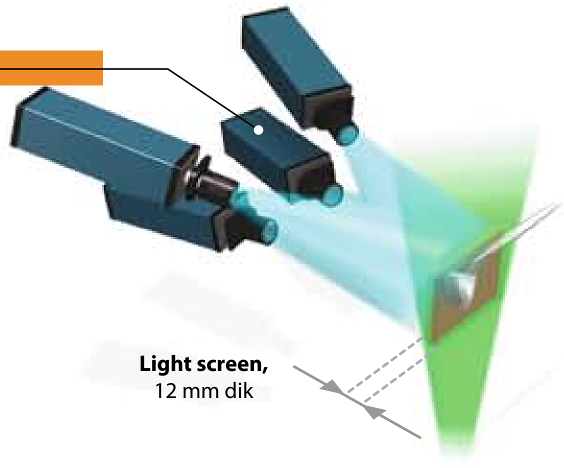
Mach number
The Mach number (Ma) represents the ratio between the speed of an object and the speed of sound in a medium. At Mach 2 the object's speed is twice the speed of sound. At sea level the speed of sound in air is 1,224 km/h, while at an altitude of 11 km it is 1,062 km/h. Speeds are classified as subsonic (Ma < 1), supersonic (Ma >1), or hypersonic (Ma > 5).

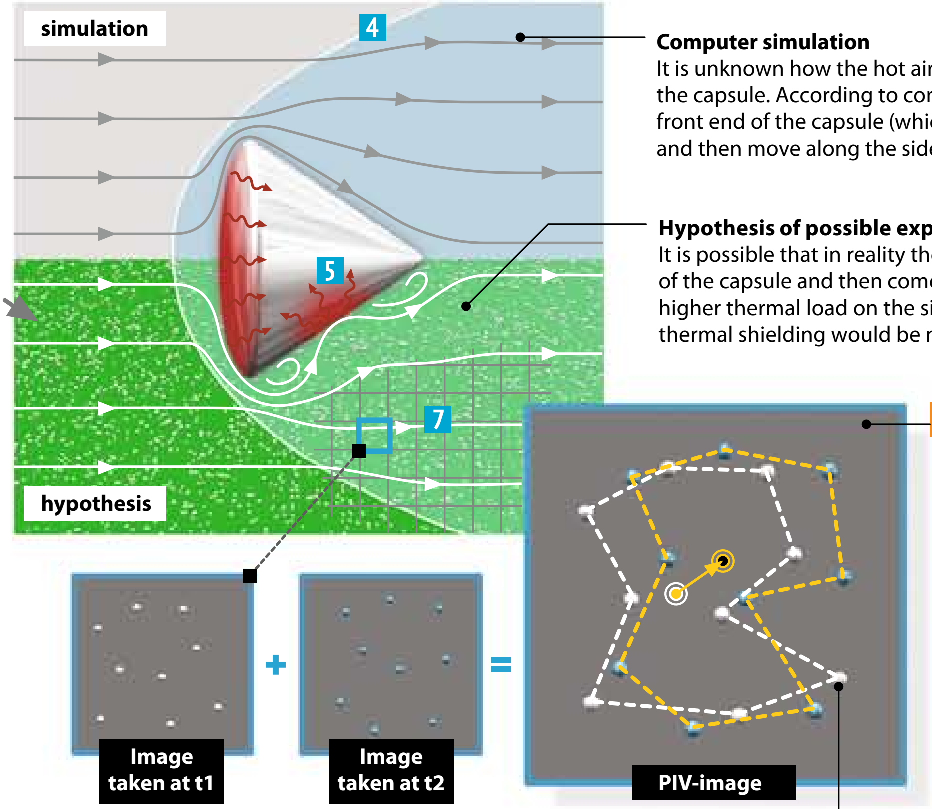
Shock wave 4

When an object exceeds the speed of sound, a large pressure differential is created just in front of the object. This pressure differential expands in all directions, but as the object is moving forward, a cone-shaped shock wave is produced. Behind this shock wave the flow speed decreases, and the temperature and pressure increase. At very high Mach numbers the temperature increases to such a level that air molecules degrade into separate atomic nuclei, creating a cloud of charged particles (plasma).

5 Three-dimensional PIV system

By using at least three cameras the depth coordinates of the white particles can be distinguished, enabling a 3-D flow pattern to be visualised in a three-dimensional volume (rather than in just a flat plane). The light screen of the laser has a thickness of approx. 12 mm.





Computer simulation

It is unknown how the hot air flows along the sides and rear end of the capsule. According to computer models the airflow hits the front end of the capsule (which as a result becomes extremely hot) and then move along the sides of the capsule.

Hypothesis of possible experimental result

It is possible that in reality the hot airflow becomes detached from the side of the capsule and then comes back into contact with it 5. This would put a higher thermal load on the side wall than originally envisaged, so additional thermal shielding would be needed in those spots to protect the capsule.

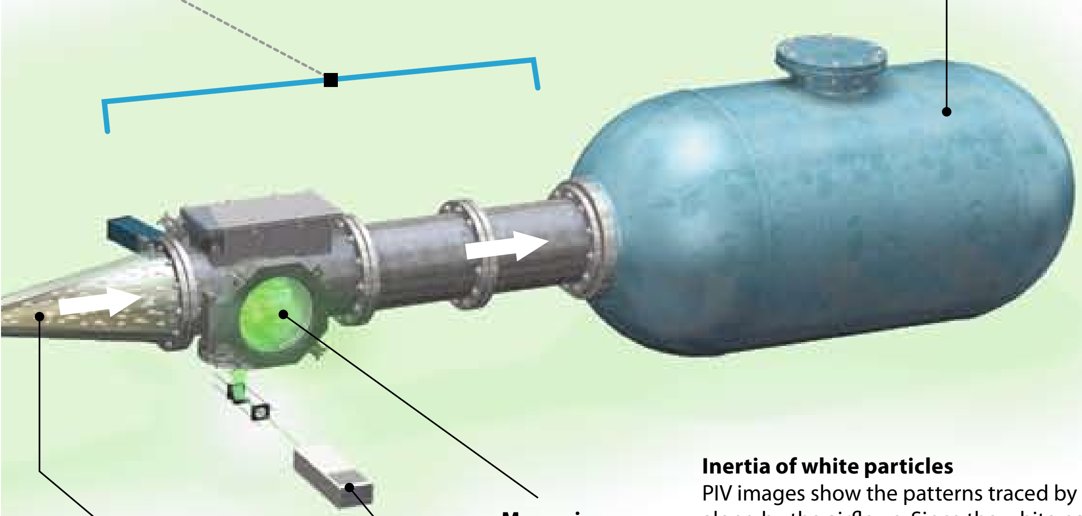
4 Particle Image Velocimetry (PIV)

Two images taken by the two successive laser pulses together form a PIV image. A computer converts the two images into a 3-D distribution of the white particles and then uses their shift in position to calculate the velocity vectors. The maximum shift is about 1 mm (1000 m/s × 1 microsecond). By moving the laser plane 6 a series of velocity profiles are produced which together form a 3-D image of the flow pattern of the air rushing past the model. By using two cameras instead of a single camera the velocity at right angles to the airflow can also be measured.

Smart algorithms

The computer has to determine how a dot moves. This is not so easy because the dots all look alike. The computer divides each image (1024 × 1024 pixels) into a grid 7 and searches for unique patterns of about 10 dots that undergo a shift and a deformation between the two images. The grid size is continuously reduced throughout the process. The smallest grid window measures 21 × 21 pixels, corresponding to 1 × 1 mm. A PIV image contains about 100,000 particles. At 10 particles per window, 10,000 velocity vectors are calculated for each measurement. If smarter image recognition and calculation algorithms can be devised, the velocity calculations could be speeded up 10,000 times.

Test set-up
hypersonic wind tunnel



Laval tube

The convergent-divergent tube (Laval tube) ensures that the airflow is accelerated to hypersonic speeds.

Inertia of white particles

PIV images show the patterns traced by the white particles as they are borne along by the airflows. Since the white particles have mass, they are slower to respond than the airflow. In a way the particles go wide at the bends, so their tracks are smoother than the actual airflow. In order better to visualise the airflows, new, lighter particles must be developed that behave more like air molecules.

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