

## Propagation speed of a pressure spike during the water-liquid nitrogen interaction

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### Abstract

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The experiments on the interaction between the liquid nitrogen and the water were conducted in order to confirm its similarity with the interaction between the molten metal and the volatile liquid coolant, the Fuel-Coolant Interaction (FCI). For the experiments, the water was injected from a pressurized water bottle into a cylindrical interaction chamber to interact with the saturated liquid nitrogen that was filled from the bottom. From the experiments, some of the obtained pressure profiles showed relatively strong and sharp pressure spikes. This suggested the possibility of vapor explosion during the experiments. The propagation speeds of these pressure spikes could be calculated based on the time differences recorded by the transducers at the top and at the bottom of the interaction chamber. Based on the results from an experiment with the injection pressure of 4 bars and the volume ratio for the water and the liquid nitrogen of 0.10, the propagation speed was calculated to be between 22 m/s to 50 m/s. This speed was found to be comparable with the theoretical value for the sound speed in a mixture of liquid nitrogen and nitrogen gas. It was concluded that the observed pressure spikes were actually the movement of the shock wave and that vapor explosion had actually occurred in this particular experiment.

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**Key words :** Fuel Coolant Interaction, vapor explosion, shock wave, multiphase flow

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## บทคัดย่อ

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อัตราเร็วการย้ายตำแหน่งยอดความดันในอันตรกิริยาระหว่างน้ำและไนโตรเจนเหลว

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การทดลองเรื่องอันตรกิริยาระหว่างไนโตรเจนเหลวและน้ำเป็นการศึกษาเพื่อยืนยันความคล้ายคลึงกันของอันตรกิริยาดังกล่าวกับอันตรกิริยาระหว่างเชื้อเพลิงหลอมเหลวและของเหลวระเหยง่าย ในการทดลองนี้จะฉีดน้ำจากกระบอกอัดความดันเข้าไปในท่ออันตรกิริยาทรงกระบอกเพื่อให้เข้าทำอันตรกิริยากับไนโตรเจนเหลวที่บรรจุจากด้านล่าง ผลการติดตามการเปลี่ยนแปลงค่าความดันของบางการทดลองพบว่า มีลักษณะเป็นยอดแหลมชัดเจนนิ่งซึ่งบ่งชี้ถึงอันตรกิริยาอันรุนแรงภายในระบบ โดยอาศัยอุปกรณ์ตรวจวัดค่าความดันซึ่งติดตั้งที่ส่วนล่างและที่ส่วนบนของท่ออันตรกิริยาจะสามารถคำนวณอัตราเร็วการย้ายตำแหน่งของยอดความดันเหล่านี้ได้ จากผลการทดลองซึ่งมีความดันการฉีดน้ำเป็น 4 bars และมีอัตราส่วนเชิงปริมาตรของน้ำต่อไนโตรเจนเหลวเป็น 0.10 สามารถคำนวณอัตราเร็วได้อยู่ระหว่าง 22 m/s ถึง 50 m/s อัตราเร็วนี้เทียบได้กับอัตราเร็วเสียงในตัวกลางผสมระหว่างก๊าซไนโตรเจนและไนโตรเจนเหลว ดังนั้นจึงสรุปได้ว่ายอดความดันที่สังเกตได้เป็นการเคลื่อนที่ของคลื่นกระแทกและอันตรกิริยาที่เกิดขึ้นในระบบเป็นอันตรกิริยาการระเบิดเป็นไอ

ภาควิชาวิศวกรรมเทคโนโลยี คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย กรุงเทพฯ ๑ 10330

One difficulty in the study of the Fuel-Coolant Interaction (FCI) is the complexity of preparing the experiment. Due to the very high temperature for melting the metal and its strong interaction with the volatile liquid coolant, the installation for the experiments must be able to supply enough heat for the melting process while, at the same time, it must be able to withstand the high temperature and pressure that occur during the experiments. As a result, the cost of the installation and the cost for conducting the experiments can be very expensive. Furthermore, experiments need a long time to prepare and an even longer time to clean up after they are concluded. Therefore, the number of the experiments conducted during a given period is very limited. Because of these reasons, only a small number of research facilities are able to conduct the full scale experiments in FCI and only a small number of successful experiments are publicly available for study.

### Hypothesis and Objectives

In conducting the experiments on FCI, various metals have been used to simulate the fuel

while water has been extensively used as the volatile coolant. The metals that are normally used are tin, lead, alumina, iron, zirconia, urania (mixture of uranium, zirconium and other metals) and even pure uranium. These metals are called "simulant" or "thermite," if the interaction is found to cause vapor explosion (steam explosion) [Corradini *et al.*, 1988]. As their melting points vary from several hundred Kelvins to as high as two or three thousand Kelvins, the degree of the interactions and the possible explosion are also varied. In general, however, it is found that the process is strongly affected by the temperature and the physical and thermal conditions of the simulant and the coolant.

With the hypothesis that the interaction is mainly driven by the temperature difference between the simulant and the coolant, the interaction similar to that of FCI and vapor explosion should be also possible at the much lower temperature if the materials with very low melting and boiling points are used. Even though the degree of severity of the interaction may be varied, since the properties of the materials are different, the mechanisms involved in the process are still the

same fundamentally. Consequentially, the study on the mechanism of the process of vapor explosion, if not the degree of its severity, should be possible by using such materials. With the lower cost of the materials, the installation, the operation and maintenance, the cost of conducting the experiments can be substantially reduced. At the same time, with the materials and installation being more manageable, the time needed for preparing and post-processing the experiment is shortened. Therefore, the number of the experiments that can be conducted for any given period will also be increased. Due to these possible advantages, the study of the interaction between the water and the liquid nitrogen was initiated [Archakositt *et al.*, 2002][Nilsuwankosít *et al.*, 1999][Nilsuwankosít *et al.*, 2000] with the main objective of verifying this hypothesis.

Based on the results obtained from the experiments, the specific objective of this article was to demonstrate that vapor explosions actually happened during the interaction between water and liquid nitrogen for the given condition. As an

explosion characteristically results in the strong pressurization over the very short time period, which also generates a shock wave that propagates at the sound speed in the medium, the existence of the pressure peak during the interaction and its propagation speed were the topics to be discussed.

### Installation for the Experiments

The installation for the experiments on low temperature vapor explosion, with water and the liquid nitrogen as the simulant and the coolant respectively, were composed of four components. The diagram for this setup is given in Figure 1. These components were (1) the water injection unit, (2) the liquid nitrogen supplying unit, (3) the interaction chamber and (4) the control and measuring devices. The water injection unit was located at the top of the interaction chamber. It was a pressurized steel bottle with an internal volume of 800 cc. A solenoid valve (SV1) was placed at the junction between the water injection unit and the interaction chamber. This would pre-

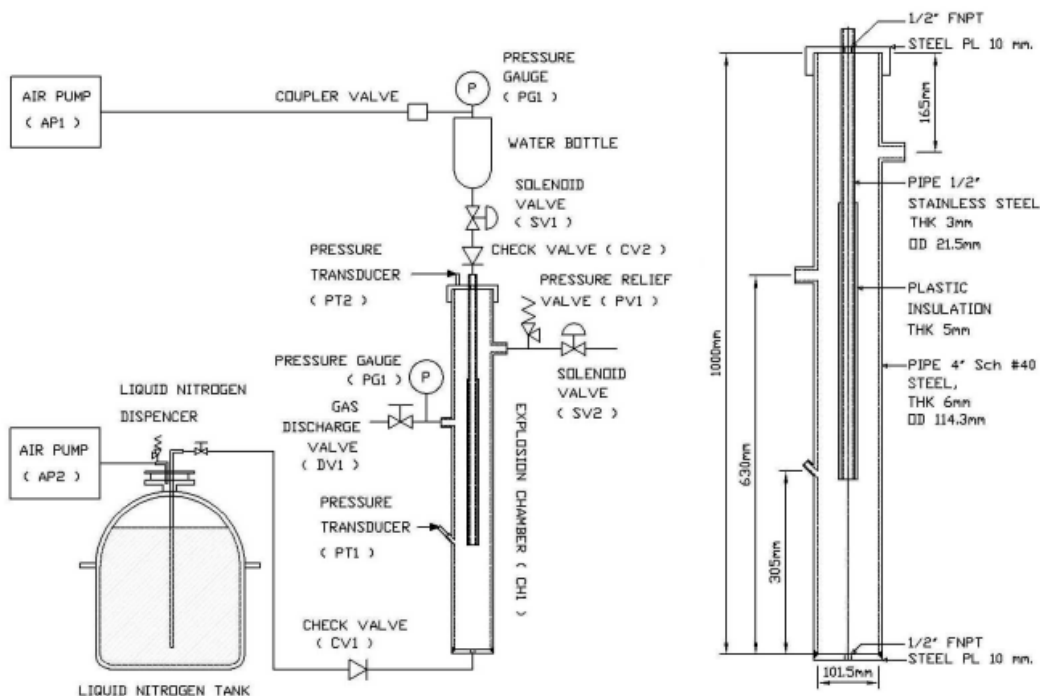


Figure 1. Installation for the low temperature vapor explosion experiment

vent the flow of the water into the chamber until the time of the injection. A regular check valve (CV2) was also placed just after the solenoid valve to prevent the back flow from the interaction chamber during the experiment. The liquid nitrogen supplying unit was connected to the interaction chamber at the bottom. A lift check valve (CV1) was also used at this junction to prevent the back flow from the interaction chamber into the liquid nitrogen tank. The interaction chamber was a cylinder made of steel with a height of 100 cm and internal volume of 8091 cc. At the top of the chamber, there was an opening that was connected with the pressure relief valve. At about one third of its height from the bottom, there was a small opening to be used by a pressure transducer (PT1). At the middle of its height, there was another opening to let the flow of the nitrogen vapor out of the chamber. A gas discharge valve (DV1) was placed here in order to stop the flow and to start the experiment. For comparison, a pressure transducer (PT2) was also placed at the top of the chamber. These transducers (PT1, PT2) were connected to a personal computer so that their measurements could be automatically recorded for later analysis. In addition of these measuring devices, a switch was also connected with the gas discharge valve (DV1) for closing the outlet for the nitrogen vapor from the chamber. By closing the gas discharge valve (DV1), the switch would open the solenoid valve (SV1) to initiate the injection of the water. At the same time, a signal was also sent to the personal computer to start recording the pressure levels. The transducers (PT1, PT2), the gas discharge valve (DV1) switch, the solenoid valve (SV1) and the personal computer were the fourth part of this installation.

To conduct an experiment, the water bottle was first filled with the desired amount of water, closed and then pressurized. At the bottom of the chamber, the liquid nitrogen was pneumatically pumped to flow through the chamber in order to lower its temperature and later to fill the chamber. Once the desired level of the liquid nitrogen in the chamber was reached, the gas discharge valve (DV1) was closed. The injection of water and the

recording of the pressure levels were automatically started. For safety purposes, the pressure relief valve at the top of the chamber was set to release the nitrogen vapor from the chamber as soon as the pressure inside the chamber reached 7 bars (gauge).

### Experiments and Results

A number of the experiments had been conducted for the interaction between the water and the liquid nitrogen to study the effects of the injection pressure and their initial volume ratio on the interaction. It was observed from the experiments that there was a certain criterion for the injection pressure and the initial volume ratio of the water and liquid nitrogen in which relatively large pressure spikes could be observed. Some of these results were as shown in Figures 2, 3 and 4.

In each figure, four pressure profiles are presented. For these profiles, time zero was the time at which the water was injected. Two profiles marked as "PT1" and "PT2" were obtained with said transducers during an actual experiment. The other two profiles that were almost identical and were marked together as "PT1&2 W/O LN2" were obtained from the experiment with the same configuration but without liquid nitrogen. The differences between these two sets of pressure profiles ensured that the interaction between the water and the liquid nitrogen actually took place. It should be noted that the profiles "PT1&2 W/O LN2" were initially flat for a period before the abrupt changes in pressure levels took place. The reason for the initially flat profile was that the water was being injected into the chamber during that period. The compressed air in the water bottle then followed after the water was totally injected. The abrupt pressurization was observed as a result.

As seen from the figures, it was clear that the injection pressure and the volume ratio of the water and liquid nitrogen could strongly affect the interaction. The question of specific interest was whether the rapid pressurization as observed was the result of vapor explosion caused by the sudden fragmentation of the water droplets or just the

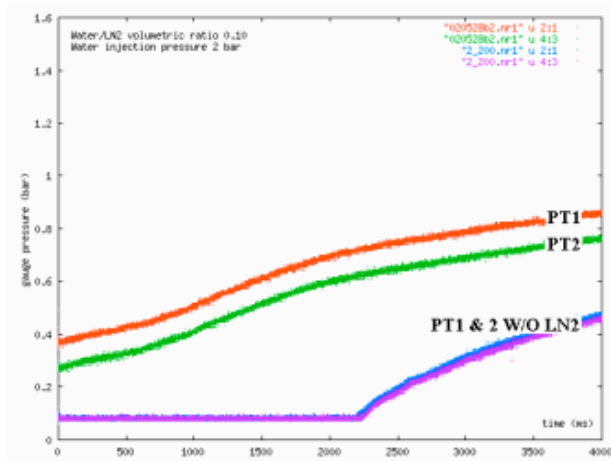


Figure 2. Pressure Profiles (Injection Pressure 2 Bars, Volume Ratio 0.10)

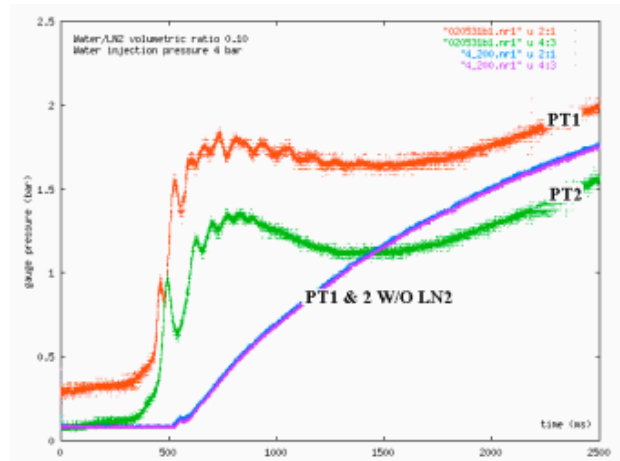


Figure 3. Pressure Profiles (Injection Pressure 4 Bars, Volume Ratio 0.10)

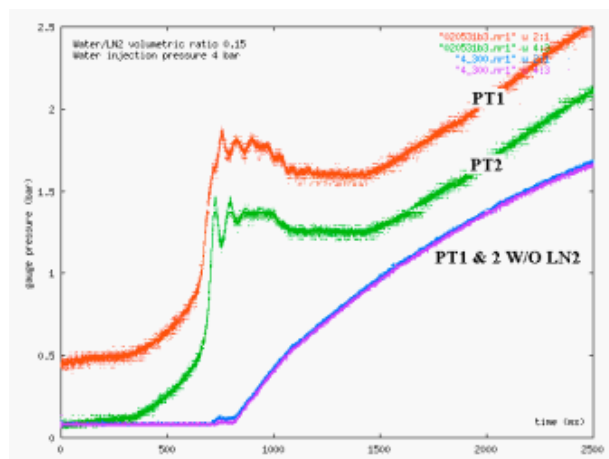


Figure 4. Pressure Profiles (Injection Pressure 4 Bars, Volume Ratio 0.15)

normal, albeit relatively very strong, mixing stage of the interaction.

Generally, two of the criteria that describe vapor explosion are the presence of the shock wave in the system and the expansion in its magnitude over a short time period. The presence of the shockwave suggests that the explosion caused by the rapid fragmentation of the water droplets is local in origin and that the pressure wave is propagating away from the originating point at sound speed. Due to the disturbance caused by the

propagating pressure wave, more fragmentation will result at the nearby location. Consequently, an expansion in magnitude of the pressure wave will be observed.

Based on the above explanation, the existence of the pressure spikes suggested that there was the rapid pressurization during the interaction. To confirm that the explosion actually happened, it must be verified that the observed spikes actually moved at sound speed. For this, the calculation of the propagating speeds for the

observed pressure spikes was attempted. It must be noted, however, that there were at least four processes that were affecting the pressure as measured. These were the effect of the heat transferred from the wall of the chamber, the effect of the mixing process, the effect of the vapor explosion and the effect of the pressurized air from the water bottle.

For the initial difference between two pressure profiles, "PT1" and "PT2," this was caused by the boiling of the liquid nitrogen due to transferred heat from the wall at the lower part of the chamber. It was also the reason for the slow pressurization before contact of the water and the liquid nitrogen. Immediately after their contact, the mixing stage of the interaction began. As the water droplets were being frozen, the liquid nitrogen was also vaporized and the pressure was increased. The sudden rising in pressure was the result of this stage. During the mixing stage, the water droplets that were not immediately frozen would experience the fragmentation induced by the hydrodynamic forces and instabilities on their surfaces. If the process was disturbed, it could be escalated and would result promptly in the total fragmentation of the droplets. Consequentially, all the energy content in the water droplets was immediately given up to vaporize the surrounding coolant. If this happened, the pressure spikes would then be observed.

For the longer period, the pressurized air from the water bottle and the system heating by the environment could also increase the pressure level in the chamber. In this study, however, only the transient during the first two seconds after the injection was of interest and the result after the first two seconds was excluded from this analysis.

### Calculation of the Propagation Speed

For the demonstration purpose, the result from an experiment identified as "020531b1" was used in this calculation. In this experiment, the initial volume of the saturated liquid nitrogen at the room condition was 2000 cc. The water was also at the room condition with the temperature of

300 K. The water/liquid nitrogen volume ratio was 0.10 while the injection pressure was 4 bars. The obtained pressure profiles were previously given in Figure 4.

In order to correctly estimate the effect of the possible vapor explosion, the part of the profiles that were the results of the initial heating by the wall and the mixing phase were consecutively deducted. The results from the deductions are as shown in Figures 5(b) and 5(c).

From Figure 4, the heating by the wall was considered to be the cause of the difference in pressure levels initially obtained by the transducers. As the pressure profile from each transducer was relatively constant and parallel to the other, the heating was considerably slow and the pressure difference was simply the result of the density gradient in the system. To exclude this effect, each obtained pressure profile was deducted by a straight line correlated from its initial part. Analytically, this was expressed as

$$P'_i = P_i - P_w(t_i) \quad (1)$$

where  $P'_i$  was the pressure after the exclusion of the heating by the wall at the recorded time  $t_i$ ,  $P_i$  was the original pressure and  $P_w(t_i)$  was the linearly correlated pressure (the straight line as seen in Figure 5(a)) for the effect of the heating by the wall. The pressure profiles as seen in Figure 5(b) are the results of this deduction under the assumption that the heating by the wall was the dominating mechanism for up to 350 ms.

As seen in Figure 5(b), with the deduction as indicated by equation (1), the initial parts of both modified pressure profiles were virtually identical and were leveled at zero. After the initial part, each profile showed a steady rise in pressure. This part was considered the result of the mixing phase. With the assumption that the pressure rose linearly with time, the pressure was again modified to reduce the effect of the mixing phase. This was expressed analytically as

$$P''_i = P'_i - P_m(t_i) \quad (2)$$

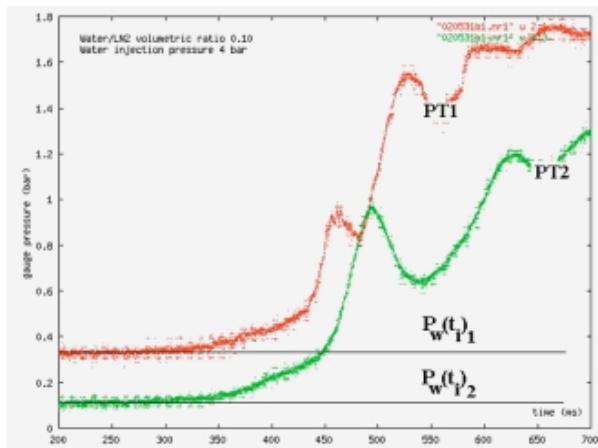


Figure 5(a). Pressure profiles for the first 700 ms of the water-liquid nitrogen interaction (Injection Pressure 4 Bars, Volume Ratio 0.10)

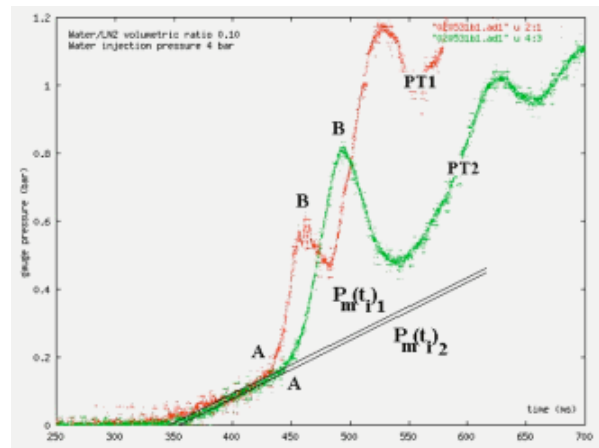


Figure 5(b). After the deduction of the possible effect from the initial wall heating

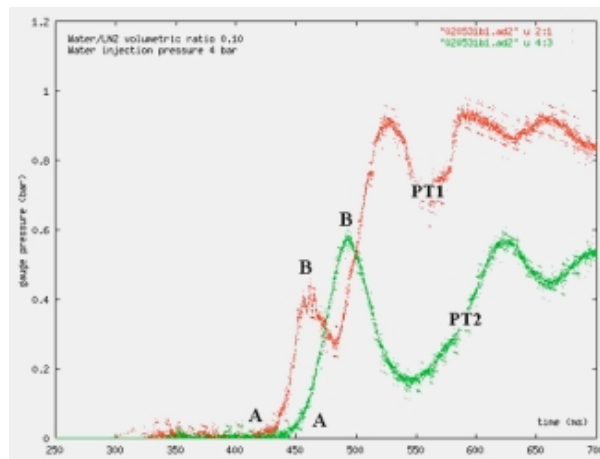


Figure 5(c). After the deduction of the possible effect from the mixing phase

For the above expression,  $P_i''$  was the pressure after exclusion of the heating by the wall and the mixing process at the recorded time  $t_r$ ,  $P_i'$  was the previously modified pressure that excluded the heating by the wall and  $P_m(t_i)$  was the linearly correlated pressure (the straight line as shown in Figure 5(b)) for the mixing process. The results of this calculation as shown in Figure 5(c) were used for the calculation of the propagation speed for the pressure spikes.

Two calculations for the propagation speed were attempted for experiment “020531b1”. The propagation speed was calculated based on the delayed period  $t$  in which the transducers could detect the same signal in the system. Since the distance between the transducers was  $L = 0.695$  m, the propagation speed  $v_p$  was calculated as

$$v_p = L / t \tag{3}$$

The difficulty with the above evaluation was to identify whether the pressure signals detected by the transducers were the same one. For this purpose, the signal identified as “A” and “B” in Figure 5(c) were used. Signal “A” was the point of inception for the pressure spike. It was identified as the point where a straight line might be extended down from the rising slope of the spike to cross the time axis. Signal “B,” on the other hand, was the point where the peak of the spike was observed. Figure 6 might better graphically explain these definitions.

The points of the inception and the pressure peak obtained from the transducers, PT1 and PT2, and the related propagation speeds were as given in Table 1.

**Table 1. Points of inception and pressure peak**

Transducer	PT1	PT2	$v_p$ (m/s)
Inception(ms)	442	456	50
Peak(ms)	461	493	22

Two values for the propagation speed were calculated based on the inception time and the time when the first peak was observed. The one calculated with the inception time was 50 m/s while the one calculated with the time of the peak was 22 m/s. This difference was considered due to the transient in void fraction in the system. As

suggested by Wallis [Wallis, 1969] for the sound speed of the binary fluid, the lower void fraction in the system at the time of the inception compared to that at the time of the peak would correspondingly result in the faster propagation speed.

To consider if the obtained pressure spikes were really due to the explosion, the comparison between the propagation speed and the sound speed in the system must be considered. For this, the relation given by Wallis (1969) was used. Wallis proposed that the sound speed in the binary fluid (liquid/vapor) could be described as

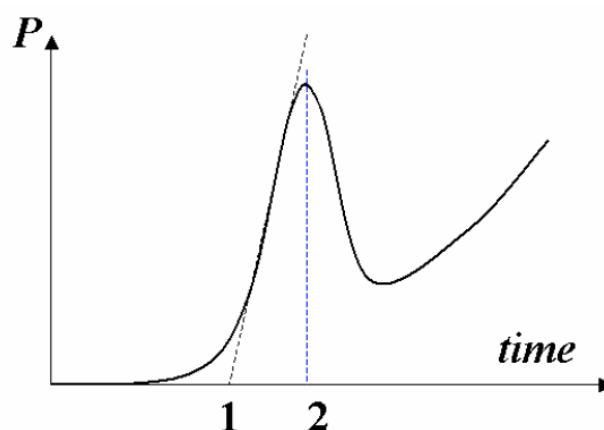
$$\frac{1}{c^2} = [\alpha\rho_2 + (1-\alpha)\rho_1] \left[ \frac{\alpha}{\rho_2 c_2^2} + \frac{1-\alpha}{\rho_1 c_1^2} \right] \quad (4)$$

where

- $c$  was the sound speed of the binary fluid,
- $\alpha$  was the void fraction,
- $\rho_1$  was the density of the vapor phase,
- $c_1$  was the sound speed of the vapor phase,
- $\rho_2$  was the density of the liquid phase and
- $c_2$  was the sound speed of the liquid phase.

Assuming that the medium in the system was mostly the liquid and the vapor nitrogen, the sound speed as a function of the void fraction was calculated as shown in Figure 7.

From Figure 7, it was estimated that the sound speed in the liquid/vapor nitrogen mixture was 26.2 m/s at the void fraction of 0.5 and would



**Figure 6. Diagram for identifying the pressure signal**



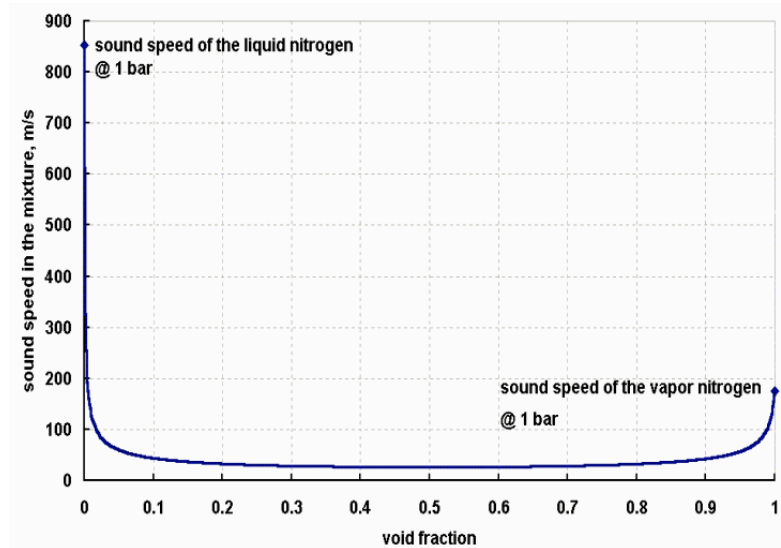


Figure 7. Sound speed in the liquid/vapor nitrogen mixture

be under 50 m/s for the void fraction between 0.1-0.9. Upon considering the uncertainty involved in identifying the pressure signals, these results were comparable with the calculated propagation speed. In addition, the dependence of the sound speed on the void fraction also concurred with the explanation on how the different propagation speeds could result.

### Summary

As the pressure spikes could be observed in the experiments on the water/liquid nitrogen interaction, the possibility of the strong interaction between water and liquid nitrogen was verified. Since the propagation speed of the observed spike and the sound speed in the system filled with the liquid/vapor nitrogen were comparable, it was considered that the strong interaction as observed was actually the result of the vapor explosion.

The effect of the void fraction transient on the propagation speed was also observed. The reduction of the propagation speed as calculated by the time of the peak compared to that calculated by the inception time of the pressure spike was because of the low void fraction at the inception time compared to that at the time of the peak where

the interaction had already increased the void fraction.

However, since there were only two pressure transducers in the system and since the distance between them was not very long compared with the time scale of the interaction and the propagation speed, the inaccuracy of the measurement could give a very misleading result. Therefore, it was suggested that the very sensitive measuring devices be installed in order to obtain accurate results. On the other hand, since each transducer was essentially located on each end of the interaction chamber, the obtained propagation speed was the value averaged over the distance between the transducers and was not the local speed at the point of the interaction. To obtain the actual local speed, it was recommended that two pressure transducers be located close to each other. In addition, more pressure transducers should be employed in order to measure the propagation speeds at various locations along the height of the chamber.

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