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Suppression of Steam Explosion Using Dilute Hydrogel Aqueous Solutions

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1. Introduction

Fuel-Coolant Interaction (FCI) is a phenomenon in which hot molten fuel (corium) interacts with surrounding coolant during a nuclear reactor severe accident and the potential explosive outcome of such an event could threaten the reactor containment integrity. For severe accident mitigation purpose, pre-flooding the reactor cavity is preferred to dry cavity for pressurized water reactors (PWRs).

In this approach, when a cold liquid is brought into contact with a molten corium-based material at a temperature significantly higher than the liquid boiling point, an explosive interaction can occur due to sudden fragmentation of the melt and rapid evaporation of the liquid. This phenomenon is referred to as a steam explosion. Such an explosion is a major concern for FCI. As the hot melt falls into the liquid coolant, it breaks up into globules (fragmentation) in the case of molten corium and water. Large-scale vapor explosions initiating from FCI are known to go through four distinct phases; namely, coarse mixing, triggering, propagation, and expansion.

In this case, the fragmentation process of the FCI is hindered when the viscosity of the aqueous coolant is increased by adding some polymeric substances. The effect has been studied and reported [1-3]. The higher viscosity was believed to increase vapor layer stability and thus reduce fragmentation. Some of the coolant additives can alter the coolant viscosity or surface tension and have shown promise in suppressing steam explosions. However, the unstable nature of these aqueous solutions, including property deteriorating aging problem, limits their practical application to nuclear plants.

Sodium (Na) silicate solutions (waterglass) have been found to be remarkably useful in a variety of applications but pure silicate solutions have physical and chemical heterogeneities and instability. The most interesting and characteristic property of silicate solutions is their ability to form stable hydrogels of different viscosities through chemical reactions with some organics, especially those classified as water-soluble polymers.

In this study, a dilute hydrogel-type aqueous solution as a new coolant candidate of PWRs has been prepared. The potential for steam explosion suppression of this aqueous solution has been experimentally investigated. A single drop of molten tin was dropped into a pool of the aqueous solution. The temperature of molten tin drop was as high as 800℃. Implication of steam explosion suppression is discussed based on high-speed video observations.

2. Experimental

2.1. Preparation of dilute hydrogel

A commercial sodium silicate solution of 50 wt% having viscosity of ~200 mm^2/s was used. Sodium silicate solutions have their own high viscosity depending on their water contents. However, the stability of the silicate solutions is too low due to their unstable and heterogeneous nature. To increase the solution stability of the silicate solutions, Na-polyacrylate, one of the superabsorbent polymers, with a molecular weight of 20~70,000, was added. Adding 6 g of Na-polyacrylate to 1 liter of Na-silicate solution yields a highly viscous solution of ~600 mm^2/s, up from ~200 mm^2/s in the unmodified solution. To apply the solutions to a new practical coolant solution, the solution that was too viscous was diluted by adding extra water and the viscosity was lowered to 2 mm^2/s to define the viscosity limit for the steam explosion suppression.

2.2. Single-drop steam explosion test

The experimental apparatus mainly consists of an electric tube furnace, a quartz crucible with a plug rod inside, a cross-shape test section with two viewing ports for visualization. A schematic of the experimental apparatus is shown in Fig. 1. The usual set up for these experiments involves dropping the molten material into the coolant solution by unplugging a melt container of quartz tube. The drops fall a few centimeters into a coolant container holding the viscosity-controlled coolant water. One gram of molten tin was dropped into the aqueous solution pool under study. The temperature of molten tin drop was as high as 800℃. One gram of melt usually formed a few drops of melt when it was released by gravity from the 5 mm diameter hole of the crucible. The coolant depth was typically 220 mm and the free fall height of molten metal from the crucible hole to the water surface was 185 mm. The coolant temperature was kept to room temperature of 25±1℃.

A black-and-white high-speed video camera (FASTCAM SA4) captured the moment of steam explosions. The typical framing rate was 4000 fps.

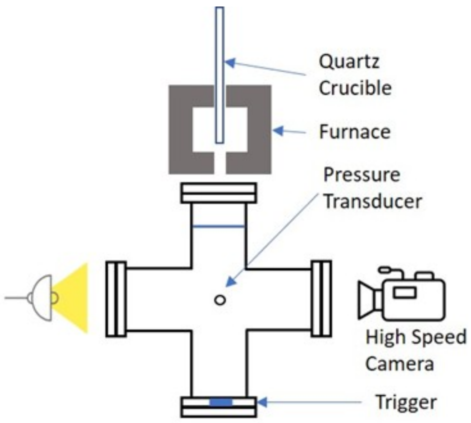

Fig. 1. Schematic of experimental apparatus

3. Results and discussion

3.1. Dilute hydrogel preparation

The most interesting and characteristic property of silicate solutions is their ability to form gels having various viscosities with organic and/or inorganic additives, pH, and temperature. A new Na-silicate hydrogel material of the hydrophilic water-borne gel having very high viscosity was produced with Na-polyacrylate. A free-flowing Na-silicate aqueous solution has turned into a highly viscous solution as the polyacrylate chains became entangled in the sodium silicate networks as shown in Fig. 2. Figure 3 shows the highly viscous hydrogel solution prepared by this preparation process.

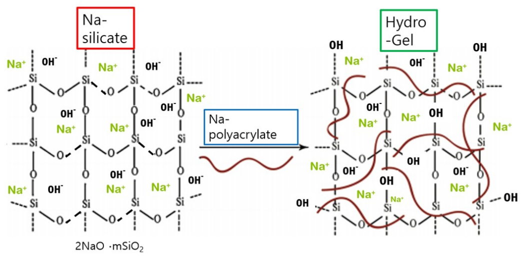

Fig. 2. Networked hydrogel formation by Na-polyacrylate chains on Na-silicate aqueous solution

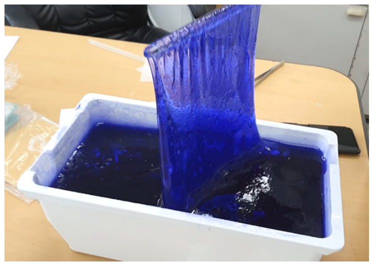

Fig. 3. The prepared viscous (600 mm^2/s) hydrogel before dilution

The uniform boiling behavior of the stable hydrogel compared to the pure Na-silicate solution is shown in Fig. 4. For the pure Na-silicate solution, the inhomogeneous hard crust and bottom residue were formed, while the hydrogel boiled homogeneously like pure water. The stable nature of the hydrogel solution was assumed by the networked structure and the solution has no property deterioration with time (aging).

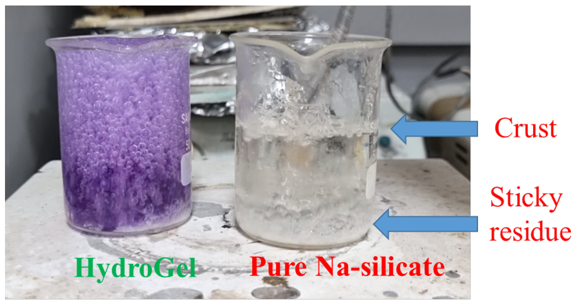

Fig. 4. Comparison of boiling behavior between the hydrogel and pure Na-silicate aqueous solution

The mixing ratio of water and the hydrogel can alter the viscosity of the solution significantly. The kinematic viscosity of pure water at room temperature is about 0.9 mm^2/s. The viscosity of the diluted hydrogel was controlled as low as close to 2 mm^2/s by adding pure water to the viscous hydrogel solution having the higher viscosity over 600 mm^2/s.

3.2. Single-drop steam explosion test

The molten tin of one gram was first tested with pure distilled water. About half of the 30 tests showed spontaneous interactions. Figure 5 showed selected frames of spontaneous interaction and non-interaction for dilute hydrogel solutions with viscosities of 2 and 4 mm^2/s, respectively. The evolution of the viscosity and the explosion limit are summarized in Fig. 6.

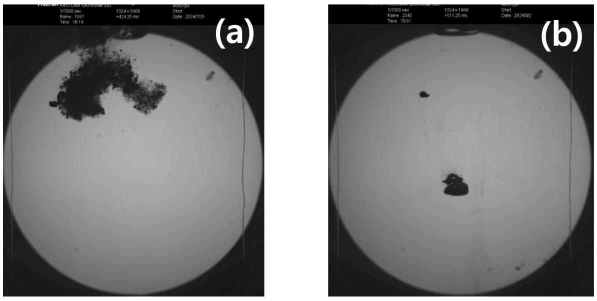

Fig. 5. Spontaneous interaction of lower viscous solution (a): viscosity, 2 mm^2/s; no interaction of higher viscous solution (b): viscosity, 4 mm^2/s

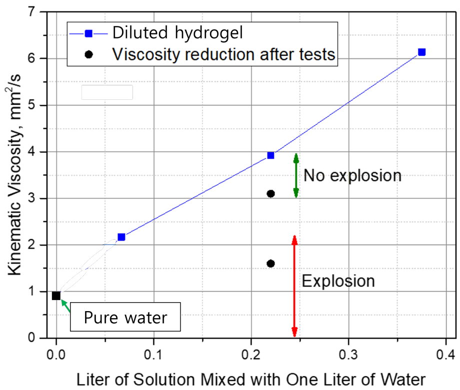

Fig. 6. Interaction of molten tin with dilute hydrogels of adjusted viscosities

The tests with aqueous hydrogel solutions showed a distinct behavior depending on the viscosity. Where the higher the viscosity above 4 mm^2/s, no spontaneous interaction has been seen in the tests. Interestingly, the viscosity of the tested solution continued to decrease as the test progressed.

4. Conclusions

The preparation and characterization of dilute hydrogel-type aqueous solutions as a novel coolant candidate of PWRs has been studied. Hydrogel-type aqueous solutions with higher viscosities over 4 mm^2/s have been prepared and tested to suppress steam explosion. Initially, a highly viscous Na-silicate solution gelled with Na-polyacrylate has been prepared and then diluted to create the proper viscosities over 4 mm^2/s to prevent spontaneous interaction with molten tin. Pure water and low-viscosity solutions below 2 mm^2/s showed about 50% probability of steam explosion occurrence, while high-viscosity solutions over 4 mm^2/s suppressed the steam explosion. It is speculated that the suppression is probably due to high viscosity and stability of the networked hydrogel solution, but it will be further investigated in more systematic way including surface tension study.

Acknowledgement

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