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Vapour explosions (fuel-coolant interactions) resulting from the sub-surface projection of water into molten metals: preliminary results *injection*

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VAPOUR EXPLOSIONS (FUEL-COOLANT INTERACTIONS) RESULTING
FROM THE SUB-SURFACE INJECTION OF WATER INTO MOLTEN METALS:

PRELIMINARY RESULTS

R.C. Asher, D. Bullen and D. Davies

ABSTRACT

Preliminary experiments are reported on the relationship between the injection mode of contact and the occurrence and magnitude of vapour explosions. Water was injected beneath the surface of molten metals, chiefly tin at 250 - 900°C. Vapour explosions occurred in many, but not all, cases. The results are compared with Dullforce's observations on the dropping mode of contact and it appears that rather different behaviour is found; in particular, the present results suggest that the Temperature Interaction Zone is different for the two modes of contact.

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2	Experimental equipment used for the sub-surface injection of water into molten tin. (Ready to inject)
3	Comparison of dropping mode and injection mode of contact for tin-water

1. Introduction

The term Fuel-Coolant Interaction (or Vapour Explosion) refers to the violent interaction which sometimes, but not always, occurs when a hot, non-volatile liquid is brought into contact with a cooler volatile liquid. The violent interaction is physical rather than chemical in origin, and results basically from the rapid production of a large volume of vapour of the volatile liquid. Spectacular and highly damaging examples have occurred in foundries when liquid metal has inadvertently come into contact with water.

In the nuclear field, interest centres on the remotely conceivable accident in which molten fuel comes in contact with the coolant and a vapour explosion follows; hence the expression Fuel-Coolant Interaction has been adopted. Molten uranium dioxide at above $\sim 2900^{\circ}\text{C}$ and liquid sodium at $\sim 600^{\circ}\text{C}$ could be the interacting pair of liquids in the case of a sodium-cooled fast reactor, but the interaction between molten stainless steel (from the cladding) and liquid sodium is also of great interest for that reactor. Different 'fuels' and 'coolants' are significant for other reactor systems.

Experimental work using fluids of direct relevance to reactors (eg the UO_2/Na system) is not easy but nevertheless is being undertaken at several UK laboratories, including Harwell. However, much of the experimental work in progress world-wide utilises 'modelling' liquids instead of real 'fuel' and 'coolants'. For example, molten tin is frequently used to simulate the fuel, and water to represent the coolant. Modelling experiments of this type are the foundation of many of the theoretical interpretations of the mechanism of FCI; in the UK they are being carried out by Culham⁽¹⁾, the CEBG⁽²⁾, Harwell⁽³⁾ and elsewhere.

One important observation of the Culham work carried out by Dullforce and colleagues⁽¹⁾ is that, in the tin-water system, FCI's occurred only in a range of fuel and coolant temperatures defined by a Temperature Interaction Zone (TIZ). If either (or both) the 'fuel' temperature t_f or the 'coolant' temperature t_c are outside the TIZ, violent interaction does not occur (Fig. 1). The precise position of the fuel temperature threshold line AC depends on the mass of fuel and the figure of approximately 300°C shown in Fig. 1 relates to 12 g of tin. Decreasing the mass has a considerable effect on the threshold temperature, which increases rapidly becoming $\sim 500^{\circ}\text{C}$ with 4.3 g tin and $\sim 700^{\circ}\text{C}$ with 2.3 g tin. Experimental evidence on the effect of increasing the mass is not available but there are theoretical grounds for expecting a slight decrease in the threshold temperature. It was also

found that, within the TIZ, the violence of the interaction increases as the conditions become closer to the line AB. Beyond AB there is an immediate cessation of vapour explosions.

These conclusions were reached from simple experiments in which molten tin (normally ~ 12 g) at $t_f^{\circ}\text{C}$ was tipped into a vessel containing ~ 4 kg of water at $t_c^{\circ}\text{C}$. There are untested theoretical arguments⁽⁴⁾ which suggest that the occurrence of a vapour explosion in a given system could be determined by the mode of contact and in particular by whether a small volume of 'fuel' is poured into a larger volume of 'coolant' or a small volume of 'coolant' is injected into a considerably larger volume of 'fuel'.

The present work was initiated at Harwell with the intention of establishing whether a different TIZ is obtained when a small quantity (1 ml) of water is injected into molten tin and other metals. The experiments bear a direct relationship to a more ambitious Harwell programme of injecting a similar quantity of liquid sodium into molten stainless steel or molten uranium dioxide; preliminary experiments on the stainless steel/sodium system have already been performed⁽⁵⁾.

2. Experimental

The apparatus is shown in Fig. 2. The water was injected below the surface of the molten metal by a device which was essentially a hypodermic syringe full of water. Removal of the locking pins shown in the figure releases a compression spring which then performs two successive functions. Firstly, the injector tube is rapidly lowered into the molten metal. Secondly, the plunger of the hypodermic syringe strikes the adjustable 'anvil' forcing the piston into the cylinder by a controlled distance and expelling 1 ml of water from the nozzle.

High speed cine-photography of the equipment in operation, using ink instead of water and liquid paraffin instead of tin, showed that the time taken for the end of the nozzle to travel from the surface of the fuel to the point at which injection started was 7 ms; the nozzle was then typically 18 mm beneath the surface. A further 134 ms was required to inject the water and during that period the nozzle descended another 5 mm. The nozzle diameter was 2 mm, the velocity of injection 240 cm sec^{-1} and the Weber number was ~ 1000 ; hence it is to be expected that the jet of water will break up into small droplets (diameter $\sim 150\mu$) a few mm below the end of the nozzle.

In all the reported experiments the injector unit was kept well away from the unit containing the molten tin and only moved into position at the last moment. This ensured that the water in the nozzle did not boil prematurely. Calculations show that the increase in temperature of the water in the nozzle, due to immersion in the molten tin for the short time (~7 ms) before injection commenced, was negligible.

Degassed water was used throughout and care was taken to displace all air from the nozzle before injection. Oxidation of the molten tin in the crucible was minimised by using argon/2% hydrogen as a cover gas.

The violence of the interaction was assessed semi-quantitatively from the amount of tin expelled from the crucible and also, more subjectively, from the noise.

A series of thirty-one experiments was carried out in which the temperature of the tin was varied in the range 250 - 900°C; the weight of tin was not varied systematically and was, except when stated otherwise, between 300 and 350 g. No significant variation of the temperature of the water was possible in these preliminary experiments and therefore a constant temperature of 22°C was used. Two exploratory experiments were performed in which different amounts of tin and water were used. In the first the weight of tin was reduced to 100 g but the normal volume of water (1 ml) was used. In the second not only was the weight of tin reduced to 100 g but also the volume of water was decreased to 0.5 ml.

In addition to the programme on liquid tin, experiments were carried out in which water was injected into liquid lead and liquid aluminium in the temperature ranges 350 - 500°C and 790 - 920°C respectively.

3. Results

The results for the tin-water system, the lead-water system and the aluminium-water system are given in Tables 1, 2 and 3 respectively.

4. Discussion

Tin

Fig. 3a shows the results of the present experiments superimposed on a graph of the TIZ taken from Dullforce's work. There are three striking features.

a. As the temperature of the tin in our experiments was increased there was no violent interaction until a threshold 'fuel' temperature of

300°C was reached; at this temperature a violent vapour explosion occurred. The observed threshold fuel temperature agrees precisely with the figure of 300°C which would be predicted from Dullforce's results. These refer, however, to experiments with no more than 12 g of tin compared with ~300 g used in the present work and it is not known how much the threshold temperature decreases with increasing mass of tin; simple theoretical grounds⁽⁶⁾ suggest that the threshold temperature might be as low as 240°C for 300 g of tin but other factors may prevent the threshold temperature falling as low as this (T. Dullforce; personal communication). It appears therefore that the increase in threshold temperature for the injection mode of contact compared with the dropping mode is at most 60°C and may be considerably less.

b. No violent interactions were ever observed when the tin temperature was above 450°C. This contrasts very strongly with Dullforce's observation that with the dropping mode of contact violent interaction occurs with tin temperatures up to 1000°C.

c. At an intermediate temperature (380°C) no violent interaction was found despite the fact that at only slightly higher or lower temperatures (390°C and 360°C) quite significant explosions did occur, resulting in more than half of the tin being expelled from the crucible. The absence of the violent interaction at 380°C was reproducible and was observed in each of three experiments.*

d. Fig. 3b shows how the violence of the interaction, expressed in the arbitrary and subjective units used in this work, varies with tin temperature. The absence of violent interactions below 300°C and above 450°C and at the intermediate temperature of 380°C are well illustrated and it appears reasonable to assume that violence of interaction rises to fairly sharp maxima in the ranges 300 - 350°C and 390 - 450°C.

e. The weight of expelled tin (a measure of the explosive force) tends to increase as the temperature of the tin is increased (but within the TIZ), as was found in Dullforce's work.

f. The preliminary results on the effects of varying the volume of water and the weight of tin given in Table 1b strongly suggest that there is an important relationship but there are too few results to draw firm conclusions about trends.

*Subsequent experiments, using a similar, but not identical, technique gave violent interactions even at 380°C. These experiments and their implications will be discussed in a forthcoming memorandum.

Lead and Aluminium

The results in the lead-water and aluminium-water systems given in Tables 2 and 3 demonstrate that the interaction was, at worst, only mild. The ratio of fuel/coolant in the aluminium experiments was ~100/1; a similar ratio in the tin experiments also gave no vapour explosion. However, in contrast the high ratio in the lead experiments (~500/1) gave no vapour explosion.

5. Conclusions

- a. Violent vapour explosions can occur when water at 22°C is injected into molten tin.
- b. The violent interaction occurred only if the tin was in the temperature range 300 - 450°C but even within this range there was an anomalous but apparently reproducible observation that no explosion took place when the tin temperature was 380°C.
- c. It appears therefore that the injection mode of contact results in different vapour explosion behaviour than does the dropping mode of contact. In particular the Temperature Interaction Zone derived from dropping experiments is not applicable to injection experiments.
- d. For the injection mode of contact the violence of the interaction seems to depend on the relative volumes of the tin and the water.
- e. For the lead-water and aluminium-water systems no violent interactions have been found in exploratory experiments over the temperature ranges 350 - 500°C and 790 - 920°C respectively.

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TABLE 1

Fuel-Coolant Interactions resulting fromSub-surface Injection of Water into Molten Tin1a. Results for 1 ml water into ~300 g tin

Water Temperature: 22°C. Injection depth: 18 mm.

Tin Temperature (°C)	Tin Expelled % TOTAL	Violence of Interaction
250	<1.7	0
270	<1.7	0
290	<1.7	0
300	70	4
310	60	2
330	70	4
350	63	2
360	53	2
370	55	1
380	<1.7	0 (a)
390	67	2
400	92	4 (b)
410	98	3
420	65	2
430	60	2
440	95	4
450	<1.5	0 (a)
500	4.5	0
600	<1.5	0
700	10	0
800	<1.5	0
900	<1.6	0

0. Boiling only - no violent interaction

1. Weak interaction

2. Mild interaction

3. Moderate interaction

4. Violent interaction

(a) Three injections; no violent interaction

(b) Six injections; all caused violent interaction

1b. Effect of varying volume of water and weight of tin (preliminary results)

Water temperature: 22°C. Injection depth: 18 - 20 mm.

Tin temperature: 400°C.

Tin Weight (g)	Tin Volume (ml)	Violence of Interaction
100	1	0
310	1	4 (cf Table 1a)
100	0.5	2

TABLE 2

Fuel-Coolant Interactions resulting fromSub-surface Injection of Water in Molten Lead

Water temperature: 22°C. Water volume: 1 ml.

Lead Temperature (°C)	Lead Weight (g)	Injection Depth (mm)	Lead Expelled (%)	Violence of Interaction
350	500	18	7	0
400	500	18	17	1
400	450	14	10	1
450	450	14	18	0
500	500	20	30	0

TABLE 3

Fuel-Coolant Interactions resulting fromSub-surface Injection of Water into Molten Aluminium

Water temperature: 22°C. Water volume: 1 ml.

Lead Temperature (°C)	Aluminium Weight (g)	Injection Depth (mm)	Aluminium Expelled (%)	Violence of Interaction
790	105	15	<5	0
810	100	15	<5	0
830	100	15	<5	0
850	100	15	<5	0
920	125	15	10	0

Fig. 1 TEMPERATURE INTERACTION ZONE FOR TIN DROPPED INTO WATER. (Taken from Culham report CLM P424.)

Fig. 2 EXPERIMENTAL EQUIPMENT USED FOR THE SUBSURFACE INJECTION OF WATER INTO MOLTEN TIN (Ready to inject)

Fig.3 COMPARISON OF DROPPING MODE AND INJECTION MODE
OF CONTACT FOR TIN-WATER.

Fig.3a

Fig.3b