EVALUATION OF THE CONSEQUENCES OF FUEL DISPERSION AND INTERACTION WITH COOLANT FOLLOWING A CLADDING FAILURE INDUCED BY A RIA

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ABSTRACT

Let us assume that, following a reactivity initiated accident in a nuclear reactor, some fuel rods fail leading to violent thermal interaction and subsequent mechanical stress to surroundings: a so-called fuel coolant interaction. For nuclear power plants, this could only concern a very low number of rods having some hypothetical defect. Nevertheless the evaluation of a single rod event is still very roughly validated. The paper presents an overview of the actual understanding as well as recent research works initiated by the french Institut de Radioprotection et de Sûreté Nucléaire. The phenomenology is described as well as the corresponding models. To further validate the proposed approach some recent results concerning (i) the ejection kinetics of a granular material out of a rod and (ii) the violent thermal interaction are presented.

1. Introduction

For many safety related reasons, failure of the cladding of fuel rod and possible release of fuel fragments toward the coolant has to be avoided. Experimental studies have shown that if it follows a rapid high energy overpower event, such as in the accidental scenarios related to reactivity initiated power pulse (RIA) violent phenomena could occur within the surroundings: a so-called fuel-coolant interaction (FCI). Main concern for RIA related safety studies is therefore to demonstrate that such clad failure and fuel ejection can not occur, [1]. But, as many risks, the probability that, during a hypothetical RIA, a very low number of, or even a single, failure occurs is low but still irreducible: it is practically impossible to ensure that none rod would be subjected to a defect that could affect its mechanical resistance during the power transient. In order to fully analyse the possible consequences of a RIA, the need for an estimation of the potential damage of such interaction event remains. As an example, the case of waterlogged fuel rods has been therefore a safety concern, more especially studied in Japan, [2], and more recently in France. At the origin, a small hole causes water entering the rod, leading to possible lower cladding mechanical resistance by clad internal hydriding. Overpower pulse induces, due to the water contents, a sharp pressure increase within the rod and mechanical loading: large failure and quasi-total fuel ejection occur even for relatively low levels of fuel enthalpy increase. The main mitigation for this risk is currently achieved thanks to a high level of quality for the fuel manufacturing to minimize potential defects, [3], combined with an efficient detection of leakers within the core.

The paper is organized as follows. First we present in section 2 the main understanding of the FCI phenomena and their models. We briefly present the corresponding numerical simulation tool CIGALON, developed at the french Institut de Radioprotection et de Sûreté Nucléaire (IRSN). This introduces the problematic of validation of such a tool and the need for experimental data, both in-pile and in simpler lab configurations. Section 3 is devoted to the presentation of some R&D activities performed at IRSN on separate phenomena concerning the fuel ejection and the thermal interaction.

2. State of the art understanding and modelling

2.1 Main data available

Several in-pile tests have been performed on rodlets within a capsule to estimate their failure threshold. Several parameters could have been tested and among them, the level of enthalpy deposited within the fuel during the power pulse, the clad material, the fuel materials, the fuel burnup, or the thermal-hydraulic conditions of the surrounding fluid. When both clad failure and fuel ejection toward water coolant occured, a thermal interaction has been observed. Some related reviews can be found for such events in the NSRR reactor in Japan, [3], in the TREAT, SPERT and PBF reactors in the USA [4].

As far as RIA scenario in LWR are considered as initiating fuel coolant interactions, the levels of energy deposition in fuel rods is bounded by the design, [OCDE]. Therefore, the fuel is considered as being if not totally, at least mostly solid and the order of magnitude of fuel temperature could reach around 2000 K. Above the fusion threshold, the interaction could be even more violent, [5]: higher fuel temperature increases the heat transfer per unit area toward coolant and liquid fuel could be finely fragmented that increases the contact area between fuel and coolant. We restrict our attention to sufficiently low fuel enthalpy increase to neglect fuel melting and therefore to the ejection of solid fragments of fuel pellet.

The fuel fragments that have been collected after the interaction are relatively small with respect to the initial pellet size and their average size (as a Sauter diameter, i.e. the ratio between their volume and surface) can be as low as 10µm. This size has been shown to depend on the combined effect of the burnup [6] and of the interaction itself such as in the case, [3].

Following the failure event, series of short (a few ms) pressure pulses have been recorded within the capsule, their intensity being of several MPa. It is followed by large momentum transfer toward the surrounding and water hammer within the capsule. Those large motions can occur during several tens of ms, [3]. The steam pocket around the fragments can reach surrounding rods causing their clad temperature to overpass 1000 K during several seconds, thus enhancing risk of their failure for relatively large levels of enthalpy deposited, [7]. The latter study has been performed using a waterlogged rodlet surrounded by fresh fuel rodlets. As stated recently [8], the extrapolation to irradiated fuels remains unclear.

All those phenomena occur on a very short period and are localized in the very near region of the clad failure. They are therefore very difficult to characterize, all the more for in-pile experimental conditions. The violence of the interaction depends on the amount of fragments in contact with the coolant just after the failure: this quantity being hard to deduce from the experiments. The data have been obtained in atmospheric conditions (0.1 MPa, 20°C, stagnant water), i.e. in thermal-hydraulic conditions far from those of a light water reactor (for PWR 15.5 MPa, 280°C, liquid water flowing at 5m/s). There are large differences between those conditions in terms of water properties (more particularly the latent heat for vaporization, the vapour density, the liquid isothermal compressibility or the thermal diffusivity). This affects directly the order of magnitude of the phenomena. Extrapolation from the experimental results to the hypothetical accidental scenario is therefore not obvious and requires accurate understanding and modelling. Let us note that the ongoing CABRI international program, driven by IRSN is devoted to fuel rods RIA experiments within a water loop at 15.5 MPa [9]. Some of the tests will be devoted to the study of FCI in those typical PWR conditions.

2.2 Sketch of a fuel-coolant interaction

Even if we do not have experimental direct observations of the phenomena following the clad failure, the fuel coolant interaction has been idealized by several authors as being a succession of events, as illustrated by Fig. 1.

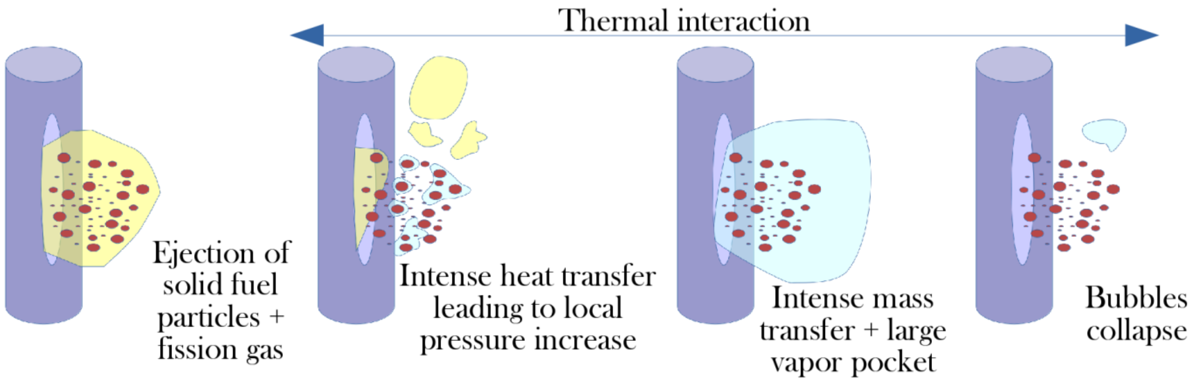

Fig. 1: Schematic sequence of phenomena following rod failure during a RIA

First, as in the left hand side picture of the figure, the fuel and the fission gases that have stressed the clad till its failure, are ejected through its opening, and therefore put in contact to the surrounding coolant. This could actually generate a pressure increase of the surrounding and has to be more especially considered in the case of waterlogged induced failure: in the latter case, internal rod pressure till 100MPa has been recorded before failure, [10].

Pressure increase due to first times heat transfer is typical of very fast heat transfer: a thin fluid layer over the particles evaporates quickly and is intensively heated (second picture of Fig. 1). Transfer to the surrounding and more massive evaporation is delayed by the time for pressure relief through the surroundings: the expansion rate of the coolant is limited by the acoustic waves speed. This has been theorized by Cho, [11], and is used in the context of vapour explosions that could result from melting of the core during a severe accident, [12]. Since volume expansion is constrained, pressure increases.

Steam formation and associated coolant expansion induce energy transfer through work against the surrounding. In many capsules used for RIA tests, an air layer lies above a liquid coolant column. Associated to the large steam pocket formation (third picture of Fig. 1), the whole liquid column of the capsule rises and its interface movement has been recorded in some cases. It allows estimating the corresponding kinetic energy of the water column. This amount of mechanical energy can be compared to the energy deposited through the fuel that has been dispersed in the coolant. The ratio between both quantities is then defined as an integral quantity of interest, e.g. [13]. Its maximal theoretical value can be deduced from the estimation of a hypothetic ideal mixing of the dispersed fuel with an arbitrary mass of coolant and considering isentropic expansion, [14].

Successive peaks have been often recorded during FCI. It could be induced by the collapse of steam leading, as suggested by Sugiyama [15], either to violent bubble collapse or to direct contact between liquid coolant and still hot fragments.

The whole set of phenomena can be modelled to deduce from a hypothetical rod's failure scenario at a given time of a RIA, the time evolution of the coolant pressure and of the steam formation.

2.3 An out-of-equilibrium model for the coolant in interaction

Several separated but interacting systems can be considered to idealize the process of such a fuel-coolant interaction as illustrated by the scheme of Fig. 2. IRSN developed a numerical code, CIGALON, to simulate the coupling between those systems. It is a lumped parameter approach for which the main heat, mass and momentum transfers between the different systems are explicitly described.

The fuel rod is modelled as a reservoir of matter containing an initial amount of fuel fragments (with two sub-groups of respectively large and small size fragments) as well as fission gases. Models drive their transfer toward the surrounding coolant zone in front of the clad opening, their temperature being derived from the RIA scenario.

The coolant that interacts with the ejected materials has an initial arbitrary mass. The zone that contains the mixing of two sizes fuel fragments, liquid coolant and gas (steam and fission gases) is an adiabatic volume with moving boundaries. Mass and energy balances for each component are solved following the non-equilibrium approach, [12]. Convective and radiative heat transfers are solved at each interface allowing deducing the intensity of the coolant phase change rate. Accurate numerical scheme and thermodynamic properties are required for solving the possible sharp evolution of the thermodynamic state in this zone.

Expansion of this zone is constrained by the motion of the surrounding liquid coolant. This surrounding coolant is a quasi-incompressible column of liquid below an air layer (mainly non-condensable). This configuration is typical of most of the capsules used in fuel rod RIA experiments, for which the FCI data are available. It is not representative of a PWR case or of the CABRI water loop device. Then, the compressibility of the surrounding liquid has to be taken into account.

In the very first time of the interaction, the expansion rate is evaluated in the frame of the acoustic regime as defined by Cho, [11]. After a time delay corresponding to the pressure wave propagation through the capsule, the momentum balance of the liquid in the capsule is solved. The liquid volume is discretized in 1D elements bounded by moving boundaries with (i) the interaction zone and (ii) the air layer at the top of the capsule. Volume variation of the air layer is simply modelled as adiabatic ideal gas behaviour.

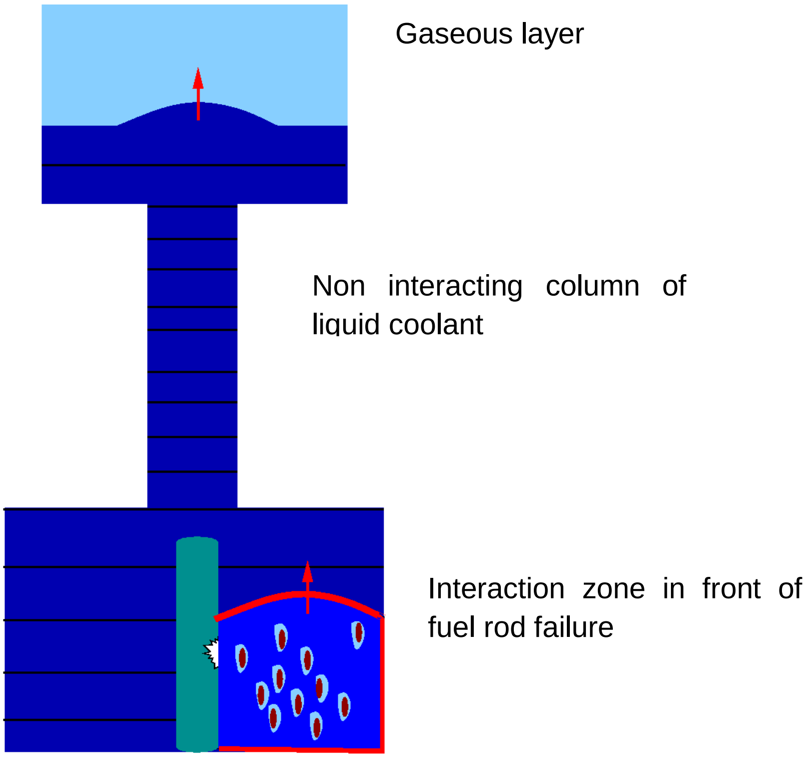

Fig. 2 : The different systems described in CIGALON.

The numerical code is able to simulate the main features of the sequence of the phenomena described in the previous section. The order of magnitude of the predicted pressure peak is in good agreement with some past experiments but the validation database is still very restricted.

3. On-going research on related phenomena

Different phenomena occur simultaneously during an interaction: the intensity of the heat transfer toward the coolant is the combination of the dynamics of the particles flowing out of the rod and of the heat flux for each particle. The intensity of this heat transfer is directly related to the pressure peak and to the violence of the interaction. It is not possible from the measurements of a FCI to identify separately the kinetics of ejection or the first times heat transfer from the particles toward the coolant. The two processes are of very different nature and the model for the intensity of an interaction has to consider them accurately. As an illustrative example, the fragment size could often be determined by post-mortem exam, and it is known as being a key parameter, [13]. But this parameter plays a very different role in the ejection and in the heat transfer. It is therefore not obvious that a model for a FCI provides the correct scaling of the intensity of the interaction with respect to the fragment size. It is therefore required to better qualify the models for the different transfers based on separate effect tests in addition to the analysis of FCI events during in-pile tests.

3.1 Fuel ejection and kinetics

Motivation

As introduced in the previous section, the intensity of the interaction is mainly a question of kinetics and, to be explosive, individual sub processes have to be intense and rapid. It is straightforward that if the fuel flows very slowly toward the coolant, even though the amount of energy received by the latter is large, the interaction will be negligible. On the other hand, the hypothesis of an instantaneous contact between all the ejected fine fragments and the surrounding coolant would result to an unrealistically violent interaction. Unfortunately, none of the available experimental data allows determining the amount of fuel in contact with the coolant at the time of the measured interaction. Let us analyse the fragments dynamics out of the rod.

Fragmented fuel as a granular media

Inside the rod, the fuel is initially a collection of grains of uranium oxide agglomerated. Due to burn-up, [16], but also during the power pulse, [9], and, if any, during the interaction with the coolant, [3], this pellet is fragmented. There is still an active R&D on those processes. But as a result the collected fragments are approximately of 10µm size, [15]. Therefore, the materials ejected out of the rod can be seen as a collection of individual small particles around tens of micron with a very dense initial packing. This defines a granular material. The estimation of the flowrate of fuel particles out of the rod after the clad failure is therefore related to the model for the relation between momentum and driving forces through a granular material. In absence of any surrounding fluid flow, contact forces prevail. In certain conditions (and more especially for a waterlogged rod), the gas inside the rod could be at higher pressure at the failure time than the surrounding. This induces a gas flow that could play a role in the ejection dynamics by dragging the particles. Let us consider models for those flows.

Discharge without clogging assumption

The mass of ejected fuel could be either measured for experimental cases or modelled. The total amount of fuel that could be ejected could be limited by either a larger fragment obstructing the orifice (the clad failure) or the formation of an arch. On one hand, for failure of PWR rods induced by Pellet Clad Mechanical Interaction at peak fuel enthalpies below 500 $J(gUO_2)^{-1}$, only a few percent of the fissile mass that lies in front of the opening, [17]. On the other hand, all the pellets (above but also below the opening) have been expelled out of the rod-let for several waterlogged rods cases. The latter case obviously covers by maximization of potential consequences any other case and the corresponding hypothesis has been retained for past safety studies, e.g. [2]. Since we assume ejection of materials, let us neglect any possible initial clogging of granular materials through the orifice. Therefore, for a given amount of fuel ejected, let us focus on the discharge rate out of the rod.

Models for the reservoir and the rod gases

The analogy we consider is therefore the following: the rod is an elongated cylindrical reservoir that contains a fragmented material and that has a lateral opening (i.e. whose normal direction is perpendicular to the gravity. In a first step, one considers a rather simple and ideal granular matter as a collection of spherical beads filling the reservoir. The interstitial fluid is also considered and modelled as a simple constant flow-rate of air throughout the reservoir: it represents the possible interaction with fissile gases (or steam for waterlogged rods) escaping out of the rod. Due to the thermal interaction, the surrounding of the rod could undergo sharp variations of state (from liquid to steam) and of pressure (with one or several peaks). This could affect, and certainly lower, the fuel fragments flow rate. As a first simple case, let us nevertheless consider the surrounding as a large air domain at constant (atmospheric) pressure.

Classical reservoir discharge dynamics

At first order, when particle size is sufficiently small with respect to opening dimension and when coupling with interstitial fluid flow is negligible, the flowrate of granular materials out of a wide reservoir does not depend on the grains (size, materials, shape) or of the filling height. This property is well known for its use in hour glasses. The flow rate is therefore only dependent on the local granular configuration over a length scale on the order of the opening size. It is therefore a priori sufficient to evaluate the stress over the fragmented material in this area. To study the relation between stress and flowrate, let us consider the study of discharge rate out of the cylindrical reservoir under several configurations.

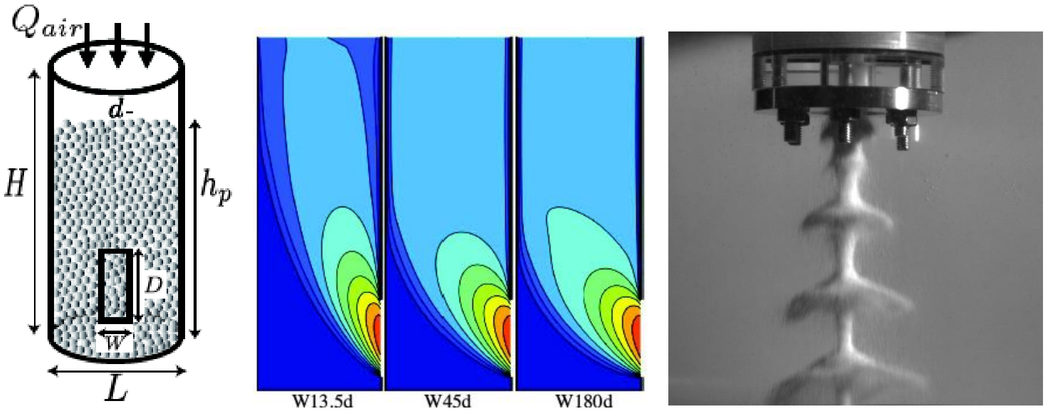

Fig. 3 : From left to right. Schematic view of the cylindircal reservoir configuration. Three velocity field map for the numerical simulation of a continuum model for the granulat flow (decreasing intensity of friction along the reservoir walls from left to right affects the flow rate and the flow orientation). High speed camera picture of the flow of beads just after membrane rupture.

Our main results

In [18], we showed that the flowrate of particles out of a reservoir without air flow depends mainly on the dimensions D and W of the opening and not on the particle size (as long as the number of beads across the opening is more than 50). For sufficiently thin reservoirs (small L, see left hand side picture of Fig. 3), we identified two flow regimes: the particle velocity scales as $\sqrt{gD}$ for large W/D and as $\sqrt{gW}$ for small W/D. We showed that the latter regime is partially governed by friction of the particles along the reservoir walls. This experimental study, supported by fine numerical simulation of contact dynamics allow therefore to state that such granular flow is driven by the configuration in a very narrow region around the opening. Moreover, we showed that such granular materials flows can be well simulated by a rather simplified continuum model of fluid dynamics with specific rheological law. Such 2D numerical simulation of the flow of a granular material out of a reservoir with an opening at the bottom of the right hand side boundary is illustrated by the 3 pictures in the middle of Fig. 3. The coupling with an air flow has been studied both experimentally and theoretically, [19]. The permeability of the granular materials plays a major role and we showed that the unique pertinent force that impacts the ejection rate is the drag force evaluated on the very near region of the opening. This can also be simulated thanks to simple continuum model for two-fluid dynamics.

Perspectives

Those first results allow improving basic understanding of particles dynamics escaping out of an elongated reservoir with possible coupling with a gas flow. It inspired a more advanced model to estimate the characteristic time for fuel ejection out of a rod in CIGALON code. Those preliminary studies were restricted to quasi-steady flows configuration. Ongoing experiments consider the ejection rate just after the rupture of a membrane that separates a pressurized reservoir containing particles from outside (as illustrated by the right hand side picture of Fig. 3). We also plan to perform experiments of such ejection toward liquid and to vary the shape and size of particles.

3.2 Pressure and void impulses due to thermal interaction

The phenomena

Studying the thermal interaction as a separate phenomenon requires focusing on the fluid response to an intense thermal heat transfer. The explosive nature of the fuel-coolant interaction is related to the fact that a large amount of energy, sufficient to vaporize it, is released within a fluid in a short time. If this time is shorter with respect to the one required to expand its volume, pressure in the fluid builds up, leading to the observed pressure peak.

The constraints with PWR conditions

Reproducing the phenomena requires considering high power systems to transfer energy to a fluid. A level of $5.76\ 10^4$ W is sufficient to vaporize 1cm^3 of saturated liquid water at 155 bar in 0.01 s. Such a transfer through a 1cm^2 area, implicates extremely high heat flux of $5.76\ 10^8\ \text{Wm}^{-2}$ (the small fragments size can induce very large surface exchange area). The coolant thermodynamics properties (and more especially the liquid to vapour enthalpy difference- the latent heat of evaporation- but also the volumetric mass ratio) play a great role on the pressure peak for a given amount of energy. These properties vary a lot according to absolute pressure level for water. Since our final objective is to have experimental data to validate the model as presented in section 2.3, it is also required to have sufficient information on the parameters of the interaction, namely the instantaneous rate of energy transferred to the fluid and its evolution (at least the pressure peak generated).

The choice for a dedicated design

The challenge of dealing with the hereinabove constraints has been solved by considering: (i) the similarity between reduced (with respect to the critical point) thermodynamics properties between water and CO_2 and (ii) the use of capacitors discharge through a thin wire to generate intense Joule effect. More details of these choices can be found in [20]. The experimental device is therefore the following: at the extremity of a tube of 3 cm diameter, a coiled tungsten wire is in contact with pressurized liquid CO_2. The wire is connected to an electrical circuit where energy is initially stored in capacitors. The pressurized CO_2 tube of cm long is connected to an upper tank. At the time of the discharge, the wire heats up very rapidly. In an adiabatic hypothesis for the wire, the latter could increase of 1000 K in less than 20ms. As a consequence, the surrounding CO_2 is rapidly heated up. Thanks to a dedicated high-fidelity measurement of the instantaneous current and voltage through the wire and according to the dependency of its resistance with temperature, it is possible to estimate the latter. From the energy balance over the wire, it is possible to deduce the heat flux toward the CO_2 from the estimated specific heat of the wire and the Joule effect power.

This is illustrated by the left hand side curves of Fig. 4. The measurement of the capacitor discharge determines the instantaneous energy deposited in the wire. The corresponding blue curve is the deduced theoretical wire temperature in absence of any heat transfer toward surrounding CO_2. Resistance measurement allows deducing the instantaneous wire temperature (red curve).

Experimental results

On the right hand side curves of Fig. 4, the discharge is illustrated by the decreasing voltage of the capacitors. Two pressure sensors are located in the liquid close to the wire. Shortly after the beginning of the discharge, the pressure increases notably at the nearest location (sensor 1, red curve). It is followed by a rather similar signal with a small delay measured by sensor 2 (green curve). A planar pressure wave generated at the wire travels without significant damping at the acoustic velocity along the tube above the wire.

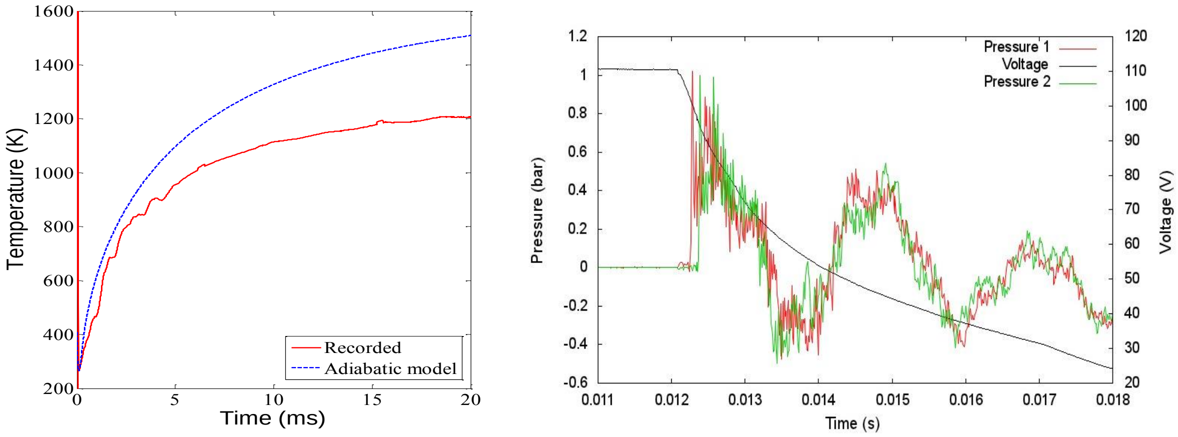

Fig. 4 : Wire temperature and CO_2 pressure following the capacitors discharge

This pressure peak is clearly the consequence of a thermal interaction and it has been shown to increase with the amount of energy released in the wire. After the peak, an increase of the pressure in the gas layer at the top of the device has been recorded. It corresponds to a compression of this layer and it has been related to the volume of CO_2 vapour generated around the wire. The instantaneous heat flux between the wire and the CO_2 has been deduced from our measurements. Its value of the order of $1MW/m^2$ is in good agreement with related violent heat transfer studies of the literature such as wire quenching or rapid heating up.

Perspectives

The first results are very promising since they demonstrate clearly that it is possible to reproduce and to measure a thermal interaction in lab conditions. Nevertheless, we are interested also to more energetic cases. Those energy levels can be released by the capacitors but we observed, still not understood, wire failures. Improvements of the experimental device are foreseen in a very near future and would provide additional valuable information including cases with larger vapour volumes. Ongoing work also considers the comparison between experimental results and CIGALON numerical simulations of the tests.

4. Concluding remarks

The fuel coolant interaction during a RIA has to be evaluated for safety reasons. The phenomena that could be violent have been observed in several fuel rod tests but the extrapolation toward hypothetical accident conditions is not straightforward. Several processes are involved during the interaction that implies mass, energy and momentum transfers like during steam explosions. IRSN develops the numerical simulation tool CIGALON to support the interpretation of tests of the Cabri international program. It is nevertheless also required to validate the models for separate effect tests. R&D activities driven by IRSN have been presented on two topics. The ejection rate of fuel fragments has been idealized as a discharge rate of granular media. The crucial role of the opening size but also of the friction against cladding and gas flow has been demonstrated. A mechanistic model for the ejection rate has been deduced from this study and implemented in CIGALON. Very unsteady processes of discharge are currently under study. A device has been designed for the study of the thermal interaction. Using CO_2 instead of water allows simulating PWR thermal hydraulic conditions. Violent thermal interactions, that generate pressure peaks, have been produced. Those data are currently used to validate CIGALON. Future work will be devoted performing tests with higher levels of energy deposition.

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