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Tube and shell side coupled thermal analysis of an HTGR helical tube once through steam generator using porous media method

Joshua Tanner Olson [a,b], Xiaowei Li [a,*], Xinxin Wu [a]

[a] *Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, PR China*
[b] *2605 Berniece Drive, Champaign, IL 61822, USA*

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ABSTRACT

To ensure the safety and efficiency of high temperature gas-cooled reactors, it is critical to understand the temperature non-uniformity of their once through steam generators. Large temperature non-uniformity can cause overheating of the tubes and may require a reduction in output. In order to correctly predict the thermal distribution in the tube bundles of the steam generators, the effect of thermal mixing and coupled heat transfer between the primary and secondary sides should be considered. A two-dimensional computer code based on the porous media method, coupling the tube and shell side of the steam generator was developed. This code was used to predict the thermal performance of the once through steam generator under normal operating conditions. The temperature non-uniformities caused by geometric and thermal–hydraulic deviations were also analyzed. It was found that a 1% change in the flow rate for a given tube line resulted in a temperature variation of 5 °C while shifting a tube line by 1 mm caused a temperature variance of 7 °C. It was also found that a plugged tube caused a large increase in temperature for the remaining tubes in the tube line. Finally, the influence of Peclet number on temperature was analyzed.

1. Introduction

The High Temperature Gas-cooled Reactor (HTGR) has characteristics of the 4th generation reactor, which is characterized by its inherent safety (Zhang et al., 2009). The HTGR can help to solve the energy and environmental problems in China. A key component in the HTGR is the once through steam generator. It is responsible for transferring heat from the reactor primary loop to the secondary loop. The steam generator of an HTGR is a helical tube Once Through Steam Generator (OTSG) which is very compact and can reliably withstand high operating temperatures (750 °C). A non-uniform temperature distribution in the OTSG can greatly reduce its reliability and lifecycle. The primary reason for a non-uniform temperature distribution in the OTSG become critical is that the heat capacity of superheat steam is much less than that of water. Transferring a small amount of heat to the steam will cause a large increase in temperature. As a result, the temperature difference between the different layers (or lines) of tubes in the OTSG will become extreme, and some layers will reach very high temperatures. Such extreme temperatures may cause the tube metal to creep, increasing the possibility of rupture.

A one-dimensional (1D) thermal hydraulic model is insufficient to analyze and design an HTGR once through steam generator. One example of this was the Advanced Gas-cooled Reactors (AGRs) built in the UK during the 1960s (Mathews, 1987; Newell, 1987; Fallows et al., 1985; Collier and Whitmarsh-Everiss, 1985). A 1D model was used to design the thermal hydraulic of the once through steam generator of AGRs. When the once through steam generator was put into operation, a large variation was observed in the temperature across the tube bundles. The 1D model was not able to predict this thermal non-uniformity. The cause of the thermal non-uniformity was geometrical or thermal hydraulic differences between different layers of tubes. Thermal hydraulic difference may be caused by either a non-uniform mass flow rate or inlet temperature in the secondary side or non-uniform velocity fields in the tube bundles (primary side). Geometrical differences may be the results of large manufacturing tolerances between different layers of tubes and different rates of thermal expansion between the materials. Two and three-dimensional (2D, 3D) methods should be developed to predict the thermal mixing in tube bundles. Using these methods, the temperature distribution inside the steam generator can be correctly predicted. A direct 2D or 3D simulation of the helium flow and heat transfer over the tube bundle requires immense computer resources, which is not feasible for large-scale applications. The porous media method makes it possible to simulate tube bundle in 2D and 3D using significantly less computer resources.

The porous media method is commonly used to simulate the flow and heat transfer in large volume tube bundles. Pioneer work

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[*] Corresponding author. Tel.: +86 10 62784825; fax: +86 10 62797136.
E-mail address: lixiaowei@tsinghua.edu.cn (X. Li).

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Nomenclature

a	thermal diffusivity (m^2s^{-1})
A_c	cross sectional area (m^2)
A_w	tube wall area (m^2)
C_p	specific heat ($kJ\ kg^{-1}\ C^{-1}$)
C_r	correction factor, dimensionless
d	tube diameter (m)
D	helical diameter (m)
f	friction factor, dimensionless
F	momentum source (Nm^{-3})
g	gravity ($m\ s^{-2}$)
G	mass flux ($kg\ m^{-2}\ s^{-1}$)
h	enthalpy ($kJ\ kg^{-1}$) or heat transfer coefficient ($W\ m^{-2}$ - C^{-1})
K	total heat transfer coefficient ($W\ m^{-2}\ C^{-1}$)
L	tube length (m)
Nu	Nusselt number, dimensionless
p	pressure (Pa)
Pe	Peclet number, Pe = Re Pr , dimensionless
Pr	Prandtl number, dimensionless
q	heat flux ($W\ m^{-2}$)
r	tube radius (m)
R	helical radius (m)
Re	Reynolds number, $Re = \frac{\rho u_{\max} D}{\mu}$, dimensionless
$R_{fouling}$	fouling thermal resistance ($m^2\ C\ W^{-1}$)
R_w	tube wall thermal resistance ($m^2\ C\ W^{-1}$)
S_1	transverse pitch of tube bundle (m)
S_2	longitudinal pitch of tube bundle (m)
T	temperature (°C)
u	velocity (m/s)
V	volume (m^3)
x	steam quality, dimensionless

Greek symbols

Φ	energy source term ($W\ m^{-3}$)
γ	latent heat (kJ/kg)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
θ	inclination angle (°)
ρ	density ($kg\ m^{-3}$)
ξ	resistance factor, dimensionless

Subscripts

helium	helium side
i	inside
o	outside
s	smooth tube
water	water side

Superscripts

$'$	water
$''$	steam

was done to investigate the AGR once through steam generators using the porous media method. Mathews (1987) used the porous media method to simulate the flow and heat transfer uniformity of the AGR steam generator. Their model was rough and the predicted results were not very accurate. Zhang and Bokil (1997) and Zeng et al. (2012) investigated power plant condensers using the porous media method. Zhang and Bokil's numerical results agree well with their experimental measurements. Conventional shell and tube heat exchangers were also simulated using the porous media method (Deng and Tao, 2004). Fallows et al. (1985) developed a code named PODMIX based on the porous media method to investigate the thermal non-uniformity in the tube bundles of the AGR steam generator. Their code was used to predict the temperature distribution in the tube bundles of the AGR steam generators. In order to improve temperature distribution in the tube bundles and raise reactor power, the secondary side flow rate was adjusted based on the predictions made by their code (Newell, 1987). Olson (2012) conducted a detailed investigation using the porous media method of the various factors causing thermal non-uniformity in an HTGR steam generator.

This paper introduces a 2D method for investigating the thermal non-uniformity of the HTGR once through steam generator tube bundle using the porous media method. Several factors causing non-uniformity were analyzed. The first analysis was the secondary side flow rate discrepancy among different layers of tubes. Due to construction and measurement tolerances, the actual flow rates may vary slightly from the design. Thus the influence of a discrepancy in the flow rate needs to be understood. The second analysis looked at the effects of having a tube line shifted, slightly out of place. This may be caused by manufacturing tolerances or thermal expansion. The last analysis looked at the effects of having a plugged tube. When one of the tubes in a steam generator is damaged, it is a common practice to block the damaged tube. The Peclet number was set at 30 for all the three scenarios. The analysis and review of Li and Wu (2013) showed that the thermal mixing Peclet number for a tube bundle should be less than 30.

2. Numerical method

The code used in this paper is based on the preliminary work done by Khan (1988). Khan's work only considers a few tube rows, and the tube side only considers single-phase water flow. The code is similar to the PODMIX code (Gane et al., 1985) used to model the AGRs steam generators in the UK. The shell side was modeled in two-dimension and the tube side in one-dimension. The code was written in FORTRAN 77 and was designed to model a very small system. The discretization and the solving strategy were rewritten in this work. The rows of tubes were extended to 310, and number of layers changed to 5. Phase change heat transfer in the tube side was also added. The grid spacing was also significantly reduced. Some corrections in the solving strategy were also made to the original code (Olson, 2012).

2.1. Governing equations and assumptions

2.1.1. Gas side governing equations

The two-dimensional gas side governing equations are composed of the mass conservation, momentum conservation and energy conservation equations.

Mass conservation:

$$\frac{\partial}{\partial x_j}(\rho u_j) = 0 \tag{1}$$

Momentum conservation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + F_i \tag{2}$$

where F_i is the momentum source term, $F_i = -\xi\frac{0.5\rho u_i^2}{\Delta x_i}$.