Nuclear Engineering and Design 293 (2015) 112–118

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

# A choice of pure steam vertical in-tube condensation model for simulating a passive residual heat removal system

Yuxian Rao[a,*], Lei Yu[a], Weitong Li[a], Fan Zhang[b]

[a] Department of Nuclear Energy Science and Engineering, Naval University of Engineering, Wuhan 430033, China
[b] China Ship Development and Design Center, Wuhan 430064, China

## HIGHLIGHTS

- We present three PSVCMs for laminar conditions and two for turbulent conditions.
- Six PSVCMs are formed and implemented into RELAP5/MOD3.2 code.
- We simulate a test facility of SGSPRHRS using modified RELAP5/MOD3.2 codes.
- A PSVCM is favored by comparisons of simulation results with experimental data.

## ARTICLE INFO

*Article history:*
Received 5 February 2015
Received in revised form 20 July 2015
Accepted 28 July 2015

*JEL classification:*
K. Thermal hydraulics

## ABSTRACT

The steam generator secondary passive residual heat removal system (SGSPRHRS) is designed with three natural circulation loops. Its thermal-hydraulic characteristics are often simulated using the RELAP5 code. A test facility is simulated with the same size as one type of SGSPRHRS using RELAP5/MOD3.2 code and it is found that in some conditions, due to the limitation of the default pure steam vertical in-tube condensation model (PSVCM) in RELAP5/MOD3.2 code, the simulation results signify cantly under-estimate the experimental data of heat exchanger (HX) water level while over-estimate the experimental data of HX outlet condensed water temperature and ascending pipe (AP) steam volumetric flow rate. To find out the PSVCM simulating condensation heat transfer for this type of SGSPRHRS more accurately, the solutions of three PSVCMs (modified UCB, Oh and Lee models) for laminar conditions and two PSVCMs (Shah and Kim models) for turbulent conditions are presented in detail and six different PSVCMs are formed from the combinations of selected PSVCMs for laminar and turbulent conditions. The six different PSVCMs are implemented into the RELAP5/MOD3.2 code and simulations of the test facility are performed using the modified RELAP5/MOD3.2 codes. By the comparisons of simulation results with the experimental data, a PSVCM (Oh model for laminar conditions and Kim model for turbulent conditions) is favored due to its most accuracy of simulating condensation heat transfer for the test facility of this type of SGSPRHRS in the six different PSVCMs.

© 2015 Elsevier B.V. All rights reserved.

## 1. Introduction

The passive residual heat removal system (PRHRS) is designed to remove the reactor decay heat and primary loop stored heat by natural circulation for the goal of improving inherent safety in the presence of emergency conditions (Wang et al., 2013). Due to the capabilities of high heat transfer rate and large natural circulation flow rate, a steam generator secondary passive residual heat removal system (SGSPRHRS) is often adopted by some advanced reactor types such as WWER-640 (V-407) and AC600 (Juhn et al., 2000).

One type of SGSPRHRS (Fig. 1) consists of three natural circulation loops: (1) reactor coolant loop by which the decay heat is transferred to the secondary side of steam generator (SG), (2) steam-water loop including a SG and a heat exchanger (HX), and (3) cooling water loop which provides an ultimate heat sink. When blackout or other accident happens, the valve V1 (Fig. 1) is closed by a reactor shutdown signal and simultaneously the valves V2 and V3 (Fig. 1) are opened. Then the steam produced by the SG condenses into water in the HX and simultaneously the heat is transferred to the cooling water loop. After that, the condensed water returns to the secondary side of SG and absorbs the heat during its

* Corresponding author. Tel.: +86 13349945030.
*E-mail address:* raoyuxian@qq.com (Y. Rao).

http://dx.doi.org/10.1016/j.nucengdes.2015.07.039
0029-5493/© 2015 Elsevier B.V. All rights reserved.

## Nomenclature

| | |
|---|---|
| $b_f$ | momentum blowing parameter |
| $c_p$ | specific heat capacity at constant pressure (J/kg K) |
| $d$ | tube inner diameter (m) |
| $e_1, e_2$ | constants, Eq. (30) |
| $f$ | friction factor |
| $f_d$ | diameter factor |
| $F_1$ | degradation factor |
| $g$ | gravitational acceleration (9.8 m/s$^2$) |
| $h$ | heat transfer coefficient (W/m$^2$ K) |
| $h_{fg}$ | phase change enthalpy (J/kg) |
| $h_{pfg}$ | phase change enthalpy including subcooling term (J/kg) |
| $k$ | thermal conductivity (W/m K) |
| $L$ | characteristic length scale (m) |
| $m$ | mass flow rate (kg/s) |
| $m''_c$ | condensation mass flux (kg/m$^2$ s) |
| $P$ | pressure (Pa) |
| $P_{critical}$ | critical pressure (Pa) |
| $Pr$ | Prandtl number |
| $Re$ | Reynolds number |
| $T$ | temperature (K) |
| $u$ | fluid velocity (m/s) |
| $x$ | static quality |
| $X_{tt}$ | Martinelli parameter |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | volume fraction |
| $\beta$ | McAdams modifier |
| $\delta$ | liquid film thickness (m) |
| $\mu$ | dynamic viscosity (Pa s) |
| $\rho$ | density (kg/m$^3$) |
| $\tau_I$ | interfacial shear stress (N/m$^2$) |

*Subscripts*

| | |
|---|---|
| d | hydraulic diameter given by tube inner diameter |
| dittus | Dittus–Boelter's solution |
| lam | laminar |
| L | liquid |
| m | vapor/liquid mixture |
| Nusselt | Nusselt's solution |
| shear | interfacial shear effect |
| S | saturation |
| tur | turbulent |
| V | vapor |
| W | wall |
| 0 | without suction effect |

*Superscripts*

| | |
|---|---|
| * | dimensionless form |

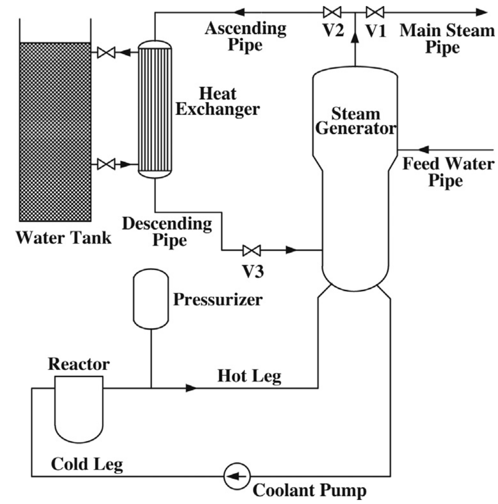


**Fig. 1.** Schematic of one type of SGSPRHRS.

transformation into steam, thereby establishing a continuous natural circulation flow.

Many researchers have performed a thermal-hydraulic calculation of SGSPRHRS by RELAP5 code (Bai and Zang, 2004; Wang et al., 2013; Zhang et al., 2011, 2013), so in the work the RELAP5/MOD3.2 code is used to simulate the thermal-hydraulic characteristics of a test facility which has the same size as this type of SGSPRHRS. However, it is found that in some conditions the simulation results significantly under-estimate the experimental data of HX water level while over-estimate the experimental data of HX outlet condensed water temperature and ascending pipe (AP) steam volumetric flow rate. It is well known that if the condensation heat transfer coefficient is under-estimated, more steam in HX will not be condensed into water, which results in larger AP steam volumetric flow rate and lower HX water level. Because of shorter single-phase heat transfer length HX outlet condensed water temperature value will be over-estimated. Thus to reduce the discrepancy between the simulation and test results, the pure steam vertical in-tube condensation model (PSVCM) in RELAP5/MOD3.2 code needs to be improved.

The default PSVCM of RELAP5/MOD3.2 code applies the Nusselt correlation to calculate the heat transfer coefficient in laminar conditions and the Shah correlation in turbulent conditions (Ransom et al., 1995). The maximum of calculation results from the laminar and turbulent correlations is used as the condensation film heat transfer coefficient. For laminar conditions, the Nusselt correlation has some limitations for predicting accurately the real heat transfer phenomena on the vertically steam condensation due to its several assumptions: (1) constant fluid properties, (2) no liquid film subcooling effect, (3) zero interfacial shear stress between the liquid and vapor, and (4) constant momentum in the liquid film (Ransom et al., 1995). Thus, many researches have been performed to remove the assumptions of Nusselt model (Vierow and Schrock, 1991; Muñoz-Cobo et al., 1996; Oh, 2004; Lee and Kim, 2008). Vierow and Schrock (1991) developed a correlation with a degradation factor, $F_1$, which considers the effect of the interfacial shear. The degradation factor, $F_1$, is the ratio of the experimental heat transfer coefficient to the Nusselt solution and a function of local vapor Reynolds number. The correlation was called UCB (University of California at Berkeley) model by Oh (2004) and its modification was implemented into the RELAP5/MOD3.2 code as an alternate PSVCM. Muñoz-Cobo et al. (1996) developed a theoretical model for turbulent vapor condensation in a vertical tube instead of over a flat vertical plate and an approximate method to calculate the condensation film thickness was also developed, which does not need any iteration to solve the transcendental equation for the film thickness. The calculation results showed a good agreement with the experimental data, but it comes with the cost of introducing this PSVCM a parameter z, the axial distance from the top of the tube. Thus this PSVCM is difficult to be implemented into the RELAP5/MOD3.2 code. Oh (2004) also established a PSVCM theoretically by incorporating the interfacial shear term into the mass balance equation in liquid film. In his PSVCM, the McAdams modifier, $\beta$, was used to account for the effects of film waviness and rippling and the suction boundary layer effect was also considered. The comparison of calculation results with the experimental data showed a good agreement. Although the film thickness needs

Download English Version:

https://daneshyari.com/en/article/6760731

Download Persian Version:

https://daneshyari.com/article/6760731

Daneshyari.com