Dynamic Simulation of Nuclear Hydrogen Production Systems

by

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Abstract

Nuclear hydrogen production processes have been proposed as a solution to rising CO$_2$ emissions and low fuel yields in the production of liquid transportation fuels. In these processes, the heat of a nuclear reactor is used to run the chemical reactions in a hydrogen plant. The resulting system is tightly interconnected and operates at very high temperature and pressure, which can lead to operational disruptions and accidents. For this reason, computational studies validating the safe operation of the system are required by regulatory authorities. In the past, safety studies have been conducted by using legacy codes, such as RELAP and MELCOR, and their focus has been the operation of nuclear power plants.

However, traditional legacy codes are not appropriate to simulate nuclear hydrogen production. The simulation of a nuclear reactor itself is already complex because it involves simulating reactor kinetics and transport phenomena. To that complexity, nuclear hydrogen production adds the need to simulate chemical reactions in the hydrogen plant. These chemical reactions cannot be represented easily in legacy codes because these codes lack the flexibility, speed and accuracy required to simulate them. Therefore, only a limited number of studies on the safety of these systems exist.

Instead of using legacy codes, this thesis proposes using equation-based simulators developed by the chemical engineering community to model and study the safety of a nuclear hydrogen production plant. Equation-based simulators were designed to be flexible, extensible and fast because they have to simulate a vast range of processes from the chemical industry. Thus, they provide a good platform for the simulation of nuclear hydrogen production systems. This thesis explains the models used for the different parts in the nuclear hydrogen production plant, and then presents the response of this plant model to different accident scenarios.

The first contribution of this thesis is a novel equation-based model for the heat transfer loop connecting a nuclear reactor and a hydrogen production plant. This heat transfer loop uses helium as the heat transfer fluid, which makes simulating its behavior difficult because
of the need to model gas dynamics. To resolve this, three models for gas dynamics and two set of coupling conditions for boundary variables were tested in JACOBIAN, an equation-based simulator. The three models for gas dynamics in combination with a novel approach to set coupling conditions for boundary variables were able to represent the interesting time scales accurately in transient scenarios. The accuracy and computational speed of these simulations outperformed those produced by a reference model created in RELAP, a legacy code.

The second contribution is a model of a nuclear hydrogen production plant using high-temperature steam electrolysis to produce hydrogen. This model was created to study the effect of potential accidents on the nuclear reactor. It included detailed models of the nuclear reactor and heat transfer loop, and a partial model of the electrolysis plant. The nuclear reactor was modeled as a pebble bed modular reactor, which is one of the safest designs available. The reactor was connected to the hydrogen production plant using the heat transfer loop model already developed in this thesis. The hydrogen production plant was partially represented as a steam superheater in the heat transfer loop.

The third contribution is the demonstration of the safety characteristics of the nuclear hydrogen production plant by subjecting the plant model to three accident scenarios. The scenarios involved disruptions in the hydrogen plant or in the heat transfer loop, and all of them—directly or indirectly—lead to a loss of heat sink capacity for the nuclear reactor. This resulted in an increase of the nuclear reactor core temperature, which was quickly moderated by the fission power reduction at the fuel pebbles and by the safe design of the nuclear reactor. As a consequence, the maximum temperature reached in the core was always less than the fuel melting point and the reactor was always in a safe condition. The heat transfer loop could suffer the rupture of a pipe in one of the scenarios, and design modifications to address this were suggested.

This thesis' results partially prove that nuclear hydrogen production plants could be safe, and simultaneously, that equation-based simulators are good platforms to demonstrate the safety of these plants. Developing these models and tests further will help guarantee the safety of the plant and obtain regulatory and public approval for this new nuclear application.

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