Annals of Nuclear Energy 109 (2017) 41–51

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Investigation of density wave instability in once-through superheated steam generators using SIGHT

Yang Tang, Zhiwei Zhou *, Dabin Zhang

Institute of Nuclear and New Energy Technology, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form 21 January 2017
Accepted 9 May 2017

Keywords:
Density wave instability
Steam generator
Frequence domain method
SIGHT

ABSTRACT

Density-wave oscillation is the most common type of two-phase flow instability in the steam generators. A computer code SIGHT was derived to study on flow instability for the superheated steam generator under high pressure. The drift flux model was used for two-phase flow analysis. Linear, frequency-domain method was used for modeling and the flow stability was evaluated by Nyquist stability criterion. The unified and representative variables, namely water/steam mass flow density, water/steam enthalpy and liquid sodium temperature were selected to describe steady state and perturbations. The density perturbation of subcooled water was taken into account since the large subcooling degree of feedwater. The code has been tested against the existing experimental data and compared with results of past analysis code. Also the effect on flow stability caused by system parameters and density changes in subcooled water was analyzed. Lastly, preliminary stability thresholds were given for Steam Generator of China Fast Reactor 600 (CFR600) using SIGHT.

1. Introduction

Density wave oscillations are probably the most common type of instabilities encountered in steam generators, result from the multiple feedbacks between the flow rate, the vapor generation rate, and the pressure drop in the boiling channel, which can cause heat transfer crisis, structure vibration, and system control problems. To ensure system operation and safety, sodium- or helium-heated steam generators for nuclear applications often must be stabilized by orificing the flow at the inlet of the tubes, at the expense of pumping power (Yadigaroglu, 1978).

The flow stability in the secondary side of steam generators is influenced by the coupling with the primary side. Chan and Yadigaroglu (1986) used a frequency-domain analysis to study the stability of sodium-to-water steam generators for breeder reactors, considering heat-flux/flow coupling between the primary and secondary fluids in space and time. Also the STEAMFREQ code was developed. Niu et al. (2014) used the multi-variable frequency domain method to study the flow instability in the helical tube helium-heated steam generators of HTR-10.

As mentioned above, the linear frequency-domain method is used for stability analysis, since it costs far less computer time, eliminats the mathematical instability, and the threshold of instability can be predicted accurately. In this method, the conservation equations is linearized perturbed and Laplace transformed near the steady state. The secondary side can be divided into three regions, namely subcooled, boiling and superheated region. Different from previous researches, the unified and representative variables are used to describe each region, which makes the solution procedure more simple, especially the solving of perturbation equations and boundary conditions between the regions. The derivation process of partial derivative terms were presented in details. The change of density can't be ignored since the large subcooling degree of feedwater, thus effect on flow stability caused by density perturbation of subcooled region was analyzed.

2. Fundamental equations

2.1. Assumptions and equations

The following assumptions are made in the model derivation process.

1. The steady state assumes a constant pressure channel like many codes do.
2. One-dimensional conservation equations are used for both the primary and the secondary side in the axial direction.

* Corresponding author.
E-mail address: zhouzhw@tsinghua.edu.cn (Z. Zhou).

http://dx.doi.org/10.1016/j.anucene.2017.05.027
0306-4549/

Nomenclature

Latin symbols

A	cross-sectional area
c	specific heat
C_0	drift-flux model parameter
D	tube diameter
f	friction factor
g	gravitational acceleration
G	mass flow density
h	enthalpy
H	heat transfer coefficient
j	volumetric flux density
K	flow resistance
p	pressure
P	heated perimeter
q	heat flux
r	radial coordinate
s	Laplace transform variable
t	time
T	temperature
V	velocity
V_{gj}	drift veloxity of vapor with respect to j
W	mass flow rate
x	quality
z	length coordinate

Greek letters

α	void fraction
η	superheat boundary
κ	thermal diffusivity
λ	boiling boundary
ρ	density
Δ	difference
δ	perturbation
∂	partial differential

Superscript

^	Laplace transformed

Subscripts

ex	exit of water side
f	liquid phase
fg	difference between vapor and liquid phase
g	vapor phase
i	the Number of node
in	inlet of water side
n	the max Number of node
N	sodium (primary) side
s	superheat region
t	tube wall
W	water (secondary) side
1	water side wall condition
2	sodium side wall condition
1Φ	subcooled region
2Φ	two-phase region

3. The secondary side is divided into a subcooled region, a two-phase region and a superheated region. Subcooled boiling is not considered.
4. The single phase (both subcooled water and superheated steam) density is a function of the local enthalpy.
5. Thermal non-equilibrium in the boiling region is not considered.

The one-dimensional forms of the continuity and energy equations for the water side are

$$\frac{\partial \rho_W}{\partial t} + \frac{\partial G_W}{\partial z} = 0 \tag{1}$$

$$\frac{\partial(\rho_W h_W)}{\partial t} + \frac{\partial(G_W h_W)}{\partial z} = \frac{q_1 P_W}{A_W} \tag{2}$$

and the engery equation of sodium channel is

$$\frac{\partial T_N}{\partial t} - V_N \frac{\partial T_N}{\partial z} = -\frac{q_2 P_N}{\rho_N c_N A_N} \tag{3}$$

Previous work (Niu et al., 2014) assumes that the single phase flow is incompressible. However, the density significantly changes based on the local enthalpy, yielding some influence on the performance both in steady state and perturbations. In two-phase region, drift-flux model is used. A density propagation equation is derivated from the basic energy equation. The density propagation equation is complicated including various variables of drift-flux model, even more when linearized perturbed. On the other hand, the different variables need to be converted at the boundary between regions. Actually, the variables in two-phase region can be derivated from enthalpy. For example, the quality and the relevant perturbation are

$$x = \frac{h_W - h_f}{h_{fg}}; \delta x = \frac{1}{h_{fg}} \delta h_W$$

Therefore, the unified and representative variables are used, namely mass flow density G_W for continuity equation, enthalpy h_W for energy equation and liquid sodium temperature T_N for sodium channel. The same set of governing equations is used for each region, and the variables selected are continuous without boundary problem.

Heat transport across the tube wall is considered only radially since the radial temperature gradient is several orders of magnitude larger than the axial temperature gradient for steam generator tubes. The conduction equation of heated tube wall is

$$\frac{\partial T_t}{\partial t} = \kappa \frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T_t}{\partial r}\right)$$

with the boundary conditions

$$T_t(r_1, t) = T_1(t)$$
$$T_t(r_2, t) = T_2(t)$$

The heat transfer rates on the inner and outer wall respectively, can be written as

$$q_1 = H_1(T_1 - T_W) \tag{4}$$
$$q_2 = H_2(T_N - T_2) \tag{5}$$

2.2. Steady state solution

The mass and energy equations for the steady-state solution are obtained by setting $\partial/\partial t = 0$ in Eqs. (1) and (2), for water and steam

$$\frac{dG_W}{dz} = 0 \tag{6}$$

$$\frac{dh_W}{dz} = \frac{q_1 P_W}{G_W A_W} \tag{7}$$