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Insect inspiration

Insights gained from studying the remarkable defence mechanism of the bombardier beetle are helping to improve the spray technology used in drug-delivery devices, car engines and fire extinguishers, explain **Andy McIntosh** and **Novid Beheshti**

The innocuous looking bombardier beetle is one of the most remarkable creatures around. This tiny insect is endowed with a defence mechanism that would be the envy of any comic-strip superhero – it can fight off any spider, frog, ant or bird that comes too close by blasting the attacker with a powerful jet of hot, toxic fluid. Furthermore, the beetle can aim its weapon in any direction (even over its head) with pinpoint accuracy, and can reach distances of up to 20 cm with its spray.

The bombardier beetle, which is rare in Europe but common in Africa, Asia and warmer parts of the US, forms its noxious spray by reacting small amounts of hydroquinone with hydrogen peroxide in the presence of the catalysts catalase and peroxidase in a pair of combustion chambers in its abdomen. This exothermic reaction produces a toxic solution of benzoquinone, other chemicals and water, and heats the solution (which is mainly water) to above its boiling point. Although some details of the chemical process have been known for years, until recently scientists did not understand how the beetle managed to eject this solution so powerfully. We now have the answer to this puzzle, and that knowledge could revolutionize industrial spray technology.

On the pulse

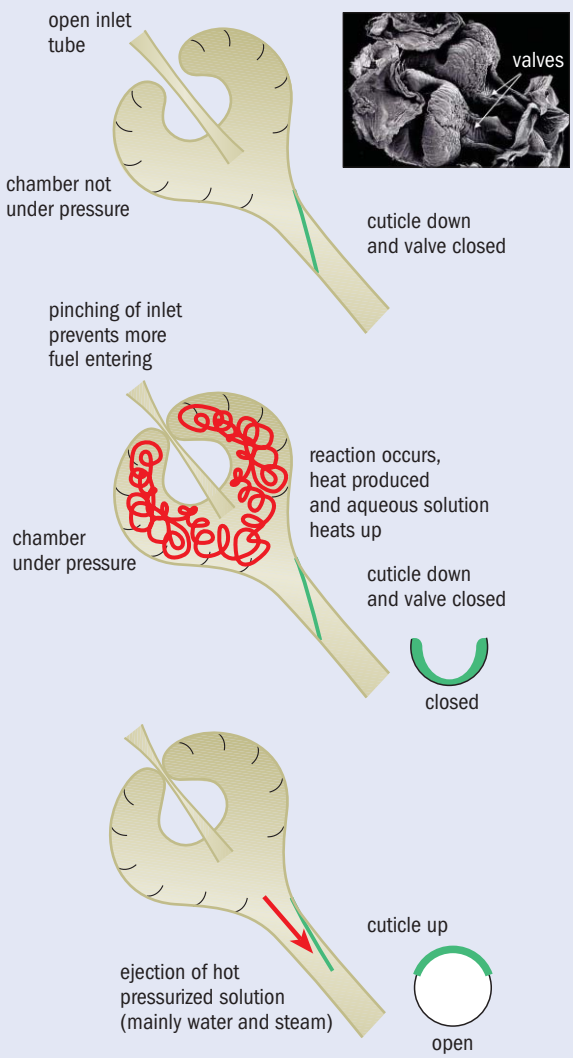
The bombardier beetle began to give up its secrets in the 1980s and 1990s when Tom Eisner, a chemical ecologist at Cornell University in the US, used a high-speed camera to film how the insect sprays. The resulting award-winning BBC film *Secret Weapons* (released in 1984) and images (1999 *Proc. Natl Acad. Sci. USA* **96** 9705) show that the noxious mixture is not ejected continuously but is in fact fired out in a high-frequency (400–500 Hz) series of explosions. This is similar to pulse combustion, whereby a limited amount of fuel and air ignite in a combustion chamber and cause the pressure inside the chamber to rise due to the heat produced as the mixture reacts. Once the pressure is high enough, the pressurized gases are released and can be used, for example, to propel a rocket. More fuel and air are then allowed into the chamber and the process repeats itself.

Something similar takes place inside the bombardier beetle: the reactants fill the chamber, react and are ejected, before more reactants enter and the cycle is repeated. When our group at Leeds University heard about Eisner's work, we were stunned by this example of true combustion in nature. We wanted to figure out how the beetle achieved its amazing feat and began working, initially with Eisner, to investigate the physics of the beetle's combustion chamber.

We first realized how the beetle's ejection system actually works while looking at one of the dissections Eisner had made of the insect's combustion chamber. Although we still do not fully understand how the beetle makes and transports its fuel of hydroquinone and hydrogen peroxide, the dissection clearly shows that once these two reagents have filled the chamber –

Andy McIntosh is at the Energy and Resources Research Institute in the School of Process, Environmental and Materials Engineering at Leeds University in the UK and **Novid Beheshti** works for Swedish Biomimetics 3000 ® Ltd, e-mail a.c.mcintosh@leeds.ac.uk

1 Beetle combustion



The bombardier beetle achieves its powerful ejection through a process similar to pulse combustion. When the combustion chamber is empty (top) and at atmospheric pressure, the inlet tube is open and the exit tube is closed by a membrane that sticks to the bottom part of the tube. This allows the reactants to enter the chamber. Insert shows the twin combustion chambers and nozzles from a bombardier beetle dissected by Tom Eisner of Cornell University. Once the chamber is full (middle) the extremities of the chamber itself, which is shaped like a boxing glove, pinch the inlet tube shut. As the chemical reaction in the chamber progresses, heat is generated and the pressure in the chamber increases until the membrane is forced to come unstuck from the bottom of the exit tube (bottom). The hot pressurized fluid is then ejected, the pressure in the chamber drops and the process is repeated until all of the reactants have been exhausted.

The beetle's spray process is governed by "flash evaporation", which occurs whenever pressurized water is heated above 100 °C and then the pressure is suddenly reduced

which has a volume of about 0.1 mm^3 – then the extremities of the chamber itself pinch the inlet tubes shut. At the other end of the chamber is an exit tube, through which the hot fluid is eventually ejected. We at first presumed that this tube had been sliced, and that we were therefore seeing the inside of the exit tube. Eisner, however, assured us that this was not the case, and that the entire chamber was being seen from an external perspective (inset to figure 1).

Once this was established, it became evident (from the photograph) that the exit tube has a membrane keeping the tube closed. However, when the pressure inside the chamber rises above a certain threshold, the membrane is forced open, thus allowing the hot fluid to be ejected. But once the pressure in the chamber has dropped, the membrane shuts again. The overall ejection mechanism then became clear: the low pressure following such an explosion enables the inlet valve to open, thereby allowing more fuel to enter the chamber, before the pressure rises again as a result of further combustion. The cycle is then repeated (figure 1).

These observations revealed that the process is governed by "flash evaporation" – which occurs whenever pressurized water is heated to above 100 °C and then the pressure is suddenly reduced. Lowering the pressure allows the hot water to evaporate, which it does extremely rapidly in the form of an explosion of steam. In the beetle, the aqueous solution in the chamber is brought to boiling point by the heat of the reaction, but with the exit valve closed it cannot boil. So when the trigger pressure is reached and the exit valve opens, the fluid boils under the sudden decompression, thus pushing the hot fluid and steam out rapidly.

A model system

Having deduced the process behind the beetle's remarkable spray system, the next step was to estimate the trigger pressure and other key characteristics, such as the temperature of the liquid and the diameter of the exit nozzle. In 2004 we therefore began to model the combustion chamber using computational fluid dynamics (CFD). These investigations were supported by the Engineering and Physical Sciences Research Council (see www.personal.leeds.ac.uk/~fue6acm). Our model used a small cylindrical chamber measuring 0.6 mm in diameter and 0.3 mm in length, which is about the same size and volume (0.1 mm^3) as real beetle chambers. The cylinder was then joined to an exit nozzle 0.1 mm in length that could have any diameter in the range 0.1–0.5 mm.

The CFD simulations began with the water in the main chamber under pressure, and then the separation between the chamber and the exit nozzle was removed as an initial condition. We ran the simulation at a range of trigger pressures (1.15, 1.1 and 1.05×10^5 Pa), each of which has an associated "saturation temperature" – i.e. after the valve is opened, the liquid in the chamber is assumed to be at the saturation temperature for the particular trigger pressure. For 1.1×10^5 Pa, for example, this is approximately 105 °C. We also modelled a chamber without an exit valve, where the fluid is allowed to boil as soon as it is hot enough, and compared the results from the two scenarios.

The important finding was that the flash-evaporation process is much more powerful than direct boiling without a pressure-release valve. This is because the increased pressure exerted on the fluid significantly increases the ejection velocity. This reduces the time taken to squirt all the fluid out from over 10 ms without the pressure valve, to as little as 1 ms with it in place. The CFD model also managed to closely reproduce the velocities and timescales observed with real beetles for a trigger pressure of 1.1×10^5 Pa and a nozzle diameter of 0.2 mm. (For more on the CFD work see 2007 *Bioinspir. Biomim.* **2** 57.)

Inspiring industry

Our CFD simulations suggested that the technology based on the spray mechanism of the bombardier beetle was worth investigating, since it would allow the size and temperature of the droplets to be closely controlled. The ability to control spray droplets in this way is highly desirable for several industrial applications, including fire-suppression systems, but is impossible to achieve with existing technology. This potential for commercialization led to keen interest from Swedish Biomimetics 3000 ® Ltd, a philanthropic organization that funds translational research into biomimetic concepts. It provided generous financial support that allowed us to build an experimental rig that successfully mimicked the physics of the beetle's combustion chamber and valve system (figure 2).

The catalytic chemistry of the beetle was not copied in these experiments – instead we heated water inside the chamber electrically – but even so, the results we obtained were excellent. For example, the throw ratio, which is the maximum distance the fluid can be fired divided by the length of the combustion chamber, was the same for both the beetle and the rig. The beetle's combustion chamber is less than 1 mm long and is able to throw to a distance of about 20 cm, while the experimental rig has a chamber length of approximately 2 cm and can fire spray to an impressive 4 m.

Initially we explored single blasts of spray and then, as we gained more confidence, we moved on to experiments with repeated blasts, which required a computerized control system for opening and closing the valves. We found that a wide range of droplet sizes and spray temperatures could be achieved by altering the settings of the rig. The minimum droplet diameter is 0.002 mm, while the largest droplet sizes that can be achieved are about 0.1 mm. The temperature of the spray varies from a warm 45 °C at a distance of 20 cm from the nozzle for large droplets, to room temperature for the smallest droplets. The frequency of ejection can be varied from 1–20 Hz and the velocity of ejection is typically in the range 5–30 m s^{-1}.

Environmental advantages

These qualities make the technology, called μMist, ideal for any application in which the properties of the spray are critical. This is particularly the case for drug-delivery devices such as nebulizers and inhalers, fuel-injection systems in cars and other vehicles, as well as fire extinguishers. Nebulizers administer medication to patients such as asthmatics in the form of a fine liquid mist that can be easily inhaled, but many existing devices use mechanical springs, which are not always reliable. Current fuel-injection technology atomizes fuel by forcing it through a sieve at very high pressure (above 1×10^8 Pa), but producing such high pressures consumes a lot of energy and is therefore expensive. The μMist system, on the other hand, enables the fuel to be atomized using much lower pressures that require less energy to produce. As for fire control, μMist excels because one can produce a system for a fine mist or a separate system for large droplets. A fine mist has a smothering action and can also quickly reduce the temperature of a fire, thus making it ideal for the automatic fire-suppression systems found in many vehicles and buildings; while large droplets are more suited to extinguishing certain types of fire.

What is perhaps of most significance for all of these applications, however, is the reduction in the environmental impact that μMist offers over current high-performance mist technologies. This is particularly the case with pharmaceutical sprays and certain types of fire extinguisher in which polluting gases like propane – which combine with oxygen in the atmosphere to produce carbon dioxide – are used as propellants. The μMist spray system for these applications would not only be entirely water based, it would also require much less power than conventional systems to produce the same spray quality.

Car engines are also damaging to the environment because of the carbon dioxide and other emissions that they produce. A μMist-based fuel-injection system would produce smaller droplets of fuel than can be achieved currently. These droplets would burn more efficiently due to their greater surface area, resulting in improved engine performance, lower fuel consumption and therefore a lower level of harmful emissions.

Swedish Biomimetics 3000 ® Ltd has taken out the licence on the μMist spray system and is currently in the process of bringing the technology to market. At present the development of the nebulizer and fuel-injection systems are attracting interest from a number of key pharmaceutical and engine manufacturers, and we have also received expressions of interest in μMist's fire-fighting capability. We are currently at the pre-prototype stage, with a generic rig that demonstrates the major principle of the technology. It is possible that μMist-based nebulizers, fuel injectors and fire extinguishers could be on the market in 5–10 years' time.

The bombardier beetle itself will, therefore, not go unrewarded. As well as making life easier for humans, the technology based on the amazing natural mechanism that keeps this unusual insect safe from predators could soon be helping to improve fire safety and preserve the environment. ■

2 Mimicking nature

The experimental rig inspired by the bombardier beetle's combustion chamber. It is 2 cm in length and can fire liquid up to distances of 4 m. It can eject very fine mist with droplets 2 μm in diameter as well as much larger droplets 100 μm across.