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Transient safety analysis for simplified accelerator driven system with gas-lift pump

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ABSTRACT

Owing to remarkable advantage for transmutation of the long-lived nuclear waste, Accelerator Driven System (ADS) is one of the most promising systems in nuclear power field. In this study, the transient analysis of a simplified lead bismuth alloy cooling accelerator driven system with gas-lift pump has been numerically simulated. By using point reactor neutron kinetics equation and related thermal-hydraulic models, TASAR (Transient Analysis of Simplified ADS Reactor) code is developed. The five kinds of transient cases are simulated: Starting gas-lift pump (SG), Unprotected loss of flow (ULOF), Beam interruption (BI), Unprotected transient over current (UTOC), Unprotected transient overpower (UTOP). Meanwhile, the calculation results of TASAR code are validated by the experimental data of NACIE (Natural Circulation Experiment) facility. The analysis is as following: In SG and ULOF conditions, the introduction of gas-lift pump has a remarkable influence of loop natural circulation capability. In BT and UTOC conditions, the short-time beam cutting off and a 100% increase of the external neutron source would not lead to the immediate fuel melting. In UTOP condition, a reactivity jump of 2$ would not lead to the damage of fuel and the cladding. The above numerical results show that, the accelerator and gas-lift pump influence the loop mass flow rate and core temperatures of research system in this paper greatly, and the simplified accelerator driven system with gas-lift pump has a very good safety performance.

1. Introduction

Accelerator Driven System (ADS) is a subcritical reactor with a significant effect in the terms of minor actinides (MAs) transmutation. As shown in Fig. 1(Suzuki et al., 2005), the ADS constitutes of particle accelerator, subcritical reactor, heat exchanger, gas-lift pump system, liquid lead bismuth alloy cycle and argon cycle. In the typical ADS, protons are produced by the accelerator and then transferred to hit the lead target, this process generates a lot of neutrons. All of these neutrons are supplied to the core and react with nuclear fuel. The heat generated from the core is carried away by the lead bismuth alloy (LBE). And the coolant circulation flow in the primary circuit is enhanced by the gas-lift pump (Cinotti and Gherardi, 2002).

During these years, many transient analysis works for LBE-cooled ADS have been performed. W. M. Schikor evaluated the neutron kinetics and transient dynamic behavior of Pb-cooled accelerator driven system, and compared with critical reactor (Schikor, 2001). On the basis of SAS-4A program, X. Cheng made the transient analysis of ADS including metal uranium fuel-sodium coolant, uranium oxide fuel-sodium coolant, metal uranium fuel-lead bismuth alloy coolant and uranium oxide fuel-LBE coolant (Cheng et al., 2004). Besides, X.-N Chen and T. Suzuki made the comparison of transient security features between small ADS with MOX fuel and 800 MW ADT with ceramic fuel (Chen et al., 2004). Meanwhile, Suzuki and Tobita made modification and improvement of SIMMER-III (Suzuki et al., 2003). Based on TRAC/AAA code, K. Mikityuk compared LBE-cooled ADS with helium-cooled ADS (Mikityuk et al., 2006). Weimin Ma et al. studied the transmutation verification of LBE-cooled accelerator driven system. They made research of steady and transient thermal hydraulic property on TALL experiment equipment, the results provided a good data base for safety analysis program, and showed the good natural circulation characteristics of LBE-cooled system (Weimin et al., 2006). Ciacomino Bandini et al. made the safety assessment of EFIT system. The steady calculation results showed, the core with MOX fuel can be adapted to higher temperature and power density, compared with earlier ADS system design (Bandini et al., 2007). Zhan Liu, from Shanghai Jiaotong University, conducted thermo-hydraulic analysis on the ADS principle verification device (Liu, 2010). Juanli Zuo (author) have made research about the natural circulation capability in lead-bismuth alloy cooled reactor with gas-lift pump (Zuo et al., 2013). However, all of these

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Nomenclature

A	Cross sectional area (m^2)
C	Fission power of delayed neutron(W)
C_D	Drag coefficient
Eo	Eotvos number
K	Form resistance coefficient
L	Pipe length (m)
Nu	Nusselt number
N	Fission power of reactor(W)
P	Pressure (Pa)
Pe	Peclet number
Q	External power(W)
Q_v	Volumetric heat release rate (W/m^3)
Re	Reynolds number
T	Temperature(K)
Ue	Perimeter(m)
W	Mass flow rate (kg/s)
Z	Axial length(m)
c	Specific heat at constant pressure (J/(kg·K))
f	Friction coefficient
g	Gravitational acceleration (m/s^2)
k	Heat conductivity coefficient (W/(m^2·K))
q	Heat flux (W/m^2)
r	Radius(m)
t	Time (s)
x	Quality

Greek symbols

Λ	Average neutron generation time(s)
$(\Phi_{lo})^2$	Two phase friction pressure drop multiples
α	Void fraction
β	Fraction of delayed neutron
λ	Decay constant of delayed neutron
τ	Shear stress
μ	Viscosity (Pa·s)
ρ	Density (kg/s); reactivity ($)

Superscript/subscript

c	Cladding
ci	Inner surface of cladding
co	Outside surface of cladding
core	Reactor core
CP	Cool stage
DP	Descent stage
f	Friction
g	Gas
gm	Ascent stage
HP	Hot stage
HX	Heat exchanger
in	Entrance
l	Liquid
out	Exit
u	Fuel pellet

transient analysis works have their own limitations. Many existing system codes are not just for ADS, the program flexibility and autonomy are not very good.

In this paper, the transient safety analysis work for simplified accelerator system with gas-lift pump cooled by Pb-Bi was carried out, TASAR (Transient Analysis of Simplified ADS Reactor) code was developed. And the following transient accident cases were analyzed: Starting gas-lift pump (SG), unprotected loss of flow (ULOF), Beam interruption (BI), unprotected transient over current (UTOC), and unprotected transient overpower (UTOP). In my code, I set up the physical properties modules of material, fluid and gas, so the type and physical properties of fuel, coolant and gas can be changed according to researcher's requirement. The neutron physics and thermal hydraulic of accelerator driven subcritical reactor are coupled. And in the two-phase flow model, the friction resistance coefficients of flow patterns can be calculated very well. Besides, my code focuses on the gas-lift pump and spallation target in system. Thus, my work results will provide theoretical basis of the optimization design in gas-lift pump and spallation target. Meanwhile, the study is helpful to the research of transient analysis of accelerator driven subcritical reactor.

2. System structure

In this work, the calculation model of simplified ADS is shown in Fig. 2. The loop combines reactor core, accelerator, target, ascent stage, hot stage, heat exchanger, descent stage, and cool stage. The original values of system design can be seen in Table 1 referred XADS design parameters. The fuel subassemblies in reactor core are triangular lattice arrangement. U-Pu MOX and AISI316L stainless steel are employed as pellet fuel and cladding material, respectively (Cinotti and Gherardi, 2002; Umnrello et al., 2007). Helium is used to fill in the gap between fuel pellet and cladding (Sobolev et al., 2009). The heat exchanger is a

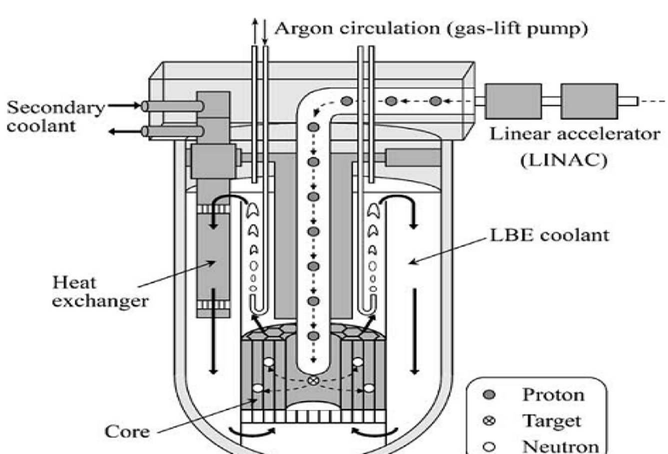

Fig. 1. Configuration of typical LBE-cooled ADS.

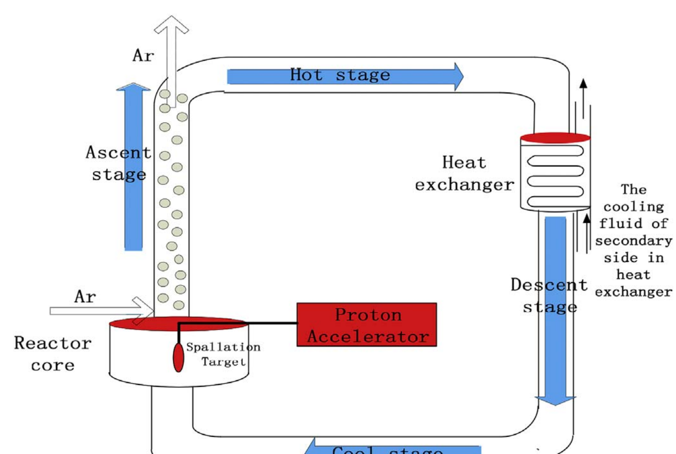

Fig. 2. The schematic of simplified accelerator driven system.