Biomimetic Study of Explosive Discharge of Bombardier Beetle

N. Beheshti
A. C. McIntosh

Energy and Resources Research Institute
School of Process, Environmental and Materials Engineering
University of Leeds, Leeds, West Yorkshire, LS2 9JT, UK

Corresponding author, A. C. McIntosh: a.c.mcintosh@leeds.ac.uk

Introduction

A unique mechanism of discharge of hot products has been found to be used by the brachina beetles living in South America, Africa and Asia. The defence mechanism of the brachina beetle – commonly known as the bombardier beetle (Fig. 1) – is most unusual in that an aqueous combustible mixture of hydroquinone and hydrogen peroxide is catalysed by catalase which then heats the solution to boiling point and evaporation within a few milliseconds and is ejected at 100ºC against predators using a variable angle outlet nozzle which is directed at pin point accuracy. The nozzle itself is so versatile that it can even be aimed forwards over back of the beetle [1]

These findings about this creature by Eisner and his group at Cornell University, NY have inspired research into whether there are advantages in the design of this discharge mechanism. This is particularly pertinent to the matter of reignition devices [2] in that the beetle has the surprising ability of being able to send a hot discharge to around 20 times the length of its combustor (which for the beetle is about 1mm).

In this paper we briefly describe the combustion mechanism of the actual beetle device. In that the application to other devices is the main motivation of this work, we then discuss the modelling of the water steam explosion in a cylindrical chamber with about the same volume as the one for the beetle. Specifically we conduct a study of the phase change and two-phase flow in the beetle's device and the effect of the exit nozzle diameter on its efficiency. Then a scaled up chamber for application to gas turbine relight is simulated with a hydrocarbon fuel (hexane) instead of water. All the CFD simulations are performed using the CFX 5.7 code.

The Chemistry and Specifications of the Bombardier Beetle Discharge Apparatus

The beetle's discharge apparatus is shown in Fig.3. It consists of two sets of reservoirs, reactors and exit nozzles. On this figure, only one chamber is sketched. The outer view of the twin chambers and their exit nozzles from an electron micrograph is shown in Fig.2.

The aqueous solution of reactants is stored in a reservoir, and is composed of hydroquinone $C_6H_6O_2$ and hydrogen peroxide at concentrations of 25% and 10% respectively. When the reservoir is squeezed, the mixture of reactants is introduced into the reaction chamber through a valve. Once the reactants are present in the chamber, the enzyme catalysts (catalase and peroxidase) are introduced through the combustor walls. An extremely fast catalytic reaction then takes place. The reaction mechanism [3] can be described with the global chemical reaction:

$$C_6H_6O_2(aq) + H_2O_2(aq) \longrightarrow C_6H_4O_2(aq) + 2H_2O(aq) \qquad (1)$$

While the reactant storage and delivery system is driven by muscle contraction, the reaction chamber is rigid. Dean et al [4] reports spectrographic measurements of the discharges and concludes that the discharge duration average was 11.9 ms with a mean of 6.7 pulses per discharge and mean frequency of pulses being 531 Hz. The average velocity of the spray emerging from the tip of the abdomen of the beetle was measured to be 11.63 m/s (ranging from 3.25 to 19.5 m/s). The spray can reach as far as 2 to 3 centimetres.

Fig.1. A bombardier beetle (brachina);ejecting its water-steam jet at 100°C forward from the tip of its abdomen (from left to right).

Fig.2. The twin combustion chambers and nozzles in the Carabidae Crepidogastrini Beetle from a dissection by Eisner [4].

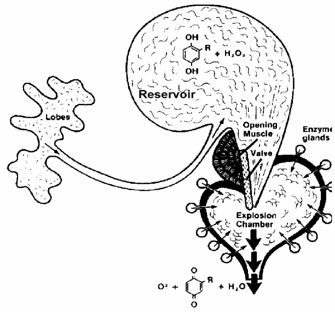

Fig.3. Bombardier beetle discharge apparatus

Numerical Modelling of the Beetle Combustion Chamber

Steam Explosion (Cavitation) Model

From a recent visit to Cornell it was noticed from electron micrographs that the beetle's chamber has a very effective pressure relief valve which obstructs the chamber opening to the exit nozzle and opens only after a certain pressure is built behind it by creation of boiling nuclei in the water. This observation then revealed that the major physics is in fact governed by a steam explosion, so that the CFD numerical simulations required the inclusion of the 2-phase boiling of water to encapsulate the essence of the explosion mechanism.

To perform the CFD calculations, first a tiny cylindrical chamber with 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 with 100μm in length and 7 different diameters of 60, 100, 150, 200, 300, 400, and 500μm was attached to it. As the initial condition, the chamber was filled with pure liquid water at saturation temperature (378K) with a pressure of 1.1 bar and the nozzle with pure steam at the same temperature but at a lower pressure of 1.0 bar. This latter assumption is for ease of the calculation and is no different in essence to the case where the nozzle is filled with pure air, but avoids the need to solve for three species. The numerical model then only solves the conservation equations for 2 species; liquid water and water vapour. At time $t = 0$ it is assumed that the two parts (nozzle and chamber) are separated with an infinitely thin membrane (a rough model for the pressure relief valve in beetle) and that this is removed at time $t = 0+$, allowing the two parts to then be in direct contact. As the pressure in the nozzle is lower than the saturation pressure for water at $T = 378$K, the water will rapidly vaporize leading to a cavitation explosion.

The basic assumptions are:

1. Full transient simulation
2. The boiling is assumed to be an isothermal phenomenon occurring at the saturation temperature of water at P = 1.1 bar (T = 378K)
3. An Eulerian (homogeneous) two-phase flow model is employed [5] with the Rayleigh-Plesset model for cavitation [6] as the phase change model. This model is available in CFX.
4. The flow is assumed laminar, since Reynolds numbers based on exit diameter are well below 2000.
5. Axial symmetry is assumed and only a 3D slice of the cylindrical chamber with an angle of 36º is solved with symmetry BC's on its sliced sides.

To resolve the rapid changes which occur by the cavitating phase change, a very small time step of 2.5μs was needed, and the calculations were terminated after a total time of 3 ms which was sufficient for wider nozzle diameters (200μm and above) to discharge all their dischargeable mass. The steam was assumed to be compressible (as an ideal gas).

Numerical modelling of the scaled up cylindrical combustion chamber

In order to consider biomimetic application of the combustion chamber of the beetle, a scaled up chamber of 20mm in diameter and 10mm in length was chosen filled with liquid hexane at 10 bar and at saturation temperature for this pressure (about 170°C). The exit nozzle was then 7mm long and with three different diameters of 3, 5 and 7mm. The nozzle was initially filled with gaseous hexane at 9bar and with the same temperature as the chamber. The assumptions used were identical to those used in modelling of the beetle combustion chamber.

Results and discussion

Beetle combustion chamber

Shown in Fig. 4 is the mass (water/steam) exit rate from the nozzle for the beetle combustion chamber with different nozzle diameters. As one can see, the wider the nozzle, the higher the exit rate and the sooner the ejection process ends. However, as shown in Fig. 5, the maximum of section averaged exit velocities increase with decreasing nozzle diameters up to 200μm and then decrease with smaller diameters.

For the defence mechanism of the beetle (and also for gas turbine relighters or a similar mass ejection device) it is important to deliver the charge *at the maximum possible velocity.* As the velocity increases, so the longer will be the effective range for the jet. Consequently, there is an optimum size for the nozzle diameter which is found to be approximately 200μm in these simulations since for which the section averaged velocity is at a maximum and the ejection is completed in just 2ms. Surprisingly enough, measuring the nozzle diameter from the electron microscopic slides taken in Cornell by Eisner [2] (like Fig. 2), gives very close values to 200μm (±10%). This shows that nozzle diameter in the beetle device is carefully designed and this principle can be duplicated for engineering applications.

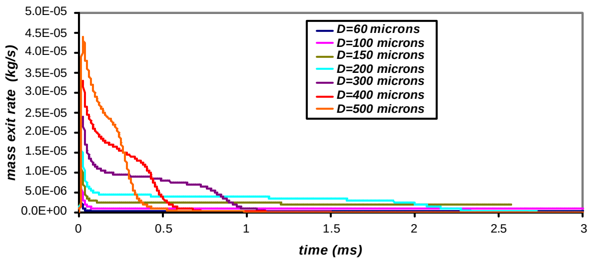

Fig. 4. mass exit rate for 7 different nozzle diameters for the beetle combustion chamber

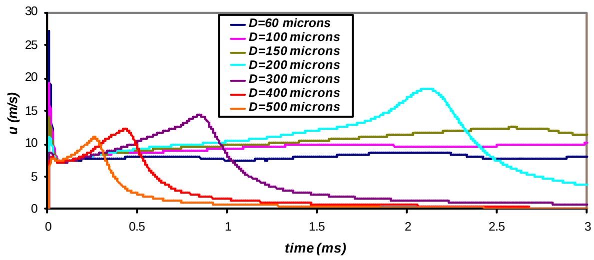

Fig. 5. Section averaged exit velocity for 7 different nozzle diameters for the beetle combustion chamber

Scaled-up chamber

Simulation of the vapour explosion in the scaled-up chamber, filled with pure hexane as the vaporising liquid, gives similar results to those observed in the beetle's chamber filled with water. However, there are some apparent differences easily observed.

The most significant difference is that the resulted curves of mass exit rates and velocities are not smooth like the beetle's chamber case. This is mainly due to the larger size of the chamber and much higher exit velocities that induce local instabilities and turbulence. Also, as the chamber is much larger, and the time scale of cavitation phase change is roughly the same, the time required for vaporising all of the liquid is much longer. Condensation occurs slower than vaporisation and this gives enough time to the created vapour in the chamber, which is under high compression due to its own required higher volume, to condense at some points where the local pressure exceeds the saturation pressure.

A schematic of a proposed new relighter based on the vapour explosion idea inspired by this study (which is purely a new idea for such applications of mass ejection devices) which can also benefit from the optimum nozzle size found here, is given in Fig. 8.

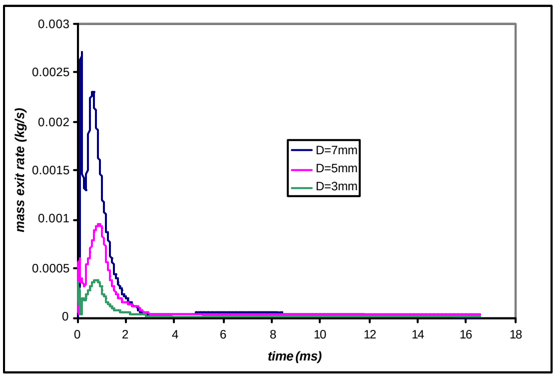

Fig. 6. mass exit rate for 3 different nozzle diameters with the scaled-up chamber

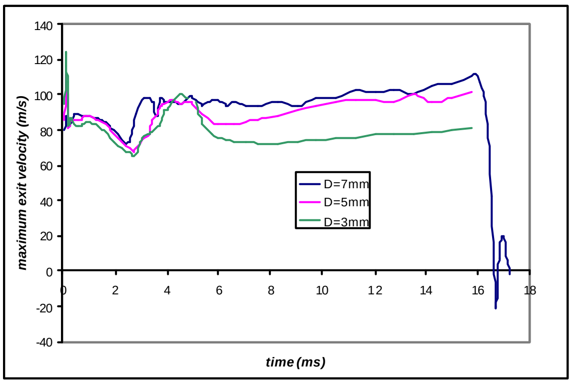

Fig. 7. Maximum section exit velocities for 3 different nozzle diameters with the scaled-up chamber with hexane.

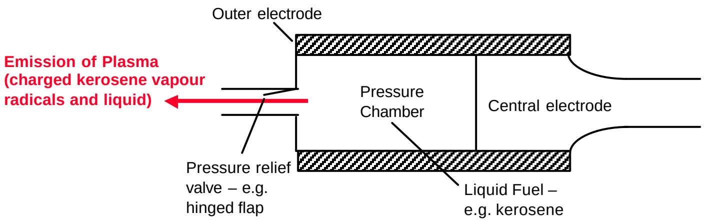

Fig. 8. Possible pressure relief valve relighter for gas turbines (based on bombardier beetle principle)

Conclusions

A numerical model of the bombardier beetle combustion chamber (approx 1mm long) has demonstrated that the major physics behind the remarkable repeated mass ejection efficiency is a steam explosion from compressed hot water, where the addition of sudden decompression kicks the boiling liquid out of its moveable turret rear nozzle.

A scaled up version of the same type of combustion chamber has been numerically modelled using the vapour explosion technique and good mass ejection efficiency is evident, such that there are possible applications to new designs of gas turbine relighters.

Acknowledgement

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