Annals of Nuclear Energy 38 (2011) 860–875

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Discrete event dynamic system (DES)-based modeling for dynamic material flow in the pyroprocess

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ARTICLE INFO

Article history:
Received 27 May 2010
Received in revised form 22 October 2010
Accepted 9 November 2010
Available online 30 December 2010

Keywords:
Discrete event dynamic system (DES)
Dynamic mass balance
Pyroprocess
Voloxidation equivalent mass (VEM)

ABSTRACT

A modeling and simulation methodology was proposed in order to implement the dynamic material flow of the pyroprocess. Since the static mass balance provides the limited information on the material flow, it is hard to predict dynamic behavior according to event. Therefore, a discrete event system (DES)-based model named, PyroFlow, was developed at the Korea Atomic Energy Research Institute (KAERI). PyroFlow is able to calculate dynamic mass balance and also show various dynamic operational results in real time. By using PyroFlow, it is easy to rapidly predict unforeseeable results, such as throughput in unit process, accumulated product in buffer and operation status. As preliminary simulations, bottleneck analyses in the pyroprocess were carried out and consequently it was presented that operation strategy had influence on the productivity of the pyroprocess.

1. Introduction

Next generation nuclear fuel cycles require innovative features such as an environmental load reduction, safety, efficient recycle of resources, nuclear proliferation resistance and economics. From this viewpoint, pyrometallurgical processing of spent nuclear fuel (SNF) is now considered as one of the most promising options for future nuclear cycles in the Republic of Korea (Kim, 2006). KAERI has been developing pyroprocess technology, which could reduce the increasing amount of SNF and dramatically decrease the disposal load through recycling and destroying toxic waste such as long-life fission products in SNF (You et al., 2007). The pyroprocess contains more than a dozen unit processes and various types of nuclear material flow into and out of the unit processes according to operational procedures. The unit processes may have different batch capacities and different processing times. There are also many different types of output materials that have different streams even at a unit process. Such a complex material flow can be implemented provided that an operational procedure of the pyroprocess is well addressed and then the material flow according to operational event can be well defined. In order to carry out the modeling of the pyroprocess based on the operational procedure of the pyroprocess, a discrete event dynamic system (DES)-based modeling approach is preferred.

There are a few examples regarding studies on operational modeling and simulation in the field of nuclear. The Idaho National Laboratory (INL) has been performing various operational modeling and simulation studies based on discrete event system modeling and simulation at its own nuclear facilities such as its Experimental Breeder Reactor-II (EBR-II), Hot Fuel Examination Facility (HFEF), Fuel Conditioning Facility (FCF). Through DES modeling and simulation, INL analyzed operational scheduling, annual throughput, process equipment capacity and bottleneck process, and as a result, INL suggested an efficient and enhanced facility operation strategy (Garcia, 2000; Garcia et al., 1995; Garcia and Houshyar, 1998; Houshyar, 1997; Houshyar and Imel, 1996). This study suggested that the annual throughput in the FCF can be enhanced drastically. The Sandia National Laboratory (SNL) has developed and utilized a number of simulation models to represent the processing, transportation, and disposal of radioactive waste (Trone et al., 2000). SNL has developed a supply chain model for the cradle to grave management of a radioactive waste and used this model to assist the Department of Energy (DOE) in developing a cost effective, regulatory compliant and efficient approach to dispose of radioactive waste from 25 sites across the country over the next 35 years. The simulation model was also developed on the basis of a DES simulation scheme. KAERI has also suggested DES-based operational modeling and simulation to analyze the head-end process which is a part of the pyroprocess (Lee et al., 2009).

Unlike the above studies, this paper focuses on how the dynamic material flow can be implemented by DES-based modeling and simulation. Simple material flow in the pyroprocess can be

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doi:10.1016/j.anucene.2010.11.005

easily understood by static mass balance. However, this does not reflect the change of mass balance according to operational event, so it cannot yield insight into the complex dynamic behavior of the material flow. Therefore, it is important to obtain a dynamic mass balance. The dynamic mass balance will make it easier to understand the complex dynamic behavior of the pyroprocess and to analyze it more quantitatively. As a modeling and simulation tool, ExtendSim was used. ExtendSim is an easy-to-use, yet extremely powerful tool for simulating a DES.

2. Pyroprocess

An integrated pyroprocess is under consideration to process the spent oxide fuel discharged from PWRs and fabricate metallic fuel containing TRU (TRansUranic) elements for a future SFR (Sodium Cooled Fast Reactor) (Yoo et al., 2008). The integrated pyroprocess is composed of the following principal unit processes: (1) chopping, (2) decladding and high temperature voloxidation, (3) electrolytic reduction, (4) electro-refining, (5) cathode processing, (6) electro-winning, (7) Cd distillation, (8) residual actinide recovery, (9) salt purification.

In order to recover the actinide elements, the spent PWR fuel is first disassembled and chopped into an appropriate size to obtain spent UO_2 pellets, followed by a voloxidation process in which the UO_2 pellet is converted and pulverized into U_3O_8 powder (Kim et al., 2008). During the voloxidation process, volatile fission product elements such as Cs, I, Tc, and so on are removed. The produced U_3O_8 powder is introduced into a LiCl molten salt bath for conversion of the spent oxide powder to metallic powder (Park et al., 2008). During the electrolytic reduction process, the oxide powder is reduced into a metal form which normally contains most of the transition elements, all of the actinides and a certain fraction of rare earth elements. The remained LiCl salt after several electrolytic reduction processes contains most of the fission products with a high heat load, such as Cs and Sr, which are separated from the metallic powder. The LiCl salt is sent to a LiCl salt purification process to recycle it by separating LiCl residue concentrated with Cs and Sr from pure LiCl. The LiCl residue is finally converted to a ceramic waste form by solidification. The metal mixture obtained from electrolytic reduction process is then transferred to the electro-refining process with LiCl–KCl eutectic salt in order to recover the pure uranium on the solid cathode (Lee et al., 2006). The cathode deposits are recovered after the desired amount of material has been collected and then sent to a cathode processor to produce a uranium ingot by distillation of eutectic salt occluded in the uranium deposits. The uranium ingot can be stored as a low-level waste or recycled as a fresh fuel material. The remaining eutectic salt, in the electro-refining reactor, after several electro-refining processes, is then transferred to the electro-winning process to collect the mixture of actinide and some rare earth elements at the liquid cadmium cathode (Kwon et al., 2009). The remaining LiCl–KCl eutectic salt, after the electro-winning process, is then sent to the residual actinide recovery (RAR) process to recover the mixture of actinide and some rare earth elements once more (Shim et al., 2009). The remaining LiCl–KCl eutectic salt after the RAR process is then sent to the LiCl–KCl purification process to recycle it by separating rare earth elements from pure LiCl–KCl (Cho et al., 2009). The separated rare earth elements are finally converted to ceramic waste form by solidification. The collected mixture of the actinide and some rare earth elements at the liquid cadmium cathode (LCC) after the electro-winning process and the RAR process is distilled by a Cd distillation unit for recovery of TRU alloy (Kwon et al., 2008), and it is then sent to a fuel fabrication process to prepare it as a fuel for transmutation of long-life radionuclides by blending it with an actinide mixture.

3. Discrete event dynamic material flow

3.1. Static vs. dynamic

A conventional approach to describe the material flow in the pyroprocess is based on static mass balance which is obtained by combining mass balances calculated at unit processes. It is useful to simply estimate a yield of product without consideration of the number of batch operations. However, what if there is a need to estimate a yield of product in the middle of process or at a specific time? What if there is a need to know how big a buffer space should be designed? What if there is a need to see where and when a bottleneck occurs? In these cases, the conventional material flow based on the static mass balance is not much help. In order to solve these problems in a more flexible way, not the static but the dynamic modeling approach is needed.

3.2. Dynamic systems for pyroprocess

Dynamic systems are generally classified into three categories: continuous variable dynamic system (CVDS), DES and hybrid system. From this point of view, the pyroprocess can be considered one of them. If a pyrometallurgical reaction at a unit process is a matter of concern, it should be modeled as a CVDS. On the other hand, if operation behavior is a matter of concern, it should be modeled as a DES. A hybrid system is a dynamic system that exhibits both CVDS and DES behavior. In the case where a pyrometallurgical reaction is not a matter of concern, the modeling and simulation approach on the basis of the DES is good enough to implement a dynamic material flow of the pyroprocess. In a DES, operation of a system is represented as a chronological sequence of events (Cassandras and Lafortune, 2008). Each event occurs at an instant in time and marks as a change of state in the system. For example, in the pyroprocess, the event of 'a feed material's arrival at a unit process' triggers the change of state from 'idleness' to 'operation' and the event of 'completion of process' triggers the change of state from 'operation' to 'idleness'. A DES has a discrete set of states which, unlike a physical system, may take symbolic value rather than real values. State transitions in such systems occur at asynchronous discrete instants of time in response to events, which may also take symbolic values. Unlike most physical systems, the relationship between state transitions and events are highly irregular and usually cannot be described by using differential or difference equations. The material flow of the pyroprocess looks like a DES because of many operational events such as a material's arrival and departure, and equipment failure and repair which consequently change the state of the unit process into idleness, operation or breakdown. Therefore, modeling of the pyroprocess could be done by using DES-based modeling techniques.

4. Dynamic material flow in the pyroprocess

The purpose to develop a dynamic model for the material flow in the pyroprocess was not only to obtain a dynamic mass balance, but also to construct a model that is able to perform various scenario analyses rapidly. In order to do that, a modeling tool for a DES should provide a full set of building blocks that allow users to build models rapidly and provide a function for hierarchical decomposition modeling. Also, in the steps of the simulation, it must provide functions for changing model parameters, so users could quickly try out assumptions and see the results dynamically. In this paper, ExtendSim was used because it is useful enough to attain these purposes. A dynamic model for the material flow of the pyroprocess was developed, and it was named PyroFlow. Currently, the first version of PyroFlow was released only at KAERI. PyroFlow has the following features: