CHAPTER 6

CONCLUSIONS, COMMENTS AND RECOMMENDATIONS

The water and the liquid nitrogen were used respectively as the molten fuel and the coolant to simulate the fuel-coolant interaction (FCI). Initially, the work was proposed to study the process of the FCI under the controllable conditions and was titled as **"The Parametric Investigation on the Low Temperature Vapor Explosion."**

As the FCI naturally involved a large number of parameters and as the possibility of the vapor explosion at the low temperature was not yet confirmed, it was considered more appropriate to limit the scope of the study and to concentrated on the more readily testable conditions.

Since one of the most important parameters in the study is the temperature difference between the hot liquid and the colder liquid, not the absolute temperature itself, the study concerned more about the initial conditions of the process that affected the fragmentation and the rapid heat transfer process. As a result, the dissertation with the title of the **"Effect of Volumetric Ratio and Injection Pressure on Liquid Nitrogen-Water Interaction"** was proposed. The volumetric ratio was the ratio of the water volume to the liquid nitrogen volume. The ratio roughly defined the size of the energy source supplied to the interaction during the metastable state or the mixing phase compared with the initial energy content in the coolant. The water injection pressure was a mean to increase the velocity of the injected water and to help breaking up the water droplets in the liquid nitrogen pool in order to increase the area of film boiling in the metastable state. In this study, the explosion was expected to occur spontaneously and, therefore, no triggering device was needed.

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The experimental system was designed to facilitate the spontaneous explosion by using the confined and close cylindrical configuration, called the explosion chamber. The dimension of the chamber was 1-m height and 10-cm diameter. The water at room temperature in the water bottle was injected via the 1.5-cm diameter guide tube into the chamber to come into contact with the 2000-cc liquid nitrogen at the atmospheric saturation. The experiments were conducted with the volumetric ratio of 0.05, 0.10, 0.15, and 0.20, and with the injection pressure of 2, 3, and 4 bar(g).

Two piezo-resistive pressure transducers were installed to measure the pressure signal inside the chamber during the water-liquid nitrogen interaction. In addition, the photographs of the ice debris were also taken after each experiment was concluded. **The pressure profiles and the ice debris were used as the basic tools to trace and compare the results in this work with the characteristics of the vapor explosion at the high temperature.**

The results were also compared with the TEXAS code, which was originally developed for the high temperature FCI and was specifically modified for the simulation at the low temperature. The code could simulate the FCI in the mixing phase and the explosion phase. As there were so many parameters that could effect the explosion phase and as the models for the explosion phase were vastly different, each gave quite the different results, the simulation of the explosion was not attempted. Instead, in this dissertation, the simulation in the mixing phase was used as a tool to classify the results received from the experiments with the assumption that:

"If the scale of the maximum pressurization from the simulation was comparable to that of the experiment, then the pressure spikes appeared in the experiment were likely the result of the mixing process. If not, the pressure spikes were possibly the results of the vapor explosion-liked interaction."

The results from the experiments and simulations were concluded as given in the following paragraphs:

The vapor explosion-liked interactions between the water and the liquid nitrogen in the confined and close system were observed in this work. The water to liquid nitrogen volumetric ratio and the water injection pressure effectively affected the interaction between the injected water and the liquid nitrogen. **The preliminary diagram for the "Interaction Zone" was created to systematically describe their effects on the interaction.** The interaction zone can be separated to (1) without interaction, (2) weak interaction, and (3) strong interaction or vapor explosion liked interaction.

Without the interaction, the observable pressure spike and the spike inception did not occur throughout the experiment. The maximum pressurization calculated from the pressure profiles was below 0.3 bar per second. The ice debris shape and its appearance at the bottom of the chamber were observed to coalesce together into a rather big lump. The debris was not found on the wall of the chamber. Also, the maximum pressurization from the experiment differed from the TEXAS mixing simulation by less than 10%.

In the weak interaction, the observable pressure spikes were observed but the spike happened at a second or more after the experiment was initiated. The effect from the void fraction possibly dominated the process and the surface of the water droplets might have been solidified. This suppressed the strong interaction between the water and the liquid nitrogen. The maximum pressurization ranged from 2 to 6 bar per second. This was greater than that without the interaction by 5-20 times. The ice debris at the bottom of the chamber was observed to coalesce together into a rather big lump with very little sharp edge. Only a small fraction of the debris was found dispersed on the wall of the chamber. The ratio of the maximum pressurization from the experiment to that from the TEXAS mixing simulation ranged from 3 to 9.

In the strong interaction or vapor explosion-liked interaction, the observable pressure spikes were observed. Its appearance and the inception time were less than or at most comparable to the time of the completion injection of the water. The maximum pressurization calculated from the pressure profiles ranged from 6 to 25 bar per second. This pressurization was almost 10 times greater than the pressurization in the weak interaction. The spike inception was occurred within 1 second after the experiment was initiated and seemed to indicate the pressure wave propagation. The strength of the pressure wave seemed to be increasing when the spike moved from the first pressure transducer to the second. The velocities of the pressure wave propagation were estimated to be above or comparable to the theoretical characteristic speed of sound in the homogeneous mixture of the vapor and the liquid nitrogen with some small amount of water. The characteristic speed of sound in the mixture of vapor and liquid nitrogen ranged from 26 to 50 meters per second with the void fraction of 0.1 to 0.9 at 1 bar condition. It was estimated to be 38 to 50 meters per second with the void fraction of 0.1 to 0.9 at 2 bar condition. The ice debris found at the bottom of the chamber tended to be powder liked. The larger pieces of the ice debris were jagged and sharp-edged. Some of them even looked like the frozen bubbles that were broken. The frozen and broken bubble shaped debris suggested that there was the vapor trapped inside the water droplet that expanded and broke out. This suggestion agreed with the model of jet penetration and entrapment proposed by Kim et al. The powder-liked ice debris at the wall in the condition of the volumetric ratio 0.10 or higher at 4-bar injection indicated the fragmentation of water during the interaction. The larger size ice debris caught at the upper part of the chamber also indicated the dispersion of the water and nitrogen mixture during the interaction. The ratio of the maximum pressurization from the experiment to that from the TEXAS mixing simulation was 25 to 110 which was considerably greater than the ratio in the weak or without interaction. **All of the above mentioned evidences agreed with the characteristics of the vapor explosion at the high temperature and, thus proved that the vapor explosion at the low temperature, such as that in the cryogenic range in the confined close system was possible.**

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Even though the experiments and the simulations strongly supported the proposed interaction zone, there were some necessary comments and recommendations that needed to be stated:

To study the water-liquid nitrogen interaction in depth, **the parametric investigation on the low temperature vapor explosion was needed.** The investigation especially on the more fundamental or physical parameters to the interaction would be highly valuable in explaining their effects on the interaction. The parameters, such as the confined geometry or the large free volume, should be defined and investigated. **Also, the velocities and the flow patterns of the injection (both in the guide tube with the nitrogen vapor and at the surface of the liquid nitrogen)**

should be measured or visualized to better explain the mixing phase. The formation of the injected water, whether it was spray liked or column liked, should also be investigated. The initial velocity of the flow could be approximated with the assumption that the built-up pressure in the chamber during the experiment did not retard the water flow in the tube. Thus, the initial Weber number in the guide tube was calculated to be from 0.2 to 6 with the diameter of the guide tube. This was less than the critical Weber numbers (10-20) for breaking up into pieces with the smaller size. On the other hand, the Weber number at the initial mixing phase was estimated with its velocity to be from 40 to 1100. The large Weber number indicated that the injected water with the assumed velocity broke up in the liquid nitrogen.

As the experiment was based on the spontaneous explosion, no external trigger was installed. In addition, the configuration of the system itself might be a factor that trigged the film boiling to collapse. The triggering might be the flow pattern of the injected water just before the completion of injection. The flow might be a two-phase flow and disturb the water-liquid nitrogen mixing. Also the injected pressure from the water storage might disturb and trig the vapor explosion in the water-liquid nitrogen interaction. The last hypothesis was possible if one looked at the spike inception time in the interaction zone. The inception time increased with the volumetric ratio.

The other possibility for conducting the experiment was to reverse the direction of the injection. The injection of liquid nitrogen from the bottom of the chamber filled with water was recommended. This was done to study the interfacial phenomena between the hot liquid and the colder and more volatile liquid. The results from the reversed direction experiments could be applied to the coolability of the hot liquid by the injection tube coolant from an injector tube or the array of injection tubes.

In the high temperature FCI, the molten metal shrinks when it is solidified. On the other hand, the water expands when it is solidified in the low temperature. The small-scale experiment is recommended to study the different effect from this factor.

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Even though the experiments and the TEXAS simulations confirmed the existence of the explosion-liked interaction, the accuracy of the experiments and the simulations should still be reminded.

The effect of the wall heating on the liquid nitrogen was considered in the experiments and the simulation because the liquid nitrogen temperature was lower than the temperature at the wall of the chamber. The heat transferring from the wall of the chamber could boil the liquid nitrogen and raise the pressure in the system. This could create the quasi-equilibrium state where the higher pressure existed at the lower part of the chamber and the lower pressure existed at the upper part. The wall heating simulations were conducted in order to compare the pressurization between the simulations and the experiments observed within the first 0.4 second. The conditions of interest were the volumetric ratio of 0.10, 0.15, and 0.20 with the injection pressure of 4 bar(g). The period of 0.4 second was required for the water to come down from the solenoid valve and make contact with the surface of the liquid nitrogen. The pressurization rate during this period ranged from 0.07 to 0.15 bar per second. The variation depended much on the surrounding temperature of the experiments. The pressurization calculated from the simulation was 0.18 bar per second. The deviation of the prediction by the simulation was 20-160%. The cause of the deviation came from the initial wall temperature assigned to each Eulerian cell in TEXAS code and the actual environment temperatures, which deviated from one to another. In any case, the scale of the pressurization was very small when compared to the scale of the spike pressurization (6-25 bar per second).

Even though the experiments confirmed the existence of the strong interaction between the water and the liquid nitrogen and that the possibility of the vapor explosion-liked interaction was suggested and the diagram that described the effects of the water injection pressure and the water/liquid nitrogen volumetric ratio was proposed, the detailed and accurate results still requires the larger installation with more number of sensitive transducers of various types and functions together with the visualization devices. Such additional devices would be also necessary to observe and confirm each phase of the interaction for further study and to ensure the control of the initial conditions.

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