International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 6 (2017) pp. 940-944

Feasibility Study of Condensation Heat Exchanger with Helical Tubes for a Passive Auxiliary Feedwater System

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Abstract
The Passive Auxiliary Feedwater System (PAFS) with nearly-horizontal heat exchangers is one of passive safety features of APR+ (Advanced Power Reactor Plus) which provides the auxiliary feedwater by means of natural circulation with condensation. It is feasible to increase the heat transfer capacity of the PAFS by employing a helically coiled heat exchanger due to additional secondary flow effect by centrifugal force. In addition, a compact and flexible design can be achieved in a fixed volume by using the helically coiled heat exchanger, which is one of the most important merits of implementing this heat exchanger. In this paper, the helically coiled heat exchanger has been employed for the PAFS instead of nearly-horizontal heat exchanger. In order to evaluate the heat transfer performance of the helically coiled heat exchanger, an in-tube condensation heat transfer correlation by Wongwises has been introduced into the system analysis code, MARS-KS. A comparative numerical study was conducted for both heat exchangers. The result shows that helically coiled heat exchanger has 20% higher heat transfer efficiency than existing nearly-horizontal heat exchanger.

Keywords: Passive, Helically coiled tube, Heat exchanger, PAFS

INTRODUCTION
The Passive Auxiliary Feedwater System (PAFS) is one of passive safety features of APR+ (Advanced Power Reactor Plus). The PAFS provides the auxiliary feedwater by means of natural circulation with condensation. Since the natural circulation with condensation within the PAFS is the most important mechanism to remove the heat from the SG, the condensation heat transfer characteristics of a heat exchanger with nearly-horizontal tubes is one of the dominant factors to decide the performance of the PAFS. Therefore, both experimental and analytical investigations on the performance of the heat exchanger of the PAFS have been conducted to finalize the prototype design [1-3].

Meanwhile, the heat transfer enhancement can be achieved by increasing heat transfer coefficient and/or by increasing surface area. Various heat exchangers including micro-fin tubes, helically coiled heat exchangers, and so on, have been developed and implemented for industrial applications. Especially, it is known that a helically coiled heat exchanger shows a high efficiency in heat transfer and allows a compact design.

In this paper, a fundamental feasibility study on using the helically coiled heat exchanger for the PAFS has been conducted on the basis of an analysis using the system code, MARS-KS [4]. In order to perform the analysis, an empirical correlation has been implemented into the MARS-KS code and the helically coiled heat exchanger has been compared with the nearly-horizontal heat exchanger in terms of heat transfer performance and design parameters.

DESIGN FEATURE OF APR+ PAFS
The PAFS replaces a conventional active feedwater system and plays a role in the ultimate heat sink for decay heat through natural circulation. Fig. 1 shows a schematic diagram of the PAFS for the APR+ [1]. As shown in Fig. 1, The PAFS consists of a steam supply line, a passive condensation heat exchanger (PCHX), a return-water line, and a passive condensation cooling tank (PCCT).

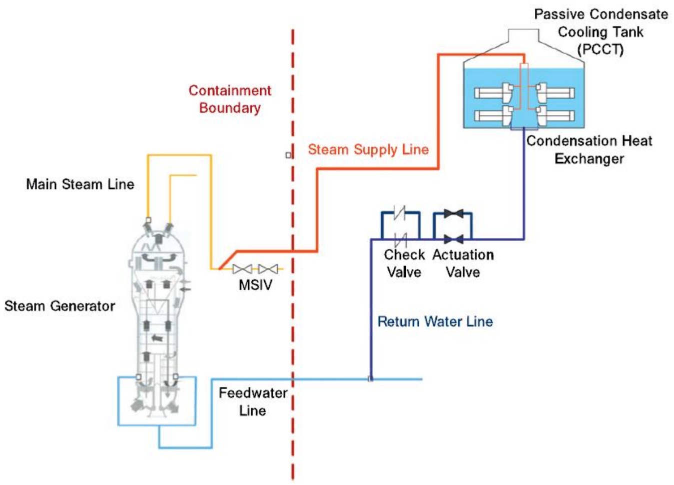

Figure 1. Schematic diagram of the PAFS in the APR+

Table 1 shows the design parameters of the PAFS [2]. The design parameters of the PCHX tube listed in Table 1 are based on single tube. The length of tube is determined as 8.4 m considering heat removal capacity per tube and prevention of water hammering [1]. Especially in order to prevent water hammering PCHX tube has been designed according to the regulatory guide of US NRC [5]. The PCCT has been designed to include enough amount of water for eight-hour operation without external water supply. Since the PCHX is designed with long nearly-horizontal tubes, the shape of the PCCT should be oblong in order to contain rather long horizontal tube.

Table 1. Design parameter of the PAFS

Parameter		Specification
PCHX Tube	Inner/outer diameter	44.8 mm / 50.8 mm
	Length	8.4 m
	Number of tubes	240
	Material	STS 304
	Fluid	Steam
	Operating condition	3.22 MPa / 239.1℃
	Flow rate	0.295 kg/s
PCCT	Pool height	8.9 m
	Pool length	13.4 m
	Pool width	6.7 m

DESIGN STUDY OF THE HELICALLY COILED TUBE HEAT EXCHANGER

Condensation Heat Transfer and Comparison of Correlations :

Since only a few studies have been conducted on the condensation heat transfer inside a helically coiled tube, it was decided to evaluate the characteristics of each correlation suggested by previous studies and to implement the most reasonable one to this feasibility study. The considered correlations and main parameters for each experiment are listed in Table 2 and Table 3. Wongwises and Polsongkram [6] have experimentally investigated two-phase condensation heat transfer and pressure drop of a helically coiled concentric tube-in-tube heat exchanger. The correlation suggested by Wongwises and Polsongkram takes into consider the effect of the geometric parameter d/D of a helically coiled tube. El-Sayed Mosaad et al. [7] carried out an experimental study to investigate condensation heat transfer and pressure drop characteristics of a helically coiled double tube with R-134a.

Table 2. Helically coiled tube condensation model

	Correlation Model
1	Wongwises and Polsongkram [6] $Nu_{tp} = 0.1352 De_{Eq}^{0.7654} Pr_l^{0.8144} \chi_{tt}^{0.0432} P_r^{-0.3356} (Bo \times 10^4)^{0.112}$ $De_{Eq} = \left[Re_l + Re_v \left(\frac{\mu_v}{\mu_l}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.5}\right]\left[\frac{d_i}{D_c}\right]^{0.5}$, $Re_l = \frac{G(1-x)d_i}{\mu_l}$, $Re_v = \frac{Gxd_i}{\mu_l}$, $Pr_l = \frac{C_p \mu_l}{k_l}$, $\chi_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1}$, $P_r = \frac{P_{sat}}{P_{crit}}$, $Bo = \frac{q}{GI_{lv}}$
2	El-Sayed Mosaad et al. [7] $Nu_{tp} = 6.39 (Re^*)^{0.4} Pr_l^{1/3} \left[1 - 0.85\left(\frac{\Delta T_s}{T_s}\right)^{0.9}\right]$, $Re^* = G\left[(1 - x_m) + x_m \sqrt{\frac{\rho_l}{\rho_v}}\right]\frac{d_i}{\mu_l}$

Table 3. Helically coiled tube condensation experiment condition

	Out dia (mm)	In dia (mm)	Pitch (mm)	Coil dia (mm)	Helix angle (°)	d/D	Sat Temp (℃)	Mass flux (kg/s·m^2)	Fluid
Wongwises [6]	9.52 /23.2	8.3 /21.2	35	305	3.3	0.027	40 /50	400 ~ 800	R-134a
El-Sayed [7]	9.54	7.39	25.6	213	3.4	0.034	32	95 ~ 710	R-134a

Fig. 2 depicts the heat transfer coefficient calculated by means of the correlations with respect to Reynolds number. The correlation by Shah [8] is a default condensation heat transfer coefficient in MARS-KS for turbulent film condensation. The figure indicates that the correlation by Wongwises and Polsongkram predicts higher condensation heat transfer coefficient than Shah correlation. Whereas El-Sayed Mosaad correlation underpredicts the condensation heat transfer coefficient than Shah correlation at high Reynolds number region (over 20,000). However, Shao Li [9] experimentally showed that the condensation heat transfer coefficient of the helically coiled tube is higher than straight tube by 4-13.8% and Wongwises and Polsongkram obtained 33-53% higher condensation heat transfer coefficient with helically coiled tube. Considering the results from previous studies and the Reynolds number dependency of the correlations, it is decided that Wongwises and Polsongkram correlation is more reasonable for this feasibility study for helically coiled condensation heat exchanger.

Figure 2. Heat transfer coefficient over Reynolds number

Determination of Design Parameters :

Basically the design parameters of the current horizontal PCHX of the PAFS are employed for the evaluation of the performance of each heat exchanger. The inner and outer diameters of the tube are 44.8 mm and 50.8 mm, respectively. The material of the tube is assumed as stainless steel 304. In order to maintain the similarity of heat transfer and pressure drop in tube, d_i/D and helix angle in the experiment by Wongwises and Polsongkram are employed. The diameter and pitch of the helix in Fig. 3 are calculated by means of the following equations:

$$D = \frac{d_i}{r}. \tag{1}$$

$$P = 2 \times D \times \tan(\alpha). \tag{2}$$

Table 4. Design parameter of helically coiled tube

	Value	**Specification**
Inner dia (d_i)	44.8 mm	PAFS
Outer dia (d_o)	50.8 mm	
d_i/D ratio (r)	0.027	Wongwises and Polsongkram [6]
Helix angle (α)	3.3 º	
Dia. of coil (D)	1,659 mm	(1)
Pitch (P)	157 mm	(2)

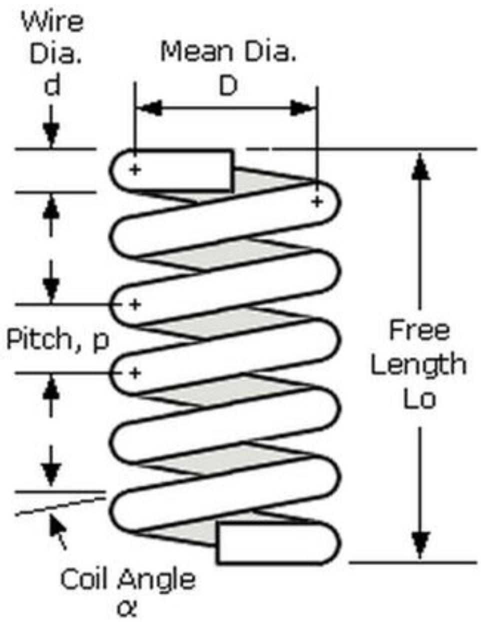

Figure 3. Helically coiled tube design parameter

COMPARISON OF HEAT REMOVAL CAPACITY WITH HORIZONTAL TUBE HEAT EXCHANGER

Development of MARS-KS Model for Analysis

The MARS-KS code which is a best-estimate system analysis code based on two-fluid model, was utilized for the evaluation of the heat removal capacity and the operational performance for horizontal and helical type condensation heat exchanger. In order to model the condensation within a helically coiled tube, Wongwises and Polsongkram correlation has been implemented into the MARS-KS code.

The geometry of the horizontal and helical type heat exchanger was modeled as depicted in Fig. 4 and Fig. 5, respectively. The PCTX was modeled as a single tube and the PCCT was described by two pipe components which allow internal natural circulation within the PCCT.

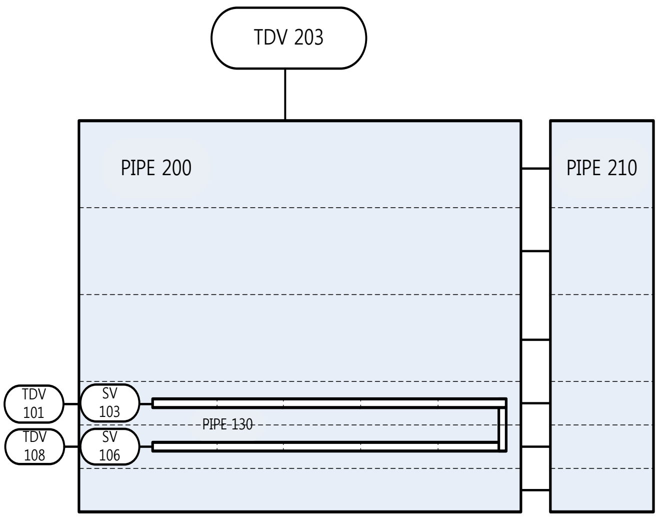

Figure 4. Node diagram of horizontal tube heat exchanger

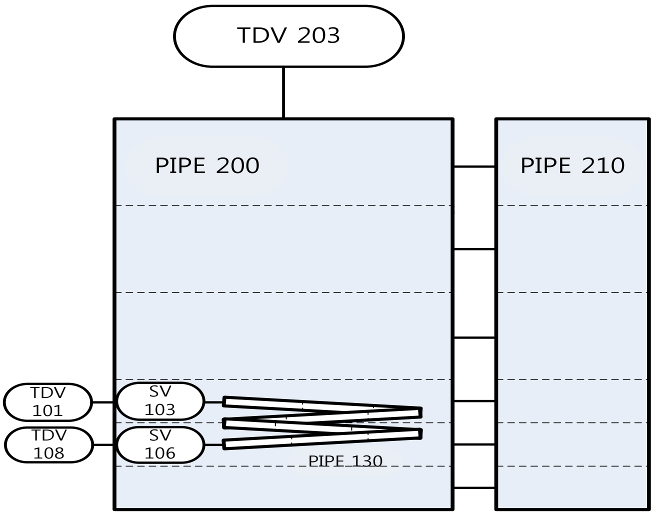

Figure 5. Node diagram of helically coiled tube heat exchanger

ANALYSIS RESULT

Fig. 6 shows the tube internal heat transfer coefficient which represents condensation heat transfer coefficient. Condensation heat transfer decrease as the flow moves toward the end of the tube for both tube types because of the decrease of quality of steam At the inlet of the tube, helically coiled tube shows 3.0% higher heat transfer coefficient comparing horizontal tube. However, as steam flows along the tube, the condensation heat transfer coefficient of helically coiled tube becomes smaller than that of the horizontal tube because more amount of steam is condensed at the inlet part so that steam quality in the helically coiled tube decreases faster than that in the horizontal tube as depicted in Fig. 7.

Fig. 8 shows integrated heat removal rate along with the tube length. As indicated, in order to remove 480 kW, the length of the horizontal tube should be 8.0 m, whereas helically coiled tube requires only 6.3 m to remove same heat. This result reveals that the heat exchanger tube length can be reduced by 20% when a horizontal heat exchanger is replaced by a helically coiled heat exchanger.

Figure 6. Heat transfer coefficient variation

Figure 7. Steam quality variation

Figure 8. Heat removal capacity according to tube length

CONCLUSIONS

In this paper, a feasibility study on a helically coiled heat exchanger for PAFS has been conducted. The heat transfer characteristics of the helically coiled heat exchanger have been evaluated by means of the MARS-KS analysis introducing an in-tube condensation heat transfer model for a helically coiled tube. It was found from the study that the heat transfer capacity is increased by applying a helically coiled heat exchanger so that the heat exchanger with reduced size can be implemented in order to remove the same amount of heat from a system.

Further experimental and analytical investigations are needed to obtain more reliable condensation heat transfer correlation or to develop a dedicated condensation heat transfer correlation for PAFS operating condition. In addition, more studies on the effects of geometric parameters (helix angle and helical circle diameter to tube inner diameter ratio, so on), taking into account of pressure drop effect, of helically coiled tube are required for optimum arrangement design.

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 6 (2017) pp. 940-944
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