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Experimental Study of Solid/Liquid Thermal Shock in Carbon Dioxide

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Abstract **-** In this paper, the generation of a thermal shock in carbon dioxide is studied experimentally. The aim of the project is to improve the knowledge of a specific phenomenon during an hypothetical nuclear accident scenario, namely a fuel coolant interaction, by studying the rapid (few milliseconds) deposit of energy in a fluid (carbon dioxide). The deposit method chosen is the Joule effect in a thin tungsten wire. This kind of transient heat deposit in the fluid should imply a shock wave. A consistent visualization of the bubble formation and behaviour had been linked to energy deposit and pressure peaks.

Keywords**:** Thermal shock, Vaporization, Visualization, Phase change.

1. Introduction

In the context of safety studies of pressurized water nuclear reactors, one of the hypothetical accident scenarios taken into account is the so-called Reactivity Insertion Accident (RIA). When considering a control rod ejection accidental scenario, reactivity transient induces a power pulse over several nuclear fuel rods will expand uranium pellets enclosed in the rods, which could imply an important increase of rod internal pressure and lead to rod failure. Excessive power transient could lead to intense stress of the rods' cladding and let us assume it leads to rod failure (See [1]–[3]). The rod could therefore release fragmented fuel (uranium particles) and non-condensable gas (initially in the rod) in the coolant (water). The resulting intense heat transfer between hot fuel particles and the (relatively) cold water would lead to a so-called fluid-coolant interaction (See [4], [5]).

In the first milliseconds (up to $100ms$), a transient pressure pulse (compression/relaxation) with a characteristic time of $10\ \mu s$ is generated and propagates in the surroundings. It is directly followed by a smoother compression (up to 10 s) due to the vaporization of the fluid with a characteristic time of $100\ ms$. It has been observed in atmospheric pressure and ambient temperature ($1\ bar$, $25\ °C$) initial conditions for in-pile experiments with failed rods in [4]. It is believed that these phenomena could be altered in more typical nuclear reactor core conditions (water at $150\ bar$, $300\ °C$), that deeply modify water properties. Those conditions remain complex to study in a lab. A similarity study [6] of fluid properties showed that those conditions in water correspond to ($50\ bar$, $-6\ °C$) in carbon dioxide. A first characterization of the phenomena in carbon dioxide is done at saturated conditions ($30\ bar$, $-6\ °C$) and presented in this paper.

To this extent, an experimental set up has been built in order to study the fluid behaviour during this kind of thermal shock and is described in section 2. First results, including phenomena visualization are presented in section 3.

2. Experimental set up

The test bench presented in Figure 1 consists of a long narrow stainless tube mounted under a large vessel placed inside a climatic chamber. The chamber allows setting the temperature between $-10\ °C$ and $-6\ °C$ in order to run the experiments in saturated carbon dioxide at acceptable pressure levels (around 30 bar). Small time scale ($\tau \sim 10\ \mu s$) phenomena only affect the narrow tube that is instrumented with two dynamic pressure probe P1 and P2, (see Figure 1) of type PCB 113B21 sensors connected to a PCB signal conditioner ($\pm 3\%$, cumulated uncertainty). The dynamic pressure measurement precision is $0.0179\ bar$.

The thermal shock is obtained by a transient discharge of high capacitance capacitors (9 capacitors of 3mF each) in a coiled tungsten wire. It permits to discharge a high quantity of energy (up to 1.4 kJ) in less than five milliseconds. Energy deposited in the tungsten wire is calculated from the intensity and voltage measurements respectively with LEM LF2010-S

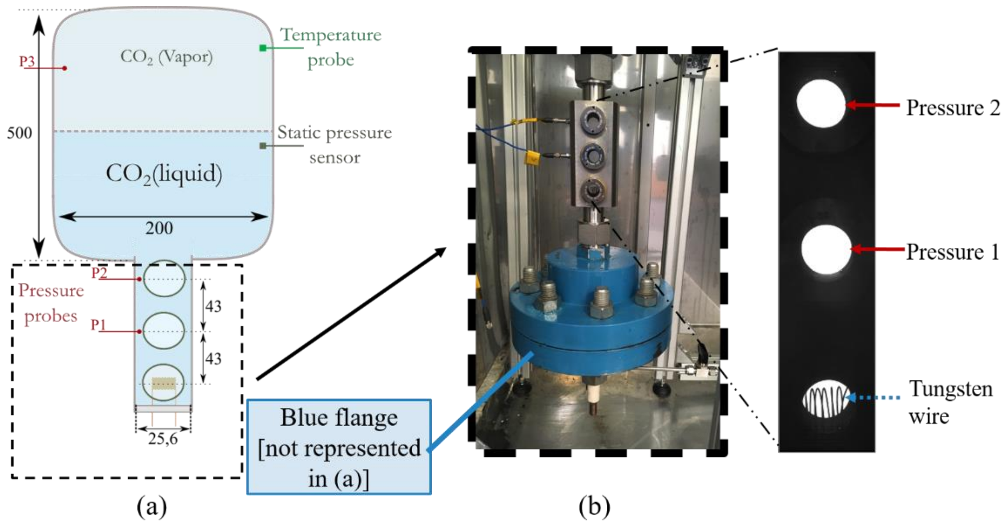

Fig. 1: Drawing of the test section (a) and corresponding picture (b).

(resolution of 200 mA) and LEM CV 3-500 sensors (resolution of 1.2 V). The dynamic acquisition is completed by two different data acquisition (DAQ) modules (one for the pressure measurement and one for the current/voltage measurement) set to a high frequency (up to 1 MHz).

Three circular viewports are arranged at equal distance on the side surface of this tube (accordingly to Figure 1, (a)). A high-speed camera (Photron Fastcam 1024 PCI, standard memory size – 2 GB) is placed close to a viewport while a square white LED backlight device (Phlow SLLUB white led Blacklight 100x100) illuminates the imaging area through the opposite viewports. The LED device produces a very intense and homogeneous light (luminance: $53000\ cd \cdot m^{-2}$, uniformity: 98.77%) which leads to an excellent contrast on the recorded pictures. The Photron Fastcam Viewer (PFV) software controlled the high-speed camera and the following settings were chosen to record videos: the image size was set to 512x128 pixels and the frame rate to 5000 frames per second, allowing for a 2 s long video. The diameter of the viewports (see circles on Figure 1, (a)) is 16.5 mm which gives a resolution of 0.448 mm per pixel height. The acquisition system was developed to synchronize the pressure measurements with the high-speed visualization.
The large vessel acts as a buffer layer that plays a role at relatively larger time scale ($\tau \sim 100\ ms$). Fluid expansion at the energy deposit location is studied thanks to one pressure probe [P3, not studied in this paper].

Initial conditions correspond to the temperature, the static pressure and the liquid level inside the vessel, the corresponding sensors being placed in the test section according to the Figure 1.When the thermodynamic conditions are set, the capacitors are loaded till a voltage limit that determines the energy deposit level. Test conditions are therefore the initial pressure and the liquid temperature (that can be either saturated or subcooled) and the energy deposit level.

3. Results and Discussion

In this paper, we consider the results from a single test corresponding to $-6.1\ °C$ ($\pm 0.1\ °C$) and 29.36 bar initial conditions. The capacitors discharged an 80 V signal in the coiled tungsten wire of 0.5 mm ($\pm 10\%$) diameter and 1.07 g ($\pm 0.01\ g$) mass leading to an 86 J energy deposit. Figure 2-(a) illustrates the electrical power transient from the discharge ($t = 0\ s$) and during 50 ms. The power peak occurs within 1 ms and the main part of the power is released within less than 10 ms. The dashed lines outline instants corresponding to some frames seen on figure 3 that coincides to some snapshots ($[0.6; 0.8;\ 3;\ 5;\ 30]\ ms$).

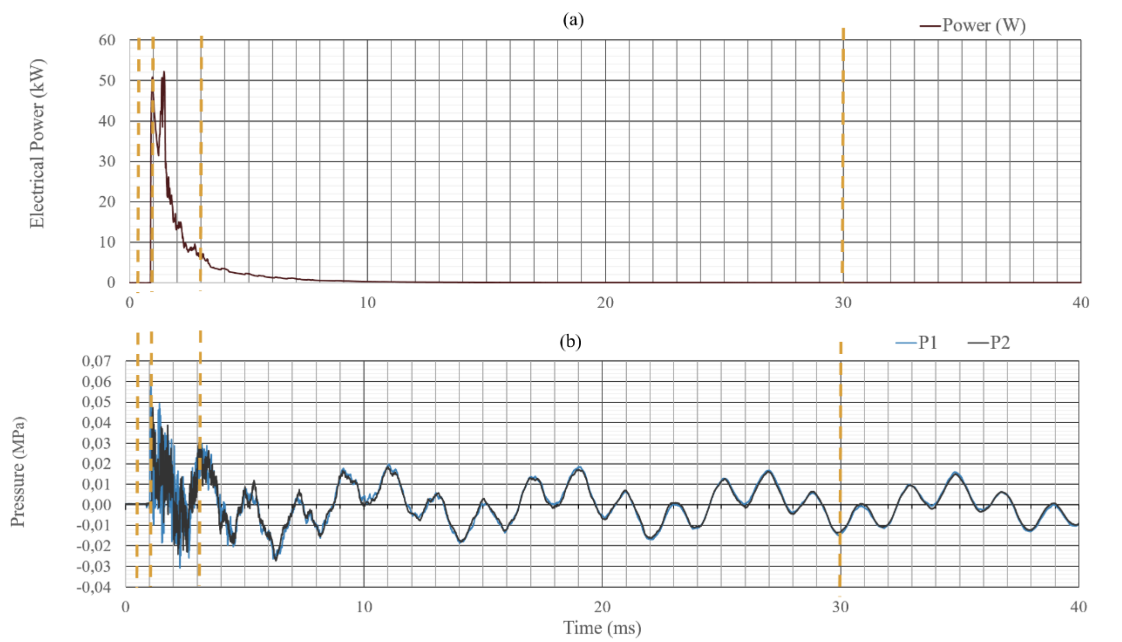

Fig. 2: Power and pressure transients for 86 J discharge experiments (logarithmic scale for the time).

The pressure signal (Figure 2-(b)) has two peaks within the first milliseconds of the transient. It is a relatively noisy signal at high frequency around $f \sim 3000\ Hz$. After $t = 10\ ms$, the pressure signal exhibits characteristics frequencies: $f_1 = 122\ Hz$, $f_2 = 455\ Hz$ and $f_3 = 500\ Hz$. Fluid mechanics numerical simulations of pressure wave propagation through the geometry of the device are planned to better analyse those frequencies and identify those related to the heat and mass transfer kinetics and those related to the acoustic. The pressure signal of the P1 and P2 probes placed at $43mm$ distance exposed two characteristics: a noisy transient signal (before 5ms) and smoother lower signal (after $5\ ms$). Signals P1 and P2 are delayed of $\Delta t = 1.12e - 4\ s$ which gives a first-peak wave of $v = 384\ m.s^{-1}$ which is less than the sound velocity: $c = 583\ m.s^{-1}$ $[v/c\ = Ma = 0.66]$.The first four pictures (See Figure 3) correspond to the first five milliseconds following the beginning of the energy deposit. They reveal a coil vibration due to high electrical power transient leading to some intermittent spires contact and corresponding sparks. These relatively short events explain the non-smooth electrical power signal but do not determine the boiling phenomenology. Undergoing tests with a different heater geometry allow to avoid such sparks. Tiny vaporization of CO_2 can be guessed from $3\ ms$. The three frames last ($t = 30\ ms$; $t = 309\ ms$; $t = 609\ ms$) outline the formation and coalescence of carbon dioxide bubbles. Note that at 30 ms the discharge is over, the wire is covered by several small bubbles which will coalesce (see $t = 309\ ms$). As a first approach, the rising time of the bubbles was computed by picture treatment (luminosity changes) to $0.29\ s$ between the middle and the top viewports, leading to a transport velocity of the vapour of $0.147\ m \cdot s^{-1}$.

According to those analyses, we recover a rapid and intense boiling as suggested by the interpretation of past fuel-coolant interaction experiments (detailed in introduction) and the instrumentation of our device will help relating heat transfer toward the fluid to mass transfer and pressure variation.

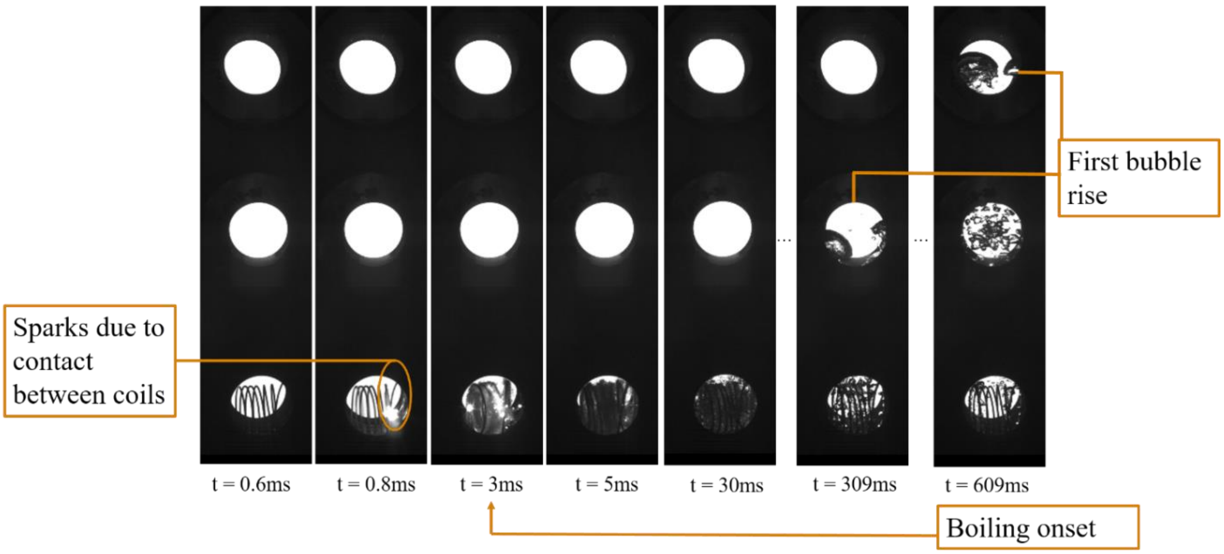

Fig. 3: Visualization of an 80 V discharge in a tungsten wire.

4. Conclusion

An original test bench allowing characterizing transient phenomenon during a high-energy deposit in a fluid has been presented. From high-speed camera recording linked to pressure and energy measurements, it was possible to observe and describe several phenomena. During energy deposit, a pressure shock is observed while no phase change occurs. After five milliseconds, the pressure decreases and boiling occurs. Boiling phenomena intensifies until large bubble departures are observed. This shows that this experimental study allows to simulate the phenomenology involved in so-called fluid-coolant interaction in the context of nuclear safety. Following these results in saturated conditions, future work will focus on thermal shock characterization under various conditions (power levels, fluid initial subcooling, initial pressure, heating element size and geometry).Ongoing analysis of those latter tests already reveal similar phenomenology and allow avoiding sparks artefacts. Modelling of transient heat and mass transfer will then be developed.

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