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Safety Philosophy in Process Heat Plants Coupled to High Temperature Reactors

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1. Introduction

With the future availability of fossil fuel resources in doubt, high temperature nuclear reactors have the potential to be an important technology in the near term. Due to a high coolant outlet temperature, high temperature reactors (HTR) can be used to drive chemical plants that directly utilize process heat. Additionally, the high temperature improves the thermodynamic efficiency of the energy utilization.

Many applications of high temperature reactors exist as a thermal driving vector for endothermic chemical process plants. Hydrogen generation using the General Atomics (GA) sulfur iodine (SI) cycle is one promising application of high temperature nuclear heat. The main chemical reactions in the SI cycle are:

1. $I_2+SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$ (Bunsen reaction)
2. $H_2SO_4 \rightarrow H_2O + SO_2 + 1/2O_2$ (Sulfuric acid decomposition)
3. $2HI \rightarrow H_2 + I_2$ (Hydrogen Iodide decomposition)

With the exception of hydrogen and oxygen, all relevant reactants are recycled within the process. However, there are many unresolved safety and operational issues related to implementation of such a coupled plant.

2. Philosophy for safety evaluation of a nuclear hydrogen generation system

Because a nuclear reactor has never been coupled to a chemical process heat plant, a new safety analysis paradigm is required. This paradigm is essentially an integration of the fields of nuclear reactor and chemical process safety. The main steps in evaluation of the safety of a given endothermic chemical plant coupled to a high temperature nuclear reactor are:

1. Consideration of scaling issues in the chemical plant,
2. Development of tools for simulation of operational transients or accident events in either the nuclear or chemical plant of a coupled nuclear hydrogen generation system,
3. Conceptual identification of potential operational or safety related events in the coupled plant,
4. Simulation of steady-state, time-dependent, off-normal, and accident scenarios, and
5. Evaluation of simulation results from the perspective of plant operation and nuclear safety.

Because no industrial scale flowsheets for these chemical processes exist, careful consideration of scaling issues in these process plants is required. Possible accidents scenarios in a chemical process plant consist of reactant flow failure, product flow failure, process holding tank failure, reaction chamber rupture, accidental injection of excess reactant, or other event.

3. Model development and validation

Modeling of the SI cycle presents significant challenges. These challenges include [1]:

1. Simplifying existing steady state flowsheets to allow rapid transient simulation.
2. Encapsulating and extracting relevant transient models from literature and applying them to complex reaction chambers.
3. Coupling reaction chamber models to a nuclear heat source, through one or more heat exchangers.

Transient or accident events within either the nuclear or SI plant will cause several dimensions of response, including the thermal response of the coupled system and the chemical species cascade response in the SI plant. The hydrogen generation plant models must be able to accurately track these responses for a diverse array of events with widely varying severity. The unique aspects of the chemical plant models utilized here include [1]:

- Implementation of two reaction chamber energy balance formulations that fully account for the pressure work: Brown, Oh, Revankar, et al. (2009) [2] and Rawlings and Ekerdt (2002) [3].
- Rigorous justification of the equation of state in the chemical reaction chambers has been performed, see Ref. [2].
- Development of a new simplified chemical plant (SI cycle) flowsheet with detailed accounting of the chemical species balance and relevant physical properties throughout the chemical plant.
- Consideration has been made of local recycling within sections of the chemical plant, as well as global recycling between sections. With the implementation of the recycling flowsheet the efficiency of the energy balance (35%) matches realistic estimates in literature.
- A momentum equation has been implemented to calculate the flow transit time and pressure drop between chemical plant sections. This accounts for the inter- and intra-chemical plant separation distance.
- A realistic design study for the flow paths between chemical plant sections has been performed for two different chemical plant flowsheets.

- A critical flow rate model is implemented so that reaction chamber rupture events may be modeled.
- Multiple intermediate and process heat exchangers are modeled. The vaporization processes are properly accounted and occur in separate heat exchangers.
- Model validation studies have been performed for the chemical kinetics, reaction chamber model, and overall SI cycle implementation.

There are several dimensions for validation of the chemical plant models. Significantly, there is no data for a high temperature reactor coupled to any process heat plant. However, there is data from high temperature reactor operation, and from bench scale and integrated loop experiments of the SI and HyS cycle.

The neutronic behavior of the HTR is dictated by the interaction probabilities of the neutrons. These cross sections are established in the relevant energy range. The physical behavior of the SI chemical plant is also established. GA has operated two integrated loop experiments of the entire cycle, two integrated loops with transient data have been operated in Japan and China, and countless bench or integrated scale experiments provide transient data for the individual chemical reactions. The principles of chemical reaction engineering were used to systematically develop and validate the various models utilized in this coupled code system. Full details of the validation process are given elsewhere [1].

The main aspects of the nuclear reactor validation and verification effort are:

- Neutron flux shape distribution,
- Point kinetics model and coefficients,
- Heat transfer processes in the nuclear reactor.

The main aspects of the SI plant validation effort are:

- Process flowsheet benchmarking and steady state integrated demonstration loop results,
- Chemical kinetics from bench scale experiments,
- Integrated-loop scale (ILS) transient data for sulfuric acid decomposition,
- Integrated-loop demonstration transient data.

4. Time-to-SCRAM for overcooling events

In this example test case, the helium inlet temperature to the nuclear reactor is overcooled due to an event in the chemical plant. Complete results for this case are given in Ref. [1], and only the most significant results are highlighted here. The event studied in this example case is the injection of sulfuric acid reactant feed to the sulfuric acid decomposition section following the opening of a valve in a process holding tank. The events proceed:

1. Steady state solution for 670 mol/sec of hydrogen generation, assuming reactant recycle within sections.
2. At 5 seconds, a valve opens in a sulfuric acid storage tank (process holding failure). This results in the continuing injection of additional sulfuric acid into the feed stream for section 2 of the chemical plant.
3. The sulfuric acid flow rate is perturbed by parametric step changes of 50, 60, ... , 140, 150 mol/sec. Thus, these changes range from 7.5 % to 22.3 %.
4. The reactor power increase due to the overcooling of the Helium inlet is monitored. When the SCRAM limit (1.06) is reached, the reactor is scrammed by the insertion of all control rods within 0.1 seconds.

Results from this test case are shown in Fig. 1 and Fig. 2. Further test cases are presented in a companion paper [4].

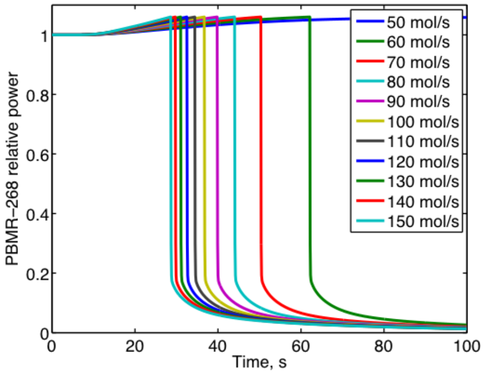

Fig. 1. Time-to-SCRAM for varying rate of sulfuric acid injection.

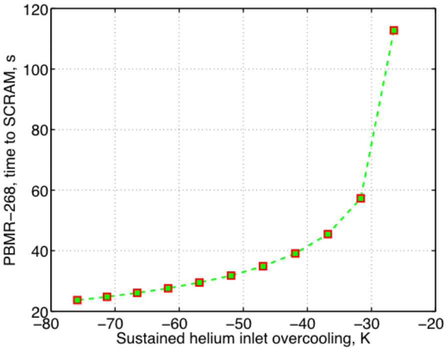

Fig. 2. Time-to-SCRAM as a function of sustained inlet overcooling.

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