THE EFFECT OF THERMAL CONDITIONS AND JET PROPERTIES ON STEAM EXPLOSION

I. Baruch1, G. Widenfeld2

1Ben Guriun University of the Negev, Ben Guriun 1, Beer-Sheva, Israel

2NRCN, Israel

idanbaro@post.bgu.ac.il; galitm@post.bgu.ac.il

ABSTRACT

Coolant injection (CI) into a pool of molten metal might leads to Steam Explosion (SE). This study, experimentally investigates the effects of thermal conditions and jet dynamic properties on the SE phenomenon in coolant injection mode of contact. The experiments conducted in a close vessel using a water jet injected into 2 to 4.5 kg of pure molten metals, such as: Aluminium (Al), Tin (Sn) and Bismuth (Bi). The melt initial temperatures ranged between 300[℃] - 900[℃], and the water temperatures varied from 25[℃] to 70[℃]. The influence of the melt and water initial temperatures, was first investigated by using Thermal Interaction Zone (TIZ) map as Dullfore et al[1] suggested. However, experiments inside the TIZ boundaries did not end in explosion, as been expected. Moreover, outside the TIZ boundaries in some cases explosions did occur. These observations indicate that other parameters, that did not took into account in the TIZ map (Dullfore et al[1]), are affecting the likelihood of the phenomena to occur, such as: the jet dynamic properties, the injection method (thin spray or jet). The effect of hydrodynamic instabilities also examined by using two adjacent parallel water jets. These experiments show higher-pressure pulse in shorter delay time. This fact indicates that there is a significant influence of the hydrodynamic instabilities on the mixing phase and vapor film stability. The current study presents a new method to predict steam explosion by using TIZ boundaries together with the dynamic properties.

KEYWORDS

Steam Explosion, Coolant Injection, experimental study.

1. INTRODUCTION

Violent thermal interactions resulting from the sudden contact of a cold vaporizable liquid and a hot liquid may cause high-pressure explosions. Understanding Steam explosion phenomena is important since such explosive interaction might risk the reactor structure and the containment integrity, the environment for years to come. Cooling the melt using water injection might cause strong steam explosion in given conditions.

Fuel Coolant Interaction (FCI) can be form in one of these scenarios: Melt Injection (MI), Coolant Injection (CI), and Free Fall Melt Drop (FFMD) into coolant. The different scenarios differ in the method of the contact between the melt and coolant. TIZ (Thermal Interaction Zone) map is the most conventional method to display the initial conditions leading to SE (see fig. 1) [1]. These maps depict the areas where SE occur or does not occur depending on the initial melt and water temperatures. TIZ theoretical boundaries commonly defined as melting point (MP) temperature or homogenous nucleation (HN) temperature and minimum film boiling (MFB) temperature, at the interface temperature (Ti) between the liquids. Where Ti expressed as,

$$T_i = T_{jet} + \frac{T_{melt} - T_{jet}}{1 + \beta} \quad , \quad \beta = \sqrt{\frac{(k \cdot \rho \cdot Cp)_{jet}}{(k \cdot \rho \cdot Cp)_{melt}}} \tag{1}$$

Tjet and Tmelt present the jet and the melt temperature respectively

The minimum film boiling temperature (T_{MFB}) expressed as V. K. Dhir and G. P. Purohit [2] suggested:

$$T_{MFB} = 201 + 8(T_{sat} - T_{jet}) \tag{2}$$

This form is commonly used in many researches ([1, 3, 5]) to estimate the minimum film boiling temperature.

Fig 1 presents Thermal interaction zone (TIZ) Map for Tin – water system. The TIZ Map presents the water temperature vs. the melt initial temperature and defines the conditions under which a steam explosion will occur. At the first moment of contact between high temperatures melt and water, the two liquids separate by a stable layer of vapor. Then the vapor film locally collapse due to local temperature decrease, allowing a direct contact between the two liquids that may generates explosive reaction. The water temperature remains almost constant due to the large water mass compared to the melt mass (red arrow in fig.1). In CI configuration, the cold liquid temperature continues to rise with the jet penetration while the melt at the interface cooled down (black arrow in fig. 1). A stable vapor layer is expected to be created due to the increase in water temperature and prevent SE to occur. According to hydrodynamic instabilities the vapor layer stability impaired by local film vapor collapsing.

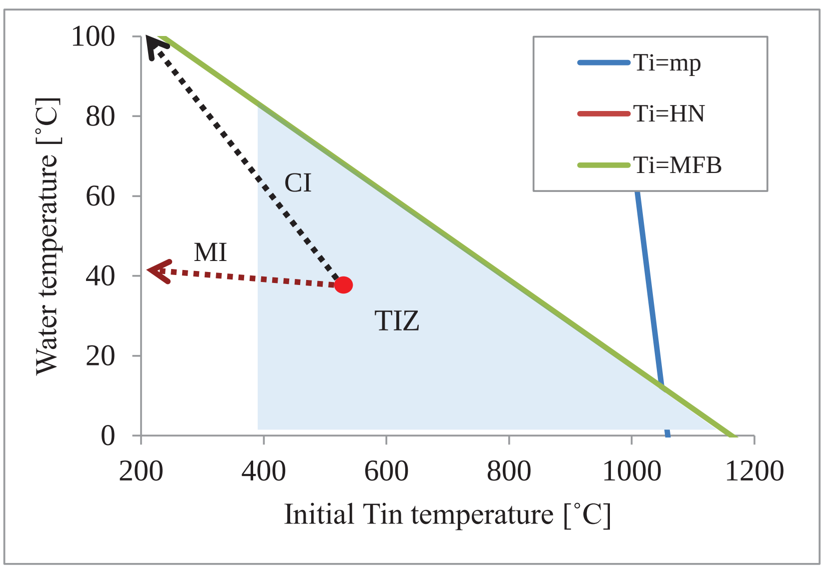


Fig. 1: Thermal interaction zone, TIZ (Tin – water system)

Due to the complexity of the CI experimental system, there is a lack of experimental data in the literature. Therefore, CI experiments results usually have been compared with the TIZ boundaries that found for a melt dropped into water. Although the TIZ map analysis is commonly used, this map does not provide sufficient information of other parameters affecting the feasibility for SE to occur in CI mode. Parameters like jet diameter and velocity, coolant and melt thermal conductivity, specific heat, melting temperature, density, surface tension, latent heat, melting point and more, do not take into consideration.

The influence of the jet dynamic properties and the material properties is complex, since in the CI contact mode several processes are involved mainly during the pre-mixing phase and the triggering stage. The influence of these parameters may change the results of FCI from stable film boiling through mild reaction to high-pressure steam explosion. The following affect the CI contact mode:

- Injection method – High-speed jet injection enables the coolant to penetrate deeper into the molten metal and creates larger water volume inside the molten metal. While thin spray creates only a thin film of coolant on the melt surface without penetration.
- Jet velocity - Jet velocity affects the depth of water penetration and the liquids mixing quality. High velocity increases the hydrodynamic perturbations and as a result, the mixing quality rises as well.
- Coolant flow rate – Coolant flow rate affects the molten metal cooling rate. Higher flow rates allow faster cooling process.
- Surface tension – High surface tension of the molten metal may decrease the liquids mixing quality. Low velocity jet may not penetrate the melt due to the lack of inertial energy compared to the surface tension.. In case that the jet did penetrate the melt, high surface tension may create smooth surface at the liquids interface, decreasing the mixing quality.
- Melt - coolant density ratio – High melt - coolant density ratio increases the resistance of the melt to be penetrated by coolant and increases the buoyancy forces acting on the coolant and vapor inside the melt.
- Thermal conductivity – High thermal conductivity of the melt encouraging fast heat transfer from the melt to the mixing area, which improves the stability of the vapor layer around the coolant and delaying the crust formation at the interface.
- Thermal inertia – The resistance of a material to temperature change In this study β represent the thermal inertia ratio of coolant and melt $\frac{(\sqrt{k\cdot\rho\cdot Cp})_c}{(\sqrt{k\cdot\rho\cdot Cp})_m}$). Material with high thermal inertia will be less influenced by temperature changes, caused by the coolant jet.
- Solidification rate – Material with high Solidification rate creates crust that prevents the direct contact between the two liquids.
- Melting temperature – Low temperature melting point increases the chances that the metal will be in liquid form at the moment of contact with the water at the time of quenching.

The above list is not complete, but emphasizes some of the reciprocal relations between the dynamic properties, thermal conditions and material properties. These hypotheses will be discussed and analysed experimentally in this study.

2. EXPERIMENTAL ARRANGEMENT

The affecting parameters list that has been reviewed above shows that the jet dynamic properties, initial thermal conditions and the material properties have great effect on the phenomena lead to SE. In order to understand the effect of each one of those parameters, an experimental apparatus was used with three different well-known materials (Aluminium, Bismuth and Tin) in wide range of temperatures, jet velocities and diameters with different methods of coolant injection.
A schematic view of the experimental apparatus is present in fig 2. The apparatus include a furnace (capable of a maximum temperature of 1470 K) that has been used to heat the material placed in the crucible up to the initial temperature that was required, a pressure vessel in which the experiment is performed, water vessel (tank) and measuring system.

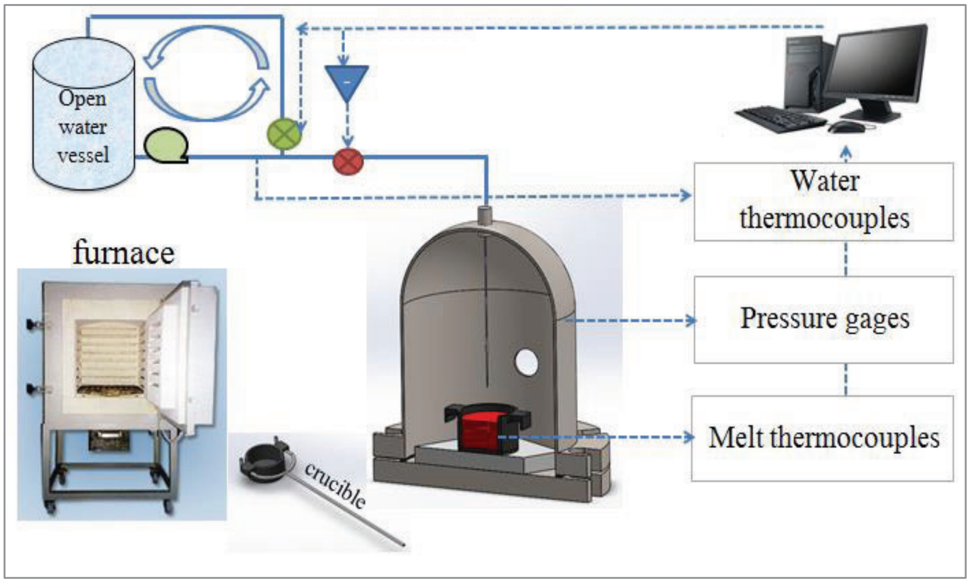


Fig. 2: Schematic view of the experiment system.

The tested metal was placed inside a grey cast iron crucible (inner diameter 100 mm, height 80 mm, wall thickens 6mm). In order to measure the temperature of the molten metal inside that crucible, 4 thermocouples were located along a stainless steel (3 mm) wire as shown in fig 3.

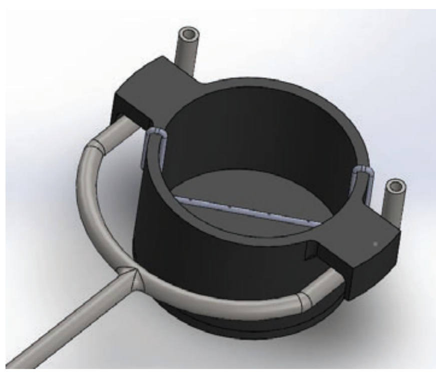


Fig. 3: Crucible with thermocouples fixture.

The heated crucible was transferred to the experiment vessel and set on thermal insulated ceramic brick. When the crucible set in place, three operators close the vessel using bridge crane to lower the vessel top toward the base, and seal the vessel with eight bolts. Due to the high risk of injury from melt splashes, the command to open the injection valve done remotely from protected workstation.
The water temperature and pressure are pre-set to the desirable value. While the system is in a standby mode, the water circulates, in order to maintain the initial temperature near the injection line. Steam line enables to heat the water in the vessel, and the temperature was monitored. The water jet injected towards the center of the crucible from a nozzle located 50 mm above the melt surface. The jet nozzles made from stainless steel tube, inner diameter: 1.8mm, 3.2mm and at length of 180 mm.
Both the water and melt temperature monitored by sheeted chromel - alumel thermocouples using a data logger. Water temperature measurements placed at the water vessel and at the circulation loop near the injection line.
The pressure built up in the vessel measured with piezoelectric absolute pressure gage (capable of 80 kHz rate), and another Piezoelectric differential pressure gage (capable of 80 kHz rate) measured the pressure pulse at the time of explosion.

3. METHOD AND CONDITIONS

The experiment method divided into 3 different parts that check different parameters and eliminate unnecessary experiments. At first, the three materials tested inside the TIZ boundaries, the velocity of the jet set to maximum (20 m/s, 1.8 mm diameter) in order to ensure water penetration into the melt. The second part tested the jet dynamic properties inside and outside the TIZ boundaries. At last, different method of water injection were tested, including two parallel jets, Water spraying and a single jet injected alternately. The use of three different materials adds knowledge about the material properties influence. The experimental conditions are shown in Table 1.

Table 1: Experimental conditions

Material	Melt temperature	Water temperature	Melt mass	Water mass
Tin	360 to 580 ℃	25 to 70 ℃	2 to 4 kg	500 g
Bismuth	320 to 670 ℃	25 to 60 ℃	1 to 4.5 kg	500 g
Aluminium	750 to 850 ℃	25 to 30 ℃	0.8 to 2.5 kg	500 g

The injection methods are shown in table 2.

Table 2: Water injection methods

Injection method	Materials tested	Jet diameter	Jet velocity	Flow rate
Single water jet	Al, Bi, Sn	1.8, 3.2 mm	5 to 20 m/s	1 to 3 liter/min
Two adjacent parallel jets	Al, Bi, Sn	1.8 mm	4 to 8 m/s	1 to 3 liter/min
Single jet injected alternately	Al	1.8 mm	5 to 20 m/s	1 to 3 liter/min
Water spray	Al, Bi, Sn	3, 5.6 mm	NA	2 to 5 liter/min

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. EXPLOSION INTENSITY INDICATORS

The indicators for explosion include the pressure pulse, the melt splatters and the sound of explosion. Fig. 4 demonstrate the typical pressure pulse measured at experiment in which the SE occur (B1.1) compared with experiment in which SE not occurred (B1.2). The pressure pulse is well seen in experiment B1.1, 0.15 seconds after the injection started, another explosion occurred after 0.6 sec. Experiment B1.2 show a moderated pressure increase due to the vapor generation.

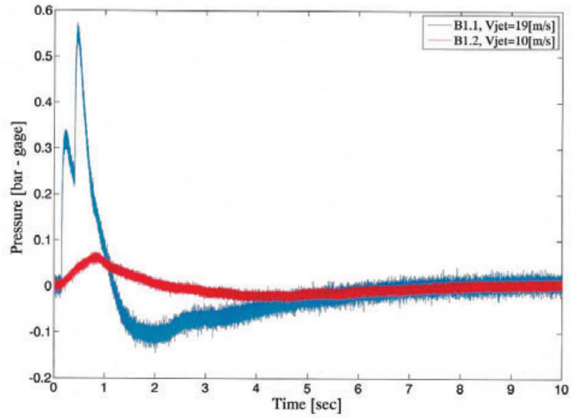
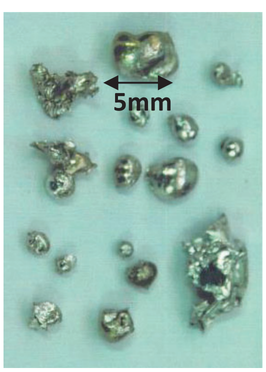


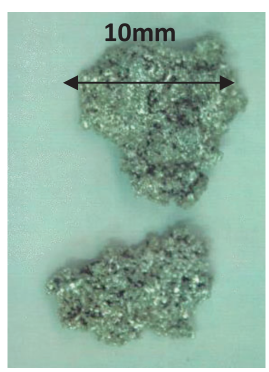
Fig.4. Pressure as function of time. Bismuth initial temperature 400℃, water initial temperature 26℃, B1.1 jet velocity is 19 m/s and B1.2 jet velocity is 10 m/s.

In order to understand how the parameters affect the explosion intensity, the impulse per area compared between the experiments. The amount of melt splattered was measured and compared with the impulse. A linear relation was found between the impulse and the melt mass dispersed from the crucible.

The particles shape and size, which splattered from the crucible, was found as another indicator for SE and the mixing quality. Particles created by experiments in which SE occur found relatively smaller (0.1-0.5 mm, Fig.5 b, c) than particles created by experiments in which SE did not occur (2-5 mm, Fig.5 a).



Tin 580°C , Water 71°C
No Explosion
(a)



Tin 575°C , Water 25°C
Explosion occur
(b)

Bismuth 408°C , Water 26°C
Explosion occur
(c)

Fig.5. Particles size as function of experiment results.

(a) Large Tin drops from experiment without explosion. (b, c) Bulk of small particles from experiments that explosion occur.

4.2. TIZ BOUNDARIES

All of the experiments results were paged on TIZ maps (Fig. 6-8), when the "x" sign is for no SE and the red circle is for SE event. The reproducibility of experimental data was confirmed by repeating the experiments under the same initial conditions for each data point. The boundaries drawn represent the interface temperature of theoretical boundaries. The blue vertical line represents the melting point, the red vertical line represents the homogenous temperature and the green line represents the minimum film boiling temperature. Marking the thermal initial conditions and results of each experiment on TIZ map shows that SE did not occur inside the TIZ boundaries as expected, but on the other hand, SEs did occur below the homogenous temperature ($T_i < T_{HN}$) and even below the melting point temperature of Sn ($T_i < T_{mp}$).

Fig. 6 – 8 presents a map obtained from experiments conducted with zinc, Bismuth and Aluminium respectively as the molten metal.

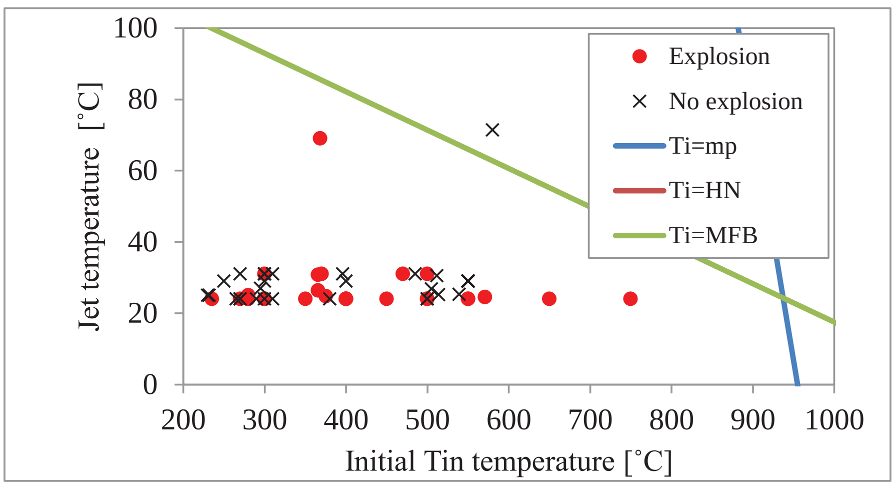


Fig.6. TIZ map of Sn – water experiments.

As can be seen from Fig 6 and 7 the experiments conducted with Bismuth show the same results as the experiments conducted with zinc, except from one experiment that ended in explosion above the MFB temperature. (Fig.7)

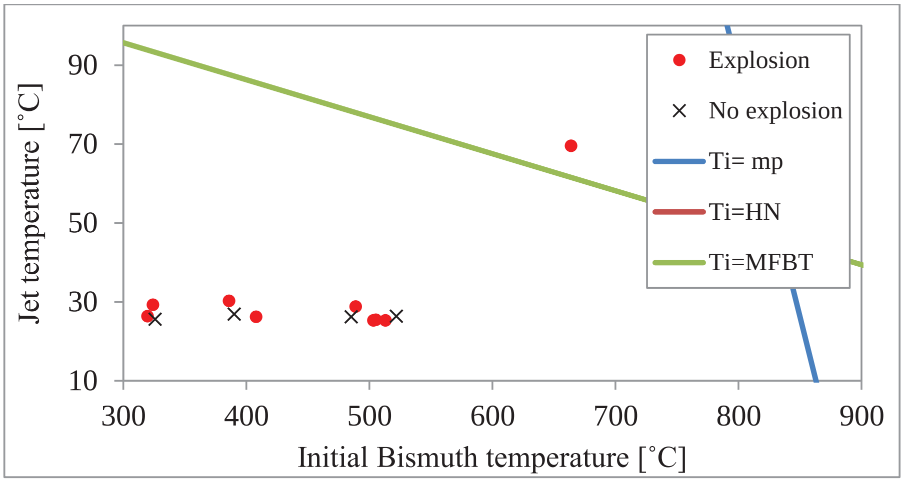


Fig.7. TIZ map of Bi – water experiments.

Experiments conducted with Aluminium did not end with explosion at all. Different methods of injection were tested in order to check the effect of hydrodynamic perturbations on the vapor film stability, but none of these methods triggered an explosion.

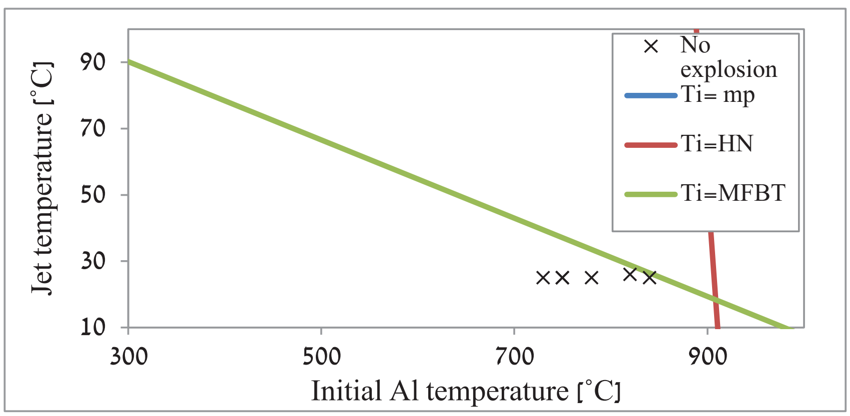


Fig.8. TIZ map of Al – water experiments

4.3. MATERIAL PROPERTIES EFFECTS

The uses of three different materials, which differ by their thermal properties, enable us to understand the effects of material properties on the phenomena. The first and most effecting property is the materials melting point. A sample of Aluminium was taken from the crucible; the solidified melt sliced into three pieces that revealed the jet path and voids formed inside melt. The experimental conditions were as follow jet diameter 1.8 mm, velocity 7.8 m/s, 800 g of water injected into 2.4 kg of Aluminium. The surface quality of these voids is very smooth, indicating that a stable film boiling sustain at the time of solidification. When the boiling regime changed from stable film boiling to transfer boiling the aluminium was already in solid state, which prevents further mixing. Materials with higher melting points than the minimum film boiling temperature may classify as non-self-triggering materials at this range of temperatures. The fact that the melt solidified before the film boiling collapse prevent a direct contact between liquids, and a violent boiling formed on a solid surface.

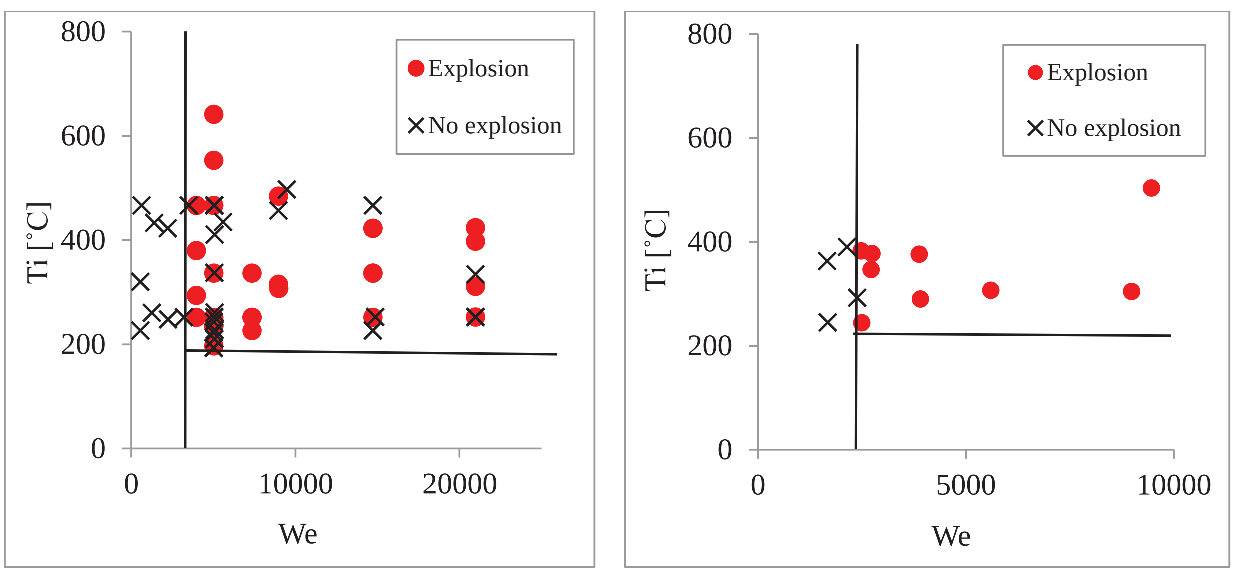
4.4. DYNAMIC PROPERTIES AFFECTS

The jet dynamic properties affect the probability for SE to occur. The coolant flow rate, the ability of the jet to penetrate into the melt and the hydrodynamic instabilities at the liquids interface are some of the effecting parameters. The jet velocity have great influence on the mixing phase, low velocity jets did not penetrate the melt surface and prevent the essential pre mixing. Results show that the velocity did not affect the explosion intensity. However, it affects in a binary manner, above certain velocity explosions occur, and below it, no explosions occur. This behaviour indicates that there is a dynamic limit for SE to occur in CI configuration.

Weber number is commonly used to analyse fluid flows where there is an interface between two different fluids.

$$\mathrm{We_{jet}} = \frac{\rho V^2 d}{\sigma} \quad (3)$$

Where ρ is the water density, V is the jet velocity, d is the jet diameter and σ is the water surface tension. Weber number describe the ratio between the fluid inertia to surface tension, or in other words the tendency of the fluid to break into drops compared to the tendency to keep the fluid unite. Analysing the Weber number effect on the feasibility for SE to occur, reveal a conditional Weber value for SE to occur. Figure 9 shows a plot of two areas: spontaneous explosions area and the other where explosions do not occur. Those areas describe the thermal and dynamic initial conditions.



(a) (b)

Fig.9. Thermal and Dynamic conditions map for Tin (a) and Bismuth (b).

These maps reveal another dimension of conditions to the commonly use TIZ map and gives the reason why experiments inside the TIZ boundaries did not lead to SE.

4.5. INJECTION METHOD AFFECTS

The dynamic condition mentioned above was found by using in the experiments single jet configuration. In order to understand the effects of the injection method on the feasibility of SE to occur, experiments using spray nozzle were carried out for the same initial conditions that enable explosion using Jet injection. No SE occurs in those experiments although different spray nozzles and flow rates were tried. The main reason for that is the lack of mixing between the liquids. By using spray for cooling, the water reaches the melt surface and rapidly evaporates.

5. CONCLUSIONS

Coolant injection (CI) into a pool of molten metal might leads to Steam Explosion (SE). The commonly use TIZ boundaries were found as too narrow limits to describe the explosion thermal conditions for Bismuth and Tin in CI mode. In order to improve the prediction of SE occurrence a new thermal – dynamic conditions map is suggested. This map was developed based on experimental study presents in this work. The following conclusions were made:

The injection method significantly affects the pre mixing phase, spray injection enable safe cooling of the melts without the risk of explosion, mainly due to the poor mixing at the melt surface.

The jet Weber number affects the phenomena in a binary manner under a minimal value no explosions has been occurred. The velocity and jet diameter affects the ability of the water to penetrate the molten metal. Low velocity jets breaks up upon the melt surface, preventing the liquids mixing

All experiments conducted with Aluminium did not lead to SE. The jet velocity and diameter did not affect the system response. The jet flow rate affect only the cooling rate and the maximum pressure built up inside the experiment vessel.

Melting point temperature is the main parameter that prevents SE in Aluminium, evidence for stable film boiling found inside the melt while solidification occur. Material with higher melting temperatures than the minimum film boiling temperatures may classified as non-self-triggered materials at temperatures less than 1000℃, mainly due to the early solidification process that limits the heat transfer area.

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