



Phenomenological study of the pre-mixing step of sodium-water explosive interaction



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ARTICLE INFO

Keywords:

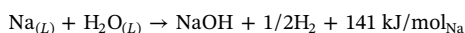
Sodium-water interaction
Experiment
Mixing conditions
Vapor explosion

ABSTRACT

The present experimental study aims at better understanding sodium-water explosive interaction in a hypothetical situation. Various experiments were performed in the past, but they still lead to large uncertainties in both interpreting experimental results and predicting accident-scale processes. From the moment it was considered that the explosive nature of the reaction could be due to a very fast water vaporization, sodium-water explosive interaction is studied by addressing the influence of the pre-mixing step (i.e. time between contact and explosion) on its consequences. A better understanding of the phenomena, and especially of the quantity and the rate of energy release, is needed to estimate the consequences of large term source accidents. The experimental measurements and their analytical discussion demonstrate that bubble destabilization is at the origin of pressure wave emission in the surroundings. Under the studied mixing conditions, sodium-water interaction severity depends mainly on the liquid sodium into water penetration limits (kinematic and thermodynamic). Only a fraction of the initial available reaction energy is likely to produce explosive effects, in accordance with the phenomenological model based on the steam explosion assumption.

1. Introduction

During the last 40 years much research was performed to study the interaction between sodium and water, including both experimental and numerical investigations. Sodium-water interaction may occur during the course of an incident in a sodium-cooled fast reactor, in particular following the loss of a tube sealing in a steam generator unit.¹ The high-pressure steam leaks into liquid sodium have been the focus of many studies and collaborations around the world [1,2]. In another context, sodium-water reaction can be exploited in controlled processes for the elimination of sodium residues on metal pieces [3]. In the first case, the main focus is the under-expanded jet produced combined with a highly exothermic reaction with formation of corrosive products [4], whereas in washing operations the principal issue is hydrogen production and its potential combustion in presence of air. The sodium-water reaction is usually described as follows:



The ability of the reactional system to accumulate the energy production

depends on the way reactants come into contact. Indeed this heat can be progressively carried away, resulting in a self-limited chemical reaction (controlled water inflow, small contact area, accumulation of solid products at sodium's surface). But the system may also accumulate a high quantity of energy thanks to the formation of an isolating gas layer around sodium. Favorable conditions leading to instantaneous energy release were thus the main focus of attention with regard to sodium-water reaction safety issues. More specifically, washing operations were the framework for some previous experiments with solid sodium samples being progressively submerged by water [5]. These tests led to the development of a first CEA modelling approach called PREDIRE to assess the adiabatic equilibrium pressure due to hydrogen production and steam formation in a closed and inert gas volume [6]. The model did not predict an explosive nature and it was believed that the explosions were resulting from a hydrogen fast combustion with the oxygen of air. But it was further observed that even without air explosive interaction took place. To better understand this phenomenon, a basic model was recently proposed, addressing the reaction energetics [6]. In agreement with other experimental observations [7,8], an immediate and uniform production of a gas film (hydrogen and steam) between the sodium sample

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¹ Component where liquid sodium transfers its heat to water in order to produce steam.

and the liquid water environment is presumed, considering that the initial reaction at the sodium surface is infinitely fast. This adiabatic reaction is only limited by the steam diffusion throughout this film, the energy production leading to sodium uniform heating until its boiling point. At this moment, it is assumed that the film collapses because the “flame” (sodium-steam reaction front) leaves the sodium surface and rushes towards the liquid water interface. The subsequent mixing between heated sodium and liquid water would then vaporize, very quickly, an amount of water corresponding approximately to the stored energy, giving rise to a steam explosion. This simplified mechanism seems to be strengthened by the recent compilation of experimental evidence [6]. As a result, an analytical method was developed to predict the physical effects of a sodium-water interaction. In water excess, the calculated amount of 15 kJ/mol_{Na} transmitted to the shock wave is in global accordance with experimental results. This corresponds to a ratio between the shock wave energy and the available chemical energy of approximately 10%, which appears as the theoretical optimum explosion efficiency.

However, previous experiments indicate also that the process conditions should strongly influence the intensity of the explosion, which is not taken into account in this phenomenological modelling.

Improvements of nuclear safety demonstration require studying in details even hypothetical major accidents (safety barriers failures). The stated objective is to be able to demonstrate that the consequences would be still under control. But, as far as sodium-water interaction is concerned, there are still large uncertainties in both interpreting experimental results and predicting accident-scale processes. In particular, the consequences of large term source accidents would be overestimated [9].

The presence of a gas layer around sodium immersed into water seems to play a major role in the explosive mechanism. But what are the required conditions for the onset of an explosion? It is proposed in this study to investigate the influence of initial mixing conditions on the sodium-water explosive interaction in a situation that may approach the hypothetical accident conditions (coincident or successive losses of confinement of water and sodium circuits or components): a liquid sodium discharge into an excess of liquid stagnant water.

2. Experimental arrangement

Experiments, called DINAMO, were performed at the LTRS/CEA laboratory. Liquefied sodium (heated) is released from a crucible, flows through a tube and falls freely and vertically into a water tank (tube exit nozzle 0.4 m away from the free water surface). The crucible containing sodium is a cylinder of 0.21 m in diameter and 0.16 m height which is connected at its base to a 20 mm diameter tube of 2 m in length via an electro-pneumatic valve. The overall system is thermally insulated and electrically heated on its external surface to provide the required sodium temperature (from 225 °C to 450 °C). The end of the ejection line is terminated with an orifice holder permitting sodium jet diameter variation from 5 to 25 mm. The crucible is argon pressurized to vary the jet velocity (pressures from 0.35 to 1 bar rel. before the valve opening). The sodium volume was varied up to a maximum of 1 L so that a steady jet situation was ensured. The water tank was 1 × 1 × 1.2 m with the volume filled to 1 m³, consisting of a metallic structure with transparent polycarbonate plates. The overall apparatus is implemented inside an explosion cell (Fig. 1).

Operating instrumentation consists in thermocouples installed on the outer surface of the ejection system and a pressure sensor in the crucible. Considering experimental procedure, an accurate control of the jet parameters and thus of the sodium-water interaction parameters was out of reach (see Appendix A).

Visualization was performed by means of a high speed color video system providing perpendicular views with respect to the jet direction (10,000 fps for a 512 × 704 pixel resolution). The camera was placed inside a protection box to prevent damages from liquid projection. In order to provide exposure times from 1/10,000 to 1/100,000 s good backlighting conditions were achieved with a uniform and high

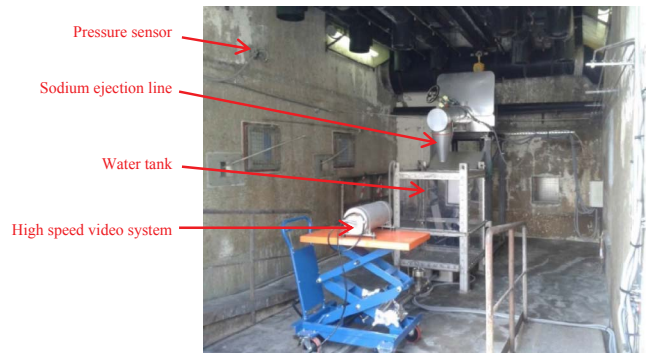


Fig. 1. DINAMO apparatus photography.

luminance LED panel. Sharp still-pictures without noticeable smearing out of the interfaces could thus be obtained.

Pressure wave propagation was recorded using six piezoelectric pressure transducers. Two Kistler sensors (IEPE 211B2, 345 bar, 500 kHz) were placed inside the water tank. These sensors were located at 0.8–1.1 m from the jet impact point on water surface. The four other sensors were displayed in the atmosphere of the explosive cell (two Kistler 211M017, 7 bar, 150 kHz, and two PCB 113B26, 70 bar, 500 kHz), located at distances ranging from 1 to 3 m from the impact point (Fig. 2).

Temporal synchronization between the pressure signals and the high speed visualization is about ± 0.2 ms. Appendix A presents the uncertainties on the experimental parameters and pressure signals but noteworthy the analysis of the structure of the signals (frequency content for instance) is at least as informative as the peaks values (see Appendix B).

3. Results and discussion

Eleven tests were performed, varying four process parameters: the sodium initial mass $m_{Na,i}$ stored into the crucible, the injection pressure P_{inj} , the sodium temperature T_{Na} and the nominal jet diameter Φ_{jet} .

As sodium-water interaction is deeply dependent on the way the reactants come into contact (film formation and energy dissipation are very local), and knowing that the contact is not fully under control (a small and localized expansion may destabilize the overall system), the following discussion intends to better understand the phenomenology. As such, a comprehensive analysis is performed hereafter and lessons are highlighted with the help of a body of evidence (qualitative and quantitative data).

3.1. Observations

Three successive steps are observed (Fig. 3): (i) jet formation as a sort of column, (ii) sodium penetration into water and (iii) explosion. The first step corresponds to the establishment of the steady jet (image 2 of Fig. 3). The nearly undisturbed penetration of the jet (second step) into the water is made possible by the immediate formation of a gas layer between the liquid water and the sodium (image 3). A flame rushes out from the gaseous layer (image 4). Since no pressure elevation is produced, this phenomenon is interpreted as being a diffusion flame in which the hydrogen released by the inevitable sodium water reaction is burning with the air of the cell. At the early beginning of the third step (iii) a sharp flash at the border between the gas and the liquid water is visible (image 5), immediately followed by a fast expansion of the gaseous volume (image 6). As explained later, the various recorded pressures pulses correspond to this third step.

The triggering of the flash always occurs quickly (< 0.1 ms) and locally before spreading to the entire jet. This phase, and especially the vapor explosion process, cannot be observed clearly as it is not possible

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