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Thermal hydraulics analysis of a helical coil steam generator of a small modular reactor

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ABSTRACT

In the present study, thermal hydraulic investigation of a steam generator of an integral small modular reactor (SMR) has been performed. For this investigation, a helical coil steam generator of IRIS design is selected due to availability of its design parameters in literature. Steam generator model is developed in RELAP5/Mod 4.0. At first, steady state simulation has been performed for this model and results are found in good agreement with the IRIS design data. In order to evaluate the behavior of steam generator under accidental conditions, transient analysis has also been performed. Steam generator performance is assessed for two transients, namely, feed line break (FLB) and loss of flow accident (LOFA). Exponential losses of secondary side pressures (inlet and outlet) are considered for FLB, whereas an exponential loss of primary flow rate is considered for LOFA. The results indicate safe and reliable operation of IRIS steam generator for both transients.

1. Introduction

Over the past few years, small modular reactors (SMRs) have been gaining significant attention all over the world. Enhanced safety features, low carbon emission, incremental capacity expansion, proliferation resistance and short construction period make SMRs a center of focus in post Fukushima era (Besides and Kuznetsov, 2012).

One of these SMRs is International Reactor Innovative and Secure (IRIS). This concept was initially started by international consortium led by Westinghouse. However, recently its R&D activities are being pursued by POLIMI and other Italian organizations . The design is currently under basic design stage and will be available for commercial deployment by 2025–30 time frame (IAEA, 2016; Hadid Subki, 2016). IRIS is a light water cooled reactor having electric power of 335 MWe (Cinotti and Bruzzone, 2002). IRIS utilizes the concept of an integral reactor vessel which houses all the components of primary coolant system including reactor core, coolant pumps, steam generators (SGs) and pressurizer. Eight helical-coil steam generators are placed in the annulus region between core barrel and reactor pressure vessel as shown in Fig. 1. Each IRIS steam generator module contains a central inner column that supports the tube support system and an outer wrapper. The central column is attached to the reactor vessel (RV) wall via cantilevered arms, so that the weight of the SG is supported from the reactor vessel wall. The feed water and steam headers are bolted separately to the vessel from the inside of the feed inlet and steam outlet pipes. A 3D rendering of an IRIS steam generator is shown in Fig. 2. In operation, feed water enters the lower feed water header through a nozzle provided in the RV wall. The feed water then enters the steam generator tubes, and becomes superheated steam as it flows to the upper steam header (Westinghouse et al., 2003). Steam then takes exit from the steam generator through the nozzle provided in the RV wall.

Helical coils are compact, have increased heat transfer as compared to U-tubes, and hence these are considered as an attractive option for SMRs. Compactness and efficiency improvement are instrumental for these reactors, as all the primary loop components are placed inside the reactor vessel. In addition, heat transfer coefficient of helical coil heat exchangers is 16–43% higher than straight tube heat exchangers (Prabhanjan et al., 2002). Therefore, understanding of thermal hydraulic behavior of helical coil steam generator is very important.

Hoffer et al. (2011) performed modeling of a helical-coil steam generator of the next generation nuclear plant using RELAP5-3D in 2011. RELAP5-3D was used to model helium on primary side of steam generator since helium as a coolant cannot be modeled in earlier models of RELAP5 whereas; simplification for helical coil is similar in both versions of RELAP code. Ricotti et al. (2003) performed steady state thermal hydraulic analysis of IRIS steam generator in RELAP5/Mod4.0 but they did not perform the transient analysis. Bajs et al. (2002) modeled IRIS whole plant in RELAP5 for steady state and non-LOCA transients, and satisfactory results

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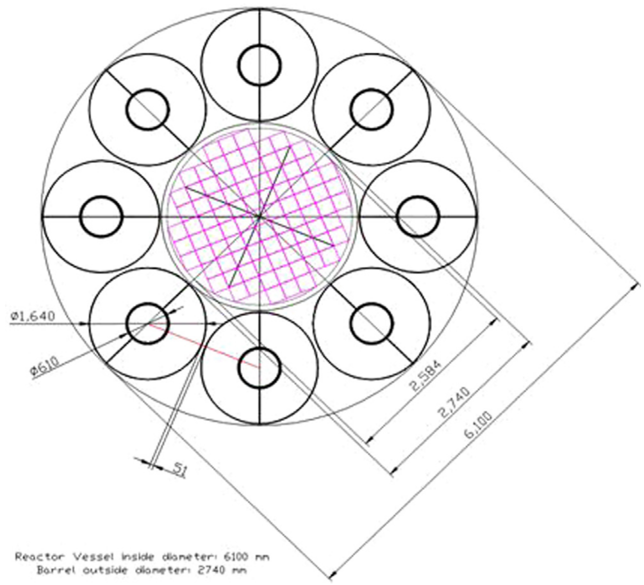

Fig. 1. IRIS Steam Generator (SG) layout in the integral reactor coolant system (all dimensions are in mm) (Cinotti et al., 2002).

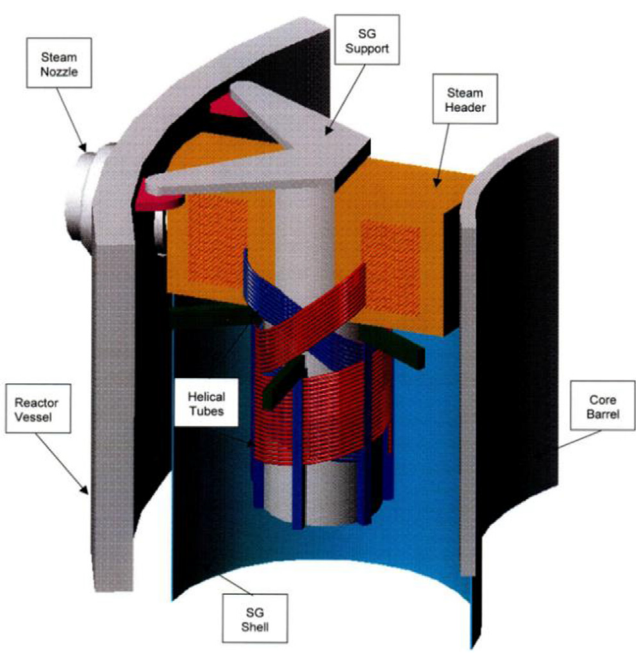

Fig. 2. Representation of an IRIS steam generator module (Westinghouse et al., 2003).

were obtained for steam generator. Apart from helical coil steam generator, C. Cilliers also modeled U-tube steam generator in RELAP5/Mod 3.4 and the results indicate that RELAP5 is an efficient code to model steam generator of any type (Cilliers, December 2012).

This paper describes the steady state and transient analyses of IRIS helical coil steam generator using RELAP5/Mod 4.0. Transients such as feed line break (FLB) and loss of flow accident (LOFA) have been modeled. This analysis alone cannot account for full safety analysis; however, coupled with others, it will allow to assess the safety and reliability of helical-coil SG as the primary heat transfer loop heat exchanger.

2. Methodology

2.1. Model Development

In order to model 3D helical coil bundle in RELAP5, several simplifying assumptions have been made as given in reference Hoffer et al. (2011). At first, the helical-coil tube bundle consisting of 655 tubes is modeled as a single tube with equivalent both flow and heat transfer surface areas, hydraulic diameter, and heated hydraulic diameter. These calculations of the single tube estimate the heat transfer and flow characteristics of the actual bundle of tubes. Single helical coil tube is again simplified by un-wrapping the coil tube to create an inclined straight pipe having same length as of single tube and a vertical change in elevation corresponding to height of bundle. A heat transfer multiplier is incorporated in the model to take into account improved heat transfer effects as observed in helical coils. With these simplifications, the helical-coil steam-generator model has been developed with boundary conditions given in Table 1.

The helical-coil SG model uses a single tube having length of 32 m in order to attain the design steam outlet temperature. Fig. 3 shows the simplification performed on helical bundles of IRIS for modeling in RELAP5/Mod4.0.

2.2. RELAP5 Model Description

Steam generator model with both primary and secondary sides is divided into numerous nodes. Similar philosophy and methodology has been adopted for modeling IRIS steam generator as used by N.V. Hoffer et al. for modeling NGNP steam generator (Hoffer et al., 2011). Nodes in RELAP5 nodal diagram for primary side with time dependent volume and time dependent junction are shown in Fig. 4. The time dependent volume acts as a source and is responsible for controlling the temperature and pressure with time. The time dependent junction is responsible for controlling the mass flow rate. PIPE 120 is connected to time-dependent volume with the time-dependent junction, having three sub volumes. PIPE 120 models the inner plenum.

ANNULUS 130 having 25 sub volumes represents bundles regions. ANNULUS 130 is joined to PIPE 140 by means of SNGLJUN 135. PIPE 140 is connected to TMDPVOL 150 by means of SNGLJUN 145. TMDPVOL 150 is acting as a sink for the primary system.

Table 1
IRIS steam generator design parameters (Cinotti et al., 2002).

Parameter	Value
Steam generator type	Inside Vessel, Once through Helical coil
Steam generator Power, MWt/unit	125
Total Number of steam generator units in Plant	8
Number of tubes per unit	655
Number of Horizontal rows/unit	20
Surface area, m /unit (ft^2/unit)_primary side	1149.7 (12375)
Tube outer diameter, mm (inches)	17.46 (0.688)
Tube wall thickness, mm (inches)	2.11 (0.083)
Tube Average Length, m (ft)	32 (104.99)
Total bundle heights, m (inches)	7.9 (311.0)
Overall height, m (inches)	8.5 (334.6)
Feed water temperature, °C (K)	223.9 (497.06)
Bundle pressure drops	296 (42.93)
Primary Side pressure drops, kPa (psia)	72 (10.44)
Exit Steam Pressure, MPa (psia)	5.8 (841)
Exit Steam Temperature, °C (K)	317 (590.16)
Steam flow, kg/s (lb/hr) per SG	62.5 (0.5×10^6)