Optimum thermal sizing and operating conditions for once through steam generator

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Transactions of the Korean Nuclear Society Autumn Meeting

Introduction

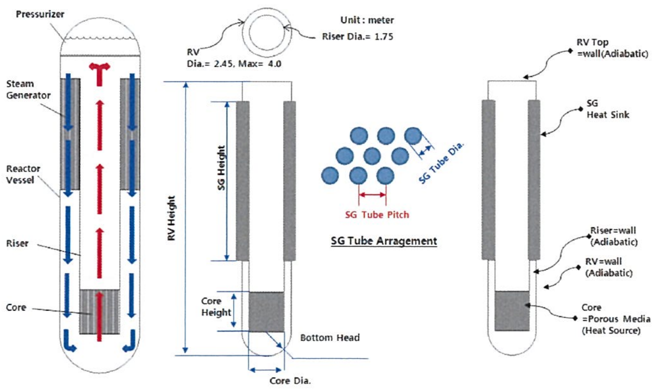
◇ Thermal-hydraulic characteristic of in-vessel Steam Generator Should be evaluated to ensure natural circulation design

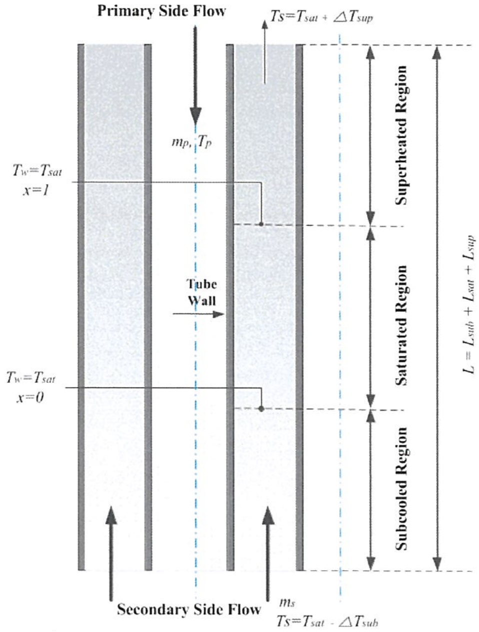
- The purpose is to predict the thermal behavior and to perform optimum thermal sizing of once through steam generator.

  ➢ To estimate the thermal sizing and operating conditions of the SG
  - the analytical modeling is employed on the basis of the empirical correlation equation and theory

  ➢ the optimized algorithm model,
  - Non-dominated sorting Genetic Algorithm(NSGA-II), uses for analysis.

Modeling of water/steam flow in SG





Schematic diagram of SG

◇ Assumptions

- one characteristic tube model
- 3-region of the tube side flow and heat transfer
- Thermal equilibrium (water and steam phase in boiling region)
- The shell side is single phase water
- The Primary mass flowrate:

$$\dot{m}_p = \frac{P_{core}}{c_p \Delta T_{core}} = \frac{P_{core}}{c_p (T_{p,outlet} - T_{p,inlet})}$$

- The feedwater flowrate of the SG

$$\dot{m}_s = \frac{P_{core}}{\Delta e_s} = \frac{P_{core}}{c_s T_{sub} + e_{lv} + c_v T_{sup}}$$

Equations

◇ Conservation equations

- *Conservation of mass*

$$M_s = c$$
$$M_p = c$$

- *Conservation of momentum*

$$\Delta P_{,i} = \Delta P_{acc.i} + \Delta P_{fric,i} + \Delta P_{gravity,i}$$

$$\Delta P_{acc,i} = \left(\frac{G^2}{\rho}\right)_{i+1} - \left(\frac{G^2}{\rho}\right)_i \quad \Delta P_{fric,i} = f \frac{L}{D_h} \frac{G^2}{2\rho_f} \overline{\phi_{lo}^2} \qquad \Delta P_{grav,i} = \int_i^{i+1} \rho g dz$$

$$\langle \overline{\rho g} \rangle_i = \frac{\langle \rho_H \rangle_i + \langle \rho_H \rangle_{i+1}}{2} \qquad \langle \rho_H \rangle_i = \frac{1}{v_f + \langle x_i \rangle_i v_{fg}} \qquad \langle x_i \rangle_i = \frac{\langle h \rangle_i - h_f}{h_{fg}}$$

- *Conservation of energy*

$$dQ_i = M_s (h_{s,i} - h_{s,i+1}) = M_p C_p (T_{p,i} - T_{p,i+1})$$
$$T_{s,i} = f(P_{s,i}, H_{s,i})$$

Boiling Correlation

◇ Heat transfer coefficient correlations $(BTU/hr-ft^2-{}^\circ F)$

- *Constant*

$$h = 4605.28$$

- **Thom**

$$h = \frac{1}{0.072}\exp\left(\frac{p_{sat}}{1260}\right)(q'')^{1/2}$$

- *Jens & Lottes*

$$h = \frac{10^{3/2}}{60}\exp\left(\frac{p_{sat}}{900}\right)(q'')^{3/4}$$

- *Rhosenow*

$$\frac{q''}{\mu_l h_{lv}}\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{1/2} = \left(\frac{1}{C_{sf}}\right)^{1/r} \Pr_l^{-s/r}\left\{\frac{C_{pl}[T_w - T_{sat}]}{h_{lv}}\right\}^{1/r} \quad \left\{\begin{matrix} r=1/3 \\ s=1.7\end{matrix}\right.$$

$$T_w - T_{sat} = \frac{h_{fg}}{c_{P,l}}\Pr_l^s C_{sf}\left[\frac{q''}{\mu_l h_{fg}}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}\right]^{1/3}$$

$$h = K_R\left(q''\right)^{2/3}$$

$$K_R = f\left(P_{sat}\right)$$

Csf = 0.013

$$h = \left(0.294 - 1.393\times10^{-4}\cdot P_{sat} + 3.492\times10^{-8}\cdot P_{sat}^2\right)^{-1}(q'')^{2/3}$$

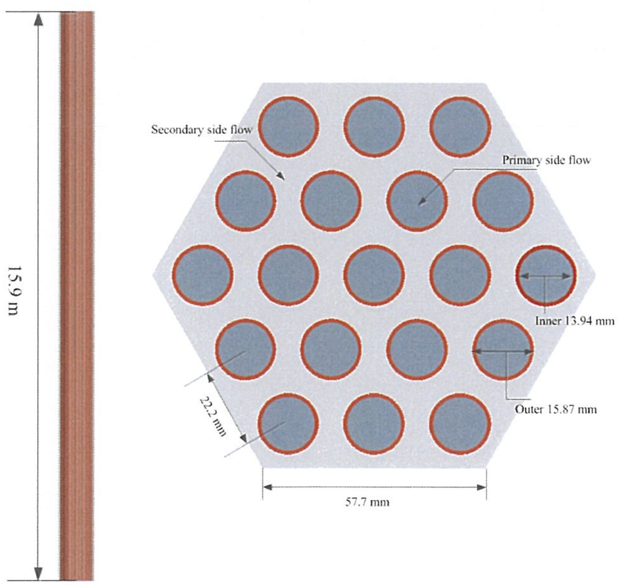
Csf = 0.015

$$h = \left(0.339 - 1.606\times10^{-4}\cdot P_{sat} + 4.026\times10^{-8}\cdot P_{sat}^2\right)^{-1}(q'')^{2/3}$$

Verification/Validation

◇ The 19-tube SG experiment (Masahiro, 1989)

- **B&W type once through straight-tube steam generator**



Operations of experiment

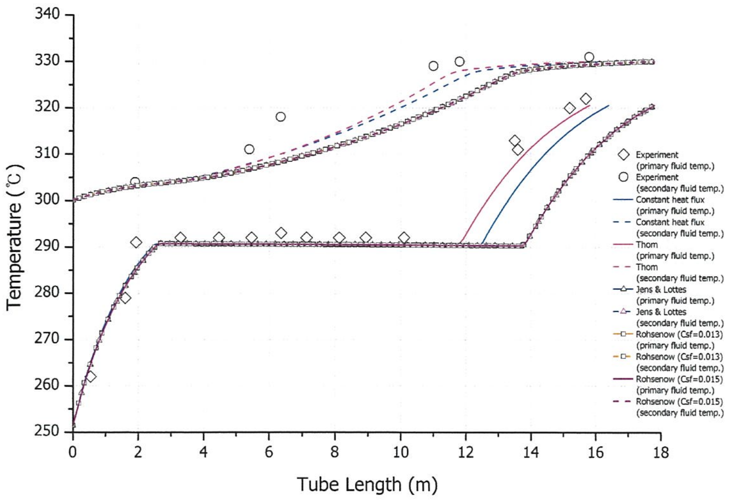
Primary outlet temperature	°C	300.0
Primary outlet velocity	m/s	5.6
Primary pressure	MPa	15.3
Secondary inlet temperature	°C	251.7
Secondary inlet velocity	m/s	0.3
Secondary pressure	MPa	7.4
Secondary sat. temperature	°C	289.6
Superheated temperature	°C	319.6

Thermal conductivity (tube)

$$\lambda = 13.2 + 0.013\cdot T \quad \left(\frac{W}{m\cdot K}\right)$$

Reference:
Thermal-Hydraulic Study of integrated Steam Generator in PWR, Masahiro OSKABE, Journal of Nuclear Science and Technology, 1989

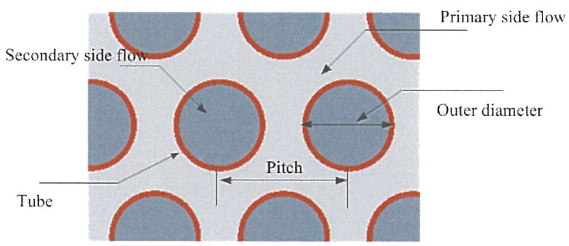
Verification/Validation



Boiling Correlations	Average tube length
Experiment	15.9 m
Constant	16.4 m
Thom	15.8 m
Jens & Lottes	16.8 m
Rhosenow (Csf=0.013)	17.8 m
Rhosenow (Csf=0.015)	17.8 m

◆ The effect of the entrainment on the dry out process is ignored
- the secondary mas flux is relatively small
- the experimental and calculation results agree well ("Thom" boiling correlation equation)

Boundary/Constraint conditions



Steam generator initial parameter

Core/SG Thermal Rating	MW_{th}	200
Tube pitch	mm	25.4
Tube side		
Operating pressure	MPa	6.5
Superheated temperature	°C	300.87
Shell side		
Operating pressure	MPa	15.5
Primary inlet temperature	°C	310.0

Constraint conditions of DOE

Parameter	Range Properties	Resolution
Tube OD	17.0 ~ 20.0 mm	16
Tube wall thickness	1.0 ~ 1.4 mm	21
Tube Number	2000 ~ 6000 ea	81
Tube side		
Mass flow rate	102.684 ~ 125.503 kg/s	38
Shell side		
Mass flowrate	1643.84 ~ 2009.13 kg/s	24

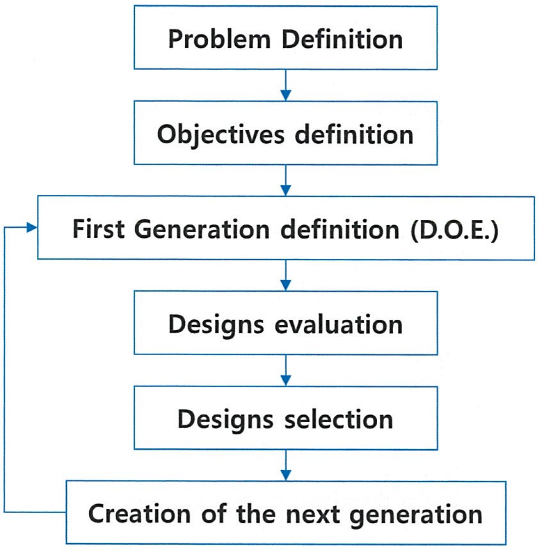
Thermal conductivity (tube)

$$\lambda = 11.396 + 0.0187 \cdot T \ \left(\frac{W}{m \cdot {}^{o}c}\right)$$

Optimization Procedure

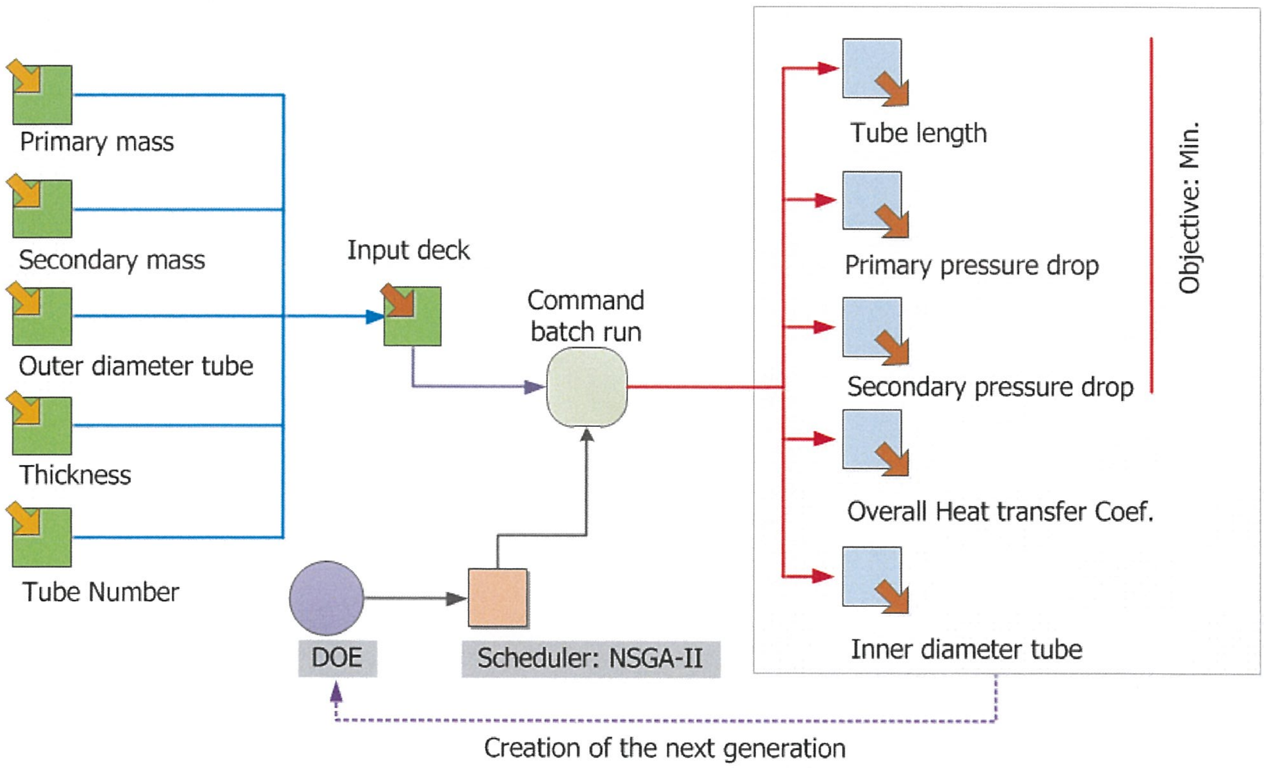
◇ NSGA-II

- Non-dominated Sorting Genetic Algorithm II
  - Developed by prof. K. Deb- KanGAL
  - A fast and clever non-dominated sorting procedure is implemented
  - It implements elitism for multi-objective search, using an elitism-preserving approach

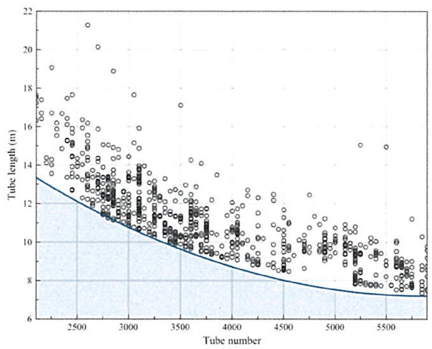


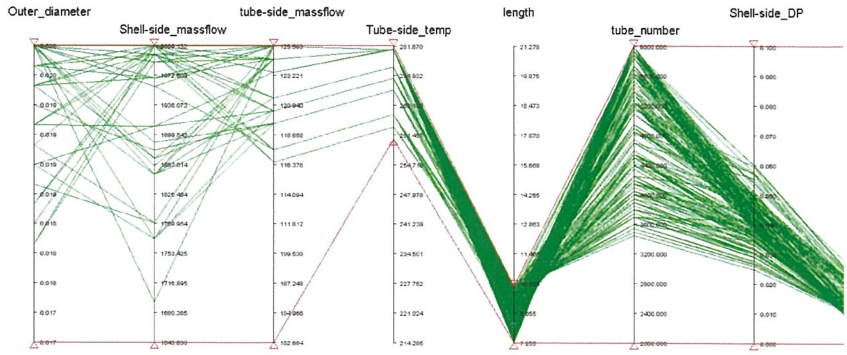
Reference:
[1] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. 2000,
A Fast and Elitist Multi-Objective Genetic Algorithm-NSGA-II, KanGAL Report Number 2000001

Optimization methodology



Results





- If number of tube is 2500ea, the tube length is 12.0m or more. The length of tubes is greater than 8.0m for number of tubes, 4500ea.
- multi-objective optimization are to minimize tube length, pressure drop and tube number. Feedwater flow rate up to 115.425kg/s is selected so as to have margin of feedwater temperature 20°C.
- Assuming that length of tube is less than 10.0m with the constraint of feedwater temperature below 260°C, outer diameter of tube 19.0mm and the number of tube more than 3000ea. The shell-side mass flow has a range from 1789.95kg/s to 2009.132kg/s and the tube-side mass flowrate has a range from 289.38kg/s to 291.91kg/s.

Conclusions

- This research is focused on the design of in-vessel steam generator. An one dimensional analysis code is developed to evaluate previous researches and to optimize steam generator design parameters.
- Goals of multi-objective optimization are to minimize tube length, pressure drop and tube number. Feedwater flow rate up to 115.425kg/s is selected so as to have margin of feedwater temperature 20°C.
- For the design of 200MWth once through steam generator, it is evaluated that the tube length shall be over 12.0m for the number of tubes, 2500ea, and the length of the tube shall be over 8.0m for the number of tubes, 4500ea.
- The parallel coordinates chart can be provided to determine the optimal combination of number of tube, pressure drop, tube diameter and length.