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The bombardier beetle and its use of a pressure relief valve system to deliver a periodic pulsed spray

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Abstract

In this paper the combustion chamber of the bombardier beetle is considered and recent findings are presented which demonstrate that certain parts of the anatomy are in fact inlet and outlet valves. In particular, the authors show that the intake and exhaust valve mechanism involves a repeated (pulsating) steam explosion, the principle of which was up till now unclear. New research here has now shown the characteristics of the ejections and the role of important valves. In this paper numerical simulations of the two-phase flow ejection are presented which demonstrate that the principle of cyclic water injection followed by water and steam decompression explosions is the fundamental mechanism used to create the repeated ejections.

Bombardier beetles are armed with a unique defence mechanism that squirts a hot spray of water/steam (figure 1) at 100 °C with additional noxious chemicals dissolved in the water, on any predators such as ants, frogs, birds, etc. This stunning defence mechanism has attracted the curiosity of scientists for several decades. Eisner [1, 2] found that this spray is formed by a pair of glands which open at the tip of the beetle's abdomen and that each discharge is accompanied by audible explosions.

Chemistry. Schildknecht and Holoubek [3] discovered that each gland consists of two compartments: a reservoir and a reaction chamber which are connected through a valve. In figure 2, the details of the two compartments are illustrated for one of the glands. The reservoir contains an aqueous solution of hydroquinones and hydrogen peroxide, while the reaction chamber is filled with a mixture of catalase and peroxidases dissolved in water. Muscles on the reservoir squeeze it and push the quinone/peroxide solution into the reaction chamber which, with the waiting catalysts, triggers an extremely fast reaction in the reaction chamber. The catalase decomposes the hydrogen peroxide and the peroxidases oxidize the hydroquinone to benzoquinone. Current thinking suggests these enzymes (catalase and peroxidases) are either injected from tiny glands in the reaction chamber wall, or that they exist in a crystalline form on the inside of a thick fibrous hair-like material which exists on the inside of the chamber. Aneshansley *et al* [4] describe the reaction mechanism as

$$C_6H_6O_2(aq) + H_2O_2(aq) \longrightarrow C_6H_4O_2(aq) + 2H_2O(l) \quad (a)$$

with three main decomposition steps:

$$C_6H_6O_2(aq) \longrightarrow C_6H_4O_2(aq) + H_2(g) \quad (b)$$

$$H_2O_2(aq) \longrightarrow H_2O(l) + \tfrac{1}{2}O_2(g) \quad (c)$$

$$H_2(g) + \tfrac{1}{2}O_2(g) \longrightarrow H_2O(l) \quad (d)$$

and calculated the overall heat of reaction by summing the three individual heats of reactions. The overall heat release is -202.8 kJ mol^{-1}. Noting the concentrations of the reactants from [3] the heat content of the reservoir solution is found to be 0.794 J per milligram of the solution. Calorimetric measurements of the ejected sprays from beetles confirmed the accuracy of this estimate. The heats of reaction for each step are listed by Schildneckt and Houloubek [3]. At 25 °C, they are +177.2 kJ mol^{-1}, -94.5 kJ mol^{-1} and -285.5 kJ mol^{-1} respectively. The spray temperature at the exit point was measured to be 100 °C. The above-mentioned amount of heat

Figure 1. A bombardier beetle (*Stenaptinus insignis*); ejecting its water–steam jet at 100 °C forward from the tip of its abdomen (from left to right). Photograph by Eisner—from reference [2].

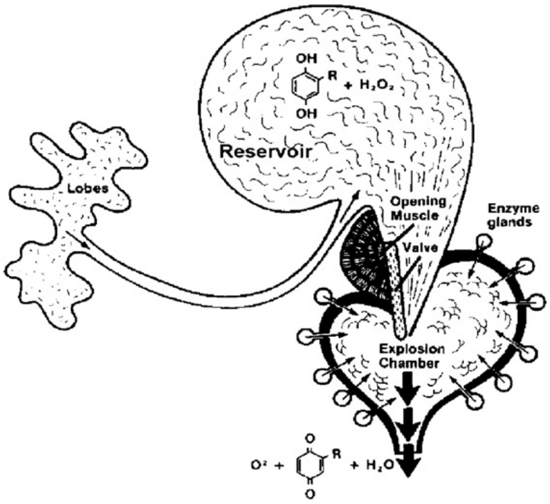

Figure 2. Bombardier beetle discharge apparatus.

is sufficient to bring all the spray from the ambient temperature to the boiling point and vaporize one-fifth of it.

Pulsation. Eisner reported that the bombardier beetles can spray repeatedly up to 29 discharges [1] and by rotating the tip of their abdomen they can aim their enemy in any direction with pin point accuracy and even forward on their back [2].

In a later work, the Cornell team [5] found that the bombardier beetle's spray is not a continuous stream but in fact a series of mini-explosions which together form a pulse jet. This was discovered using acoustic recordings of the discharges and spectrographs. Through these spectrographs from several beetles, it was found that each discharge lasted from 2.6 to 24.1 ms (with a mean of 11.9 ms) and is made of several pulses (2 to 12). The frequency of the pulses ranged from 368 to 735 Hz with a mean of 531 Hz (2 ms for each pulse). They also proved that this pulsation is not due to physical vibration of the gland openings. In addition, high-speed cinematography of the spray confirmed its pulsating nature. By these visualizations, the spray emergence velocity was found to be 11.63 m s^{-1} (ranging from 3.25 to 19.5). They also report that this velocity is much higher than the exit velocity in another species of the bombardier beetle [6] which ejects its spray in a non-pulsating constant velocity stream of 2.4 m s^{-1}. They therefore deduced that this is a direct result of the unsteady flow involved in the pulsating spray case. Higher exit velocities actually mean longer effective ranges for the defensive spray and also a quicker response time to an attack. In the case of one beetle (the African variety *Stenaptinus insignis)*, the spray can reach as far as 20 to 30 cm from a reaction chamber only 1 mm in size.

Earlier theories of pulsation. In [5], it was also suggested that the mechanism responsible for pulsation is solely the oscillation of the inlet valve. Thus the pressure was thought to rise at the start of each pulse due to the chemical reaction. Then when the valve is opened and the ejection of the hot materials takes place, the pressure drops in the chamber and the valve closes again. Also, it was noted by comparison of the ejection velocities of two different species *Goniotropis nicaraguensis* (with non-pulsating spray, velocity 2.4 m s^{-1}) and *Stenaptinus insignis* (pulsating spray, velocity 11.6 m s^{-1}) that the pulsation itself is of great benefit in producing higher ejection velocities.

It should be noted that Eisner and Aneshansley observed that a throw distance of approximately 0.2 m is perfectly possible from the beetle combustion chamber. With a typical combustion chamber size of less than 0.001 m, this implies an astonishing throw ratio (throw distance divided by device size) of 200.

These remarkable findings concerning this creature have inspired further research into understanding the fluid dynamic and combustion principles behind the bombardier beetle's defence mechanism. Of particular interest is how this beetle pulsates its spray and whether there are advantages in this mechanism for engineering applications.

Numerical simulation of the combustion chamber

Separation of physics and chemistry

To simulate the beetle chamber it was deemed wise to concentrate on first the physics of the chamber and regard the chemical reaction as separated from the overall spray generation mechanism. In this simplified formulation the heat generation is then assumed as a given input condition. Dealing with two-phase flow (water and steam) would be a sufficiently complex task, without modelling the chemistry as well. The catalytic chemistry is of great interest as a separate investigation, but for now it was deemed better to concentrate on the ejection of the hot fluid. Consequently, we assumed that we had some form of heating available, such that hot water near boiling is readily available. In reality, the Beetle has a mixture of benzoquinone and water, but the major part of the ejection is water and steam.

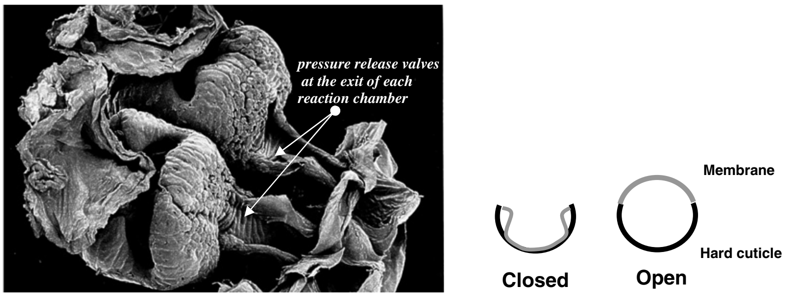

Figure 3. The twin combustion chambers and nozzles in the bombardier beetle (*Stenaptinus insignis*) from a dissection by Eisner [7] and their pressure release exit valves. On the right a schematic diagram of the cross section of the exit valve in open and closed conditions is shown. These valves are in fact in a closed condition in the photo on the left.

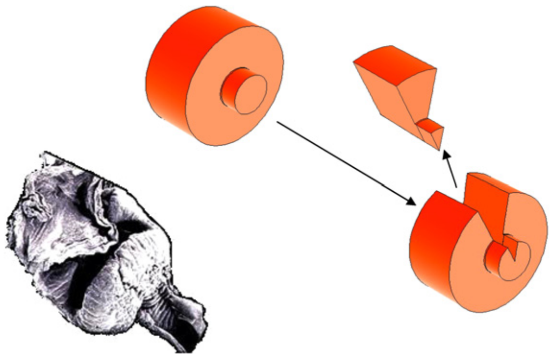

Figure 4. The beetle combustion chamber with nozzle on the left, and the simulated sliced chamber on the right.

Combustion chamber

The other consideration was how to simulate the chamber itself. To model the tiny combustion chamber exactly (as illustrated in figures 3 and 4) would require much effort in constructing a numerical grid to simulate the heart-shaped chamber. In that the preliminary simulations [8] showed that the shape of the chamber was not significant; it was decided to model the pulse jet phenomenon using a much simpler cylindrical geometry which proved very successful in showing the decompression explosion that we discuss later in this paper. Then assuming axial symmetry, a 3D slice of the cylindrical chamber was taken for simulations, as shown in figure 4.

The CFD (computational fluid dynamics) investigations of the water/steam explosion were thus achieved in a cylindrical chamber with about the same length and volume as the beetle reaction chamber. Specifically, we conducted a study of the evaporation and subsequent two-phase flow within the beetle device, and the effect of the exit nozzle diameter on its mass ejection efficiency. All the CFD simulations were performed using the CFX 5.7 code which as a commercial finite volume code has been widely validated.

Steam explosion (cavitation) model

The details of this modelling are given in [9], but briefly the path which led us to the understanding of the physical principles of the beetle explosion is described here.

Electron micrographs of the beetle chamber indicated a flap or a membrane, which at closer examination showed that there was in reality a valve operating at the exit of the reaction chamber. This is in fact a very effective pressure relief valve which obstructs the chamber opening to the exit nozzle and opens only after a certain pressure has built behind it by the creation of boiling nuclei in the water. This valve mechanism is shown in figure 3. It includes the elastic membrane at the top and a hard cuticle wall on the bottom. Under normal conditions, this membrane sticks to the bottom part and closes the chamber exit. But at a certain pressure, which is built up after the reaction in the chamber is ignited, the membrane flap moves upwards and opens the way for the hot discharge. The flap then goes back to its original place after each discharge (and a certain amount of the steam/water mixture is ejected), during which time the pressure falls back below the trigger pressure. This observation revealed that the major physics is in fact governed by a steam (cavitation) explosion. The aqueous solution in the chamber is brought to the boiling point by the heat of reaction and as the exit valve is closed, it reaches a temperature slightly higher than 100 °C under pressure. Once the trigger pressure is reached and the exit valve is opened, then the charge is pushed out. In these calculations, we have checked three different trigger pressures of 1.15, 1.1 and 1.05 bar. After the valve is opened, the liquid in the chamber is at the saturation temperature for this trigger pressure. This is approximately 105 °C for 1.1 bar. Consequently, the decompression (cavitation) explosion causes flash evaporation as the fluid suddenly senses the reduced (ambient) pressure. Such a process is more powerful than the previously thought direct boiling by the heat of reaction without a pressure release valve [8]. As the results show in the next section, this model gives realistic results in close agreement to the velocities and time scales observed in the experiments on these beetles [5].

To perform the CFD calculations, a small cylindrical chamber 600 μm in diameter and 300 μm in length was chosen which is about the same size and volume of the actual beetle chamber and an exit nozzle 100 μm in length with six different diameters of 100, 150, 200, 250, 300 and 500 μm was attached to it. The total number of numerical cells is approximately 140 000 in all the above cases.

The model assumes that the flow is laminar based on the observed velocities in the experiments of Eisner [1, 2, 4, 5] and

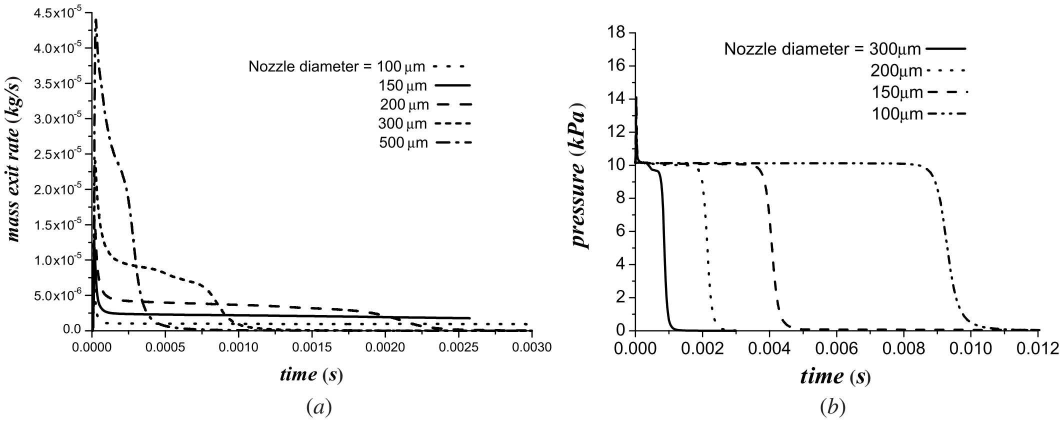

Figure 5. (*a*) Mass exit rate and (*b*) pressure at the chamber centre for different nozzle diameters.

on the velocities generated numerically here. Consequently, the Reynolds number is low and at its maximum is of the order of 100.

Results

Shown in figure 5(*a*) is the mass (water/steam) exit rate from the nozzle for the beetle combustion chamber with different nozzle diameters. As expected, the wider the nozzle, the higher the exit rate becomes and the sooner the ejection process ends. However, as shown in figure 6, the mass flow weighted section averaged exit velocities are in fact increasing with decreasing nozzle diameters. The calculation of this average velocity and detailed interpretation of these results are given later.

For the defence mechanism of the beetle, it is important to deliver the charge at the maximum possible velocity and in the shortest time. As the velocity increases, so the longer will be the effective range for the jet and it will also reach the predator sooner. Consequently, there is an optimum size for the nozzle diameter which is found to be approximately 200 μm in these simulations.

Section averaged velocity

In calculation of this section averaged velocity, mass-flow weighting is used. In order to calculate it, the following procedure is applied.

At each numerical grid point on the exit section (642 elements for the 200 μm nozzle), the local mass flow exit rate is multiplied by local velocity and is integrated over the whole exit section, and then this is divided by the integral of the mass flow exit rate itself over the exit section. This gives an indication of the average velocity responsible for the mass flow exit rate of the beetle's spray.

The mass flow weighted section average exit velocities are given in figures 6(*a*)–(*c*) at three different trigger pressures of 1.05, 1.1 and 1.15 bar respectively, and for five different nozzle diameters of 100, 150, 200, 250 and 300 μm. From these figures it can be easily seen that larger diameters give smaller velocities and deplete the chamber expulsive content much faster than smaller nozzles (see also figure 5(*a*) for mass

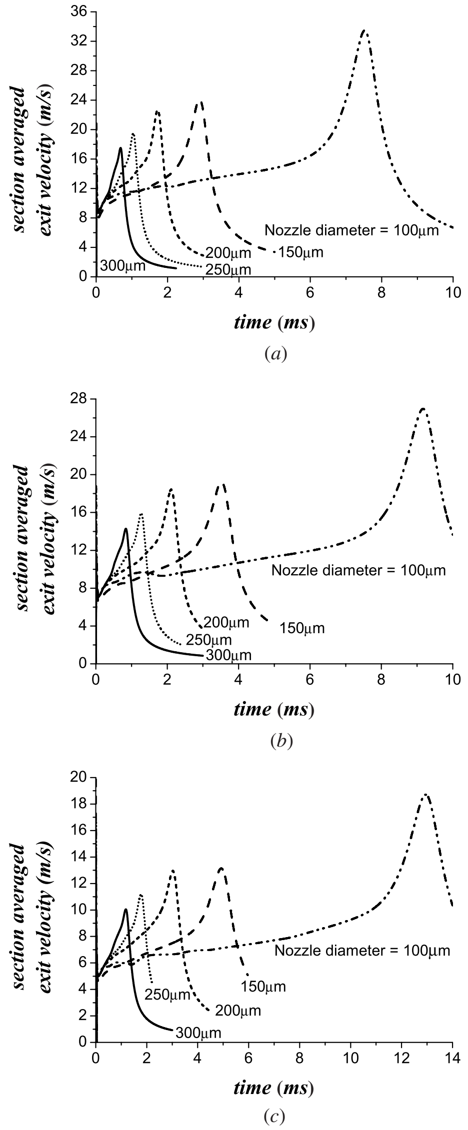

Figure 6. Section averaged exit velocities for different nozzle diameters with three different trigger pressures of (*a*) 1.15 bar, (*b*) 1.1 bar and (*c*) 1.05 bar.

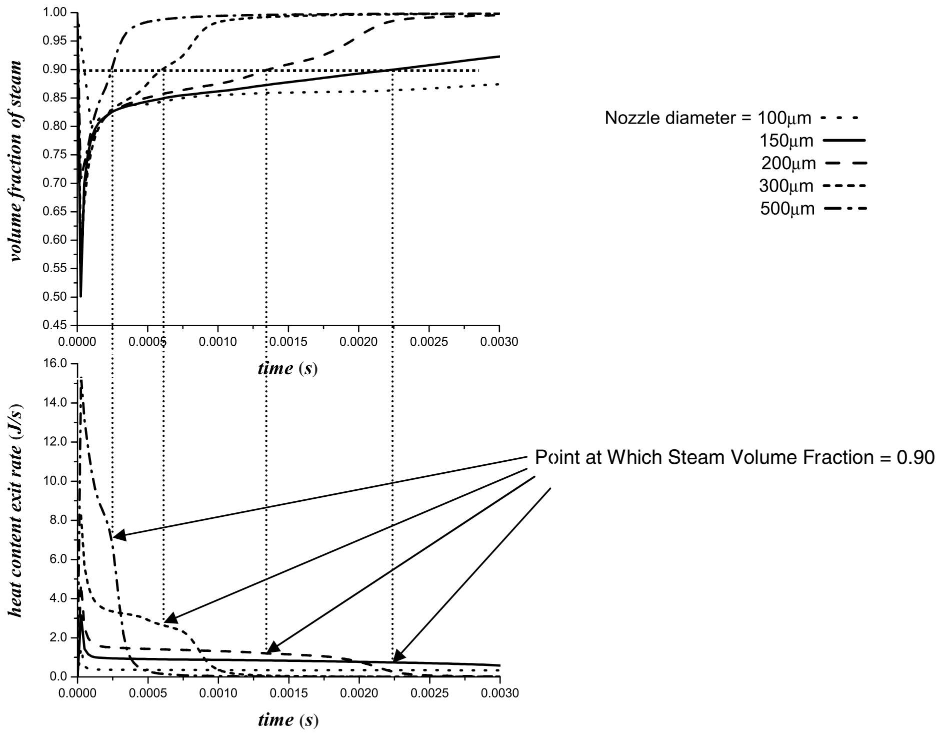

Figure 7. The volume fraction of steam (top) and heat exit rate (bottom) in time for different nozzle diameters.

flow exit rates), but smaller nozzles give higher velocities. It is also evident that there is a peak in exit velocities for each nozzle diameter which is higher and happens later for smaller nozzles. It is interesting to see that all these trends are independent of the trigger pressure. Because of this identical trend, it was decided to proceed with a single trigger pressure and as the one with 1.1 bar produces velocity and time scales in a very good agreement with the experimentally measured ones, the 1.1 bar trigger pressure was assumed to be the one that the beetle defence system is using. Further simulations are then using this trigger pressure only.

For the defence purpose of the beetle, it is more desirable to have higher exit velocities. This allows the beetle's deterring spray to reach the predator at an earlier time after being ejected from the nozzle. This idea suggests that the smaller the nozzle, the better. But on the other hand as mentioned above, the smaller nozzles give their peak velocity much later than the larger nozzles do.

Looking more carefully at figure 6, one sees that although the 100 μm diameter nozzle gives a much higher peak velocity, but gives it much later than the rest of other nozzles. Consequently, one has to take into account not just the velocity maximum but when it is delivered. There is one further issue, however, in the physical arrangement and that is the amount of heat which the spray transfers to the predator. The heat content of the spray is indeed a function of the volume fraction of the steam and liquid water in the hot spray. Figure 7 shows that the volume fractions are varying during the spray ejection and initially less steam is ejected and as time proceeds, the volume fraction of steam approaches 100% at velocity peak points (comparing with figure 6) prior to depletion. Therefore, it is necessary to see how the heat content of the spray varies in time and from that, and based on exit velocities, calculate the amount of heat delivered to the target up to that time.

Figure 7 also shows the heat content exit rate as a function of the nozzle diameter. It can be seen that this quantity is higher for the larger nozzles and also is ejected earlier than the smaller ones. But as mentioned earlier, smaller diameters give higher velocities and could deliver the spray to the target earlier. Thus, there is a trade-off here between the two effects which for a clear judgement requires the calculation of the amount of squirted heat which reaches the target in time.

Calculation of the amount of heat arrived at the predator in time

The heat content of the beetle's spray is of importance in its efficiency to deter the predator. The heat content is the sum of heat available in both steam and hot water within the spray which is a mixture of the two.

As the heat content of each phase (water and steam) is different, the total value will be dependent on the volume fraction of water and steam in the spray. The following formula has been used:

$$Q = \dot{m}_s(\Delta h_{fg} + C_{p,w}\Delta T) + \dot{m}_w C_{p,w}\Delta T$$

in which $\dot{m}_s$ and $\dot{m}_w$ are the mass flow rates of steam and water at the nozzle exit respectively; and ΔT, $C_{p,w}$ and Δh_{fg} are the temperature difference between the boiling point (100 °C) and ambient (20 °C), and latent heat of vaporization for water, respectively.

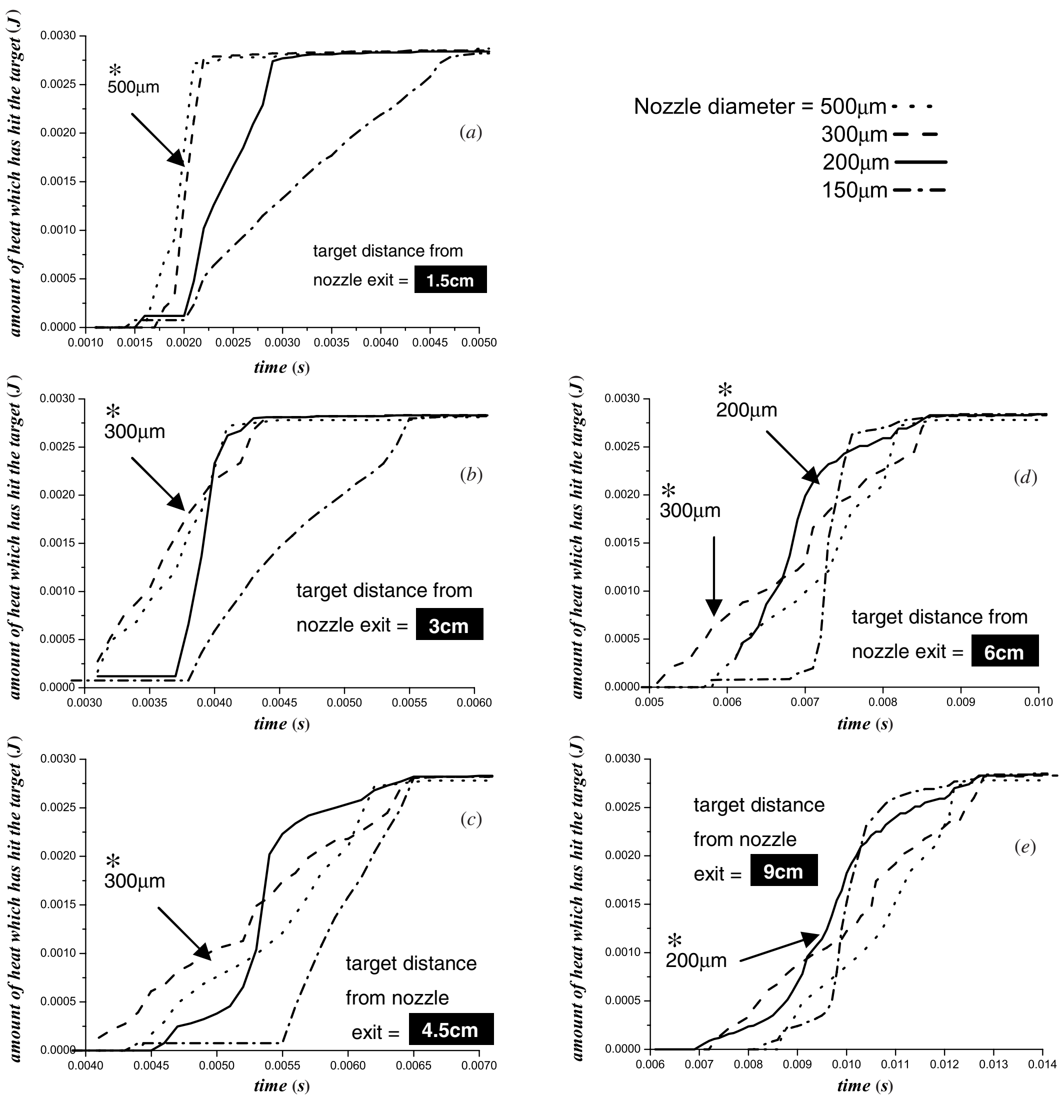

Figure 8. The amount of heat reaching the target located at different distances: (*a*) 1.5 cm, (*b*) 3 cm, (*c*) 4.5 cm, (*d*) 6 cm and (*e*) 9 cm. Shown on each graph are curves of four different nozzle diameters and also marked with an asterisk are the nozzle diameters which cause the greatest heat delivery. For small distances the optimum diameter is 500 μm. For larger distances the optimum diameter is of the order of 200–300 μm.

In figure 7 the total heat content ejection rate of the spray at the nozzle exit is given for four different nozzle diameters in time, along with volume fraction of steam. At very early times, for all nozzle diameters, the volume fraction of steam is lower and gradually increases up to almost 100%. In this figure, also the points at which the steam volume fraction reaches 90% are highlighted.

Although this figure indicates that with nozzle diameter increase, the heat ejection rate is higher, one should not assume that this is in favour of the beetle's defence. This is because it is not only the heat ejection rate which is important, but also the spray emerging velocity which is significant (already shown in figure 6). This and the time required for the defensive spray to reach the target are important factors. Since both the emerging velocity and heat ejection rates are varying in time, it is important to integrate in time the amount of heat ejected at each instant of time and its velocity to calculate each heat parcel's arrival time at a target located at a certain distance from the nozzle exit.

Therefore, at each time step of the numerical simulations, the amount of ejected heat is calculated and its arrival time (t) at a target at a distance L is obtained by the simple equation, $t = L/v$ where v is the section average velocity at the nozzle exit. A table is thus generated showing at each time step how much heat has been released from the nozzle and how long it takes for this heat parcel to reach the distance L. After this table is completed for all time steps, another calculation based on this table is performed. Starting from time zero with small time steps, it is noted from the table how many parcels have arrival times smaller than the current time and at each time step the total heat content is then added together. The results are illustrated as curves of the total amount of heat arrived at the target at each instant of time in figures 8(*a*)–(*e*), for the four nozzle diameters and for five different distances of

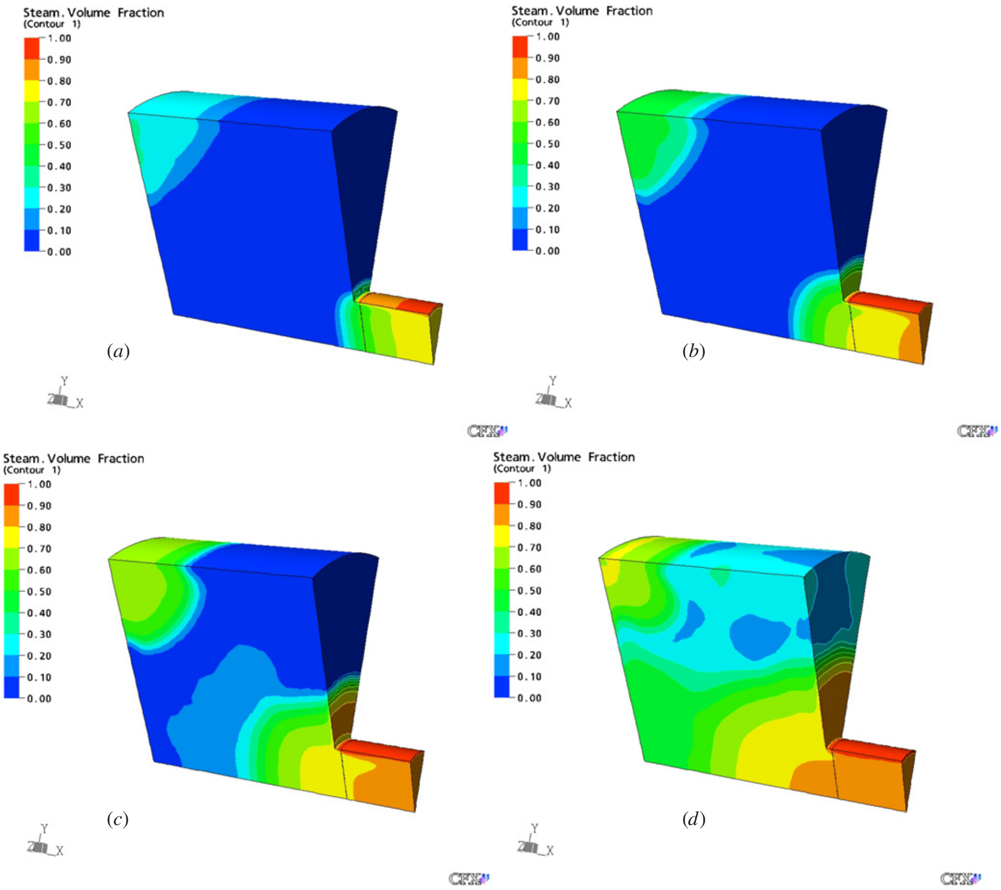

Figure 9. Slides of steam volume fraction *a*, *b*, *c* and *d*, at four instants of time: 0.1, 0.2, 0.5 and 1 ms, respectively.

the target from the nozzle exit. It should be noted that these results are based on the assumption that the ejected spray is travelling at the exit velocity throughout its path to the target. Clearly, in practice, the velocity of each packet will in fact decrease with the distance from the ejection point. However, these results give a reasonable estimate as to the heat reaching the target. An accurate calculation can only be performed by the extension of our simulations to the emerging spray out of the nozzle and in the ambient.

Discussion

Figures 8(*a*)–(*e*) show that for shorter distances from the nozzle exit (3 cm and less), larger nozzles deliver greater heat content to the given target. When the distance is increased, gradually smaller nozzles show preference. In total, it seems that except for very short distances (1.5 cm and less) the 300 μm nozzle has the optimum performance, but is closely followed by the 200 μm one. Though the spray can reach as far as 20 to 30 cm from the beetle, the practical distance that the beetle ranges a direct attack would be up to about half that distance when a wolf spider or ant, frog or bird attacks it (see [10], p 187, figure 1, for a dramatic example of the beetle's typical firing strategy). This would typically be up to about 4–5 body lengths.

An excellent confirmation that the optimum diameter size lies in the region of 200–300 μm was the measurement of the nozzle diameter from the electron microscopic slides taken in Cornell by Eisner [7] (like figure 3). These showed that the diameter was indeed close to 200 μm ($\pm$10%). This indicates that the nozzle diameter in the beetle device is optimized to deliver the highest heat content in the shortest time, highest possible velocity while keeping the ejection time at the shortest possible, and having the longest effective range.

Another interesting output of the simulations with this nozzle diameter of 200 μm is that the average velocity during the discharge time is about 12 m s^{-1} and that its maximum (figure 6) is about 18.5 m s^{-1}. This is in very close agreement to the experimental values of 11.63 m s^{-1} and 19.5 m s^{-1} respectively. Also, at this diameter, the ejection is completed in just 2 ms which is in accordance with observations of 2–3 ms for each pulse by Dean *et al* [5]. This then leaves sufficient time for replenishment for the next pulse. The amount of mass discharged per pulse is about 0.084 mg. This is in agreement with the estimated order of magnitude of mass ejection from the beetle itself, and supports the accuracy and validity of our model assumptions and numerical simulations.

In figure 9 the colour contours of the steam volume fraction at four instants of time for the 200 μm nozzle case are displayed. These contours show that the vapour explosion starts at the assumed location of the valve and then (rather like a flame) a vaporization front proceeds through the bulk of the liquid in the chamber until the rest of the liquid is turned into vapour. However, this does not mean that there is no vaporization at the locations where this front has not reached; there is still partial vaporization everywhere but the maximum is on this front.

For example, at the top left corner of the chamber it is seen that there is considerable vaporization. This is particularly caused by the motion of the bulk of the fluid content in the chamber being driven towards the exit as a result of high velocity discharge. This motion leads to lower pressures at the far corner, and induces vaporization.

From these results obtained from the steam explosion model with the pressure release valve and the fact that the electron micrographs of the beetle reaction chamber clearly showed the valve, it can be confidently concluded that the pulsating spray of the bombardier beetle (*Stenaptinus insignis*) explosion is due to pulses that are actually induced by the presence of the pressure release exit valve of the reaction chamber. The repeated blasts are each a steam (cavitation) explosion. In [5] it was proposed that the creation of the free oxygen as a product of the reaction [3] is the major source of the pressure rise and explosion. But as our results show, the steam production is also a major source for the pressure rise. In summary, the overall process of production of the pulse spray in the beetle's glands is as follows.

The beetle, by contraction of its muscles, squeezes the fluid in the reservoir containing the reactants (hydroquinone and hydrogen peroxide). This opens the one-way inlet valve to the reaction chamber and injects some of this fluid into the chamber, which already contains the catalase and peroxidases. The catalytic reactions are triggered and the aqueous solution in the reaction chamber is brought to a temperature of about 105 °C and by creation of tiny steam nuclei in the chamber and also by thermal expansion of the water, the pressure rises to about 1.1 bar. At such a pressure the exit valve shown in figure 3 opens and lets the hot pressurized water expand to the ambient pressure and vaporize. This steam explosion rapidly leads to slightly higher pressures in the chamber and closes the inlet valve (between the reservoir and the reaction chamber). As shown in figure 5(*b*), the pressure inside the chamber remains for the rest of the ejection period at 1.1 bar, and just very near the depletion point falls dramatically. Thus, after the rest of water in the chamber is vaporized and ejected, the pressure inside the chamber drops to lower values than the initial 1.1 bar and therefore the pressure release valve at the chamber exit closes. Meanwhile, this low pressure reopens the inlet valve to the chamber and injects more reactants and liquid water into it. The cycle is now repeated until the beetle relaxes its muscles to the reservoir.

Further observations

This is probably the smallest biological example of a pressure relief valve and possibly unique in that the system operates by the principle of a steam cavitation explosion. As a result of these findings, it was planned to build an experimental rig to show the principle in action based on the numerical simulation. This will be reported on in a separate paper [11].

Conclusions

Numerical computational fluid dynamics modelling of the bombardier beetle combustion chamber (approximately 1 mm long) has demonstrated that the major physics behind the remarkable repeated mass ejection efficiency is a steam explosion from saturated water, where the pressure relief exit valve plays a key role as the addition of sudden decompression causes the boiling liquid and steam to move out of the moveable rear nozzle. The exit nozzle diameter plays an important role in optimizing the exit velocity, and the heat content reaching a specified target distance. The numerical simulations show that the nozzle diameter in bombardier beetles appears to be at an optimum value for these two considerations.

The effective mass ejection from so small a device is deemed of great biomimetic advantage—particularly with possible application to gas turbine igniters in the aerospace industry, but other applications may well be possible.

Acknowledgment

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