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Transient behavior of the sodium–potassium alloy heat pipe in passive residual heat removal system of molten salt reactor

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A B S T R A C T

High temperature heat pipes, as highly-effective heat transfer elements, have been extensively employed in thermal management for their remarkable advantages in conductivity, isothermality and self-actuating. It is of significance to apply heat pipes to new concept passive residual heat removal system (PRHRS) of molten salt reactor (MSR). In this paper, the new concept PRHRS of MSR using sodium–potassium alloy (NaK) heat pipes is proposed in detail, and then the transient behavior of high temperature NaK heat pipe is numerically investigated using the Finite Element Method (FEM) in the case of MSR accident. The two-dimensional transient conduction model for the heat pipe wall and wick structure is coupled with the one-dimensional quasi-steady model for the vapor flow when vaporization and condensation occur at the liquid–vapor interface. The governing equations coupled with boundary conditions are solved by FORTRAN code to obtain the distributions of the temperature, velocity and pressure for the heat pipe transient operation. Numerical results indicated that high temperature NaK heat pipe had a good operating performance and removed the residual heat of fuel salt significantly for the accident of MSR.

1. Introduction

The molten salt reactor (MSR) has a long history, which was firstly proposed by Bettis and Briant of Oak Ridge National Laboratory (ORNL) during the post-World War II to develop a nuclear engine for a military jet aircraft (Bettis et al., 1957). In 1954, the Aircraft Reactor Experiment (ARE), a small reactor using a circulating molten fuel salt, was carried out successfully, and then the Molten Salt Reactor Experiment (MSRE) followed at a power level of 8 MW for 13,000 equivalent full-power hours from 1956 to 1968 (Rosenthal et al., 1970). These two experiments establish the basic technologies for MSR, and demonstrate its major advantages, including good neutron economy, inherent safety and on-line refueling, which make the MSR attractive also for the present Generation IV International Forum (GIF), and be one of the six candidates of the Generation IV Reactor (GIF, 2002). While much research has been devoted to the reactor core of MSR, little information is available on the passive residual heat removal system (PRHRS) of MSR. In 1970s, ORNL carried out a number of studies on the PRHRS of MSRs (MSRE, MSBE and MSBR). They used coolant salt which consists of 66 mol% 7LiF and 34 mol% BeF_2 to remove the residual heat of fuel salt by natural circulation. In addition, they proposed a new concept drain tank cooling system using NaK as the coolant (McWherter, 1970; Robertson, 1971). However, owing to the limitation of technology and fund, the research on PRHRS of MSRs was terminated in 1975. In recent years, some new MSR concepts had been proposed, such as the small molten salt reactor (SMSR) (Mitachi et al., 1995), the actinides molten salt transmuter (AMSTER) (MOST-PROJECT, 2004), MOSART (Ignatiev et al., 2006) and thorium molten salt reactor (TMSR) (Merle-Lucotte et al., 2008). All of these reactors adopted drain tank cooling system using coolant salt designed by ORNL to remove the residual heat during the accidents of MSR. In 2007, a new passive decay-heat cooling system had been invented that was actuated by increased temperature of the salt under accident conditions and used radiant heat transfer from and through the salt to a heat exchanger for the liquid-salt-cooled very high temperature reactor (LS-AHTR) (Forsberg, 2007). In 2011, Shanghai Institute of Applied Physics

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Nomenclature

a	evaporation or condensation coefficient
A_c	cross-section area of the vapor space, m^2
C	volumetric heat capacity, J/m^3 K
C_{eff}	effective volumetric heat capacity for a wrapped screen wick, J/m^3 K
D	height of vapor space, m
E_f	energy factor
F	friction factor
h	enthalpy, J/kg
h_{conv}	heat transfer coefficient, $W/(m^2\ K)$
h_{fg}	latent heat of vaporization, J/kg
h_o	vapor enthalpy at the liquid–vapor interface, J/kg
k	thermal conductivity, W/(m K)
k_{eff}	effective thermal conductivity for a wrapped screen wick, W/(m K)
Kn	Knudsen number
l	total length of heat pipe, m
Ma	Mach number
$\dot{m}_o$	rate of condensation or evaporation per unit area, kg/(m^2 s)
M	molecular weight, g/mol
M_f	momentum factor
P	pressure, Pa
$\dot{Q}$	heat flux at the interface, W/m^2
$\dot{Q}_{in}$	heat flux for the outer wall surface of evaporator, W/m^2
Q_s	sonic limitation of a heat pipe, W
R_u	universal gas constant, J/(K mol)
Re	wall Reynolds number
t	time, s
T	temperature, K
T_o	initial or ambient temperature, K
T^*	vapor transition temperature from free molecular to continuum flow, K
T_{st}	vapor temperature at the beginning of the evaporator, K
v	specific volume of vapor, m^3/kg
v_l	specific volume of saturated liquid, m^3/kg
v_g	specific volume of saturated vapor, m^3/kg
V	average velocity at cross-section, m/s
V_o	normal velocity of vapor at the liquid–vapor interface, m/s
z	coordinate direction, m
x_v	quality of vapor
r	coordinate direction, m

Greek symbols

γ	ratio of specific heats
ε	porosity of wick structure
λ	length of mean free path, m
ρ	density, kg/m^3
ρ_{st}	saturated vapor density at the beginning of the evaporator, kg/m^3
μ	vapor dynamic viscosity, Pa s

Subscripts

w	heat pipe wall
ws	wick structure
s	wrapped screen wick material
l	liquid state
g	vapor state

(SINAP) led the efforts to build a 2 MW thorium molten salt research reactor (TMSR) in five years, including its new concept residual heat removal system(SINAP, 2011).

Heat pipes are thermal management devices which can efficiently and rapidly transfer heat from heat source to heat sink by internal phase change with a small temperature difference. Owing to their high conductivity and almost no heat loss, many investigators have examined the transient behavior of high temperature heat pipes. Cotter studied the dynamics of heat pipe startup and developed different transient models for the heat pipe startup (Cotter, 1965). Tolubinsky et al. investigated transient performance of sodium and potassium heat pipes (Tolubinskii et al., 1978). Colwell et al. and Jang developed a simple mathematical model to simulate transient behavior of sodium heat pipe with finite element method, and the results are in agreement with the experimental data given by Camarda (Camarda, 1977; Colwell et al., 1987; Jang, 1988). Tournier et al. built a two-dimensional transient model to predict vapor flow in heat pipe and developed a code named HPTAM to investigate the startup of a radiatively-cooled sodium heat pipe from frozen state, and the results are compared with experimental data given by Faghri et al. (Faghri et al., 1991; Tournier and El-Genk, 1996). Tournier et al. used HPTAM to simulate the startup transient of the lithium–molybdenum heat pipe and compared the model's results with experimental measurements given by Reid et al. (Reid et al., 1999; Tournier and El-Genk, 2003). From the investigations above, due to the rapid development of heat pipe technology and its remarkable advantages, the application of heat pipe to nuclear engineering, especially in PRHRS, becomes more and more achievable.

Sodium–potassium alloy (NaK) is one of the most promising working fluid employed in high temperature heat pipes because of the low melting points of some compositions. The eutectic mixture freezes at −12.6 °C at 77.8% K by weight and boils at 785 °C under atmosphere pressure, which is usually in the liquid state at the ambient temperature. This feature can avoid liquid NaK to solidify at heat pipe condenser during the startup, so that it can prevent the heat pipe evaporator from dry-out and overheating. Owing to the rapid development of heat pipe technology and its inherent advantages, it is essential to apply high temperature NaK heat pipes to the PRHRS of MSR. Under an MSR accident, the fuel salt of primary loop generates vast amounts of heat with 650 °C–850 °C, the reactor would melt if the residual heat cannot be removed timely.

In our previous studies, we proposed a new concept PRHRS of MSR using sodium heat pipe and studied the transient characteristics of sodium heat pipe (Wang et al., 2012). In this work, an advanced PRHRS of MSR using NaK heat pipe is proposed, which is more safe, efficient and passive. Then we investigate the transient performance of a NaK heat pipe under an MSR accident with finite element method. The temperature distributions of the wall, wick and vapor regime, and the velocity and pressure distributions of the vapor space and the compressibility of vapor varied with time are simulated by numerical method.

2. System description

Fig. 1 shows the system schematic diagram of the new concept PRHRS of MSR using NaK heat pipes. The system fundamentally consists of reactor vessel, freeze valve, drain tank, NaK heat pipe,