Annals of Nuclear Energy 115 (2018) 315–322

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Numerical study on flow inversion in UTSG under natural circulation

Bo-shen Bian [a], Gang Hong [a,*], Ning Li [a], Zhi-gang Xu [a], Yan-ping Huang [b], Jian-jun Xu [b], Yu Tang [b]

[a] School of Energy, Xiamen University, Xiamen 361000, China
[b] CNNC Key Laboratory on Nuclear Reactor Thermal Hydraulics Technology, Chengdu 610041, China

ARTICLE INFO

Article history:
Received 23 February 2017
Received in revised form 5 January 2018
Accepted 10 January 2018
Available online 7 February 2018

Keywords:
Natural circulation
UTSG
Reverse flow
Mass flow

ABSTRACT

For natural circulation, it is shown that reverse flows may occur in some U-tubes of UTSG, which is harmful. In this study, the effects on reverse flow phenomenon of approaching natural circulation by changing the inlet mass flow of UTSG in different ways are compared. Numerical model of a given UTSG is established by best estimate code RELAP5/MOD3.3. Three kinds of circulation condition are simulated to validate this model with the experimental results from NPIC. Two conditions reaching a certain natural circulation by changing the UTSG inlet mass flow upwards and downwards are compared. Also, another case is simulated in order to compare the UTSG inlet mass flow of reverse flows occurring and that of the disappearance of existing reverse flows. Results show that approaching the natural circulation by decreasing the inlet mass flow will lead to less reverse flow U-tubes than increasing the inlet mass flux from zero does, and the UTSG mass flow of reverse occurring in the decreasing method is much smaller than that of existing reverse flow being eliminated the increasing method. The reasons are discussed based on the quantitative characteristic curves of steady-state pressure drop versus inlet mass flux of the parallel U-tubes. Two conclusions are drawn: (1) Approaching the natural circulation by decreasing the inlet mass flux lead to comparatively less reverse flow U-tubes and flow resistance than the increasing way. (2) It is difficult to eliminate the existing reverse flows in UTSG thoroughly by adding UTSG inlet mass flow.

1. Introduction

To enhance passive safety and reduce operating costs, the concept of natural circulation is introduced in nuclear power plant design. In PWRs and PHWRs, inverted U-tube steam generator is widely used as an essential heat sink component of natural circulation system (IAEA, 2005). Different from forced circulation, without external power provided by pumps, natural circulation only depends on fluid density difference and position difference. Consequently, the mass flow rate in natural circulation is always much smaller than forced circulation, which results in more complicated flow and heat transfer condition (IAEA, 2002).

The flow reverse phenomenon in parallel inverted U-tubes under natural circulation was first observed in some experiments on PWR Integral Test Facilities such as Semiscale (Loomis and Soda, 1982), LSTF (Kukita, 1988) and LOBI (De Santi and Mayinge, 1993). Wangfei investigated flow characteristics of UTSG primary side fluid under single-phase steady state natural circulation condition on natural circulation test facility in Nuclear Power Institute of China (NPIC) (Wang et al., 2007). When reverse flow occurs, the fluid temperature inside the reflux U-tube was similar to the second side saturated temperature, as well as an apparent temperature decrease in the UTSG inlet plenum. Heat transfer between primary and second side decreases due to reverse flow which also adds flow resistance to natural circulation. Additionally, Reverse flow phenomenon is more complicated under moving frame condition such as ship rolling and shaking movements and several studies are focused specifically on this issue (Hao et al., 2014; Chu et al., 2014a,b, Chu et al., 2016). Hence, avoiding reverse flow has important significance.

Amounts of analytical studies and numerical simulations were issued on the mechanism of flow instability in UTSG under natural circulation. Sanders assumed that the density of the primary side fluid was a function of the second side fluid temperature and the fluid density under this temperature based on Oberbeck-Boussinesq equation (Sanders, 1988). In Jeong's works, characteristic curves of steady-state pressure drop versus inlet mass flux of the parallel U-tubes were depicted, and the excursion between reverse and normal flow was explained by using a linear perturbation analysis. Simulation by Best estimate code MARS was perform to validate his theory (Jeong et al., 2013).

* Corresponding author.
E-mail address: honggang@xmu.edu.cn (G. Hong).

https://doi.org/10.1016/j.anucene.2018.01.005
0306-4549/

Nomenclature

A	flow area, m^2
c_p	specific heat capacity, $J/(kg \cdot K)$
d	inner diameter, m
f	frictional resistance coefficient, –
g	gravity acceleration, m/s^2
h	coefficient of heat transfer between the inside and outside of the tube, $W/(m^2 \cdot K$
L	pipe length, m
M	mass flow, kg/s
P	tube outer circumference, m
p	pressure drop, Pa
s	coordinate, –
T	fluid temperature, K
T_s	second side temperature, K
T_{in}	inlet side temperature, K
v	flow velocity, m/s

Greek symbols

β	thermal expansion coefficient, –
ρ	density, kg/m^3
ρ_0	reference density, kg/m^3
$\bar{\rho}$	average density, kg/m^3
ξ	shape resistance coefficient, –

Hao predicted the distribution of reverse flow in different scale UTSGS by comparing the critical flow excursion pressure drop of different length U-tubes and validated it using best estimate code RELAP5/MOD3.3 Hao et al. (2013). Wang Chuan put forward a new method on nodalization of Inverted U-Tubes in RELAP5 Wang and Lei (2011). Watanabe et al. (2014) analyzed the flow instability in steam generator U tubes by REPLAP5-CFD coupled numerical simulations.

Until now, existence experiments were most performed on large scale test facilities, and previous analytical works on UTSG reverse flow almost focused on mechanism of reverse flow occurrence and its influential factors. The mechanism of transition process from reverse flow to normal flow has not been analyzed clearly. Qualitative analysis was much more than quantitative analysis. Few method were suggested to prevent reverse flow. In this paper, a quantitative numerical model of a given small scale UTSG is established in RELAP5. Three kinds of conditions are simulated by using this model, and the results are compared with corresponding experimental ones to validate the model. After validation, to investigate the influence of the UTSG inlet flow loading method. Two conditions with different ways to approach a given natural circulation are simulated. One is decreasing the UTSG inlet mass flux from forced circulation level to the aimed value, the other is increasing the inlet mass flux from zero. The flow distribution and the flow resistance are compared in the two cases. Meanwhile, another case is simulated. the value of UTSG inlet mass flows which triggers the occurrence of reverse flows in decreasing loading method and that which causes the total disappearance of reverse flows in increasing loading method are obtained. The results are discussed based on the quantitative characteristic curves of steady-state pressure drop versus inlet mass flow of the parallel U-tubes.

2. Simulation

2.1. UTSG simulator description

The primary side of the test UTSG is schematically shown in Fig. 1. It includes 49 parallel U-tubes with 9 different lengths, an inlet plenum and an outlet plenum. The U-tubes have the same straight length and different radiuses. Their main parameters are listed in Table 1. Primary side water flows from inlet plenum to outlet plenum, through the U-tubes. During this time, the heat in the primary side water conducts to the statured water inside the UTSG second side cylinder. If reverse flow occurs in a U-tube, the temperature at the U-tube inlet will be nearly the same as it at the UTSG outlet.

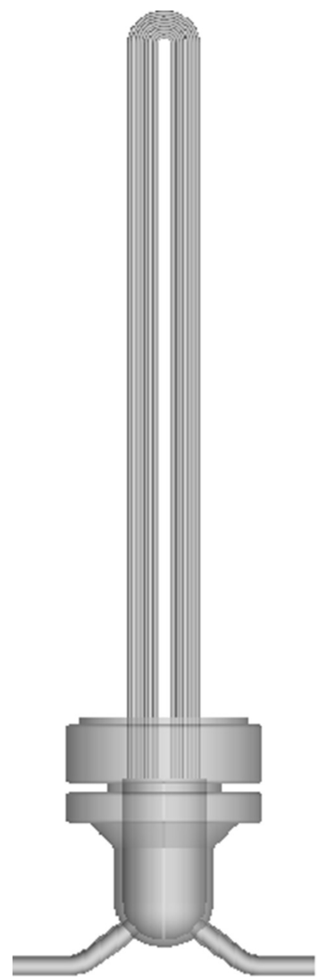

Fig. 1. Schematic diagram of UTSG primary side.

2.2. Numerical model

According to the experiment apparatus, a numerical model is established by using best estimate code RELAP5 /MOD3.3. Nodalization of the test inverted U-tube steam generator is shown in Fig. 2. In the primary side, U-tubes with the same length are equivalent to one pipe component with 24 volumes. Consequently, there are nine parallel pipes connecting to two branch components which model the inlet and outlet plenum. The second side cylinder is modeled as an annular component, and heat structures are used