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Thermal-hydraulic analysis of the improved TOPAZ-II power system using a heat pipe radiator

Wenwen Zhang, Dalin Zhang *, Wenxi Tian, Suizheng Qiu, G.H. Su

School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- The system thermal-hydraulic model of the improved space thermionic reactor is developed.
- The temperature reactivity feedback effects of the moderator, UO2 fuel, electrodes and reflector are considered.
- The alkali metal heat pipe radiator is modeled with the two dimensional heat pipe model.
- The steady state and the start-up procedure of the system are analyzed.

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ABSTRACT

A system analysis code coupled with the heat pipe model is developed to analyze the thermal-hydraulic characteristics of the improved TOPAZ-II reactor power system with a heat pipe radiator. The core thermal-hydraulic model, neutron physics model, and the coolant loop component models (including pump, volume accumulator, pipes and plenums) are established. The designed heat pipe radiator, which replaces the original pumped loop radiator, is also modeled, including two-dimensional heat pipe analysis model, fin model and coolant transport duct model. The system analysis code and the heat pipe model is coupled in the transport duct model. Steady state condition and start-up procedure of the improved TOPAZ-II system are calculated. The results show that the designed radiator can satisfy the waste heat rejection requirement of the improved power system. Meanwhile, the code can be used to obtained the thermal characteristics of the system transients such as the start-up process.

1. Introduction

A space nuclear power system converts the energy from a nuclear heat source into electricity to power a particular load or application. Nuclear power sources are attractive for using in space for its high power-to-mass ratio and efficiency, long lifetime, self-sufficiency and design flexibility. A generic space nuclear power system consists of the energy source, primary heat transport system, an energy conversion technique and a radiator for heat rejection (Diwekar and Morel, 1993). The TOPAZ-II power system developed by the former Soviet Union is the most technologically advanced and experienced thermionic system ever built (Bennett et al., 1996). It provides electricity by means of thermionic static energy conversion and releases the waste heat by a pumped loop radiator. Radiators in orbit around the Earth are exposed to an environment of micro-meteoroids and space debris particles. Although the original pumped loop radiator has a simple structure, but it has the problem of potential single point failure, which means the rupture of any radiation tube would lead to the LOCA of the whole system.

Long duration space missions impose very strict reliability requirements. In order to avoid the single point failure, a heat pipe radiator comprised of a pumped fluid in a transport duct that moves across the evaporator section of a heat pipe array is designed for the TOPAZ-II system in our former work. Each heat pipe of the radiator can be considered as an independent element. Heat pipe failures due to environment hazards don't mean the overall heat rejection system failure. The heat pipe radiators are widely used in the advanced space nuclear power system design, such as the SPACE-R thermionic reactor system (Von Arx and Alan Vincent, 1999), thermocouple reactor system SP-100 system (El-Genk and Seo, 1990), SAIRS system (El-Genk and Tournier, 2004a,b,c), SC-SCoRe system (Schriener and El-Genk, 2014), HP-STMCs power system (El-Genk and Tournier, 2004a,b,c). To analyze the heat pipe used in the space applications, Tournier and El-Genk (1992, 1995) developed a two-dimensional heat pipe transient analysis model (HPTAM) to simulate the transient operation of

* Corresponding author. Fax: +86 29 82664460.
E-mail address: dlzhang@mail.xjtu.edu.cn (D. Zhang).

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Nomenclature

t	time (s)
P	power (W)
C	delayed neutron precursor concentration (m^{-3})
c	specific heat ($j \cdot kg^{-1} \cdot K^{-1}$)
Q	heat source ($W \cdot m^{-3}$)
Π	surface area (m^2)
D	diameter (m)
U	perimeter (m), z-component of velocity ($m \cdot s^{-1}$)
L	length (m)
h	enthalpy ($j \cdot kg^{-1}$)
p	pressure (Pa)
T	temperature (K)
A	area (m^2)
H	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
f	view factor
V	volume (m^3), average velocity at cross-section ($m \cdot s^{-1}$)
R	perfect gas constant, radial position (m)
Z	axial position (m)
v	specific volume ($m^3 \cdot kg^{-1}$)
X	quality of vapor
m	mass (kg)
M	molecular weight (mol^{-1})
Greek symbols	
β	delayed neutron fraction
λ	heat conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
	decay constant of precursors (s^{-1})
Λ	neutron generation time (s)
δ	wall thickness (m)
ρ	density ($kg \cdot m^{-3}$)
ε	emissivity
θ	angle (degree)
σ	Stefan–Boltzmann constant ($W \cdot m^{-2} \cdot K^{-4}$)
Subscripts	
f	fission, fluid
U	fuel
G	gap
e	electrode
E	emitter
C	collector
SI	inner steel pipe
SO	outer steel pipe
M	moderator
R	reflector
v	vapor
l	liquid
wc	welded copper
pw	pipe wall
s	surrounding, solid
sin	inner surface
$sout$	outer surface

fully-thawed heat pipes and the startup of heat pipes from a frozen state. The NASA Lewis Research Center developed a heat transfer analysis code to analyze the heat pipe radiator (Hainley, 1991).

Numerical simulations are also performed for the TOPAZ-II power system. A system analysis code, CENTAR (The Code for Extended Non-linear Transient Analysis of Extraterrestrial Reactors), was developed and used to analyze the TOPAZ-II system following a loss of coolant accident (Standley et al., 1992). The code TITAM (Thermionic Transient Analysis Model), developed by the El-Genk group, was used to simulate the operation of the thermionic fuel element (El-Genk et al., 1992). The extended version adding the thermal-hydraulic models of the coolant loop, EM pump, radiator and other components, was used to perform steady-state and transient analysis of the TOPAZ-II system (El-Genk et al., 1994). A system model capable of evaluating the system performance under conditions from both natural and hostile threats and system startup/shutdown transients are developed for the multicell thermionic space power reactor, S-PRIME (Von Arx and Alan Vincent, 1999). The heat pipe radiator of the S-PRIME system is modeled to allow for cases of unequal irradiant heating. The heat pipe model includes the evaporation and condensation rates, as well as the freezing and thawing. This radiator model employs much experiment data and empirical correlations, and the generality and flexibility are not good.

In this work, a thermal-hydraulic system model has been developed for the improved TOPAZ-II system, which can be used to evaluate transient and steady state cases. Furthermore, coupling with the point reactor kinetic equations and the reactivity feedback model, the reactivity changes can be calculated with changes of the reactor temperatures. A two-dimensional heat pipe analysis model using the finite element method is applied to model the heat pipe radiator. The steady state condition with the nominal operation parameters and the start-up procedure are calculated and analyzed in the present study.

2. General description and mathematical model description

The TOPAZ-II is a single-cell thermionic reactor system which can produce 4.5–5.5 kWe for three years of autonomous and continuous operation in space. The major TOPAZ-II subsystems are: the reactor and combined thermionic converters, the primary coolant loop, secondary systems, such as the cesium supply system, the radiation shielding and power distribution system, the instrumentation and control (I&C) system. Highly enriched uranium fuel heats the thermionic emitter, enabling electron flow. The liquid metal coolant system transfers waste heat to the radiator, limiting collector temperature. An electromagnetic (EM) pump provides the motive force for coolant flow. The radiation shield composed of a stainless steel shell that contains lithium hydride attached to the lower part of the reactor limits the neutron and gamma dose rate to the rest of the spacecraft. The cesium system supplies cesium (Cs) to the interelectrode gap, improving converter efficiency. The I&C system monitors conditions, accomplishing start-up, operational control, and emergency shut-down functions. The main components of TOPAZ-II system are shown schematically in Fig. 1. The main design parameters of the core and heat rejection system are summarized in Table 1.

2.1. Thermal hydraulic model and neutron kinetics model of the core

The TOPAZ-II reactor is a small, zirconium hydride moderated, epi-thermal design with high enriched U-235 fuel, which contains 37 single-cell TFEs that combine the fission heat source with the thermionic converters. The TFEs are set within axial channels in the five stacked zirconium hydride moderator blocks. The reactor core is surrounded by radial and axial beryllium (Be) reflectors. The radial reflector contains three safety drums with independent drive motors, and nine control drums attached to a single control drive motor located beneath the shield. Each drum contains a