The efficiency of the explosive discharge of the bombardier beetle, with possible biomimetic applications

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Abstract

The paper investigates the remarkable combustion chamber of the bombardier beetle with a view to learning from the great efficiency of blast that the 1mm combustion chamber of this creature achieves with repeated explosions at 2-3 per ms. In reality the two chemicals are trace species in water which is then heated to boiling point by the presence of a catalyst. To simplify the numerical study presented here, a two-phase (water / steam) computation is performed to simulate the hot discharge from the brachinine bombardier beetle. The study only concentrates on the heating process within the reaction chamber rather than modelling the full kinetics of the hydroquinone and hydrogen peroxide reaction (with catalysts catalase and peroxidase). Using this approach the numerical model (based on commercial CFX software) simulates the heat generation by following an artificially assigned scalar injected from the wall. The heat assigned to the scalar then converts some of the water by pool boiling into steam. The subsequent pressure increase in the two-phase system is modelled, and the ejection of the hot mixture up to the point of emergence is discussed and evaluated for different geometrical configurations.

The aim of the study is to show the advantages of the naturally occurring design and identify the main parameters important for the high efficiency discharge. The results indicate that this rather unusual design of beetle combustion chamber does indeed have better performance in terms of efficiency of mass ejection. This is primarily due to the heart shaped combustor combined with a long narrow ejection tube.

The results support the idea of a possible practical use for pilot ignition systems, such as re-igniters in aircraft gas turbines and automobile safety air bag ignition devices.

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1 Introduction

Two main types of bombardier beetles exist within the family called Carabidae and are mainly found in Africa, South America and Asia (though some have been found in Europe). One sub grouping called the brachinoids includes the familiar and more commonly found brachinus kind. The other grouping is named the paussoids and differs from the brachinoids primarily in the arrangement of the nozzles, and in its more restricted geographical distribution [1]. The focus of the research in this paper concerns the brachinoids and in particular, the brachinine sub group. Eisner and co-workers [2, 3] have detailed the description of these bombardiers, and in particular show photographically the accurate spray-aiming mechanism of this creature, which includes the ability to even spray the hot fluid forward, over its own back. The fluid secretion is made up primarily of hot water and steam where the heat comes from the reaction of hydroquinone and hydrogen peroxide catalysed by catalase and peroxidase. The presence of the quinine in the products causes the stinging feature of the secretion, such that any predator receives a scalding sting with surprising accuracy. The Bombardier beetle senses the direction of the attacker (typically a spider, bird, frog or ant) without using eyesight to assess which direction to fire, and yet nevertheless directing the spray using a swirl nozzle facility near the abdominal tip of the beetle. Upper and lower lips surround the flexible nozzle, such that the direction of the spray is tightly controlled.

The aim of this paper is to model some of the hydrodynamic features of the two-phase flow from the reaction chamber (which is less then 1 mm long). The full kinetics is not modelled here, but the heat production of the reaction is simulated by allowing a scalar (within the CFX numerical code) to be injected from the wall of the chamber. The heat following this scalar then causes pool boiling of the water, and the raised pressure consequently then ejects the hot 100ºC mixture through a nozzle. Usually predators are temporarily immobilised and are unable to then press their attack further, due to the scalding spray that they have received. (However one rodent manages better by always attacking the beetle from the front. The creature is quickly gripped head-first, and the rear abdomen buried [4], so that the blasts are then ineffective!)

The effect of different geometrical configurations, particularly the nozzle width and length is investigated. Through this work, further insights into the pioneering work of Eisner and co-workers are obtained particularly in relation to the shape of the heart-shaped reaction chamber which enables a pressure focusing method to force more of the mass out of the abdomen tip than would occur if a conventional rectangular chamber were used.

2 Discharge mechanism of Brachina

The Brachina discharge apparatus is shown in fig.1. It consists of two sets of reservoirs and reactors channelled into one nozzle at the tip of the abdomen of the beetle. On this figure, only one (of the two reaction chambers) is sketched.

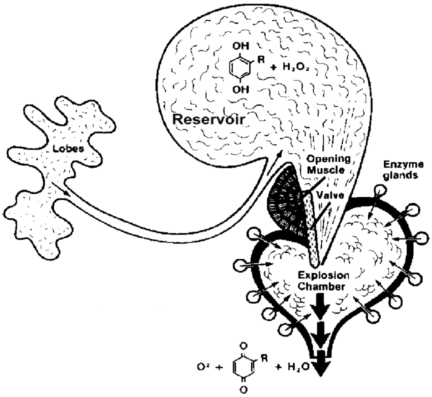

Figure 1: Brachina discharge apparatus.

The aqueous solution of reactants is stored in a reservoir, and is composed of hydroquinone $C_6H_6O_2$ at a concentration of 25% and hydrogen peroxide at concentration of 10%. From the work of Schildknecht and Holoubek [5] we assume the percentages are by mass following the work of Aneshansley et al. [2]. When the reservoir is squeezed, the mixture of reactants is introduced into the reaction chamber through a valve, which is opened in the first part of the cycle. 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. While the hydrogen peroxide is decomposed with the help of catalase to water and free oxygen, the peroxidase plays a role in oxidation of the hydroquinone. The reaction mechanism [2] can be described with the global chemical reaction:

$$C_6H_6O_2(aq) + H_2O(aq) \longrightarrow C_6H_4O_2(aq) + 2H_2O(l) \quad (1)$$

and it can be described in three main decomposition steps :

$$C_6H_6O_2(aq) \longrightarrow C_6H_4O_2(aq) + H_2(g) \quad (2)$$

$$H_2O_2(aq) \longrightarrow H_2O(l) + \tfrac{1}{2}O_2(g) \quad (3)$$

$$H_2(g) + \tfrac{1}{2}O_2(g) \longrightarrow H_2O(l) \quad (4)$$

Note that eqns. (2), (3) and (4) are not to be regarded as the breakdown of eqn. (1). Rather they represent the salient reactions in a greater number, and the important point is that the sum of the enthalpy changes from eqns. (2), (3) and (4) is equal to that from eqn. (1). The enthalpy of reaction at 25°C for eqns. (2) to (4) are $\Delta H_2 = +177{:}232\ Jmol^{-1}$, $\Delta H_3 = -94{:}5\ Jmol^{-1}$ and $\Delta H_4 = -285{:}5\ J\,mol^{-1}$ respectively. So for the overall reaction (eqn. (1)), one can regard the equivalent enthalpy as the addition of these 3 salient reactions [5] – that is $\Delta H_1 = -202.8\ Jmol^{-1}$. The total heat release for one kilogram of solution is then 794.2 $kJ/kg_{solution}$.

The full kinetic data for these reactions at the concentrations used in the beetle are not readily available, so knowing the energy release, it was decided to major on the post reaction heating and evaporation of the water. The actual mechanism of the catalytic reaction used by the bombardier beetle involves increasing the speed of the reaction of hydrogen peroxide and hydroquinone, by the presence of the enzyme decreasing the activation energies in reactions Eqn. (2a) and Eqn. (2b) at low temperatures, and thereby allowing the exothermic reaction Eqn. (2c) to commence. But much can be learnt about the fluid dynamics of the two phase flow by simply considering the flash evaporation of the water by the diffusion of a scalar to which is associated the equivalent heat release.

Aneshansley et al. [2] measured the mass of ejected liquid and gases and found that it varied from 0.1 mg to 0.5 mg for a single discharge. The correct timing of reactant input followed by catalysis injection and mixing with the products resident in the chamber has a large influence on the output of hot products in our numerical model. It is also found that there is a big effect of the pressure field formed inside the reaction chamber. While the reactant storage and delivery system is driven by muscle contraction, the reaction chamber is rigid, and the beetle does not have any valve mechanism to close or trigger the outlet nozzle. Aneshansley et al. [3] report spectrographic measurements of the discharges using 7 beetles (45 discharges) and concludes that the discharge duration average was 11.9 ms. The actual time elapsed was 2.6 - 24.1 ms; with 2 to 12 pulses per discharge recorded and thus a mean of 6.7 pulses. The frequency of the pulses is reported to range from 368 to 735 Hz, with the mean value at 531 Hz. The average velocity of the spray emerging from the tip of the abdomen of the beetle was measured with a high-speed camera 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.

3 Numerical model

For modelling the discharge mechanism of the Brachini beetles, a finite volume CFD approach was used. We summarise the model used in this section for simulating the hydrodynamics of the two-phase flow out of the heart-shaped reaction chamber using a CFD commercial program CFX version 5.6 beta.

For a description of the flow field, an Euler–Euler approach was chosen following the method of Drew [6], with an ‘inhomogeneous model’ adopted for the water as a continuous phase and water vapour as a set of dispersed bubbles of average diameter *d*. Boiling is modelled with inter–phase mass and heat transfer as described later.

The water is assumed incompressible and the physical parameters are evaluated for saturated water at 100 C and atmospheric pressure (see Table 1). For ease of calculation the vapour is approximated as an ideal gas with density defined by the ideal gas law:

$$\rho = \frac{pW}{RT} \tag{5}$$

and the physical properties are used for saturated water vapour at 100ºC (see Table 1). The heat capacity c_p is a polynomial function of the temperature and the values of the polynomial coefficients are taken from ref. [7].

The calculation is transient with a time step of 1 x 10^{-6} seconds.

Table 1: Water and water vapour thermo-dynamical and fluid flow properties. Specific heat c_p found from [7].

Property	Unit	Water	Water vapour
Density	kg m^{-3}	958.4	Ideal gas law (Eqn. 5)
Dynamic Viscosity	kg $m^{-1}s^{-1}$	2.817×10^{-4}	9.4×10^{-6}
Specific Heat Capacity	J $kg^{-1}K^{-1}$	4215.7	$c_p = f(T)$
Thermal conductivity	W $m^{-1}K^{-1}$	6.791×10^{-1}	1.93×10^{-2}

3.1 Evaporation model

The mechanism used by the Brachina beetle to discharge the hot mixture of chemicals is described above. Since limited information about the reaction kinetics was available, an alternative simplified approach was adopted for the evaporation. The propagation of reaction from the chamber walls is driven by concentration of catalysts in the beetle, and is simulated by the propagation of an inert scalar through the walls. The source of heat was then adjusted through the function of scalar concentration and the temperature of the water.

We suppose the heat input into the domain is high enough to heat the mass of the water in the domain to the boiling temperature 100ºC and that it also provides sufficient energy to evaporate part of the water to steam. Strictly the boiling temperature of course varies with the pressure, but since the changes in pressure are not large [±20 pa], we assume that the boiling temperature is unchanged. We then have the upper limit of the source of heat as:

$$Q_{in} = \Delta H_{tot}\, m\left(T_{sat} - T_o\right)c_{pL}\,\tau^{-1} \tag{6}$$

where ΔH_{tot} is the heat of reaction (see discussion in section 2), m is the mass of water in the reaction chamber (for the calculations we took $m = 9.1 \times 10^{-8}$ kg), c_{pL} is the specific heat capacity of water (4215.7 J $kg^{-1}K^{-1}$) and τ is the time of one pulse (2 ms). With these values, the heat flux Q_{in} is 1.61 x 10^{11} Wm^{-3}.

3.2 Use of the scalar approximation

To simplify the calculations so that we can concentrate on the fluid dynamics of the ejection of the secretion from the reaction chamber of the Bombardier beetle, we establish an approximation of the chemical heat source as a function of temperature and scalar mass fraction. This function has its maximum given by eqn.(6) and goes to zero as the temperature reaches saturation temperature and the scalar mass fraction goes to zero. The function is defined as:

$$S_{heat} = 1.0 \times 10^{-4}\left[1.0 - 6.0 \times 10^{-9} \exp(0.05T)\right] Y_s^4 \rho_L \Delta H_{tot} \qquad (7)$$

where T is temperature, ρ_L is the density of the liquid and Y_s is the mass fraction of the scalar. The graph of the function is plotted against temperature and the scalar in fig. 2.

The heat source is then used in the energy transport equation (not listed here) where an assumed mass diffusivity of $D = 5.0 \times 10^{-5}\ m^2s^{-1}$ is used, so that the scalar propagates through the whole volume of the chamber within 2 ms and provides a source of heat to the volume of water.

The solution method is described in [8] in parallel calculations which apply the principle of hot injection to a larger scale heart shaped geometry using methane as a fuel.

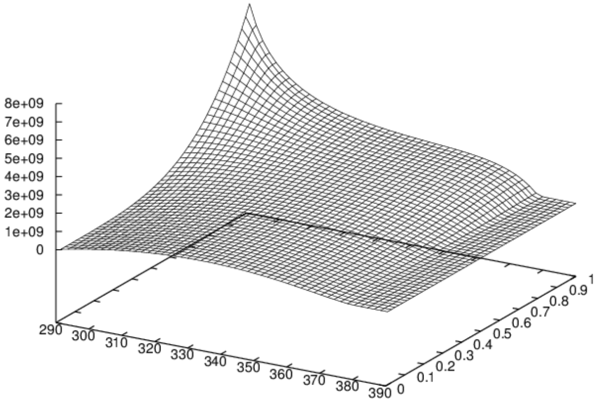

Figure 2: Approximation of heat source as function of temperature and scalar mass fraction (eqn. (7)).

3.3 Computational domain

The data from Aneshansley et al. [2] were used for the definition of computational domain.

The size and shape was deduced form the sketches as well as from scanning electron photographs provided by Professor Eisner. The size and shape of computational domain is shown in fig. 2. For simplicity, the shape is assumed rotationally symmetrical with smooth walls, so that this simplification greatly shortens the computation time.

The computations were not carried out for the whole discharge with repetitive feed of reactants into the reaction chamber, but only for approximately the initial 2ms. The aim was to investigate the effect of the shape of the reaction chamber on the discharge of the products.

The effect of the shape has also been investigated for a scaled up combustor with gas phase methane–air combustion [8, 9]. Results have shown that the heart–shape of the combustor is very important and leads to a larger percentage of mass discharged from the domain than for conventionally shaped chambers.

4 Results

A number of runs were done for different types of geometry, but with the heart shaped combustion chamber fixed. The change in geometry is such that the volume of the combustion chamber matches the volume of beetle calculated by Eisner and co-authors in earlier work [2, 3]. The dimensions used in this work were such that the maximum diameter of the chamber is 0.614×10^{-3}m with the length a similar dimension. The chamber is connected to an outer nozzle, where the diameter of the nozzle was varied from 0.12532×10^{-3}m to 0.2504×10^{-3}m, and the length of the nozzle was varied from 0.683×10^{-3}m to 1.383×10^{-3}m.

The time step used in the calculations was 2×10^{-6} s, and the reaction bringing heat is modelled by a source of heat dependent on scalar concentration, where the scalar is inserted at the wall of the heart shape and set to 0.98 at the wall.

It is found that the nozzle diameter and length are important parameters influencing the pressure inside the chamber. The pressure build up is necessary for the ejection of most of the content of the chamber. The calculation is started with no vapour, only water. Then heat is brought in by the scalar spreading from the walls heating up the water. Then the water and the volume expansion of the steam around the walls causes the ejection of the water and steam out from the domain. Fig. 3 indicates a typical set of water temperature contours at 0.2ms into the explosion.

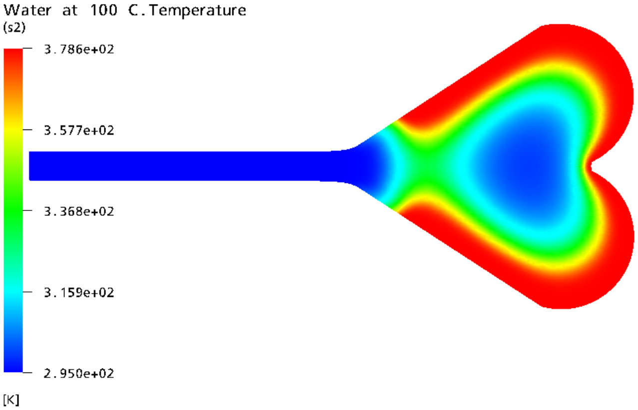

Figure 3: Water temperature contours at 0.2ms.

5 Discussion

The discharge mechanism and the physical background of the mechanism are discussed here. The rate of the reactions used by the reaction chamber of the beetle are in fact heavily dependent on the concentration of the catalysts propagating from the walls of the chamber. But the actual discharge is caused by the evaporation (not the initial catalytic reaction) and consequent steam explosion which then is released out of the anus tube of the abdomen. The role of the initial catalytic reaction using catalase and peroxidase is in generating the heat sharply enough to cause the evaporation to take place. The effect of the sudden evaporation is a push-out mechanism from the reaction chamber walls. The time for this to take place is approximately the cycle time of the discharge observed by Aneshansley and Eisner in the experiments of [3]. Eisner and co-workers also found [2] that the temperature of the discharged mass is constant, which therefore indicates that the whole volume of the solution is heated up before the actual discharge takes place. The catalytic reactions are therefore triggered at an extremely rapid rate (less than 10^{-5} s) in the whole volume, such that the energy is released into what is predominantly water. The notion of mini steam explosions is also borne out by the oscillatory nature of the discharge observed in the experiments. The cycle time of each explosion is in the region of 2-3 ms, and the mechanism acts somewhat like a pulse combustor, whereby the low pressure after each discharge effectively opens the valve upstream of the chamber to allow more fuel (hydrogen peroxide and hydroquinone) into the chamber before the next burst of catalyst causes heat to be generated and another steam explosion occurs.

Table 2: Efficiency of mass ejection for different geometries.

geometry	volume of the geometry m^3	mass released [kg]	% released
D min L short	3.65293E-11	2.00E-08	57.088%
D min L long	4.16458E-11	3.42E-08	77.342%
D max L short	3.99516E-11	2.08E-08	54.380%
D max L long	4.61946E-11	2.08E-08	52.218%

5.1 Different nozzle geometries

Table 2 shows the amount of mass of water/steam is released for the four geometries at 11.5 ms and fig. 4 illustrates the transient mass ejection for each of the four geometries considered. The plot indicates that a narrow and long nozzle is the most efficient for ejection. It is also found that the pressure build-up needed for the release of the material is delayed if the nozzle is too short and wide. Getting this combination right leads to a marked increase in the speed of ejection of the material. Notice also the large oscillatory behaviour in the first few milliseconds for the inefficient cases.

5.2 Spray formation

The details of the formation of the spray is beyond the scope of this present paper, which is mainly concerned with modelling the evaporation and subsequent discharge of the steam / water mixture from the reaction chamber. However we can make some limited observations, as follows.

As the hot solution with some steam is pushed out from the reaction chamber, it meets the stream from the neighbour chamber and a single stream then emerges from the tip of the abdomen. There are several factors playing a role in the spray formation. The surfaces of the channels, are not smooth, causing the higher friction. Thus it is found that the shape of the end of the nozzle plays an important role. The high velocity together with non-uniform concentration of steam are the main factors helping to create a fine spray from the outlet solution.

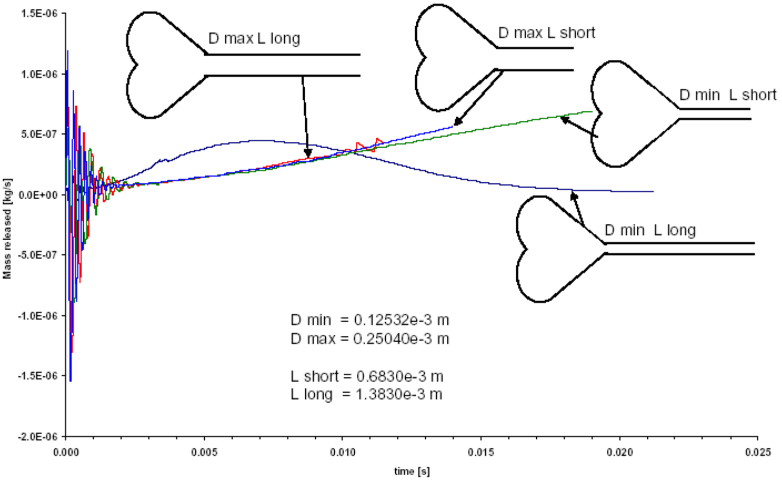

Figure 4: Mass released from different nozzle geometries.

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