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ABSTRACT

In this note it is pointed out that some explosions associated with shallow submarine vulcanism belong to a wider class of events called fuel-coolant interactions (FCI) which are a well-known industrial hazard.

Submarine volcanic hydroexplosions fall into at least two classes:

(i) 'McBirney' hydroexplosions caused by the rapid expansion of water already present in the magma. These can occur down to some limiting depth d_{McB} which is a function of the original water content of the magma.

(ii) FCI, involving the thermal interaction between sea water and the emerging hot lava. This can occur down to a threshold depth d_{th}, below which the ambient pressure inhibits the interaction. An estimate is made of d_{th}.

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Most volcanic explosions are caused by the inner pressure from within the earth's crust; however, some marine volcanoes are more violent and have a character different from volcanoes in apparently similar circumstances on land. Volcanic eruptions in shallow water have associated "hydroexplosions" and we wish to point out that these belong to a wider class of events called fuel-coolant interactions (FCI) which can occur industrially; e.g. between molten steel and water in iron foundries, between molten aluminium and water in smelting works and between water and liquified natural gas if spillage occurs. Some authors use the terms 'thermal interaction' and 'vapour explosion' instead of FCI. In this paper we illustrate the circumstances under which shallow submarine vulcanism produces hydroexplosions, we indicate what characterises industrial FCI, and using a recent theoretical model we calculate the maximum depth at which hydroexplosions in the form of FCI can occur.

The emergence of the new volcanic island Surtsey provided an opportunity for detailed study of shallow submarine vulcanism. Initially jets of tephra rose to heights of about 150 m every 30 seconds or so. These black jets had a distinctive shape, "cypressoid" or "cock's-tail", and were accompanied by clouds of steam[1,2,3]. During subsequent months these so-called hydroexplosions occurred whenever the sea had easy access to the vent from which the lava emerged. The explosions occurred at irregular intervals varying from a few seconds to a few minutes. After six months, the cone of tephra became coated with a wave resistant skin of lava, which excluded water permanently from the vent; hydroexplosions then ceased. The character of the explosions clearly was governed by the ease of access of external water into the vent[2].

The 1957 Capelinhos eruption also involved hydroexplosions[2]. The vent was submerged during the early part of the eruption and contact of the rising magma with the sea water resulted in violent hydroexplosions. Later the eruption provided a clear indication of the importance of water in the explosions. Two vents were simultaneously active - one above water producing mild Strombolian eruptions and one below water producing explosions and cypressoid jets[4].

At Krakatoa it is hard to estimate the importance (if any) of hydroexplosions in the great eruption of 1883. However, when activity resumed it consisted of cypressoid explosions until the island Anak Krakatoa was built above water; when this had been destroyed by wave action, the explosions recommenced. This cycle of activity was finally broken after 30 years when lava overflowed from the crater and coated the cone[5]. Just prior to that, although the core was 350 feet high and the vent shielded from the sea, the cone was sufficiently permeable for sea water to enter the vent, and cypressoid explosions continued to occur intermittently[6].

The accidental spillage of molten materials onto water or wet surfaces is a well-known industrial hazard[7,8,9]. For example, when 25,000 lbs. of molten steel accidentally fell into an open trough of water, the resulting explosion was heard three miles away[8]. Witte et al.[10] give a number of other illustrations of FCI from the metal industry, and it is possible that an FCI was involved in the recent fatal explosion in Scotland when 50 tons of molten steel was being poured into a mould[11]. The trapping of water and its sudden conversion into pressurised steam is believed to be an essential ingredient of such explosions.

Several instances have been reported of violent interactions

occurring during spills of liquefied natural gas (LNG) onto water[12,13].

In experiments supported by the U.S. Bureau of Mines, violent inter-
actions were deliberately produced, and in one case 265 litres of
LNG were spilled onto water. The resulting explosion occurred
∿ 0.1 sec after LNG/water contact.

The essence of an FCI is that two molten materials, one (the
fuel) much hotter than the other (the coolant), suddenly come in
contact in such a manner that rapid heat transfer takes place to the
cooler material which vaporises and expands explosively; physical
rather than chemical processes are involved, and a large amount of
thermal energy is transferred from the fuel to the coolant. To
effect this rapid transfer within the observed timescale of the
explosion (a few tens of milliseconds for metal/water explosions) an
extremely large contact area between fuel and coolant is needed if
normal heat fluxes occur.

Most volcanic eruptions are driven by pressure from within the
crust. However, an underwater volcano can bring hot molten magma in
contact with water and consequently we believe that some submarine
hydroexplosions are examples of FCI. In addition, when magma from a sub-
aerial volcano runs down to the sea, FCI take place in the form of
small 'popping' hydroexplosions producing littoral cones.

Board et al.[14] and, independently, Buchanan and Dullforce[15]
have recently proposed a model for FCI in which five stages can be
discerned: an initial perturbation which causes a bubble to form in
the coolant; the expansion of the bubble and subsequent collapse
producing a high velocity jet of coolant which penetrates into the
fuel; the break-up of that jet of coolant within the fuel thereby
increasing the contact area; the simultaneous heat transfer to the

jet; and the vaporisation and the formation of a new high-pressure bubble. The process is then repeated cyclically. Under suitable circumstances the maximum bubble size at each cycle increases with time and the overall heat transfer increases rapidly. Buchanan and Dullforce predict that the strength of the interaction is reduced as the external pressure is increased and that there exists a threshold pressure above which the interaction cannot occur.

Submarine vulcanism provides a testing ground for this model. The pressure in the sea increases at the rate of 100 bars per kilometer to about 500 bars maximum. If pressure can inhibit FCI there must be a depth below which such hydroexplosions do not occur.

Buchanan[16] has shown that the threshold pressure, P_{th}, is given by

$$P_{th} = \frac{3\alpha^3}{1 + \alpha + \alpha^2} \, P_i \qquad \ldots (1)$$

where P_i is the pressure at which the new bubble is formed during each cycle and

$$\alpha^3 = \frac{3}{16} \, \beta \, d_c^2 \, L_c \, \frac{\rho_c}{\rho_\ell} \qquad \ldots (2)$$

where L_c and d_c are constants which determine the jet characteristics. For bubble collapse adjacent to a solid wall L_c and d_c can be found from Plesset and Chapman's[17] work to be about $\frac{1}{2}$ and $\frac{1}{4}$ respectively. ρ_c is the initial density of the coolant and ρ_ℓ is the saturated liquid density of the coolant at the temperature at which the bubble is formed. β is a numerical factor dependent on the method of vaporisation. For heterogeneous nucleation (i.e. normal vaporisation at the saturation temperature) β is unity; for homogeneous nucleation (the method of vaporisation as envisaged by the LNG/water explanations) β is 0.33 for an ambient pressure

of 1 bar and decreases as the ambient pressure is increased. An upper
limit for P_i can be found as follows. Let the saturated vapour and
liquid densities be ρ_v and ρ_ℓ and the vapour pressure be P_v.
Since the density cannot change instantaneously from ρ_ℓ to ρ_v we
suppose that the expansion occurs adiabatically. Thus, using the
normally accepted γ value for water, 4/3, P_i can be found. The
implicit equation for P_{th}, eq.(1), can be solved by iteration giving
P_{th} = 67.5 bar (heterogeneous nucleation) or 13 bar (homogeneous
nucleation).

In terms of a critical depth, d_{th} corresponding to the thres-
hold pressure, this limiting case corresponds to

$$d_{th} = \begin{cases} \sim 700 \text{ m;} & \text{(heterogeneous nucleation)} \\ \sim 130 \text{ m;} & \text{(homogeneous nucleation)} \end{cases}$$

Earlier authors have obtained other estimates of a maximum depth
for hydroexplosions. A limiting value can be obtained by noting that
the critical point of water is such that the critical pressure of
water (216 bars) corresponds to a depth of about 2 km. Below that
depth there is only one water phase and quiet effusions of lava are
to be expected[18,19].

McBirney[19] considered hydroexplosions caused by the expansion of
water already present in the magma. He found that the maximum depth
at which explosive eruptions can occur was a function of the original
water content of the magma and over 2% water content would be required
to form ash at a depth of 2 km. On the basis of Friedman's[20] figures
for laboratory and field measurements of original water content
($\sim 0.1\%$) he concluded that if the magma was originally at 1000°C, a
realistic temperature[21], then explosive eruptions would not occur
at depths greater than 500 m. McBirney's results depend on an expli-
cit assumption of his - that sea water surrounding the lava will be

vaporised but will not cause significant vesiculation within the lava. Buchanan and Dullforce's model for FCI involving cyclic bubble growth and water injection due to high velocity jetting provides a mechanism which is capable of locally raising the water content of the magma to high levels, and does not depend on the solubility of the magma.

Thus submarine hydroexplosions fall into at least two classes:

(i)   'McBirney' hydroexplosions, which can occur down to some limiting depth d_{McB} which is a function of the original water content of the magma;

(ii) FCI, which can occur down to the threshold depth d_{th}, below which the ambient pressure inhibits the interaction.

It is interesting to remark that the criterion used to decide in some laboratory experiments[16] whether the FCI explosion was violent or not is the fraction of metal finely divided. If further development of the theory enables the size of the fragments produced to be correctly predicted, then the size of the glassy granules found by Tazieff[22] in Ethiopia may enable the violence of the explosion that produced them to be estimated.

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