A novel spray system inspired by the bombardier beetle

N. Beheshti[1] & A. C. McIntosh[2]
[1]*Swedish Biomimetics 3000® Ltd., Sweden*
[2]*Energy and Resources Research Institute, University of Leeds, Leeds LS2 9JT, UK*

Abstract

In this paper we describe an experimental rig which has been built as a result of inspiration from the bombardier beetle. This beetle is such that it has the capacity to fire a spray of hot water, steam and noxious chemicals from a nozzle at the rear end of its abdomen in any direction it wishes (even over its head). An example of controlled combustion in nature, it has led to first to simulations using CFD (computational fluid dynamics) of the spray system and the testing of an experimental rig replicating the physical process of the beetle system. The experiments verified the theories developed through the CFD simulations and produced excellent results that have important applications in different industries dealing with sprays such as drug delivery inhalers, fuel injectors and fire-fighting water mists. This novel spray technology has the trademark µMist™.
Keywords: sprays, mists, Bombardier beetles, biomimetics, flash evaporation, pharmaceutical, fire extinguishers, fuel injectors.

1 Introduction

Bombardier beetles have a very remarkable defence mechanism. They spray a hot irritant aqueous solution onto their predators. This is done by an ingenious mechanism such that an aqueous solution of quinones is heated up to above its boiling point (by means of exothermic catalytic chemical reactions) in a combustion chamber which remarkably is less than 1mm in size. There are two such chambers each of which ejects the noxious mixture in the form of a steamy spray from one of the twin nozzles at its posterior. Among these beetles, the Brachina branch, and in particular some variants such as the African *Stenaptinus*

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insignis (see figure 1) eject their defensive spray in pulsations. Each ejection consists of 2 to 20 pulses at very high frequencies of about 500Hz [1]. However, in a comparison made by Eisner et al. [2] those variants with non-pulsating sprays, eject their spray with very low velocities (~ 4m/s) compared to pulsating spray variants (~ 20m/s). Consequently, the effective range of the spray is also longer in beetles with pulsating sprays (~ 20cm).

Figure 1: African bombardier beetle.

Earlier studies by Dean et al. [3] revealed that there are no mechanical vibrations in the exhaust nozzle that are causing the pulsations. So, it was suggested that the source of the pulsations is possibly only in the periodic depletion and replenishment of the chamber followed by ignition of the reactants. It was also thought that the driving force (propellant) of the spray is simply the rapid boiling of water caused by the fast chemistry. Some work by the Leeds group [4] considered the shape of the chamber and whether that was significant, and came to the conclusion that this was not the case. The difficulty with any of these theories is that the high frequency of pulsation is not possible by such means. The theoretical study based on CFD (computational fluid dynamics) simulations of the bombardier beetle combustion chamber [4] showed that high velocities and fast ejection times as observed in the beetle video footage [5] are not achievable by simply assuming a rapid heating of the water in the chamber. It was found that such a means produced low ejection velocities of a maximum of $4ms^{-1}$ (compared to $\sim 20ms^{-1}$ observed from the beetle) and rather large ejection times of 15 to 25ms (compared to ~2ms observed from the beetle) based on these assumptions.

Essentially there was a need to re-examine the physics of these ejections. Discussions with Eisner and careful examination of the electron microscope graphs of the beetle combustion chamber, revealed the presence of a pressure-controlled outlet valve to the combustion chamber. This then led to very different assumptions being needed in the modelling. Beheshti and McIntosh [6,7] took a novel approach which proved decisively that the high speed ejection was due to the pressure relief valve. Based on the assumption of having the pressure relief valve at the chamber exit to the ejection nozzle, it was recognised that in order for the exit pressure-relief valve to control the phase change process, the water has to be initially heated up to above the boiling point while this process also raises the pressure to a set pressure (through thermal expansion and also generation of tiny bubbles) that suddenly releases the exit valve. Once the valve opens, flash evaporation and steam explosion takes place which rapidly pushes the water and quinones out of the chamber to the nozzle and a steamy spray emerges from the nozzle. What confirmed that this theory was indeed correct was that CFD simulations based on this approach of pressure-release valve induced flash evaporation, produced the *same* ejection velocity and ejection frequency as of the beetle spray (with a nozzle diameter of 200μm which is the nozzle diameter of the beetle, and release absolute pressure of 1.1 bar). These simulations results provided some evidence to support this theory. The CFD simulations were performed for a single ejection cycle assuming that subsequent repetitive ejections are identical.

The results showed that the presence of the exit pressure-release valve is crucial in producing higher ejection velocities and the much quicker discharge of the liquid content of the chamber (higher ejection mass flow rates) observed in the pulsating spray variants of bombardier beetles. As noted earlier, the notion of opening of the valve after the build up to a certain pressure, correlates well with the CFD evidence. It was found that with the beetle chamber at a temperature above the boiling point, of about 105°C induces a flash evaporation process which continues until the last bits of water in the chamber are vaporized and ejected. Throughout this process, the pressure in the chamber is maintained by the continuous rapid evaporation of water at the same initial set pressure that the valve had previously opened at. In cases with normal boiling – i.e. with an open exit and without the pressure controlled valve – the nozzle in that case is filled with very large volume fractions of water (because the heating process starts from the wall where catalysts come in contact with the reactants). Consequently only slow boiling happens near the exit under these conditions with the rest of the chamber still at about atmospheric temperature. Under this situation (open exit) the water near the exit (with high viscosity and density) slows down the ejection process (exit velocity ~ 4m/s). However when the pressure-release valve is present, it provides a short delay that enables the exothermic reaction to spread through the rest of the chamber and heat the whole of the water content to above 100°C and with the whole chamber above atmospheric pressure. This results in the flash evaporation as soon as the valve opens. Results from CFD simulations based on using the pressure-release valve and the consequent flash evaporation, show that the steam explosion pushes a two-phase mixture of water and steam into the nozzle. In this latter case, the key is that the nozzle wall is covered with a layer of steam during the whole ejection process, while very quickly (after only ~ 5% of the whole ejection time elapses) the nozzle becomes filled with much higher volume fractions (~ 90%) of steam. Thus the two-phase mixture of the hot water and steam is propelled out on a lubricating cushion of steam. The two-phase nature of the mixture also helps in producing higher velocities. This high steam content in the CFD results was what was also noticed in the video footage [5]. This could never be achieved by using slow boiling of water at atmospheric pressure. In that case only a very small volume fraction of steam is present in the nozzle. A combination of a slightly higher pressure in the chamber and a much higher volume fraction of steam (steam has more than 1000 times lower density than water and 10 times lower viscosity) in the nozzle, is the key to higher velocities and faster ejections observed in those variants of bombardier beetles with pulsating sprays. It can be concluded that this physical mechanism is what allows these beetles to pulsate their spray at such high frequencies of 500Hz and produce high velocities of up to 20m/s.

2 The biomimetic step

Two crucial points were noted from these simulations [6,7] with important biomimetic applications :

a) A hot spray of water and steam was generated with a large steam volume fraction of above 90% in the exhaust nozzle prior to ejection. This new approach of generating a cavitation explosion showed that it is possible to achieve small droplet sizes using this method. This could be very beneficial in spray applications where the liquid is atomized solely with a view to promoting its evaporation (through the increase of surface area by atomisation).
b) A second and most important benefit is that such a technique does not require a propellant for driving such a liquid out of its container. The only driving force required is the thermal energy applied to the liquid to eject it from the chamber. This was easily observed from the CFD simulations, as apart from a very small pressure build up of 100mbar in the chamber (which can be achieved through thermal expansion as a result of the heating process) the emerging spray requires no external forces to be exerted to the chamber to discharge all the liquid content of the chamber at average ejection velocities of around 12m/s. To achieve the same ejection velocities accompanied with atomisation using conventional spray systems through such a small orifice (200μm), a much higher pressure (of the order of 10bar) would be required with the use of a continuous flow pump.

To achieve a repeated spray, the analysis of the CFD simulations of the bombardier beetle ejection system showed that the following steps were needed :

1. heating of water (or any other liquid) under pressure in a closed chamber to above its boiling point
2. then releasing an exhaust valve when the pressure reaches a set value to let the flash evaporation and cavitation explosion take place
3. after the rest of the liquid in the chamber has ejected and pressure drops below another set value, close the exhaust valve
4. open another valve – refill valve – to refill the chamber with fresh water

5. close the refill valve
6. repeat the cycle from step 1

By this new method, one can atomise water (or any other liquid) into a spray instead of the traditional pressure or air-blast atomisation methods. The benefits here are immediate; in particular when the final objective of atomisation of the liquid is indeed its evaporation. One example of such applications is liquid fuel combustion in internal combustion engines where a liquid fuel (e.g. gasoline or diesel) spray is produced by very high injection pressures (above 1000 bar) and then vaporised and mixed with air in order to produce a combustible mixture which is subsequently ignited.

3 Scaled up beetle experimental rig

In order to verify this theory in practice, an experimental rig (figure 2) was designed and built based on the flash evaporation approach described in the previous section, where a system of solenoid valves controls the inlet and outlet conditions (6-step procedure above).

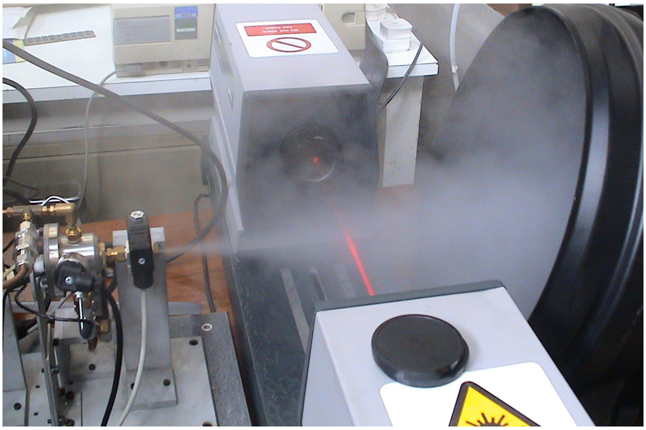

Figure 2: Spray emerging from the μMist™ rig and crossing a Malvern laser beam for droplet size measurements.

The rig consists of a small cylindrical stainless steel chamber of approximately 2–3cm in length and in internal diameter. In this work, chemical exothermic reactions are replaced by electrical heaters inserted into the chamber(it is of interest to point out that the method of heating in the beetle chamber is also of great interest – Aneshansley et al. [1] report that the heating is by catalytically controlled reactions involving hydrogen peroxide and hydroquinone. The method of catalysis is still the subject of ongoing study. It has not yet been discovered exactly how the catalysts operate, but it is believed that they are in solid crystalline form within the fibrous lining of the combustion chamber walls). There are inlet and exit (discharge) ports connected to the chamber to allow for spray ejection from it and the subsequent refilling. The solenoid valves then control the ejection and refilling ports.

It is important to monitor the temperature and pressure in the chamber, so sensors are mounted for this purpose in the chamber of the experimental rig, and their instantaneous values read to a PC monitor running monitoring software.

The first stage in the practical program was to experimentally and qualitatively validate the CFD simulations by reproducing the single ejections simulated by the earlier CFD research. Then single ejections agreed well with the CFD runs, so that the next stage was to simulate and validate the physical principles outlined above for repetitive spray ejections (as with bombardier beetles).

4 Results and discussion

Repetitive spray ejections were produced by the rig at frequencies of 0.5 to 20Hz with emerging velocities in the range of 5 to 35m/s and a very wide range of droplet sizes (1–500μm) at different operating conditions. Figure 3 is an example of these experimental runs.

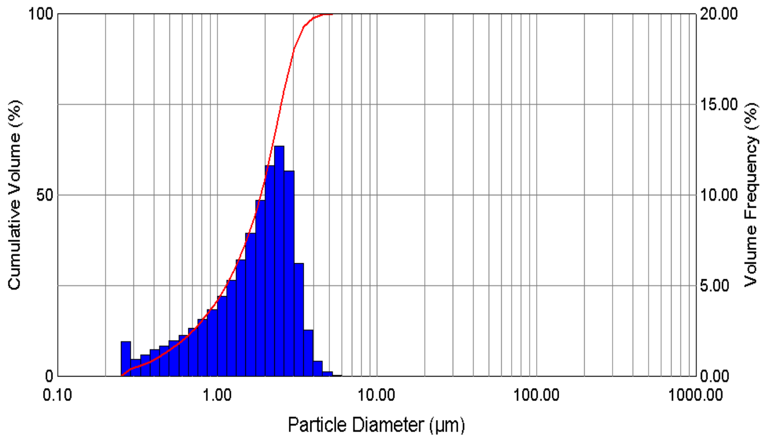

Figure 3: Droplet size distribution from the μMist® rig operating at its smallest size range. Ejection frequency in this case is 11Hz. Different indicator droplet sizes are: D_{v10} = 0.61 μm, D_{v50} = 1.87 μm, D_{v90} = 3.01 μm, D_{32} = 1.00 μm, D_{43} = 1.50 μm. Applications of this spray are drug delivery inhalers and fuel injectors.

Some of the most promising industrial applications of this spray technology are inhaled drug delivery devices, internal combustion engine fuel injectors and fire fighting water mist devices. These different and promising applications of this new spray system, led Swedish Biomimetics 3000® Ltd. to register the trade mark of μMist™ and to represent it commercially.

The spray characteristics of the pulsed water mist (frequencies of 5 to 20Hz) generated by this rig were measured. These measurements included time-averaged droplet size distributions at 18cm downstream of the exit nozzle, spray emerging velocity, spray temperature and spray mass flow rate. In this paper, only droplet size distribution – which is the most crucial spray characteristic – is reported for three typical cases. These cases are representative of suitable droplet sizes for 3 different industrial applications, namely: respiratory drug delivery inhalers, internal combustion engine fuel injectors and fire-fighting water mists.

One of the interesting features of this technology is that different droplet sizes can be produced at different operating conditions. These were measured using a laser diffraction technique using a Malvern Spraytec system.

In figure 3 a droplet size distribution of the µMist™ spray is given for a case ideal for medical inhaler applications. Only droplets of the size below 5.5µm travel deep enough into the respiratory system to deliver the medication into the lungs where it can be absorbed. Droplets larger than this threshold are deposited in the upper respiratory system without having any therapeutic effects. The same very fine droplet sizes of this case can be ideal for fuel injectors since fuel droplets have to evaporate very quickly (in a few milliseconds) in an engine to increase the combustion efficiency and reduce some of the pollutants such as un-burnt hydrocarbons, CO and soot. Current fuel injectors are only capable of atomising the fuel into droplets with a D_{v90} of approximately 25–50µm (this droplet size is on the basis that 90% of the droplets are less than the quoted value. Termed D_{V90}, this means that the D_{V50} (50%) level often quoted by manufacturers and the SMD (Sauter Mean Diameter) are smaller still).

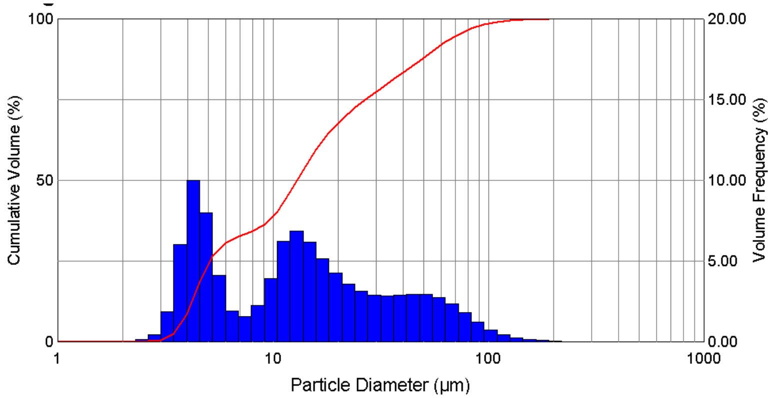

Figure 4: Droplet size distribution from the µMist® rig operating at a medium size range. Ejection frequency in this case is 20Hz. Different indicator droplet sizes are: D_{v10} = 4.1µm, D_{v50} = 12.9µm, D_{v90} = 54.8µm, D_{32} = 9.0 µm and D_{43} = 21.6µm.

For achieving larger droplets, the settings of the rig can be changed. For example, with different settings, an unusual distribution can be achieved where a rather equal share of very small (below 10µm) droplets, medium and large droplets are produced as is shown in figure 4.

With further changes to the rig settings, one can obtain very large droplets (~100µm) and a very small percentage of sub 10µm ones, as shown in figure 5. This combination is ideal for most fire-fighting applications using a water mist. This combination gives a double fire-fighting effect: Larger droplets cool down the fire source to below its reaction temperature, while the very small ones evaporate rapidly and move the oxygen away from the fire zone.

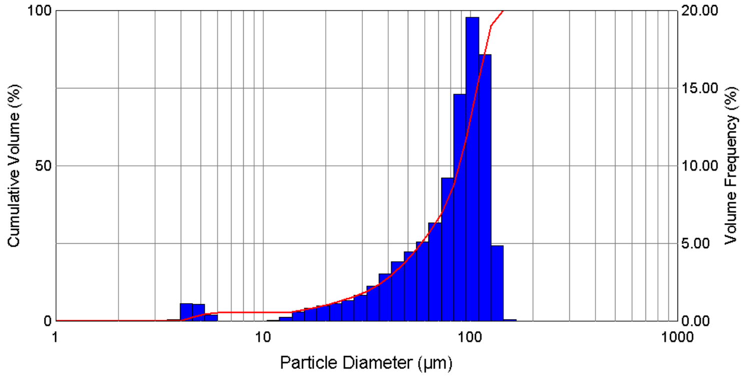

Figure 5: Droplet size distribution from the µMist® rig operating at a large size range. Ejection frequency in this case is 20Hz. Different indicator droplet sizes are: D_{v10} = 33.0µm, D_{v50} =88.0µm, D_{v90} = 121.0µm, D_{32} = 49.0 µm and D_{43} = 82.0µm. Applications of this spray is in fire-fighting water mists.

It was noteworthy that in the large droplet case such as in figure 5, the ejection distance can be as much as 4 metres. This from a chamber of the order of 2 cms in size, means that a throw ratio (ejection distance divided by the typical chamber size) of 200 was achieved. This is the same as the throw ratio for the beetle combustion chamber which with a chamber dimension of 1mm is able to send a blast to a distance of 20cms.

5 Conclusions

It has been shown that the repetitive spray of the Bombardier beetle is achieved by a combination of inlet and exhaust valves such that heating the fluid to above its natural boiling point but under pressure, leads to a fast ejection time due to a cavitation explosion involving as much as a 90% volume fraction of steam. This technique has now been thoroughly tested by an experimental rig which successfully mimics the beetle ejection system, and is able to produce sprays with a range of droplet sizes from 2µm – 100 µm

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