Thermal-Hydraulic Analysis of Helical Coil Steam Generator of Multi-Application Small Light Water Reactor (MASLWR) Test Loop using Drift Flux Model

Mansour Talebi*
Nuclear Science & Technology Research Institute, Iran
E-mail: mstalebi@aeoi.org.ir
*Corresponding author

Valiallah Ghazanfari
Nuclear Science & Technology Research Institute, Iran
E-mail: ghazanfari@yahoo.com

Received: 19 April 2018, Revised: 25 July 2018, Accepted: 25 August 2018

Abstract: The Multi-Application Small Light Water Reactor (MASLWR) test loop has been built as a proof of concept for SMRs that is scaled down in size and has electric heater rods instead of a nuclear core. In this paper with using Drift-Flux Model (DFM), the thermal-hydraulic analysis of helical steam generator in MASLWR under steady-state conditions is simulated. This simulation is performed using the finite volume method. To ensure the accuracy and stability of solutions, User Defined Function (UDF) is written in C programming language. Distributions of velocities, local void fractions, temperature and pressure in the steam generator are calculated in different heights. To validate this simulation, the calculated primary side and secondary bulk fluid temperature are compared with experimental data. The experimental data have been provided by series of measurements of parameters of heat-transfer agent at Oregon State University. The calculated data are in good agreement with measured data and consequently the accuracy of this simulation is satisfied. Accuracy of the prediction shows that it is possible to use the DFM for thermal-hydraulic analysis in advanced models in nuclear power plant and other industries.

Keywords: Drift Flux Model, Helical Coil Steam Generator, MASLWR Reactor, Thermal–Hydraulic

Reference: Talebi, M., Ghazanfari, V., "Thermal-Hydraulic Analysis of Helical Coil Steam Generator of Multi-Application Small Light Water Reactor (MASLWR) Test loop Using Drift Flux Model", Int J of Advanced Design and Manufacturing Technology, Vol. 11/No. 3, 2018, pp. 83-91.

Biographical notes: M. Talebi is Assistant Professor of Nuclear Science & Technology Research Institute, Iran. **V. Ghazanfari** is a PhD Student in Nuclear Science & Technology Research Institute.

1 INTRODUCTION

Integral type small reactors have been highlighted as a promising option for various ways of nuclear energy. The category of small modular reactors (SMRs), includes those with an equivalent electric output less than ~300 MW(e), having a high degree of factory fabrication allowing for transportation of factory-assembled reactor modules or even the whole plant by barge, rail or truck, and with an option to build power stations of flexible capacity through a multi-module approach [1-3]. In 2003, Oregon State University, in collaboration with the Idaho National Engineering Laboratory, and Nexant-Bechtel, completed a project to develop a preliminary design for an innovative reactor called the “Multi-Application Small Light Water Reactor”, or “MASLWR”. The final results were published by the project sponsor, the U.S. Department of Energy, and a description of the MASLWR design was included in IAEA-TECDOC-1536 [4]. In 2007, NuScale Power Inc. was formed to commercialize the concept, and MASLWR was renamed as the NuScale Plant to reflect the significant improvements made to the original design [5]. In early 2008, NuScale power notified the U.S. nuclear regulatory commission of its intent to begin pre-application discussions aimed at submitting an application for design certification of a twelve-module NuScale power plant. Fluor Corporation became the majority investor of NuScale power in 2011 and provided engineering, procurement and construction services for plant deployments [6].

A NuScale plant consists of 1 to 12 independent modules, each capable of producing a net electric power of 45 MWe. Each module includes an integral pressurized light water reactor operating under natural circulation primary flow conditions. Each reactor is housed within its own high pressure containment vessel which is submerged underwater in a stainless steel lined concrete pool, see “Fig. 1” [7].

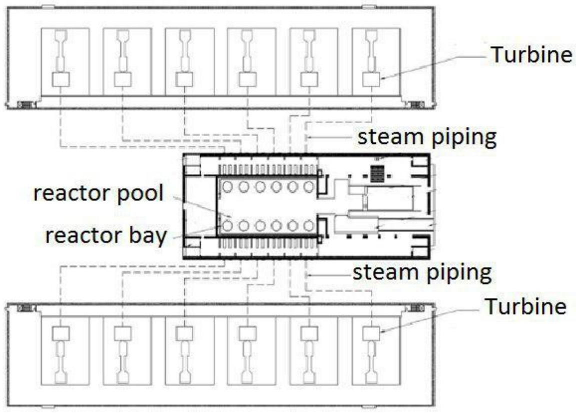

Fig. 1…Layout of a 12-Unit (540 MWe) NuScale Power Plant[7].

The basic configuration of a single NuScale reactor module is shown schematically in “Fig. 2”.

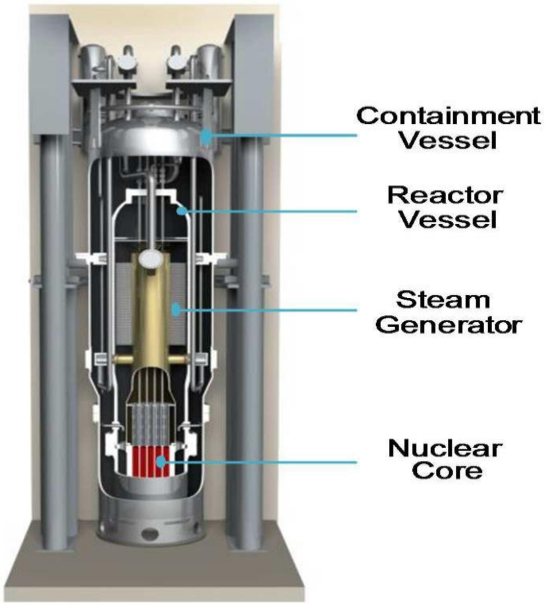

Fig. 2 Basic configuration of a single NuScale reactor module [7].

The NuScale power module is cooled by natural circulation. The primary coolant in the reactor pressure vessel is heated in the nuclear core, then it rises through a central riser, it spills over and encounters the helical coil steam generator, it is cooled as steam is generated inside the steam generator, and it is again heated in the nuclear core. “Table 1” summarizes key features of the NuScale plant design.

Table 1 Basic Plant Parameters [7]

Overall plant	
Net electrical output	540 MW(e)
Number of power generation units	12
Nominal plant capacity factor	> 90%
Power generation unit	
Number of reactors	One
Net electrical output	45 MW(e)
Number of steam generators	Two independent tube bundles
Steam generator type	Vertical helical tube
Steam cycle	Superheated
Turbine throttle conditions	3.1 MPa (450 psia)
Steam flow	71.3 kg/s (565,723 lb/hr)
Feed water temperature	149°C (300°F)
Reactor core	
Thermal power rating	160 MWt
Operating pressure	8.72 MPa (1850 psia)
fuel	UO_2 (< 4.95% enrichment)
Refuelling intervals	24 months

To analysis and design SMRs, it is necessary to perform thermo-fluid-dynamic behaviour. The steam generator is a critical component of the SMRs that plays an important role in security and efficiency of the nuclear power plant. Therefore, using assured thermoshydraulic model to simulate the nuclear steam generator has particular importance.

Recently, some studies about helical steam generator have been performed. An experimental investigation regarding two-phase adiabatic pressure drops inside a helically coiled heat exchanger has been carried out at SIET thermo-hydraulics labs in Piacenza (Italy) [8].Furthermore, a computational model was developed to describe the thermo-fluid-dynamic behaviour of a helically coiled steam generator device working with water and became widely adopted in the nuclear industry. The discretized governing equations were coupled using an implicit step by step method. Two-phase pressure drops data reduction allowed optimizing a suitable form of the friction factor multiplier required by momentum balance equation [9].

In this paper, the thermal-hydraulic analysis is performed under steady-state conditions of helical heat exchanger of MASLWR. The drift flux model is used for modelling of two-phase flow in heat exchanger. Finite volume method is used for numerical solution and FLUENT 6.3.26 code is utilized for this purpose. User Defined Function (UDF) also is written in C programming language to ensure stability of solutions. Simulation results show that this model can be used for assessment of experimental data and licensing processes.

2 HELICALSTEAM GENERATOR MODELING

In the MASLWR concept design, the primary coolant is circulated around the outside of the steam generator (SG) tubes. The test loop tube bundle is a helical coil consisting of fourteen tubes. This SG is a once through heat exchanger and is located within the pressure vessel in the annular space between the riser and the inner surface of the reactor pressure vessel. There are three separate parallel sections (coils) of stainless steel tubes. The outer coil and middle coils consist of five tubes each while the inner coil consists of four tubes. Each coil is separated from others but joined at a common inlet header to ensure pressure equilibrium within the coil (“Fig.3 and Fig. 4”).

Cold main feed water enters at the bottom of the SG and boils off after travelling a certain length in the SG. This boil off length is a function of both core power and mass flow rate and can be adjusted by varying core power, feed water flow rate or both. The value of the degree of the steam superheat is changed in order to control the facility.

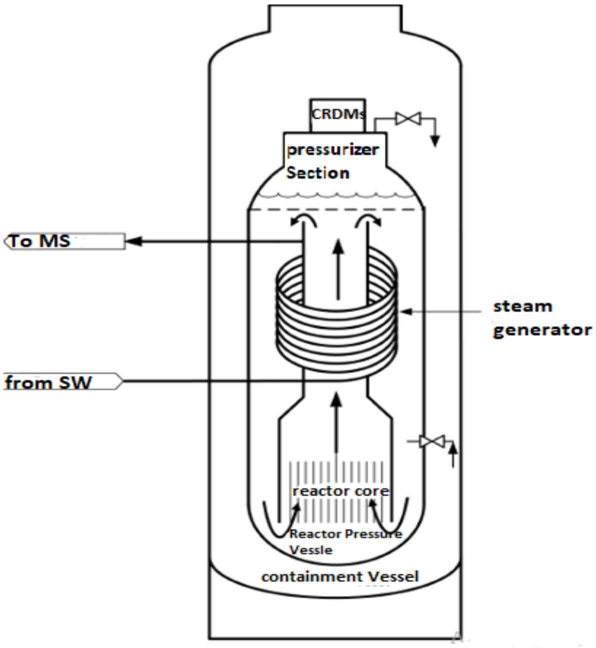

Fig. 3 A containment vessel and once-through helical-coil steam generators [7].

Fig. 4 Photographs of SG coil bundle arrangement [10].

In general, the slope of the main steam superheat curve increases if the value of the core power increases and decreases if the value of the feed water flow rate decreases. The difference between the main steam saturation temperature and the measured main steam temperature is used to estimate the value of the main steam superheat. Each SG coil exhausts the superheated steam into a common steam drum from where it is subsequently exhausted to atmosphere via the main steam system.

Each NSSS module uses two once-through helical-coil steam generators for steam production. The steam generators are located in the annular space between the hot leg riser and the reactor vessel inside diameter wall. The steam generator consists of tubes connected to upper and lower plenums with tube sheets. Preheated feed water enters the lower steam generator plenum through nozzles on the reactor pressure vessel. The electric core in the RPV (Reactor Pressure Vessel) heats the water and causes it to rise up a chimney. At the end of the chimney, the flow is turned around by a baffle plate and flows down around the outside of the chimney and steam generator. Once it reaches the bottom of the vessel, it returns to the core and circulation continues [11].

In this simulation, the SG is composed of 14 tubes that enter the vessel and then coil helically around the top portion of the chimney before exiting into a steam drum to be vented to the atmosphere. Four of the tubes comprise the inner bank while five make up both the middle and outer banks.

The SG is situated in the annulus between the chimney's outer wall and the reactor pressure vessel's inner wall. The dimensions of the section are given in “Table 2”. Inside this section, fourteen helically shaped tubes wrap around the chimney several times before exiting through the vessel wall into a steam drum that is welded onto the outside of the RPV. The tubes are split into inner coils, middle coils, and outer coils. All coils in a particular group have the same dimensions that are listed in “Table 3”.

Table 2 MASLWR steam generator section dimensions [11]

Component	Dimensions
RPV Outer Diameter (mm)	355
RPV Shell Thickness (mm)	32
Chimney Outer Diameter (mm)	114
SG Section Height (mm)	1251

Table 3 Steam tube dimensions [11]

Bank	Inner	Middle		Outer
Direction	CW	CCW		CW
Number of tubes	4	5		5
Tube length (mm)	6205	6299		6364
Coil diameter (mm)	146	203		260
Rotations	13	9.5		7.5
Pitch (mm)	19.8	21		26.1
Rise/rotation (mm)	80	105		130
Total coil rise (mm)	1028	1003		978
Lead length (mm)	15.8	15.8		15.8
Tube thickness (mm)	1.6	1.6		1.6

The geometry of the helical steam generator is very complicated so this problem is solved by the aid of CATIA code. It is imported into GAMBIT code for generating mesh and determining the boundary conditions. Triangular cells have been used for this model. The number of computational cells in the present model is 1.3 million. To improve the quality of the meshes around the boundaries, smaller meshes are used. The drawn geometry and quality of mesh are shown in “Fig. 5, Fig. 6, Fig. 7 and Fig. 8”.

Fig. 5 Scheme of the helical steam generator.

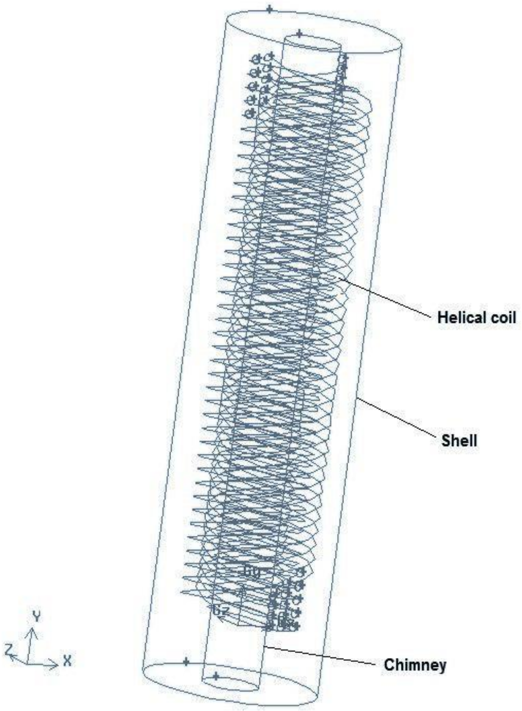

Fig. 6 Component of helical steam generator.

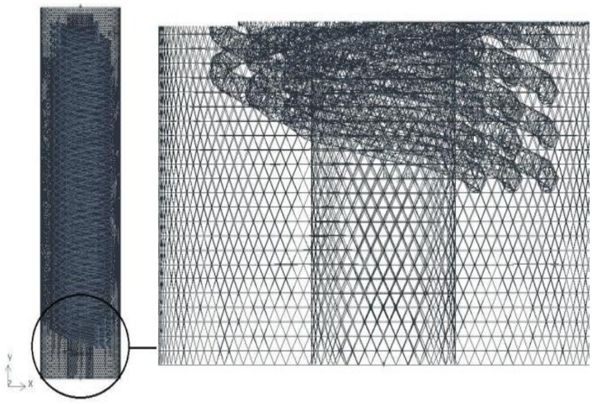

Fig. 7 Generated mesh for helical steam generator.

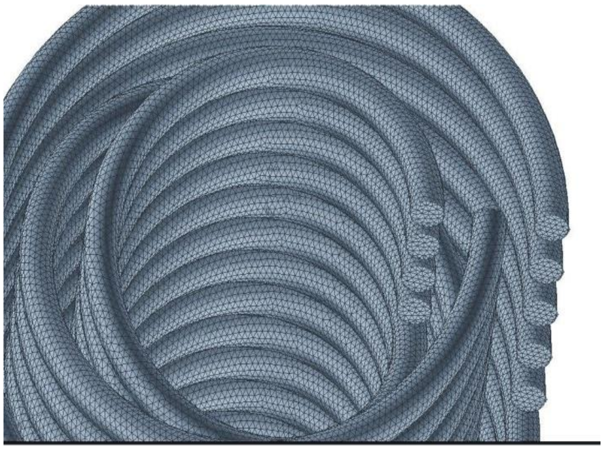

Fig. 8 Quality of mesh on tube of the helical steam generator.

3 MATHEMETICAL MODELING AND GOVERNING EQUATIONS

The main characteristic of the secondary side of the helical steam generator is the two-phase flow. Since the motions of two phases are strongly coupled, the Drift Flux Model (DFM) is one of the best models for the prediction of two-phase flows. The DFM is more simplified and practical than two-fluid model. The DFM quickly computes the void fraction and slip ratio in two-phase flow. Velocity fields are considered by taking of mixture centre of mass velocity and drift velocity of the vapour phase; the vapour velocity is taken with respect to the volume centre of the mixture. Four equations are used in DFM: continuity, momentum and energy equations for the mixture phase, and continuity equation for the gas phase. The name of this model has been adopted from the drift flux term; v_{gj}. The effect of relative velocity between the liquid and gas phases is defined with this term. DFM equations are expressed as follows [12-14]:

Mixture continuity:

$$\frac{\partial\langle\rho_m\rangle}{\partial t}+\frac{\partial}{\partial z}(\langle\rho_m\rangle\bar{v}_m)=0 \tag{1}$$

Gas continuity:

$$\frac{\partial\langle\alpha_g\rangle\rho_g}{\partial t}+\frac{\partial}{\partial z}\left(\langle\alpha_g\rangle\rho_g\bar{v}_m\right)=\langle\Gamma_g\rangle-\frac{\partial}{\partial z}\left(\frac{\langle\alpha_g\rangle\rho_g\rho_f}{\langle\rho_m\rangle}\bar{v}_{gj}\right) \tag{2}$$

Mixture momentum:

$$\frac{\partial\langle\rho_m\rangle\bar{v}_m}{\partial t}+\frac{\partial}{\partial z}(\langle\rho_m\rangle\bar{v}_m^2)=-\frac{\partial}{\partial z}\langle\rho_m\rangle+\frac{\partial}{\partial z}\langle\tau_{zz}+\tau_{zz}^T\rangle - \langle\rho_m\rangle g_z-\frac{f_m}{2D}\langle\rho_m\rangle\bar{v}_m^2-\frac{\partial}{\partial z}\left[\frac{\langle\alpha_g\rangle\rho_g\,\rho_f}{(1-\langle\alpha_g\rangle)\langle\rho_m\rangle}\bar{v}_{gj}^2\right] \tag{3}$$

Mixture energy:

$$\frac{\partial\langle\rho_m\rangle\bar{h}_m}{\partial t}+\frac{\partial}{\partial z}\left(\langle\rho_m\rangle\bar{h}_m\bar{v}_m\right) =-\frac{\partial}{\partial z}(q+q^T)+\frac{q_w''\xi_h}{A} -\frac{\partial}{\partial z}\frac{\langle\alpha_g\rangle\rho_f\rho_g}{\langle\rho_m\rangle}\Delta h_{gf}\bar{v}_{gj}+\langle\phi_m^{\mu}\rangle \tag{4}$$

The boundary conditions are necessary to solve these equations. This data is shown in “Table 4”.

Table 4 The boundary condition in helical steam generator [11]

Parameter	Value
Flow rate on Primary side (Kg/s)	2.11
Flow rate on secondary side (Kg/s)	0.135
Operating pressure on primary side (MPa)	8.6
Operating pressure on secondary side (MPa)	1.2
Inlet feed water temperature(K)	289
Inlet coolant temperature (K)	545

The governing equations associated with the boundary conditions are solved numerically using the control-volume based finite volume method. In order to couple the velocity field and pressure in the momentum equations, the well-known coupled-algorithm is adopted. Grid dependency is investigated for the standard case. The flow has been considered turbulent therefore the K-epsilon model is used in present study. The User Defined Function (UDF) written in C programming language capability of the mentioned code is utilized for the implementation of drift velocities in various two-phase flow regimes.

4 RESULTS AND DISCUSSION

In this work, the steady state operation of the helical steam generator of MASLWR model at full power (392 KW) is simulated. For validation, the calculated primary side and secondary bulk fluid temperature are compared with experimental data. The experimental data have been provided by series of measurements of parameters of heat-transfer agent under steady-state conditions of helical heat exchanger of MASLWR, performed at Oregon State University [11] (“Fig. 9 and 10”).

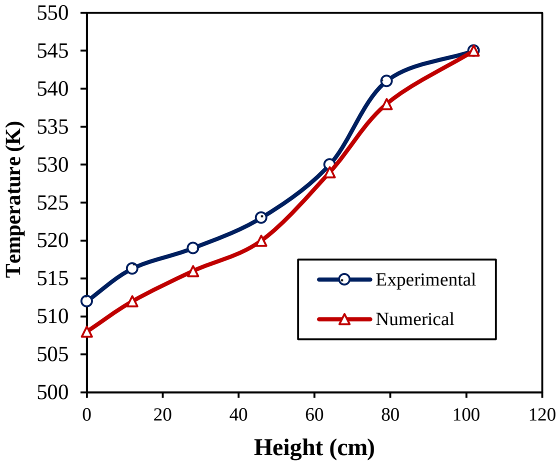

Fig. 9 Distribution of coolant temperature in the axial direction, compared with experimental data[11].

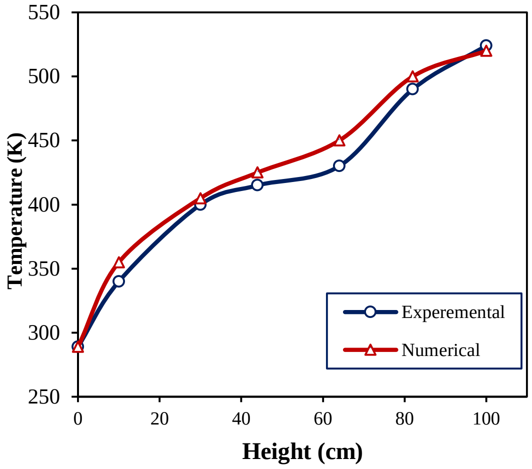

Fig. 10 Distribution of feedwater temperature in the axial direction, compared with experimental data[11].

The calculated data are in good agreement with measured data and consequently the accuracy of this simulation is satisfied.

“Fig. 11, Fig. 12 and Fig. 13” show the velocity vectors in primary and secondary side of steam generator. The circulation of fluid flow in helical tubes and shell is cleared with these vectors.

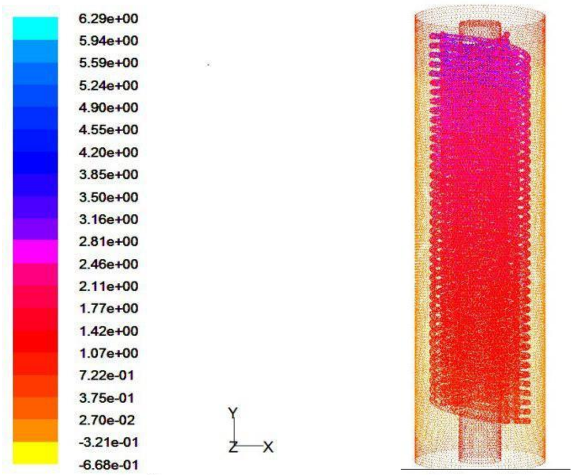

Fig. 11 Velocity vectors in helical steam generator.

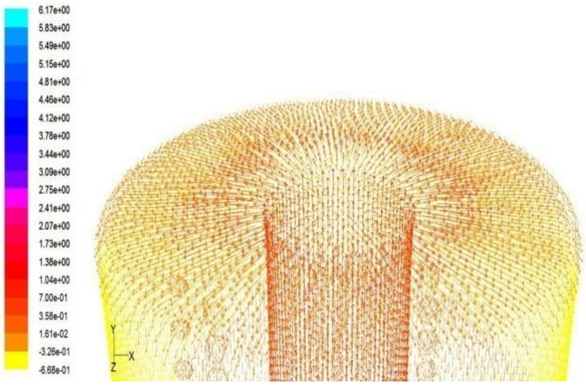

Fig. 12 Velocity vector on primary side of SG.

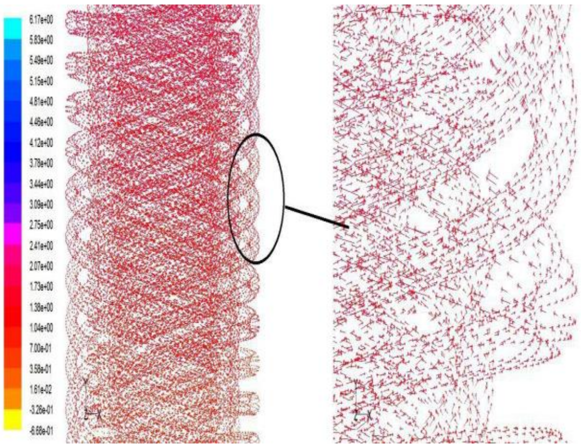

Fig. 13 Velocity vector on secondary side of steam generator.

As feed water rises through the steam generator tubes, heat is added from the reactor coolant and the feed water experiences a phase change and exits from the steam generator as superheated steam. As feed water is heated, its temperature increases and consequently the density of water will be decreased. This decrease of density makes the water come down and the flow circulate naturally.

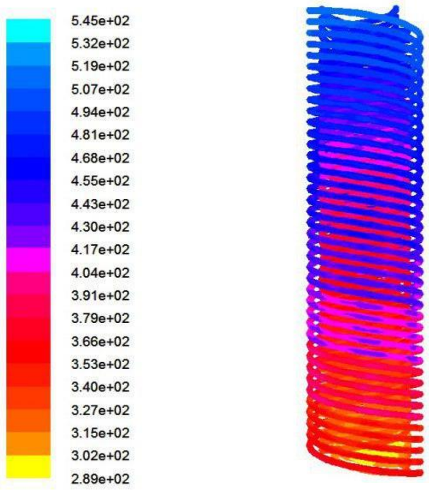

Fig. 14 Distribution of temperature in helical tube in vertical view.

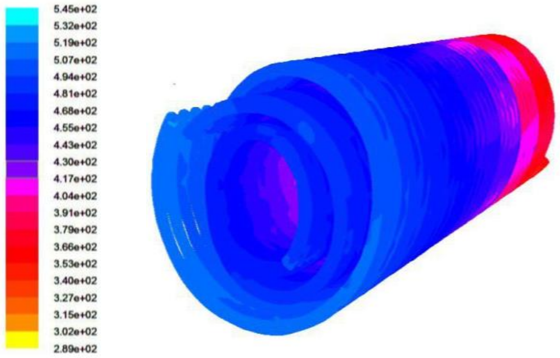

Fig. 15 Distribution of temperature in helical tube in horizontal view.

The single tubes are modelled to heat transfer from primary side to secondary side of the SG. The mechanisms of heat transfer are conduction and convection. Room temperature water enters the coils at the bottom and removes a large amount of energy from the primary coolant by boiling and turning to superheated steam. This removal of energy causes the water in the primary side to cool and condense. This adds to the flow's force in the downward direction. The distributions of temperature in SG are shown in "Fig. 14 and Fig. 15". The obtained results indicate that the temperature of feed water on inlet is 288 K and 520 K on outlet. Also as coolant enters SG, the value of temperature is 545 K and it exits with 506K.

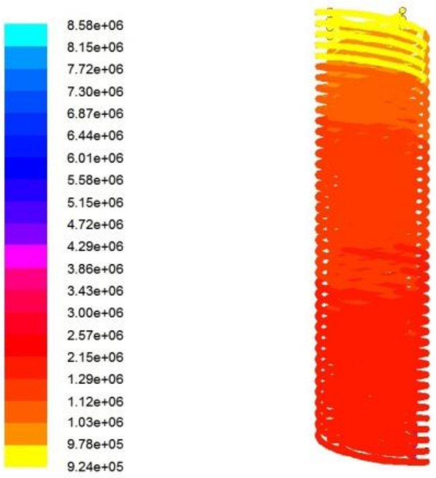

Fig. 16 Distribution of pressure in helical tube of SG.

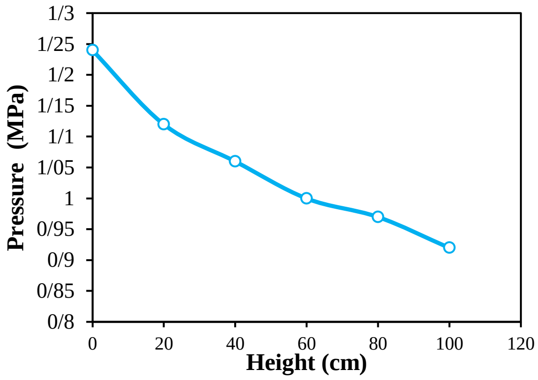

Fig. 17 Distribution of pressure in helical tube of SG.

As shown in "Fig. 16 and Fig. 17" the pressure loss along the helical tubes in SG is about 0.32 MPa. It is illustrated that the pressure of feed water on inlet is 1.24 MPa and 0.92 MPa on outlet.

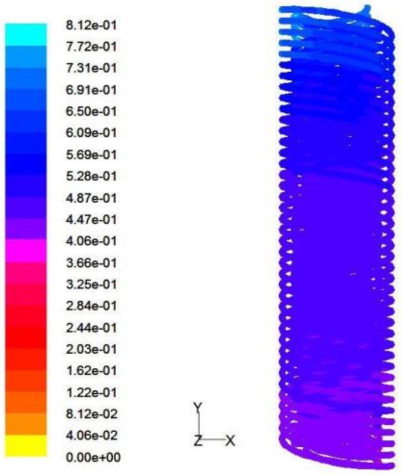

Fig. 18 Void fraction in helical tubes of SG in axial direction.

The void fraction is calculated using DFM in the present study. The contours of void fraction in steam generator are illustrated in “Figs. 18 and 19”.

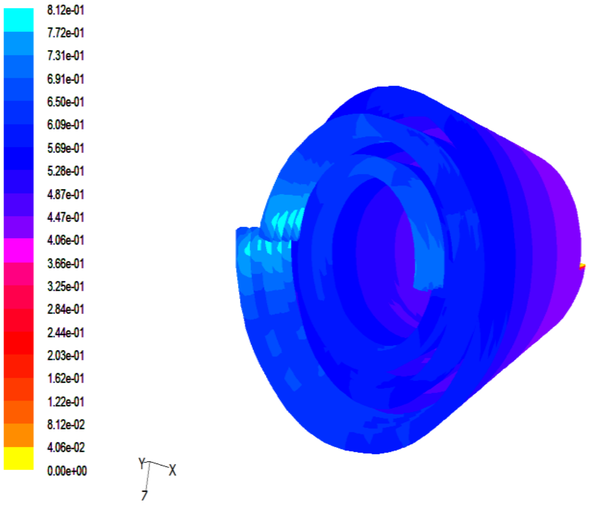

Fig. 19 Void fraction in helical tubes of SG in horizontal direction.

The void fraction distributions in vertical and horizontal directions are illustrated in these figures. The value of void fraction at the top of the helical tubes is maximum. During boiling, the feed water temperature can be assumed to be constant at the saturation temperature. This is not always true because the steam phase will be hotter than the liquid phase. Moreover, the void fraction increases with elevation. The maximum achievable void fraction at the top of helical tube is about 0.81 (“Fig. 20”).

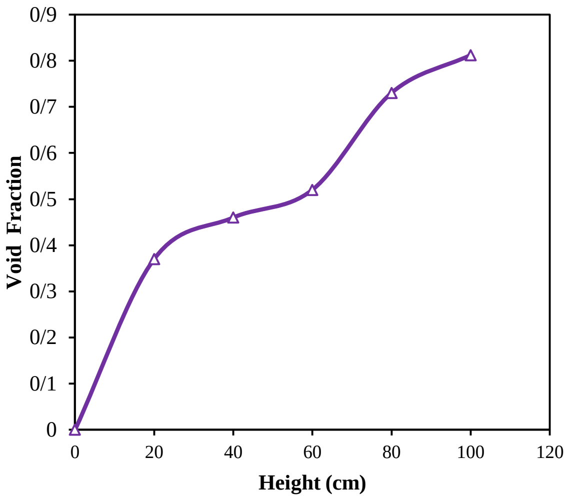

Fig. 20 Diagram of void fraction in helical tubes.

5 CONCLUSION

In this paper, the thermal-hydraulic analysis in helical steam generator of MASLWR in the steady-state conditions was studied using Drift-Flux Model. This numerical solution is performed using the finite volume method. User Defined Function also was written in C programming language to stability of solutions.

The obtained results illustrate that the temperature of feed water on inlet was 288 K and it was 520 K on outlet. Also the value of temperature of coolant on inlet and outlet was 545 K and 506K respectively. The maximum achievable void fraction at the top of helical tube was about 0.81 and the pressure loss along the helical tubes in SG was about 0.32 MPa.

The calculated data are in good agreement with measured data, performed at Oregon State University. Therefore, this simulation can be used for assessment of other studies about MASLWR and it will be helpful to progress of MASLWR and SMRs.

6 NOMENCLATURE

ρ	dendity $[\mathrm{kg\ m^{-3}}]$
t	time [s]
z	axial distance [m]
$\bar{v}$	mean velocity $[\mathrm{m\ s^{-1}}]$
Γ	mass source$[\mathrm{kg\ s^{-1}}]$
$\bar{v}_{gj}$	mean drift velocity of gas phase $[\mathrm{m\ s^{-1}}]$
h	enthalpy [j]
$\bar{h}$	mean enthalpy [j]
p	pressure [pa]
q	conduction heat flux$[\mathrm{j\ m^{-2}}]$
α	phase fraction or void fraction
A	cross sectional area $[\mathrm{m^2}]$
D	diameter of pipe [m]
D_H	hydraulic diameter [m]
g	gravitational acceleration$[\mathrm{kg\ m^{-3}}]$
σ	surface tension $[\mathrm{N\ m^{-1}}]$
q^T	turbulent heat flux$[\mathrm{j\ m^{-2}}]$
q''_w	wall heat flux$[\mathrm{j\ m^{-2}}]$
ξ_h	heated perimeter [m]
Δh_{gf}	enthalpy difference $[\mathrm{j\ kg^{-1}}]$
f	friction factor
$N_{\mu f}$	viscosity number
μ	viscosity [pa s]

Subscripts

g	gas phase
f	liquid phase
m	weighted mean mixture property
z	z-component

REFERENCES

[1] Cooper, M., Small Modular Reactors and the Future of Nuclear Power in the United States, Energy Research & Social Science, Vol. 3, 2014, pp. 161-177.

[2] Reyes, J., Lorenzini, J., NuScale Power: A Modular, Scalable Approach to Commercial Nuclear Power. Nuclear News, Nuclear News, Vol. 6, 2012, pp. 97-103.

[3] Status of Small Reactor Designs without Onsite Refueling, INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, 2007.

[4] NuScale Power, 2012. [Online]. Available: https://www.nrc.gov/docs/ML1221/ML12216A392.pdf.

[5] Ingersoll, D., NuScale Small Modular Reactor for Co-Generation of Electricity and Water, Desalination, Vol. 34, 2014, pp. 84-93.

[6] NuScale Power Modular and Scalable Reactor, 2011. [Online]. Available: https://www.iaea.org/NuclearPower/Downloadable/aris/2013/26.NuScale.pdf.

[7] Lorenzo, S., Cioncolini, A., Lombardi, C., and Ricotti, M., Two-Phase Pressure Drops in a Helically Coiled Steam Generator, International Journal of Heat and Mass Transfer, Vol. 51, 2008, pp. 4926–4939.

[8] Colorado, D., Papini, D., Hernández, J., Santini, L., and Ricotti, M., Development and Experimental Validation of a Computational Model for a Helically Coiled Steam Generator, International Journal of Thermal Sciences, Vol. 50, 2011, pp. 569-580.

[9] Hee-Kyung, K., Hyoung, S., Chung, Y., and Kim, H., Thermal-Hydraulic Analysis of SMART Steam Generator Tube Rupture Using TASS/SMR-S Code, Annals of Nuclear Energy, Vol. 55, 2013, pp. 331-340.

[10] Mascaria, F., Vellaa, G., Woodsb, B., Welterc, K., Pottorfc, J., and Youngc, E., Sensitivity Analysis of the MASLWR Helical Coil Steam Generator Using TRACE, Nuclear Engineering and Design, Vol. 241, 2011, pp. 1137–1144.

[11] Bradyn, J., Comparative Analysis of the Zukauskas Method and Data from the OSU MASLWR Test Facility Steam Generator, 2014.

[12] Ghazanfari, V., Ansarifar, G., and Esteki, M., Drift Flux Modeling of the VVER-1000 Horizontal Nuclear Steam Generator, Progress in Nuclear Energy, Vol. 76, 2014, pp. 36-43.

[13] Ishii, M., Hibiki, T., Thermo-Fluid Dynamics of Two-Phase Flow, Springer, 2006.

[14] Hibiki, T., Ishii, M., One Dimensional Drift-Flux Model and Constitutive Equations for Related Motion Between Phases in Various Two-Phase Flow Regimes, International Journal of Heat Mass Transfer, Vol. 46, 2003, pp. 4935-4948.