Nuclear Engineering and Design xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Pressure drop-flow rate curves for single-phase steam in Combustion Engineering type steam generator U-tubes during severe accidents

Douglas A. Fynan, Kwang-Il Ahn *

Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong-gu, Daejeon 305-353, Republic of Korea

HIGHLIGHTS

- Pressure drop-flow rate curves for superheated steam in U-tubes were generated.
- Forward flow of hot steam is favored in the longer and taller U-tubes.
- Reverse flow of cold steam is favored in short U-tubes.
- Steam generator U-tube bundle geometry and tube diameter are important.
- Need for correlation development for natural convention heat transfer coefficient.

ARTICLE INFO

Article history:
Received 25 August 2016
Received in revised form 1 November 2016
Accepted 4 November 2016
Available online xxxx

Keywords:
Steam generator
U-tube
Natural circulation
Pressure drop
Thermally induced steam generator tube rupture

ABSTRACT

Characteristic pressure drop-flow rate curves are generated for all row numbers of the OPR1000 steam generators (SGs), representative of Combustion Engineering (CE) type SGs featuring square bend U-tubes. The pressure drop-flow rate curves are applicable to severe accident natural circulations of single-phase superheated steam during high pressure station blackout sequences with failed auxiliary feedwater and dry secondary side which are closely related to the thermally induced steam generator tube rupture event. The pressure drop-flow rate curves which determine the recirculation rate through the SG tubes are dependent on the tube bundle geometry and hydraulic diameter of the tubes. The larger CE type SGs have greater variation of tube length and height as a function of row number with forward flow of steam favored in the longer and taller high row number tubes and reverse flow favored in the short low row number tubes. Friction loss, natural convection heat transfer coefficients, and temperature differentials from the primary to secondary side are dominant parameters affecting the recirculation rate. The need for correlation development for natural convection heat transfer coefficients for external flow over tube bundles currently not modeled in system codes is discussed.

1. Introduction

Thermally induced steam generator tube rupture (TI-SGTR) can occur in pressurized water reactors (PWRs) with U-tube steam generators (SGs) during high pressure severe accident sequences resulting in containment bypass. Robust natural circulation patterns including in-vessel natural circulation and countercurrent flow to and from the SGs of superheated steam and other hot gases heats cooler structures in the reactor coolant system (RCS). The buoyancy driven flows return cooler and denser gases back to the core slowing the progression of some core degradation phenomena and failure of the lower head. As much as 50% of the decay energy and energy produced from core degradation oxidation reactions can be transported from the core to SGs resulting in the heat up and thermal creep of RCS pressure boundary components including hot leg nozzles, pressurizer surge line, and the SG tubes, many of which contain flaws. The creep failure of an individual tube is dependent on the transitory heating of the tube, a function of the mass flow rate through the tube and local temperature history of steam entering the tube.

Buoyancy driven natural circulation flow rates are determined by changes in gravitational head, a combination of changes in fluid density due to heat transfer and change in elevation, and irreversible pressure drops resulting primarily from friction loss in the flow paths and other form losses. The nonuniform flow distribution in U-tubes of varying lengths and heights during single-phase liquid and two-phase natural circulation has been extensively studied in scaled test facilities and verified numerically in previous works (Kukita et al., 1988; Sanders, 1988; Liu et al.,

* Corresponding author.
E-mail address: kiahn@kaeri.re.kr (K.-I. Ahn).

http://dx.doi.org/10.1016/j.nucengdes.2016.11.004
0029-5493/© 2016 Elsevier B.V. All rights reserved.

1994; Jeong et al., 2003b, 2004; Hao et al., 2013, 2014). First, we hypothesize the countercurrent natural circulation of single-phase superheated steam in U-tube SGs is governed by the same characteristic pressure drop-flow rates curves of single-phase liquid and two-phase natural circulations in U-tubes connected to common plena derived in Jeong et al. (2003b, 2004). Secondly, we propose flow distribution as a function of U-tube bundle geometry: height, length, and hydraulic diameter of the individual tubes comprising the bundle. For example, the larger SGs of Combustion Engineering (CE) type 2×4 PWRs, which are the focus of this study, show greater nonuniformity in tube by tube flow rates and ratio of forward-flowing tubes to reverse-flowing tubes. This work derives characteristic pressure drop-flow rate curves for single-phase superheated steam in CE type SGs during a high pressure station blackout (SBO) sequence with failed auxiliary feedwater (AFW) and dry secondary side which is closely related to the TI-SGTR event.

This paper is organized as follows. Section 2 describes the U-tube bundle geometry of the OPR1000 (Optimized Power Reactor 1000 MWe; formerly the Korean Standard Nuclear Plant) SGs that were selected as the reference CE type SG design. A steady state formulation of the momentum equation for pressure drop in a U-tube is derived in Section 3 and a numerical scheme is developed to solve the pressure drop formula. Section 4 presents the characteristic pressure-flow rate curves for all row numbers of the OPR1000 SGs during severe accident natural circulations. Sensitivity studies are performed in Section 5 to investigate the impacts of the controlling parameters, friction losses, secondary side heat transfer, and inlet plenum mixing, affecting the severe accident natural circulations related to the TI-SGTR. Future works for developing a universal correlation for severe accident natural circulations for all U-tube SG designs are discussed with the conclusions in Section 6.

TI-SGTR research has been performed over the past 25 years with extensive use of system thermal hydraulic codes. All references to the RELAP5 code and models refer to RELAP5/MOD3.3 (Information Systems Laboratories, 2001) and all references to the MELCOR code and models refer to MELCOR Version 1.8.6 (Gauntt et al., 2005) noting that earlier TI-SGTR works may have used different versions of these system codes. In Section 3, we develop a small code to calculate the heat transfer and coupled velocity and temperature profiles of single-phase steam flowing in U-tubes. Some correlations and submodels of the RELAP5 and MELCOR system codes relevant to the severe accident natural circulation phenomena are discussed in detail in Section 3 and the correlations have been incorporated into the developed code for pressure drop calculations. The original references for specific correlations, some that date back to over a century, were not reviewed during the present study. The correlation equations presented in Section 3 are taken directly as presented in the RELAP5 and MELCOR manuals, not the original references. Bibliographic listings of the original references for the specific correlations are available in the RELAP5 and MELCOR reference manuals.

2. Combustion Engineering type steam generator geometry

CE PWRs are 2×4 plants with two hot legs, two SGs, four cold legs and four reactor coolant pumps. When the core power of a PWR is increased, the heat transfer area of SGs must also be increased. A key design feature of the 2×4 plant SGs is that heat transfer area is added by increasing the outer diameter of the SG and more tubes are installed on the periphery of the tube sheet. The addition of more rows of tubes increases the variation of tube length and height because the outer row tubes form the top of the tube bundle and must span the diameter of the SG. In Westinghouse (WH) type PWRs (2-loop, 3-loop, and 4-loop), an increase in heat transfer area is usually achieved by raising the tube bundle height, the vertical distance between the tube sheet and the start of the tube bend region, uniformly increasing the length of all tubes. If the power increase is very large, an additional coolant loop and SG is added, hence the evolution from 2-loop to 4-loop plants. Although there are many differences between the many U-tube SG models for WH type plants, the overall tube bundle geometry is relatively uniform across all plants in contrast to CE type plants where tube bundle geometry varies in proportion to the core power level.

The OPR1000 is based off of the CE System 80 technology and the OPR1000 was selected as the reference plant design for the study. The rated thermal power of the OPR1000 is 2815 MWt. For the present analysis, we assume the SGs contain 8214 tubes made of Inconel 600. Tube numbers may vary from plant to plant due to tube plugging and minor design and manufacturing differences. Newly manufactured and replacement steam generators (RSGs) for the OPR1000 are Inconel 690. Tube dimensions are 1.696 cm inner diameter (0.666 in) and tube thickness of 0.107 cm (0.042 in). OPR1000 U-tubes are 3/4 in outer diameter, a standard size of PWR U-tubes.

Fig. 1 shows a half plane of upper tube bundle geometry and the tube sheet drilling pattern. The OPR1000 SGs are similar to the original CE SGs featuring "square" tube shape with two 90° bends. Note rows 1–17 are 180° bend tubes. There are many manufactures of RSGs for CE plants that have adopted the semi-hemispherical bundle design for the tube bend region characteristic of SGs for WH type PWRs. The tube sheet drilling pattern is a triangular lattice with 1 in (25.4 mm) pitch. At the top of the U-tube bundle, the horizontal segments are separated on a square lattice with 1.23 in (31.27 mm) pitch. In the vertical direction, the centerline to centerline distance of diagonally opposite tubes is 1.75 in (44.45 mm). The height of the tube bundle from the bottom of the tube sheet to the start of the tube bend region is approximately 7.54 m (297 in). The height and length of horizontal segment at the top of the tube bundle of OPR1000 U-tubes as a function of tube sheet row number are estimated from

$$H = 0.875 \times RowNumber + 297\ [\mathrm{in}]\ \text{and} \quad (1)$$

$$l = 2 \times (1.27 \times RowNumber + 6.35)/2.54\ [\mathrm{in}]. \quad (2)$$

Row 1 tubes are the shortest with total length of approximately 15.28 m and height of 7.56 m including tube sheet segment. Row 138 tubes are approximately 24.85 m long and height of 10.61 m.

Other PWR plants in operation featuring the square bend U-tube tube bundle geometry include the Palisades plant with RSGs manufactured by CE, the APR1400 units operating in Korea and APR1400 units under construction in Korea and the United Arab Emirates, and the Pale Verde plant with RSGs designed by CE and manufactured by Ansaldo. The Palo Verde plant (System 80 design) and the APR1400 units have the largest SGs. The present work is generally applicable to and results could be scaled or extrapolated to these plants. However, numerical results are highly conditioned on the assumptions used in the analysis and deviations in the as-manufactured SG design compared to the study reference SG.

3. Steady state pressure drop in steam generator U-tube

The following work uses a steady state formulation of the conservation equations to derive pressure drop-flow rate curves for individual tubes at a snapshot in time during the SBO to gain insights into the nonuniform flow distribution in the tubes. Temperatures, pressures, and flow rates expected to be observed in the countercurrent flow loop shortly after core degradation begins are assumed. RCS pressure is 16 MPa, superheated steam leaving